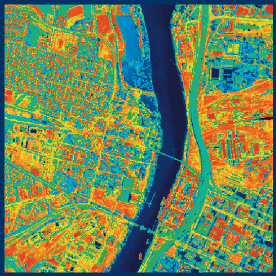
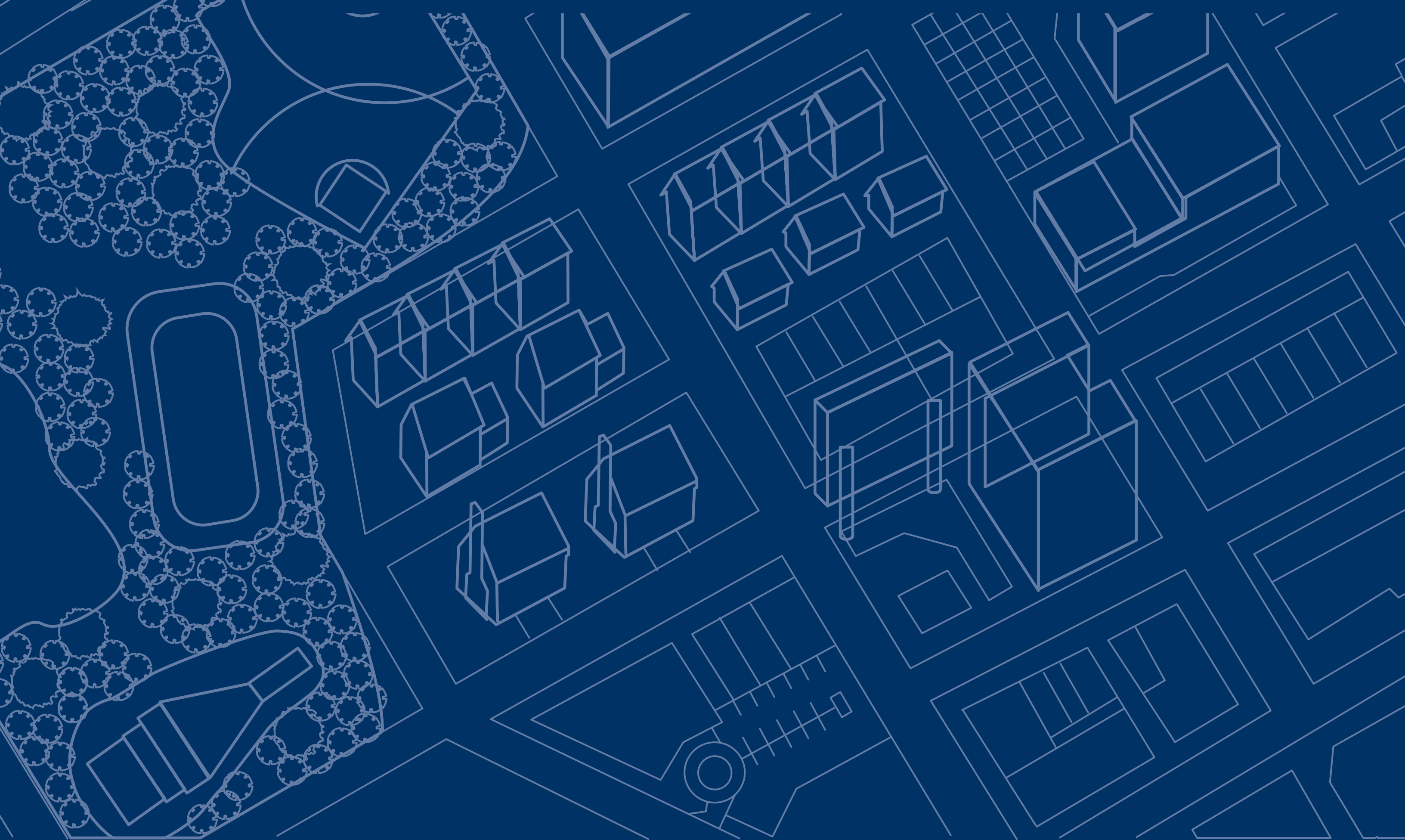




Reducing Urban Heat Islands: Compendium of Strategies

Cool Pavements



Acknowledgements

Reducing Urban Heat Islands: Compendium of Strategies describes the causes and impacts of summertime urban heat islands and promotes strategies for lowering temperatures in U.S. communities. This compendium was developed by the Climate Protection Partnership Division in the U.S. Environmental Protection Agency's Office of Atmospheric Programs. Eva Wong managed its overall development. Kathleen Hogan, Julie Rosenberg, Neelam R. Patel, and Andrea Denny provided editorial support. Numerous EPA staff in offices throughout the Agency contributed content and provided reviews. Subject area experts from other organizations around the United States and Canada also committed their time to provide technical feedback.

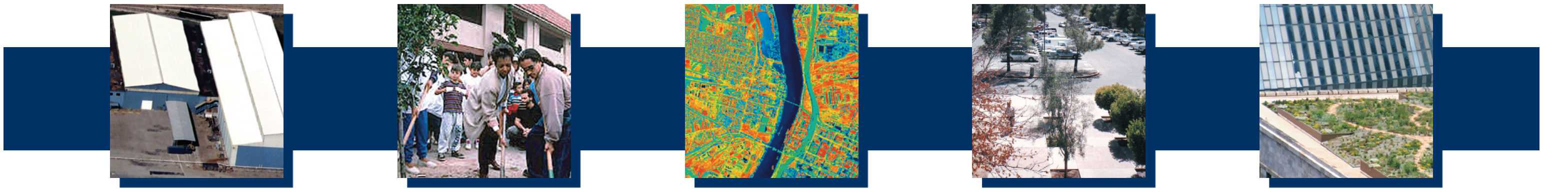
Under contracts 68-W-02-029 and EP-C-06-003, Perrin Quarles Associates, Inc. provided technical and administrative support for the entire compendium, and Eastern Research Group, Inc. provided graphics and production services.

For the Cool Pavements chapter, Cambridge Systematics, Inc. provided support in preparing a June 2005 draft report on cool pavements under contract to EPA as part of EPA's Heat Island Reduction Initiative.

Experts who helped shape this chapter include: Bruce Ferguson, Kim Fisher, Jay Golden, Lisa Hair, Liv Haselbach, David Hitchcock, Kamil Kaloush, Mel Pomerantz, Nam Tran, and Don Waye.

Suggested Citation: U.S. Environmental Protection Agency. 2012. "Cool Pavements." In: *Reducing Urban Heat Islands: Compendium of Strategies. Draft.* https://www.epa.gov/heat-islands/heat-island-compendium.

Contents



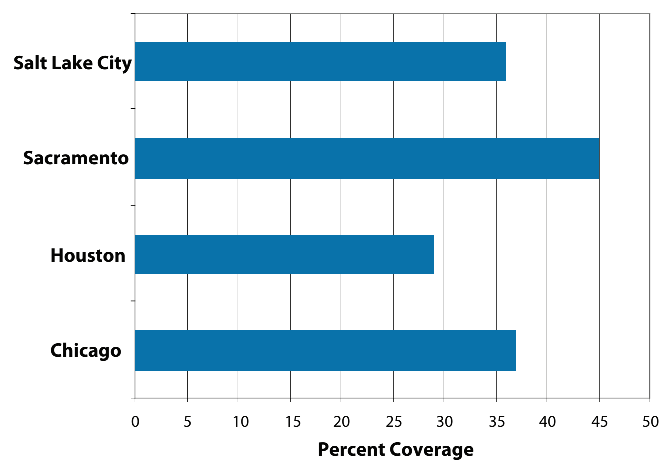
Cool Pavements

Cool pavements refer to a range of established and emerging materials. These pavement technologies tend to store less heat and may have lower surface temperatures compared with conventional products. They can help address the problem of urban heat islands, which result in part from the increased temperatures of paved surfaces in a city or suburb. Communities are exploring these pavements as part of their heat island reduction efforts.

Conventional pavements in the United States are impervious concrete* and asphalt, which can reach peak summertime surface temperatures of 120–150°F (48–67°C).[2] These surfaces can transfer heat downward to be stored in the pavement subsurface, where it is re-released as heat at night. The warmer daytime surface temperatures also can heat stormwater as it runs off the pavement into local waterways. These effects contribute to urban heat islands (especially at nighttime) and impair water quality.

In many U.S. cities, pavements represent the largest percentage of a community's land cover, compared with roof and vegetated surfaces. As part of EPA's Urban Heat Island Pilot Project, Lawrence Berkeley National Laboratory (LBNL) conducted a series of urban fabric analyses that provide baseline data on land use and land use cover, including paved surfaces for the pilot program cities.[1] Figure 1 shows the percent of paved surfaces in four of these urban areas, as viewed from below the tree canopy. The data are from 1998 through 2002, depending on the city. Paved areas, which can absorb and store much of the sun's energy contributing to the urban heat island effect, accounted for nearly 30 to 45 percent of land cover.

Figure 1: Paved Surface Statistics for Four U.S. Cities



* When new, concrete has a high solar reflectance and generally is considered a cool pavement; however, it loses reflectance over time, as discussed in Section 1.2.

Figure 2: Conventional Pavement Temperatures

National Center of Excellence on SMART Innovations at Arizona State University

This picture of Phoenix, Arizona, in the summer shows a variety of conventional pavements that reached temperatures up to 150°F (67°C).

Defining Cool Pavements

Unlike a "cool" roof, a "cool" pavement has no standard, official definition. Until recently, the term has mainly referred to reflective pavements that help lower surface temperatures and reduce the amount of heat absorbed into the pavement. With the growing interest and application of permeable pavements—which allow air, water, and water vapor into the voids of a pavement, keeping the material cool when moist—some practitioners have expanded the definition of cool pavements to include permeable pavements as well. Ongoing permeable pavement research is important because these systems, compared with conventional pavement systems, react differently and lead to different environmental impacts. Further, as we understand better how pavements affect urban climates and develop newer, more environmental technologies, additional technologies that use a variety of techniques to remain cooler are likely to emerge.

As concerns about elevated summertime temperatures rise, researchers and policymakers are directing more attention to the impact pavements have on local and global climates. This chapter discusses:

- Pavement properties and how they can be modified to reduce urban heat islands
- Conditions that affect pavement properties
- Potential cool pavement technologies
- Cool pavement benefits and costs
- Cool pavement initiatives and research efforts
- Resources for further information.

Given that cool pavements are an evolving technology and much is still unknown about them, this compendium presents basic information to give readers a general understanding of cool pavement issues to consider; it is not intended to provide decision guidance to communities. Decision-makers can work with local experts to obtain location-specific information to

Why Have Communities Promoted Cool Roofs More Than Cool Pavements?

A few decades ago when the concept of using cool roofs and pavements emerged, researchers focused on radiative properties—surface solar reflectance and thermal emittance—associated with these technologies. Scientists, engineers, and others worked together through the standards-development organization ASTM International to create test standards for these properties that could apply to both roofs and pavements. (See Section 4.1.) While researchers, industry, and supporters of energy efficiency have helped advance cool roofing into the market, cool pavement has lagged behind. Three factors, which differentiate pavements from roofs, may contribute to this difference:

1. Pavements are complex. Conditions that affect pavement temperatures, but not roofing materials, include: (a) dirtying and wearing away of a surface due to daily foot and vehicle traffic, affecting pavement surface properties; (b) convection due to traffic movement over the pavement; and (c) shading caused by people and cars, vegetation, and neighboring structures and buildings. These factors are discussed in Sections 1.2 and 2.
2. Pavement temperatures are affected by radiative and thermal characteristics, unlike cool roofs, where radiative properties are the main concern. This is discussed in Section 1.3.
3. Pavements serve a variety of functions throughout an urban area. Their uses range from walking trails to heavily trafficked highways (unlike cool roofs, which generally perform the same function and are off-the-shelf products). Different materials and specifications are needed for these different uses, and pavements are often individually specified, making it difficult to define or label a cool pavement.

further guide them in the pavement selection process. EPA expects that significant ongoing research efforts will expand the opportunities for updating existing technologies and implementing new approaches to cool pavements. At the end of Sections 4 and 5 in this document, organizations and resources with the most recent information are listed. Communities will also continue to implement new demonstration projects and cool pavement initiatives. EPA intends to provide updated information as it becomes available. Please visit <www.epa.gov/heatisland/index.htm>.

1. How It Works

Understanding how cool pavements work requires knowing how solar energy heats pavements and how pavement influences the air above it. Properties such as solar energy, solar reflectance, material heat capacities, surface roughness, heat transfer rates, thermal emittance, and permeability affect pavement temperatures.

Reducing or Shading Pavements

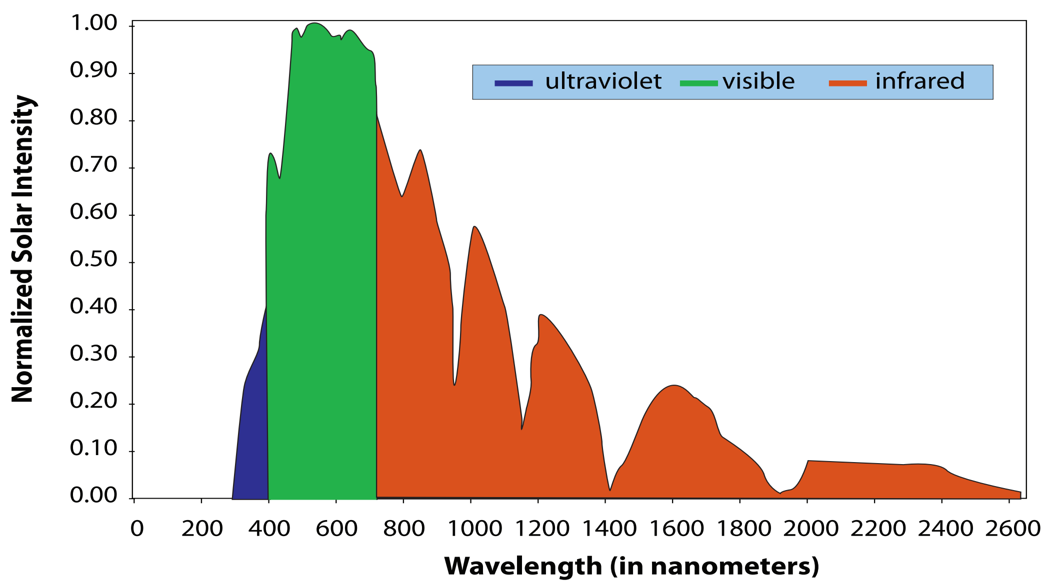
Some efforts have emerged that focus on reducing the need to pave, particularly over vegetated areas that provide many benefits, including lowering surface and air temperatures. Communities have used various options to reduce the amount of paved surface areas, such as lowering parking space requirements, connecting parking and mass transit services, allowing for narrower street widths, or providing incentives for multi-level parking versus surface lots.[3]

Concerned communities that move forward with paving often shade it with vegetation. The "Trees and Vegetation" chapter discusses the use of measures such as parking lot shading ordinances as part of a heat island mitigation strategy.

Another option some local governments and private firms are considering involves installing canopies that incorporate solar panels in parking lots. These photovoltaic canopies shade surfaces from incoming solar energy and generate electricity that can help power nearby buildings or provide energy for plug-in electric vehicles.[4]

For more information on urban planning and design approaches to minimize paved surfaces, see <www.epa.gov/smartgrowth>, and for information on vegetated surfaces, see the "Trees and Vegetation" chapter of this compendium.

Figure 3: Solar Energy versus Wavelength Reaching Earth's Surface on a Typical Clear Summer Day



Solar energy intensity varies over wavelengths from about 250 to 2,500 nanometers. Figure 3 demonstrates this variation, using a normalized measure of solar intensity on a scale of zero (minimum) to one (maximum). Currently, reflective pavements are light colored and primarily reflect visible wavelengths. However, similar to trends in the roofing market, researchers are exploring pavement products that appear dark but reflect energy in the near-infrared spectrum. [5] (See the "Cool Roofs" chapter of the compendium for more information.)

1.1 Solar Energy

Solar energy is composed of ultraviolet (UV) rays, visible light, and infrared energy, each reaching the Earth in different percentages: 5 percent of solar energy is in the UV spectrum, including the type of rays responsible for sunburn; 43 percent of solar energy is visible light, in colors ranging from violet to red; and the remaining 52 percent of solar energy is infrared, felt as heat. Energy in all of these wavelengths contributes to urban heat island formation. Figure 3 shows the typical solar energy that reaches the Earth's surface on a clear summer day.

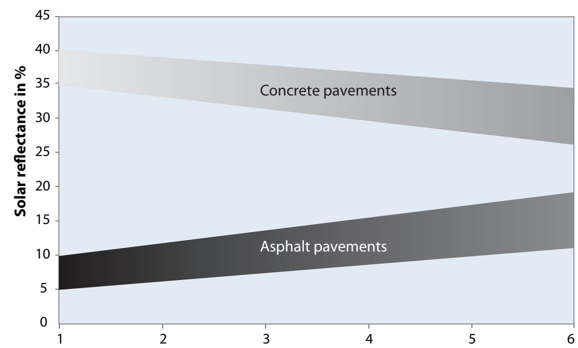
1.2 Solar Reflectance (Albedo)

Solar reflectance, or albedo, is the percentage of solar energy reflected by a surface. Most research on cool pavements has focused on this property, and it is the main determinant of a material's maximum surface temperature.[6] Albedo also affects pavement temperatures below the surface, because less heat is available at the surface to then be transferred into the pavement. Researchers, engineers, and industry have collaborated to develop methods to determine solar reflectance by measuring how well a material reflects energy at each wavelength, then calculating the weighted average of these values.* (See Table 1 on page 7.)

Conventional paving materials such as asphalt and concrete have solar reflectances of 5 to 40 percent, which means they absorb 95 to 60 percent of the energy reaching them instead of reflecting it into the atmosphere. (See Figure 4.) However, as Figure 4 also shows, these values depend on age and material, and thus usually change over time. Figure 5 shows how changing only albedo can significantly alter surface temperatures. Although researchers, including those at LBNL, have made light-colored pavements with solar reflectances greater than 75 percent,[8] these high albedo pavements do not have widespread commercial availability.

> Most existing research on cool pavements focuses on solar reflectance, which is the primary determinant of a material's maximum surface temperature. Many opportunities exist to improve this property in pavements. (See Table 2, beginning on page 15.)

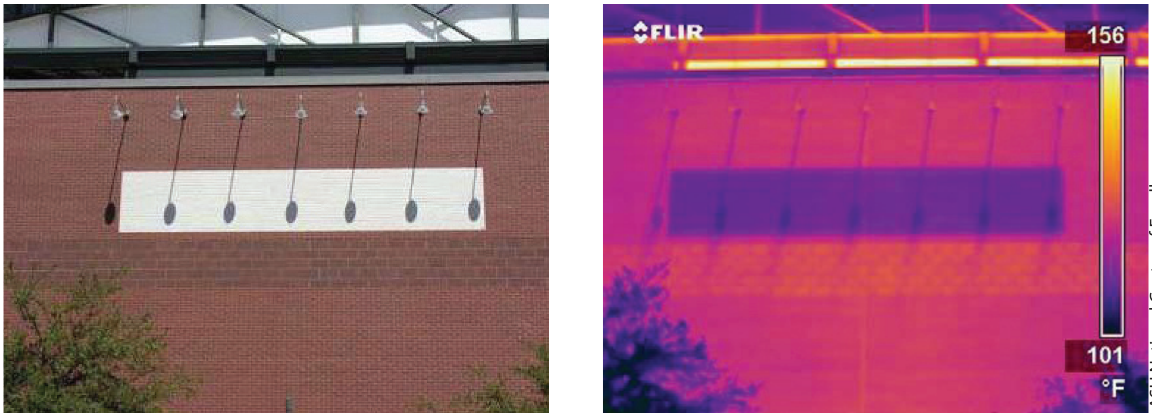
Figure 4: Typical Solar Reflectance of Conventional Asphalt and Concrete Pavements over Time



Due to weathering and the accumulation of dirt, the solar reflectances of conventional asphalt and concrete tend to change over time. Asphalt consists largely of petroleum derivatives as a binder mixed with sand or stone aggregate. Asphalt tends to lighten as the binder oxidizes and more aggregate is exposed through wear. Concrete also uses sand and stone aggregate, but in contrast to asphalt, typically uses Portland cement as a binder. [7] Foot and vehicle traffic generally dirty the cement causing it to darken over time.

* Albedo is typically measured on a scale of zero to one. For this compendium, albedo is given as a percentage, so an albedo of 0.05 corresponds to a solar reflectance of 5 percent. The "solar reflectance index" is a value on a scale of zero to 100 that incorporates both solar reflectance and thermal emittance in a single measure to represent a material's temperature in the sun. (See Table 1 on page 7 or further explanation.)

Figure 5: The Effect of Albedo on Surface Temperature



ASU National Center of Excellence

Albedo alone can significantly influence surface temperature, with the white stripe on the brick wall about 5–10°F (3–5°C) cooler than the surrounding, darker areas.

1.3 Thermal Emittance

A material's thermal emittance determines how much heat it will radiate per unit area at a given temperature, that is, how readily a surface sheds heat. Any surface exposed to radiant energy will heat up until it reaches thermal equilibrium (i.e., gives off as much heat as it receives). When exposed to sunlight, a surface with high emittance will reach thermal equilibrium at a lower temperature than a surface with low emittance, because the high-emittance surface gives off its heat more readily. As noted in Table 1 on page 7, ASTM methods can be used to measure this property.

Thermal emittance plays a role in determining a material's contribution to urban heat islands. Research from 2007 suggests albedo and emittance have the greatest influence on determining how a conventional pavement cools down or heats up, with albedo having a large impact on maximum surface temperatures, and emittance affecting minimum temperatures.[9] Although thermal emittance is an important property, there are only limited options to adopt cool pavement practices that modify it because most pavement materials inherently have high emittance values.[10]

Standards for Measuring Solar Reflectance and Thermal Emittance

To evaluate how "cool" a specific product is, ASTM International has validated laboratory and field tests and calculations to measure solar reflectance, thermal emittance, and the solar reflectance index, which was developed to try to capture the effects of both reflectance and emittance in one number. (See Table 1 below.) Laboratory measurements are typically used to examine the properties of new material samples, while field measurements evaluate how well a material has withstood the test of time, weather, and dirt.

The final method listed in Table 1 is not an actual test but a way to calculate the "solar reflectance index" or SRI. The SRI is a value that incorporates both solar reflectance and thermal emittance in a single value to represent a material's temperature in the sun. This index measures how hot a surface would get compared to a standard black and a standard white surface. In physical terms, this scenario is like laying a pavement material next to a black surface and a white surface and measuring the temperatures of all three surfaces in the sun. The SRI is a value between zero (as hot as a black surface) and 100 (as cool as a white surface).

Table 1: Solar Reflectance and Emittance Test Methods

Property	Test Method	Equipment Used	Test Location
Solar reflectance	ASTM E 903 - Standard Test Method for Solar Absorbance, Reflectance, and Transmittance of Materials Using Integrating Spheres.	Integrating sphere spectro-photometer	Laboratory
Solar reflectance	ASTM C 1549 - Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer	Portable solar reflectometer	Laboratory or field
Solar reflectance	ASTM E 1918 - Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field	Pyranometer	Field
Total emittance	ASTM E408-71 - Standard Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques	Portable, inspection-meter instruments	Laboratory or field
Solar reflectance index	ASTM E 1980 - Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces	None (calculation)	—

Pavement Surface and Subsurface Temperatures

This chapter mainly focuses on pavement surface temperatures, as most of the cited studies focus on the surface layer. For conventional pavements, most of the impacts at the surface tend to affect the subsurface similarly. For example, conventional pavements with high solar reflectance generally reduce surface and subsurface temperatures, as less heat is available at the surface to absorb into the pavement. However, permeable surfaces react differently. When dry, permeable pavement surface temperatures may be higher than their impermeable equivalent; but preliminary research shows that the subsurface generally is similar to or even cooler than the conventional equivalent, because the permeable layer reduces heat transfer below.[11] More information on subsurface heat transfer is needed to understand the potential heat island impacts because the heat stored in the subsurface may significantly affect nighttime temperature. Still, many complex interactions take place between the surface and subsurface layers. These interactions are either briefly covered in Section 1.5 or beyond the scope of this chapter.

1.4 Permeability

Although originally designed for stormwater control, permeable pavements are emerging as a potential cool pavement. These pavements allow air, water, and water vapor into the voids of the pavement. Permeable pavement technologies include porous asphalt applications, pervious concrete applications, permeable pavers, and grid pavements. To achieve both permeability objectives and structural needs for expected traffic load, these permeable pavements benefit from proper design and installation.[12]

When wet, these pavements can lower temperatures through evaporative cooling. The water passes through the voids and into the soil or supporting materials below. (See Figure 6.) Moisture within the pavement structure evaporates as the surface heats, thus drawing heat out of the pavement, similar to evaporative cooling from vegetated land cover. Some permeable pavement systems contain grass or low-lying vegetation, which can stay particularly cool because the surface temperature of well-hydrated vegetation typically is lower than the ambient air temperature.

Figure 6: Permeable versus Conventional Asphalt

U.S. Department of Agriculture

Permeable asphalt (foreground) allows water to drain from the surface and into the voids in the pavement, unlike conventional asphalt (mid- and background).

When dry, the extent to which permeable pavements can influence temperatures is more complex and uncertain. For example, the larger air voids in permeable pavements increase the available surface area. These conditions may limit heat transfer to the lower pavement structure and soils, keeping heat at the pavement's surface (and increasing daytime surface temperatures), but reducing bulk heat storage (reducing release of heat at nighttime).[13] The larger surface area also may help increase air movement—convection—over the pavement, transferring heat from the pavement to the air. Overall, the limited transfer of heat to the pavement subsurface layers would reduce the release of heat during the nighttime. Release of stored heat from urban materials is a significant contributor to the nighttime heat island experienced in many cities.

More research is needed to better understand the impacts of permeable pavement on air temperatures and urban heat island conditions. Given the complexity of these cooling mechanisms, and the wide range of conditions under which these pavements function, further field testing and validation would help to quantify and clarify the range of impacts and benefits of permeable pavements on urban climates.

Water Retentive Pavements and Water Sprinkling in Japan

Some cities in Japan, such as Tokyo and Osaka, are testing the effectiveness of water retentive pavements as part of using permeable pavements to reduce the heat island effect. These porous pavements can be asphalt or concrete-based and have a sublayer that consists of water retentive materials that absorb moisture and then evaporate it through capillary action when the pavement heats up. Some of these systems involve underground water piping to ensure the pavement stays moist. Researchers have also tested water sprinkling, where pavements are sprayed with water during the day. Some cities have used treated wastewater. Results to date are promising, as both water retentive pavements and water sprinkling have been effective in keeping pavement temperatures low.[14]

1.5 Other Factors to Consider

Pavement temperatures depend on a series of factors. Reflective pavements increase the albedo of the surface to limit heat gain, whereas permeable pavements permit evaporative cooling when the pavement is moist, helping to keep it cool. As shown in Table 2 (beginning on page 15), however, actual conditions alter pavement properties, resulting in pavements that may not be "cool" under all circumstances. This chapter presents these issues for communities to consider when making pavement choices.

Besides solar reflectance, emittance, and permeability, other properties and factors influence how readily pavements absorb or lose heat.

- **Convection.** Pavement transfers heat to the air through convection as air moves over the warm pavement. The rate of convection depends on the velocity and temperature of the air passing over the surface, pavement roughness, and the total surface area of the pavement exposed to air. Some permeable pavements have rougher surfaces than conventional pavements, which increases their effective surface area and creates air turbulence over the pavement. While this roughness can increase convection and cooling, it may also reduce a surface's net solar reflectance.

- **Thermal Conductivity.** Pavement with low thermal conductivity may heat up at the surface but will not transfer that heat throughout the other pavement layers as quickly as pavement with higher conductivity.
- **Heat Capacity.** Many artificial materials, such as pavement, can store more heat than natural materials, such as dry soil and sand. As a result, built-up areas typically capture more of the sun's energy—sometimes retaining twice as much as their rural surroundings during daytime.[15] The higher heat capacity of conventional urban materials contributes to heat islands at night, when materials in urban areas release the stored heat.
- **Thickness.** The thickness of a pavement also influences how much heat it will store, with thicker pavements storing more heat.[16]
- **Urban Geometry.** The dimensions and spacing of buildings within a city, or urban geometry, can influence how much heat pavements and other infrastructure absorb. For example, tall buildings along narrow streets create an "urban canyon." (See Figure 7.) This canyon effect can limit heat gain to the pavement during the day, when the buildings provide shade. But these same buildings may also absorb and trap the heat that is reflected and emitted by the pavement, which prevents the heat from escaping the city and exacerbates the heat island effect, especially at night. The overall impact of the urban canyon effect will depend on how a specific city is laid out, the latitude, the time of year, and other factors.

More research is needed to determine the exact impacts these properties have on pavement temperatures and the urban heat island effect.

1.6 Temperature Effects

Solar reflectance and thermal emittance have noticeable effects on surface temperatures, as discussed in Sections 1.2 and 1.3. Depending on moisture availability, permeable pavements also can lower pavement temperatures. Other properties, as noted in Section 1.5, also influence pavement surface and subsurface temperatures through a variety of complex interactions. In general, lower surface temperatures will result in lower near-surface air temperatures, with the effect decreasing as one moves farther away from the surface due to air mixing. Location-specific conditions, such as wind speed and cloud cover, can greatly influence surface and air temperatures.

Currently, few studies have measured the role pavements play in creating urban heat islands, or the impact cooler pavements can have on reducing the heat island effect. Researchers at LBNL, however, have estimated that every 10 percent increase in solar reflectance could decrease surface temperatures by 7°F (4°C). Further, they predicted that if pavement reflectance throughout a city were increased from 10 percent to 35 percent, the air temperature could potentially be reduced by 1°F (0.6°C).[17] Earlier research analyzed a combination of mitigation measures in the Los Angeles area, including pavement and roofing solar reflectance changes, and increased use of trees and vegetation. The study identified a 1.5°F (0.8°C) temperature improvement from the albedo changes.[18] A subsequent report analyzed the monetary benefits associated with these temperature improvements, and estimated the indirect benefits (energy savings and smog reductions) of the temperature reduction in Los

Figure 7: Urban Canyons

Mark Meier

The row of three- and four-story townhouses on the left creates a relatively modest urban canyon, while the skyscrapers on the right have a more pronounced effect.

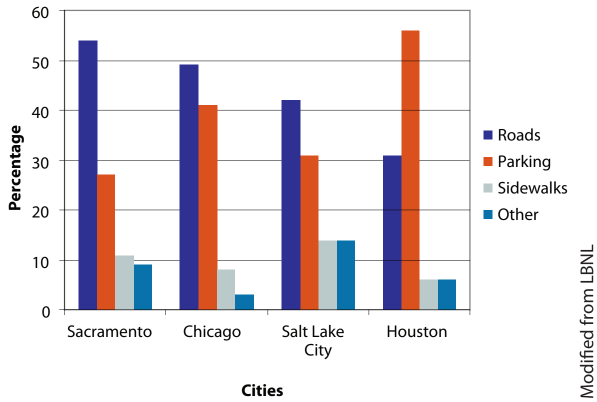
Angeles from pavement albedo improvements would be more than $90 million per year (in 1998 dollars).[19]

2. Potential Cool Pavement Types

Current cool pavements are those that have increased solar reflectance or that use a permeable material. Some of these pavements have long been established—such as conventional concrete, which initially has a high solar reflectance. Others are emerging—such as microsurfacing, which is a thin sealing layer used for maintenance.[20] Some pavement applications are for new construction, while others are used for maintenance or rehabilitation. Not all applications will be equally suited to all uses. Some are best for light traffic areas, for example. Further, depending on local conditions—such as available materials, labor costs, and experience with different applications—certain pavements may not be cost effective or feasible.

Generally, decision-makers choose paving materials based on the function they serve. Figure 8 shows the proportions of pavement used for different purposes in four cities. Parking lots typically make up a large portion of the paved surfaces in urban areas. All current cool pavement technologies can be applied to parking lots, which may explain why many research projects have been and are being conducted on them.

Figure 8: Percentage of Pavement Area by Type of Use[21]



LBNL conducted a paved surface analysis in four cities, dividing the uses into four general categories. Roads and parking lots make up the majority of paved areas.

Below are brief descriptions of potential cool pavements and their typical uses:

- **Conventional asphalt pavements,** which consist of an asphalt binder mixed with aggregate, can be modified with high albedo materials or treated after installation to raise reflectance. This material has been applied for decades in a wide range of functions from parking lots to highways.
- **Conventional concrete pavements,** made by mixing Portland cement, water, and aggregate, can be used in a wide range of applications including trails, roads, and parking lots.
- **Other reflective pavements,** made from a variety of materials, are mostly used for low-traffic areas, such as sidewalks, trails, and parking lots. Examples include:
  - **Resin based pavements,** which use clear tree resins in place of petroleum-based elements to bind an aggregate
  - **Colored asphalt and colored concrete,** with added pigments or seals to increase reflectance
- **Nonvegetated permeable pavements** contain voids and are designed to allow water to drain through the surface into the sublayers and ground below. These materials can have the same structural integrity as conventional pavements. For example, some forms of porous pavements, such as open-graded friction course (OGFC) asphalt pavements, have been in use for decades to improve roadway friction in wet weather.[22] Recently, rubberized asphalt has been used on roads and highways to reduce noise, and pervious concrete applications are being studied for roadway use. For some permeable pavement options, the typical use may be for lower traffic areas such as parking lots, alleys, or trails. Examples of nonvegetated permeable pavements include:
  - **Porous asphalt**
  - **Rubberized asphalt,** made by mixing shredded rubber into asphalt
  - **Pervious concrete**
  - **Brick or block pavers,** are generally made from clay or concrete, and filled with rocks, gravel, or soil; also available in a variety of colors and finishes designed to increase reflectance
- **Vegetated permeable pavements,** such as grass pavers and concrete grid pavers, use plastic, metal, or concrete lattices for support and allow grass or other vegetation to grow in the interstices. Although the structural integrity can support vehicle weights comparable to conventional pavements, these materials are most often used in areas where lower traffic volumes would minimize damage to the vegetation, such as alleys, parking lots, and trails, and they may be best suited to climates with adequate summer moisture.

- **Chip seals** consist of aggregate bound in liquid asphalt, and are often used to resurface low-volume asphalt roads and sometimes highways.
- **Whitetopping** is a layer of concrete greater than 4 inches (10 cm) thick, often containing fibers for added strength. Typical applications include resurfacing road segments, intersections, and parking lots.
- **Ultra-thin whitetopping** is similar to whitetopping and can be used in the same applications, but is only 2–4 inches (5–10 cm) thick.
- **Microsurfacing** is a thin sealing layer used for road maintenance. Light-colored materials can be used to increase the solar reflectance of asphalt. Researchers recently applied light-colored microsurfacing material that consisted of cement, sand, other fillers, and a liquid blend of emulsified polymer resin, and found the solar reflectance to be comparable to that of new concrete.[23]

Table 2, beginning on page 15, provides summary information for decision-makers to consider. It is meant as a preliminary guide, as more research and location-specific data are needed. Table 2 includes the following:

- A brief description of the technology
- The properties associated with it
- The potential impacts on pavement and air temperatures
- Issues to consider
- Target functions.

Regarding impacts, the "+" sign indicates a positive effect; for example, a technology generally results in lower pavement temperatures. A "-" signals a negative effect; for example, a technology may lead to higher air temperatures in certain conditions.

Slag and Fly Ash Cement

Slag and fly ash are sometimes added to concrete to improve its performance. Slag is a byproduct of processing iron ore that can be ground to produce cement, and fly ash is a byproduct of coal combustion.[24] These materials can make concrete stronger, more resistant to aggressive chemicals, and simpler to place. These cements also reduce material costs and avoid sending wastes to landfills. A key heat island benefit of slag is its lighter color, which can increase the reflectivity of the finished pavement. A 2007 study measured a solar reflectance of almost 60 percent for cement with slag, versus about 35 percent for a conventional concrete mix.[25] In contrast, fly ash tended to darken concrete unless counterbalanced, such as by added slag. However, substituting fly ash for a portion of the Portland cement reduces greenhouse gases and other emissions associated with producing Portland cement. Because of such benefits, California's Department of Transportation typically requires use of 25 percent fly ash in cement mixtures.[26]

Effects described in the table do not consider magnitude, which may be influenced by local conditions. Therefore, this information is not intended for comparison. The cool pavement technologies in Table 2 can have positive and negative impacts, depending on actual conditions such as moisture availability and urban design. The points listed under "issues and considerations" further illustrate the complexity associated with cool pavements. These bullets only discuss concerns related to urban heat islands and do not include other local factors or priorities that decision-makers generally consider when making pavement choices.

Despite its limitations, Table 2 can be used as a starting point. For example, using Table 2, a city that generally uses asphalt paving can identify alternative cool asphalt technologies for functions from bike trails to roads. They can also discern that high albedo pavements may be most effective in open areas, not surrounded by tall buildings. Most communities will further investigate the benefits and costs of the technology, as discussed in Section 3, and location-specific factors, such as political acceptance and experience with the technology.

Filling in the Gaps

As more researchers and communities install cool pavement technologies, more data will be generated and shared in forums such as the Transportation Research Board Subcommittee on Paving Materials and the Urban Climate. (See Section 4 of this chapter.)

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications

NEW CONSTRUCTION						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options						
Asphalt pavement, modified with high albedo materials or treated after installation to raise albedo.	Asphalt pavements consist of an asphalt binder mixed with sand or stone, referred to as aggregate.	• Solar reflectance, which initially may be 5%, can increase to 15–20% as conventional asphalt ages.[27] • Using light-colored aggregate, color pigments, or sealants, the reflectance of conventional asphalt can be increased. • Maintenance applications such as chip seals also can increase solar reflectance. (See below.) • Urban geometry can influence the effect of high albedo pavements.	+ Lowers pavement temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved.[28] – Reflected heat can be absorbed by the sides of surrounding buildings warming the interior of the building and contributing to the nighttime urban heat island effect, due to the additional heat that needs to be released from urban infrastructure.	• Solar reflectance increases over time, and conventional asphalt may reach a reflectance of 20% after seven years.[29] (See Section 1.2.) • Urban geometry, in particular urban canyons, influences the impact reflective pavements have on the urban climate.	• Can be used in all applications, such as trails and roads. • May be most effective when paving large, exposed areas such as parking lots.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

NEW CONSTRUCTION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options (continued)						
Concrete: • Conventional • Modified	Portland cement mixed with water and aggregate. Cured until it is strong enough to carry traffic.	• Initial solar reflectance can be 40%. • This can be raised to more than 70% using white cement instead of gray cement mixtures.[30] • Urban geometry can influence the effect of high-albedo pavements.	+ Lowers pavement temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – Reflected heat can be absorbed by the sides of surrounding buildings warming the interior of the building and contributing to the nighttime urban heat island effect, due to the additional heat that needs to be released from urban infrastructure.	• Solar reflectance decreases over time, as soiling from traffic darkens the surface. • Conventional concrete may reach a reflectance of 25% after 5 years.[31] (See Section 1.2.) • Urban geometry, in particular urban canyons, influences the impact reflective pavements have on the urban climate.	• Can be used in all applications, such as trails and roads. • May be most effective when paving large, exposed areas, such as parking lots.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

NEW CONSTRUCTION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options (continued)						
Other reflective pavements: • Resin based • Colored asphalt • Colored concrete	• Resin based pavements use clear colored tree resins in place of cement to bind the aggregate, thus albedo is mainly determined by aggregate color. • Colored asphalt or concrete involve pigments or seals that are colored and may be more reflective than the conventional equivalent. These can be applied when new or during maintenance.	• These alternative pavements will have varying solar reflectances based on the materials used to construct them. • Urban geometry can influence the effect high-albedo pavements have.	+ Lowers pavement temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – Reflected heat can be absorbed by the sides of surrounding buildings warming the interior of the building and contributing to the nighttime urban heat island effect, due to the additional heat that needs to be released from urban infrastructure.	• As with concrete, solar reflectance may decrease over time as soiling from traffic makes the pavement darker and the surface wears away. • Urban geometry, particularly urban canyons, influences the impact high-albedo pavements have on the urban climate.	• Use depends on the pavement application. In general, these alternative pavements are used for low-traffic areas, such as sidewalks, trails, and parking lots. • May be most effective when paving large, exposed areas, such as parking lots.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

NEW CONSTRUCTION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Permeable Pavement Options						
Nonvegetated permeable pavements	• Porous asphalt has more voids than conventional asphalt to allow water to drain through the surface into the base. • Rubberized asphalt, or crumb rubber, involves mixing shredded rubber into asphalt. This material is generally used to reduce noise. • Other porous asphalts or open-grade course friction surfaces can also be used for reducing noise. [32]	• Provides cooling through evaporation. • Solar reflectance of these materials depends on individual materials (e.g., gravel may be white and very reflective). In general, permeable pavements may be less reflective than their nonpermeable equivalent due to the increased surface area.[33] • Increased convection may help cool the pavement due to increased surface area. [34]	+ When wet, lowers pavement temperature through evaporative cooling. – When dry, may be hot at the surface, but subsurface generally will be same temperature as nonpermeable equivalent.	+ When moist, can contribute to lower air temperatures day and night, through evaporative cooling, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – When dry, can contribute to higher daytime surface temperatures, but may not affect or may even reduce nighttime air temperatures, although air temperatures are not directly related to surface temperatures and many complicating factors are involved.	• Cooling mechanism depends on available moisture. Supplemental watering may keep them cooler.[35] • Void structure may aid in insulating the subsurface from heat absorption. • More research needed to determine permeable pavement impacts on pavement and air temperatures.	• Structurally, available for any use. Rubberized asphalt and open-graded friction course asphalt are used on roads and highways and pervious concrete actively being considered. • Technologies often applied to lower traffic areas, such as parking lots, alleys, and trails. • May be best in climates with adequate moisture during the summer.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

NEW CONSTRUCTION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Permeable Pavement Options (continued)						
Nonvegetated permeable pavements ***(continued)***	• Pervious concrete has more voids than conventional concrete to allow water to drain through the surface into the base. • Brick or block pavers are generally made from clay or concrete blocks filled with rocks, gravel, or soil.	(see prior page)	(see prior page)	(see prior page)	(see prior page)	(see prior page)
Vegetated permeable pavements: • Grass pavers • Concrete grid pavers	• Plastic, metal, or concrete lattices provide support and allow grass or other vegetation to grow in the interstices.	• Provides cooling through evapotranspiration. • Sustainability of vegetation may vary with local conditions.	+ Lowers pavement temperatures through evapotranspiration, particularly when moist. + When dry may still be cooler than other pavement options due to the natural properties of vegetation.	+ In most conditions will contribute to lower air temperatures day and night, through evapotranspiration and natural properties of vegetation. Moisture availability will greatly increase its effectiveness.	• Cooling mechanism depends on available moisture. Supplemental moisture, for example watering pavements, may keep them cooler.[36] • More research needed to determine temperature impacts from vegetated pavements under a wide range of conditions.	• Low-traffic areas, such as alleys, parking lots, and trails. • May be best in climates with adequate moisture during the summer.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

MAINTENANCE/REHABILITATION						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options						
Chip seals made with high-albedo aggregate	• Chip seals describe aggregate used to resurface low-volume asphalt roads and sometimes for highway surfaces.	• Solar reflectance of chip seals will correlate with the albedo of the aggregate used. In San Jose, CA, researchers identified albedo of 20% for new chip seals, which then decline with age. [37] • Urban geometry can influence the effect high-albedo pavements have	+ Lowers pavement surface and subsurface temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – Reflected heat can be absorbed by the sides of surrounding buildings warming the interior of the building and contributing to the urban heat island effect.	• Solar reflectance decreases over time, as soiling from traffic makes chip seals darker. • Urban geometry, in particular urban canyons, influences the impact high-albedo pavements have on the urban climate.	• Chip seals are most often used to resurface low-volume asphalt roads, although highway applications also exist. • May be most effective when paving large, exposed areas, such as parking lots.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

MAINTENANCE/REHABILITATION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options (continued)						
Whitetopping	• Whitetopping is a thick layer (thickness greater than 4 inches or 10 cm) of concrete applied over existing asphalt when resurfacing or can be applied to new asphalt. It often contains fibers for added strength. • Ultra-thin whitetopping is generally 2–4 inches (5–10 cm) thick and similar to whitetopping.	• The solar reflectance of whitetopping material can be as high as concrete. • Urban geometry can influence the effect of high-albedo pavements.	+ Lowers pavement surface and subsurface temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – Reflected heat can be absorbed by the sides of surrounding buildings, warming the interior of the building and contributing to the urban heat island effect.	• Solar reflectance decreases over time, as soiling from traffic makes whitetopped surfaces darker. • Urban geometry, in particular urban canyons, influences the impact high-albedo pavements have on the urban climate.	• Whitetopping and ultra-thin whitetopping are generally used to resurface road segments, intersections, and parking lots. • May be most effective when paving large, exposed areas, such as parking lots.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

MAINTENANCE/REHABILITATION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options (continued)						
Microsurfacing with high-albedo materials	• A thin sealing layer used for road maintenance. • Light-colored materials can be used to increase the solar reflectance of asphalt.	• Solar reflectance of microsurfacing will correlate with the albedo of the materials used. • Researchers recently measured solar reflectances of microsurfacing applications over 35%.[38]	+ Lowers pavement surface and subsurface temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – Reflected heat can be absorbed by the sides of surrounding buildings, warming the interior of the building and contributing to the urban heat island effect.	• Solar reflectance may decrease over time, if soiling from traffic makes high-albedo microsurfacing materials darker. • Urban geometry, particularly urban canyons, influences the impact high-albedo pavements have on the urban climate.	• Used to extend pavement life and on worn pavements that need improved friction, such as low- to medium-volume roads, airport runways, and parking areas.

3. Benefits and Costs

Currently, few studies provide detailed data on the benefits and costs of cool pavements. This section aims to provide a general discussion as a starting point for decision-makers to consider and gives examples where available. Again, decision-makers will also consider location-specific factors such as functionality of pavements in the local climate, political acceptance, and experience with the technology. Resources and examples providing the latest information are listed in Sections 4 and 5.

3.1 Benefits

Installing cool pavements can be part of an overall strategy to reduce air temperatures, which can result in a wide range of benefits. The information below highlights existing research in this area.

Reduced Energy Use

As noted earlier, researchers predicted that if pavement reflectance throughout a city were increased from 10 to 35 percent, the air temperature could potentially be reduced by 1°F (0.6°C), which would result in significant benefits in terms of lower energy use and reduced ozone levels. For example, an earlier, separate study estimated over $90 million/year in savings from temperature reductions attributed to increased pavement albedo in the Los Angeles area.[39]

Similarly, when permeable pavements evaporate water and contribute to lower air temperatures, they also provide other energy benefits.[40] Permeable pavements can allow stormwater to infiltrate into the ground, which decreases stormwater runoff. With reduced runoff, communities may realize energy savings associated with pumping stormwater and maintaining conveyance structures. These cost savings may be significant in areas where there are old, combined sewers (where stormwater drains into the sanitary sewer system).

Measuring Energy Savings from Cool Roofs versus Cool Pavements

Measuring the energy impacts from a cool roof is relatively easy compared with quantifying those from pavement installations. With a roof, one can measure energy demand before and after the installation, and in a controlled experiment, the change in demand can be associated with the roofing technology. In contrast, pavements affect building energy demand through influencing air temperature, which is a more complex relationship to isolate and measure.

Air Quality and Greenhouse Gas Emissions

Depending on the electric power fuel mix, decreased energy demand associated with cool pavements will result in lower associated air pollution and greenhouse gas emissions. Cooler air temperatures also slow the rate of ground-level ozone formation and reduce evaporative emissions from vehicles. A 2007 paper estimated that increasing pavement albedo in cities worldwide, from an average of 35 to 39 percent, could achieve reductions in global carbon dioxide (CO_2) emissions worth about $400 billion.[41]

Water Quality and Stormwater Runoff

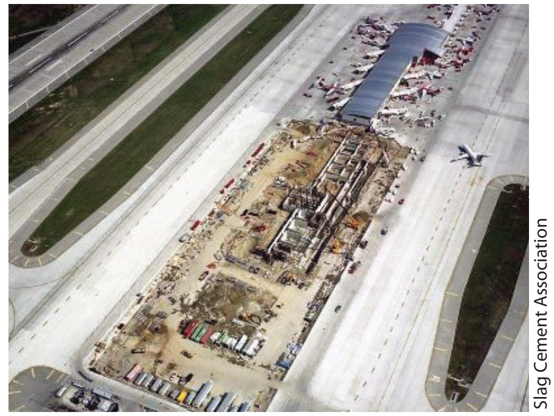
Pavements with lower surface temperatures—whether due to high solar reflectance, permeability, or other factors—can help lower the temperature of stormwater runoff, thus ameliorating thermal shock to aquatic life in the waterways into which stormwater drains.[42] Laboratory tests with permeable pavers have shown reductions in runoff temperatures of about 3–7°F (2–4°C) in comparison with conventional asphalt paving.[43]

Permeable pavements allow water to soak into the pavement and soil, thereby reducing stormwater runoff, recharging soil moisture, and improving water quality by filtering out dust, dirt, and pollutants.[44,45] Outdoor testing and laboratory measurements have found that permeable pavements can reduce runoff by up to 90 percent.[46] Reducing runoff decreases scouring of streams, and, in areas with combined sewers, this flow reduction can help minimize combined sewer overflows that discharge sewage and stormwater into receiving waters. The amount of water that these pavements collect varies based on the type of aggregate used and the porosity of the pavements, as well as on the absorptive ability of the materials supporting the pavement.

Increased Pavement Life and Waste Reduction

Reducing pavement surface temperatures can reduce the risk of premature failure of asphalt pavements by rutting (depressions in the wheelpaths) where the combination of slow heavy trucks or buses and hot temperatures make this a concern. Some full-scale testing of a typical asphalt pavement showed that it took 65 times more passes of a truck wheel to rut the pavement when the temperature just below the surface was reduced from 120°F (49°C) to 106°F (41°C).[47] In general, reducing the surface temperatures of asphalt pavements will also slow the rate of "aging" that contributes to other distresses. For concrete pavement, reducing daytime surface temperatures in locations that experience very hot temperatures in the day and cool temperatures at night will reduce the temperature-related stresses that contribute to cracking.[48]

Figure 9: Slag Cement Airport Expansion



The Detroit Metro Airport used 720,000 square feet (67,000 m^2) of slag cement in an airport terminal expansion project. In this region, the local aggregate is susceptible to alkali-silica reaction, whereas slag resists that form of corrosion better than plain cement and is easier to place in hot weather. This approach increased the life expectancy of the paved surfaces, as well as allowed for the use of a high-albedo product.[49]

Quality of Life Benefits

Cool pavements may provide additional benefits, such as:

- **Nighttime illumination.** Reflective pavements can enhance visibility at night, potentially reducing lighting requirements and saving money and energy. European road designers often take pavement color into account when planning lighting.[50]
- **Comfort improvements.** Using reflective or permeable pavements where people congregate or children play can provide localized comfort benefits through lower surface and near-surface air temperatures.[51]
- **Safety.** Permeable roadway pavements can enhance safety because better water drainage reduces water spray from moving vehicles, increases traction, and may improve visibility by draining water that increases glare.[52]

3.2 Costs

Cool pavement costs will depend on many factors including the following:

- The region
- Local climate
- Contractor
- Time of year
- Accessibility of the site
- Underlying soils
- Project size
- Expected traffic
- The desired life of the pavement.

Most cost information is project specific, and few resources exist that provide general cost information. For permeable pavement, however, the Federal Highway Administration (FHWA) has noted that porous asphalt costs approximately 10 to 15 percent more than regular asphalt, and porous concrete is about 25 percent more expensive than conventional concrete.[53] These comparisons pertain to the surface layer only.

Table 3 (below) summarizes a range of costs for conventional and cool pavements, based on available sources. The data should be read with caution, as many project-specific factors—as highlighted above—will influence costs. These costs are estimates for initial construction or performing maintenance, and do not reflect life-cycle costs. Decision-makers generally contact local paving associations and contractors to obtain more detailed, location-specific information on the costs and viability of cool pavements in their particular area.

Table 3: Comparative Costs of Various Pavements[54]

Basic Pavement Types	Example Cool Approaches	Approximate Installed Cost, $/square foot*	Estimated Service Life, Years
New Construction			
Asphalt (conventional)	Hot mix asphalt with light aggregate, if locally available	$0.10–$1.50	7–20
Concrete (conventional)	Portland cement, plain-jointed	$0.30–$4.50	15–35
Nonvegetated permeable pavement	Porous asphalt	$2.00–$2.50	7–10
	Pervious concrete	$5.00–$6.25	15–20
	Paving blocks	$5.00–$10.00	> 20
Vegetated permeable pavement	Grass/gravel pavers	$1.50–$5.75	> 10
Maintenance			
Surface applications	Chip seals with light aggregate, if locally available	$0.10–$0.15	2–8
	Microsurfacing	$0.35–$0.65	7–10
	Ultra-thin whitetopping	$1.50–$6.50	10–15

* Some technologies, such as permeable options, may reduce the need for other infrastructure, such as stormwater drains, thus lowering a project's overall expenses. Those savings, however, are not reflected in this table. (1 square foot = 0.09 m^2)

3.3 Life-Cycle Cost and Environmental Impact Considerations

The term "life cycle" refers to all the phases of a pavement's life, from materials production through construction, maintenance, and use, and finishing with the end-of-life phase where the pavement is rehabilitated, recycled, or removed. Two types of calculations are typically performed for a pavement's life cycle: cost and environmental impact.

Life-cycle cost analysis (LCCA) can help in evaluating whether long-term benefits can outweigh higher up-front costs. Many agencies use LCCA to evaluate pavement structure options. The Federal Highway Administration has software for LCCA called Real Cost.[55,56,57]

Although permeable pavement costs may be higher than conventional, impermeable technologies, these costs are often offset by savings from reduced requirements for grading, treatment ponds, or other drainage features, such as inlets and stormwater pipes.[58] For a community, the cumulative reductions in stormwater flows from sites can provide significant savings in the municipal infrastructure. If the community has combined sewers, there could also be environmental, social, and cost benefits from reducing combined sewer overflows, as well as potentially avoiding part of the increased infrastructure costs associated with combined sewer operation.

Life-cycle assessment (LCA) considers the environmental impacts throughout the life of the pavement. The International Standard Organization has published a generic LCA guideline for all industrial products (the ISO 14040 series of documents).[59] The National Institute of Standards and Technology has developed Building for Environmental and Economic Sustainability (BEES), a software tool that uses the ISO 14040 series of standards to estimate life-cycle environmental impacts from the production and use of asphalt, Portland cement, fly ash cement, and other paving materials in a building environment. The BEES software also has an LCCA module.[60] Although not directly related to urban heat island mitigation, this tool can help quantify some of the environmental and cost impacts from a variety of pavement choices.

LCA for road pavements is a nascent field. A workshop was held in May 2010 regarding implementation of ISO 14040 for roads and issues that remain to be resolved.[61] LCA has not been used to date to compare the environmental impacts of permeable or reflective versus conventional pavement. In general, until more data on cool pavement environmental impacts and costs exist, communities may need to think broadly to determine if a cool pavement application is appropriate. Sustainability initiatives, in some areas, are motivating communities to try cooler alternatives, as discussed in Section 4.

4. Cool Pavement Initiatives

The growing interest in lowering urban temperatures and designing more sustainable communities has helped spur activity in the cool pavement arena. Most of the effort has focused on research, due to information gaps and the lack of specific data quantifying cool pavement benefits. More information on resources and examples are provided at the end of this section and in Section 5. Highlights of some cool pavement efforts are below:

- **Arizona State University's National Center of Excellence (NCE) SMART Innovations for Urban Climate and Energy.**[62] This group is studying established and emerging designs that optimize albedo, emissivity, thermal conductivity, heat storage capacity, and density in laboratory and field sites. NCE is developing models, particularly for the Phoenix area but also beyond, to help decision-makers predict the effects of material properties, shading, and energy use on urban temperatures.
- **The National Academies of Science's Transportation Research Board (TRB) Subcommittee on Paving Materials and the Urban Climate.** TRB established this Subcommittee in January 2008 to help advance the science of using pavements for heat island mitigation and addressing other urban climate concerns.
- **Trade association efforts.** Representatives from the asphalt and concrete trade associations are participating in cool pavement efforts, such as the TRB Subcommittee on Paving Materials and the Urban Climate, as well supporting research and training related to cool pavement. For example, the National Asphalt Pavement Association has been investigating high-albedo asphalt pavements, the National Ready Mixed Concrete Association is leading seminars on pervious concrete, and the Interlocking Concrete Pavement Institute (ICPI) is providing professional seminars on permeable pavements in cooperation with the Low Impact Development Center and North Carolina State University.[63]

These research efforts are expanding opportunities for identifying, applying, and studying cool pavement technologies.

Sustainability or green building initiatives are helping to encourage cool pavement installations.

- **Evanston, Illinois,** includes permeable pavements in its assessment of green buildings.[64]
- **Chicago's Green Alley program** aims to use green construction techniques to repave over 1,900 miles of alleys, and offers a handbook for installing permeable pavements for heat reduction, stormwater management, and other benefits.[65]
- **Environmental rating programs** such as Leadership in Energy and Environmental Design (LEED), Green Globes, and EarthCraft award points to designs that incorporate certain permeable pavements or pavements of a certain solar reflectance index. They also give points for using local and recycled materials, such as slag, and reducing the pavement used on a site.

Table 4 on page 29 summarizes other cool pavement initiatives. Refer to the "Heat Island Reduction Activities" chapter of this compendium for further examples.

Although cool pavements are still in their infancy compared with the other heat island mitigation strategies—trees and vegetation, green roofs, and cool roofs—interest and momentum are growing. Research efforts these past few years have greatly increased, particularly in the area of permeable pavements. As local and state transportation and environmental agencies work together to address energy, sustainability, heat-health, and other concerns, communities can expect to see more cool pavement installations. Activity in the private sector has also been encouraging, as architects, developers, and others are taking leadership roles in advancing sustainable technologies. This chapter, which currently provides a starting point for communities and decision-makers, will evolve as more information becomes available.

Growing Concern about Synthetic Turf

Many communities have begun to examine the health impacts from synthetic turf surfaces, which include the effects from high temperatures. One researcher in New York found that artificial sports fields could be up to 60°F (16°C) hotter than grass, potentially causing skin injuries to athletes as well as contributing to the heat island effect. These data, though not directly related to pavements, can help advance our understanding of how different materials interact with the urban climate.[66]

Figure 11: Grass Paving

David Hitchcock, HARC

This 300,000-square-foot (28,000 m^2) parking lot outside a stadium in Houston uses plastic grid pavers that allow grass to grow in the open spaces.

Alternative Paving under the Cool Houston Plan

While most communities have no, or limited, cool pavement experience, Houston's heat island initiative recommends alternative pavements as part of the city's overall approach to improving air quality and public health. The plan's three-tiered strategy includes:

- Targeting alternative paving options for specific types of paved surfaces, such as highways or parking lots, or expanding residential or commercial roadways. This requires coordination with the Texas Department of Transportation and the Texas Commission on Environmental Quality.
- Educating local and state decision-makers about public health, environmental management, and public works maintenance benefits of alternative pavements.
- Combining and embedding alternative paving incentives into larger programs and regulations, such as meeting Clean Air or Clean Water Act standards, with the support of the Greater Houston Builders Association and the Texas Aggregates and Concrete Association.

Table 4: Examples of Cool Pavement Initiatives

Type of Initiative	Description	Links to Examples
Research	Industry	<www.nrmca.org/>—Since 1928, the National Ready Mixed Concrete Association's research laboratory has helped evaluate materials and set technical standards. Recent projects include developing permeability tests and assessing concrete with high fly-ash content.
	National laboratory	<http://eetd.lbl.gov/HeatIsland/Pavements/>—The Heat Island Group at Lawrence Berkeley National Laboratory (LBNL) provides research and information about cool paving and other heat island mitigation measures. The Cool Pavements section describes the benefits of this technology, and published reports are included under Recent Publications.
	University-supported and similar consortia	<www.asusmart.com/pavements.php>—Arizona State University's National Center of Excellence collaborates with industry and government to research and develop technologies to reduce urban heat islands, especially in desert climates.
		<www.harc.edu/Projects/CoolHouston/>—The Houston Advanced Research Center (HARC) brings together universities, local governments, and other groups interested in improving air quality and reducing heat islands. It has examined how cool paving could be implemented in the Houston area to reduce urban heat island effects.
		<http://ncsu.edu/picp/index.html> and <www.bae.ncsu.edu/info/permeable_pavement/index.html>—North Carolina State University has an active permeable pavement research program, as well as a specialized collaborative effort with ICPI and the Low Impact Development Center on permeable interlocking concrete pavements.

Table 4: Examples of Cool Pavement Initiatives (cont.)

Type of Initiative	Description	Links to Examples
Voluntary efforts	Demonstration programs	<www.cityofpoulsbo.com/CityCouncil/PDFsDOCs/Works/2007/4-25minutes.pdf>—Poulsbo, Washington, used a $263,000 grant from the Washington Department of Ecology to pave 2,000 feet of sidewalk with pervious pavement, making it one of the largest pervious surface projects in the state.
		<www.heifer.org/site/c.edJRKQNiFiG/b.1484715/>—The nonprofit Heifer International used pervious pavement and other sustainable techniques for its new headquarters in Arkansas.
	Outreach & education	< www.epa.gov/heatisland/>—EPA's Heat Island Reduction Initiative provides information on the temperature, energy, and air quality impacts from cool pavements and other heat island mitigation strategies.
		<http://cfpub.epa.gov/npdes/home.cfm?program_id=298>—EPA's Office of Water highlights design options, including permeable pavements that reduce stormwater runoff and water pollution.
		<www.greenhighways.org/>—The Green Highways Partnership, supported by a number of groups including EPA and the U.S. Department of Transportation is a public-private partnership dedicated to transforming the relationship between the environment and transportation infrastructure. The partnership's Web site includes a number of cool pavement resources, especially with respect to permeable pavements.
		<http://nemo.uconn.edu/index.htm>—The University of Connecticut runs Nonpoint Education for Municipal Officials (NEMO), which helps educate local governments about land use and environmental quality.
	Tools	<www.bfrl.nist.gov/oae/software/bees/>—The National Institute of Standards and Technology (NIST) has developed a software tool, Building for Environmental and Economic Stability (BEES). The tool enables communities to conduct life cycle cost assessments for various types of building initiatives, including pavement projects.
Policy efforts	Municipal regulations that support cool pavements	<http://files.harc.edu/Projects/CoolHouston/CoolHoustonPlan.pdf>—The Cool Houston! Plan promotes cool paving as well as other techniques to reduce the region's heat island.
		<www.toronto.ca/planning/urbdesign/greening_parking_lots.htm>—Toronto's "Design Guidelines for 'Greening' Surface Parking Lots" encourage reflective and permeable pavements to reduce surface temperatures.

5. Resources

The organizations below may provide additional information on alternative, or cool, pavement technologies.

Program/Organization	Role	Web Address
The Federal Highway Administration's (FHWA) Office of Pavement Technology	The Office of Pavement Technology conducts research and training related to asphalt and concrete pavements.	<www.fhwa.dot.gov/pavement/hq/welcome.cfm>
FHWA's Office of Planning, Environment, and Realty	This office's Web site provides information regarding transportation planning and the environment.	<www.fhwa.dot.gov/hep/index.htm>
American Association of State Highway and Transportation Officials Center for Environmental Excellence (AASHTO)	AASHTO created the Center for Environmental Excellence in cooperation with the Federal Highway Administration to offer technical assistance about environmental regulations and ways to meet them.	<http://environment.transportation.org/>
Association of Metropolitan Planning Organizations (AMPO)	AMPO supports local MPOs through training, conferences, and assistance with policy development.	<www.ampo.org/>
The American Concrete Pavement Association (ACPA)	ACPA promotes concrete pavement by working with industry and government.	<www.pavement.com>
The Asphalt Pavement Alliance (APA)	A consortium of the National Asphalt Paving Association (NAPA), the Asphalt Institute (AI), and state paving associations, APA promotes hot mix asphalt through research, development, and outreach. Individual state asphalt associations are a good source for local paving considerations.	<www.asphaltalliance.com>
Interlocking Concrete Pavement Institute (ICPI)	ICPI has a document that compares permeable pavement technologies and helps readers find certified installers.	<www.icpi.org>
National Center for Asphalt Technology (NCAT)	NCAT provides up-to-date strategies for designing and constructing asphalt pavements.	<www.ncat.us>
National Ready Mixed Concrete Association	Since 1928, the National Ready Mixed Concrete Association's research laboratory has helped evaluate materials and set technical standards. Recent projects include developing permeability tests and assessing concrete with high fly-ash content.	<www.nrmca.org>
Portland Cement Association (PCA)	PCA represents cement companies in the United States and Canada and conducts research, development, and outreach.	<www.cement.org>

Endnotes

1 Statistics are from urban fabric analyses conducted by Lawrence Berkeley National Laboratory. Rose, L.S., H. Akbari, and H. Taha. 2003. Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas. Paper LBNL-51448. Lawrence Berkeley National Laboratory, Berkeley, CA.
Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Metropolitan Chicago, Illinois. Paper LBNL-49275. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Salt Lake City, Utah. Paper LBNL-47851. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H., L.S. Rose, and H. Taha. 1999. Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California. Paper LBNL-44688. Lawrence Berkeley National Laboratory, Berkeley, CA.

2 Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. 2000. The Effect of Pavements' Temperatures on Air Temperatures in Large Cities. Paper LBNL-43442. Lawrence Berkeley National Laboratory, Berkeley, CA. See also Cambridge Systematics. 2005. Cool Pavement Draft Report. Prepared for U.S. EPA.

3 See, generally, U.S. EPA 2008. Green Parking Lot Resource Guide. EPA 510-B-08-001.

4 Golden, J.S., J. Carlson, K. Kaloush, and P. Phelan. 2006. A Comparative Study of the Thermal and Radiative Impacts of Photovoltaic Canopies on Pavement Surface Temperatures. Solar Energy. 81(7): 872-883. July 2007.

5 Kinouchi, T., T. Yoshinaka, N. Fukae, and M. Kanda. 2004. Development of Cool Pavement with Dark Colored High Albedo Coating. Paper for 5th Conference for the Urban Environment. Vancouver, Canada. Retrieved November 15, 2007, from <http://ams.confex.com/ams/pdfpapers/79804.pdf>.

6 National Center of Excellence on SMART Innovations at Arizona State University. 2007. What Factors Influence Elevated Pavement Temperatures Most During Day and Night? Case Study 1(1).

7 The Portland Cement Association thoroughly explains concrete cement at <www.cement.org/tech/cct_concrete_prod.asp>, and state and federal government sites, among others, define asphalt. Two useful ones are <www.virginiadot.org/business/resources/bu-mat-Chapt1AP.pdf> and <www.tfhrc.gov/hnr20/recycle/waste/app.htm>.

8 Levinson, R. and H. Akbari. 2001. Effects of Composition and Exposure on the Solar Reflectance of Portland Cement Concrete. Paper LBNL-48334. Lawrence Berkeley National Laboratory, Berkeley, CA.

9 National Center of Excellence on SMART Innovations at Arizona State University. 2007. What Factors Influence Elevated Pavement Temperatures Most During Day and Night? Case Study 1(1).

10 Levinson, R., H. Akbari, S. Konopacki, and S. Bretz. 2002. Inclusion of Cool Roofs in Nonresidential Title 24 Prescriptive Requirements. Paper LBNL-50451. Lawrence Berkeley National Laboratory, Berkeley, CA.

11 See:

Haselbach, L. 2008. Pervious Concrete and Mitigation of the Urban Heat Island Effect. Under review for the 2009 Transportation Research Board Annual Meeting.

Kevern, J., V.R. Schaefer, and K. Wong. 2008. Temperature Behavior of a Pervious Concrete System. Under review for the 2009 Transportation Research Board Annual Meeting.

[12] For a general overview of permeable pavements, see Ferguson, B. 2005. Porous Pavements.

[13] See, generally:

Haselbach, L. 2008. Pervious Concrete and Mitigation of the Urban Heat Island Effect. Under review for the 2009 Transportation Research Board Annual Meeting.

Kevern, J., V.R. Schaefer, and K. Wong. 2008. Temperature Behavior of a Pervious Concrete System. Under review for the 2009 Transportation Research Board Annual Meeting.

[14] There are a number of resources available on Japan's efforts with water retentive pavements, although there is no centralized source that compiles these initiatives. For examples of the research and published summaries available, see the following (all Web sites accessed September 17, 2008):

Karasawa, A., K. Toriiminami, N. Ezumi, K. Kamaya. 2006. Evaluation Of Performance Of Water-Retentive Concrete Block Pavements. 8th International Conference on Concrete Block Paving, November 6-8, 2006, San Francisco, California.

Ishizuka, R., E. Fujiwara, H. Akagawa. 2006. Study On Applicability Of Water-Feed-Type Wet Block Pavement To Roadways. 8th International Conference on Concrete Block Paving, November 6-8, 2006, San Francisco, California.

Yamamoto, Y. 2006. Measures to Mitigate Urban Heat Islands. Quarterly Review No. 18. January 2006. Available online at <www.nistep.go.jp/achiev/ftx/eng/stfc/stt018e/qr18pdf/STTqr1806.pdf>.

Yoshioka, M., H. Tosaka, K. Nakagawa 2007. Experimental and Numerical Studies of the Effects of Water Sprinkling on Urban Pavement on Heat Island Mitigation. American Geophysical Union, Fall Meeting 2007, abstract #H43D-1607.

Yamagata H., M. Nasu, M. Yoshizawa, A. Miyamoto, and M. Minamiyama. 2008. Heat island mitigation using water retentive pavement sprinkled with reclaimed wastewater. Water science and technology. 57(5): 763-771. Abstract available online at <http://cat.inist.fr/?aModele=afficheN&cpsidt=20266221>.

[15] Christen, A. and R. Vogt. 2004. Energy and radiation balance of a Central European city. International Journal of Climatology. 24(ii):1395-1421.

[16] Golden, J.S. and K. Kaloush. 2006. Meso-Scale and Micro-Scale Evaluations of Surface Pavement Impacts to the Urban Heat Island Effects. The International Journal of Pavement Engineering. 7(1): 37-52. March 2006.

[17] Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. 2000. The Effect of Pavements' Temperatures on Air Temperatures in Large Cities. Paper LBNL-43442. Lawrence Berkeley National Laboratory, Berkeley, CA.

[18] Taha, H. 1997. Modeling the impacts of large-scale albedo changes on ozone air quality in the South Coast Air Basin. Atmospheric Environment. 31(11): 1667-1676.

Taha, H. 1996. Modeling the Impacts of Increased Urban Vegetation on the Ozone Air Quality in the South Coast Air Basin. Atmospheric Environment. 30(20): 3423-3430.

[19] Rosenfeld, A.H., J.J. Romm, H. Akbari, and M. Pomerantz. 1998. Cool Communities: Strategies for Heat Islands Mitigation and Smog Reduction. Energy and Buildings. 28:51-62.

[20] Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

21 Statistics are from urban fabric analyses conducted by Lawrence Berkeley National Laboratory. Rose, L.S., H. Akbari, and H. Taha. 2003. Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas. Paper LBNL-51448. Lawrence Berkeley National Laboratory, Berkeley, CA.
Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Metropolitan Chicago, Illinois. Paper LBNL-49275. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Salt Lake City, Utah. Paper LBNL-47851. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H., L.S. Rose, and H. Taha. 1999. Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California. Paper LBNL-44688. Lawrence Berkeley National Laboratory, Berkeley, CA.

22 See, e.g., Mallick, R.B., P.S. Kandhal, L.A. Cooley, Jr., and P.E. Watson. 2000. Design, Construction, and Performance of New-generation Open-graded Friction Courses. Paper prepared for annual meeting of Association of Asphalt Paving Technologists, Reno, NV, March 13-15, 2000.

23 Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

24 More information on fly ash is available through EPA's Coal Combustion Products Partnership, <www.epa.gov/rcc/c2p2/index.htm>.

25 Boriboonsomsin, K. and F. Reza. 2007. Mix Design and Benefit Evaluation of High Solar Reflectance Concrete for Pavements. Paper for 86th Annual Meeting of the Transportation Research Board. Washington, D.C.

26 Office of the Governor. 2006. Statement by Gov. Schwarzenegger on U.S. EPA Award for California's Leadership in the Construction Use of Waste Products. Retrieved July 15, 2008, from <http://gov.ca.gov/index.php?/press-release/4839/>

27 Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. 2000. The Effect of Pavements' Temperatures On Air Temperatures in Large Cities. Paper LBNL-43442. Lawrence Berkeley National Laboratory, Berkeley, CA. See also Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

28 Aseda, T., V.T. Ca, and A. Wake. 1993. Heat Storage of Pavement and its Effect on the Lower Atmosphere. Atmospheric Environment. 30(3): 413–427. 1996.

29 Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

30 Levinson, R. and H. Akbari. 2001. Effects of Composition and Exposure on the Solar Reflectance of Portland Cement Concrete. Paper LBNL-48334. Lawrence Berkeley National Laboratory, Berkeley, CA.

31 Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

32 National Center of Excellence on SMART Innovations at Arizona State University. 2007. Alternative Paving—Recycling Crumb Rubber. Case Study, 1(3).

33 Haselbach, L. 2008. Pervious Concrete and Mitigation of the Urban Heat Island Effect. Under review for the 2009 Transportation Research Board Annual Meeting.

34 Haselbach, L. 2008. Pervious Concrete and Mitigation of the Urban Heat Island Effect. Under review for the 2009 Transportation Research Board Annual Meeting.

35 Yamagata H., M. Nasu, M. Yoshizawa, A. Miyamoto, and M. Minamiyama. 2008. Heat island mitigation using water retentive pavement sprinkled with reclaimed wastewater. Water science and technology. 57(5): 763-771. Abstract available online at <http://cat.inist.fr/?aModele=afficheN&cpsidt=20266221>.

36 Yamagata H., M. Nasu, M. Yoshizawa, A. Miyamoto, and M. Minamiyama. 2008. Heat island mitigation using water retentive pavement sprinkled with reclaimed wastewater. Water science and technology. 57(5): 763-771. Abstract available online at <http://cat.inist.fr/?aModele=afficheN&cpsidt=20266221>.

37 Pomerantz, M., H. Akbari, S.-C. Chang, R. Levinson and B. Pon. 2003. Examples of Cooler Reflective Streets for Urban Heat-Island Mitigation: Portland Cement Concrete and Chip Seals. Paper LBNL-49283. Lawrence Berkeley National Laboratory, Berkeley, CA.

38 Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

39 Rosenfeld, A.H., J.J. Romm, H. Akbari, and M. Pomerantz. 1998. "Cool Communities: Strategies for Heat Islands Mitigation and Smog Reduction," Energy and Buildings, 28, pp. 51-62.

40 Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. 2000. The Effect of Pavements' Temperatures on Air Temperatures in Large Cities. Paper LBNL-43442. Lawrence Berkeley National Laboratory, Berkeley, CA.

41 Akbari, H., and S. Menon. 2007. Global Cooling: Effect of Urban Albedo on Global Temperature. Paper for the Proceedings of the International Seminar on Planetary Emergencies. Erice, Sicily.

42 U.S. EPA. 2003. Beating the Heat: Mitigating Thermal Impacts. Nonpoint Source News-Notes. 72:23-26.

43 James, W. 2002. Green Roads: Research into Permeable Pavers. Stormwater. Retrieved May 8, 2008 from <www.stormcon.com/sw_0203_green.html>.

44 U.S. EPA. Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices. EPA 841-F-07-006, December 2007. Retrieved April 2, 2008 from <www.epa.gov/owow/nps/lid/costs07/>.

45 Booth, D. and J. Leavit. 1999. Field Evaluation of Permeable Pavement Systems for Improved Stormwater Management. Journal of the American Planning Association. 65(3): 314-325.

46 James, W. 2002. Green Roads: Research into Permeable Pavers. Stormwater. Retrieved May 8, 2008 from <www.stormcon.com/sw_0203_green.html>.

47 Pomerantz, M., H. Akbari, and J. Harvey. 2000. Durability and Visibility Benefits of Cooler Reflective Pavements. Paper LBNL-43443. Lawrence Berkeley National Laboratory, Berkeley, CA.

48 ARA Inc., ERES Consultants. 2004. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Part 3. Design Analyis, Ch. 4 Design of New and Reconstructed Rigid Pavements. Final Report Project 1-37A. National Cooperative Highway Research Program, Transportation Research Board, National Academy of Science. Washington DC.

49 Bijen, Jan. 1996. Benefits of slag and fly ash. Construction and Building Materials 10.5: 309-314. See also the Federal Highway Administration's summary of slag cement at <www.tfhrc.gov/hnr20/recycle/waste/bfs3.htm>.

50 U.S. Department of Transportation, Federal Highway Administration. European Road Lighting Technologies. International Technology Exchange Program: September 2001. Retrieved June 16, 2008, from <http://international.fhwa.dot.gov/euroroadlighting/index.cfm>. See also: International Commission on Illumination. 2007. Road Transport Lighting for Developing Countries. CIE 180:2007.

51 Kinouchi, T., T. Yoshinaka, N. Fukae, and M. Kanda. 2004. Development of Cool Pavement with Dark Colored High Albedo Coating. Paper for 5th Conference for the Urban Environment. Vancouver, Canada. Retrieved November 15, 2007, from <http://ams.confex.com/ams/pdfpapers/79804.pdf>.

52 U.S. Department of Transportation, Federal Highway Transportation Administration. 2005. Technical Advisory: Surface Texture for Asphalt and Concrete Pavements. Retrieved September 17, 2008, from <www.fhwa.dot.gov/legsregs/directives/techadvs/t504036.htm>. Michigan Department of Environmental Quality. 1992. Porous Asphalt Pavement. Retrieved 16 Sep 2008 from <www.deq.state.mi.us/documents/deq-swq-nps-pap.pdf>.

53 U.S. Department of Transportation, Federal Highway Administration. Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring. Fact Sheet - Porous Pavements. Retrieved April 2, 2008, from <www.fhwa.dot.gov/environment/ultraurb/3fs15.htm>.

54 Figures are taken from multiples sources and express the maximum range of the values: 1) Cambridge Systematics. 2005. Cool Pavement Draft Report. Prepared for U.S. EPA. 2) ASU's draft of the Phoenix Energy and Climate Guidebook. 3) Center for Watershed Protection. 2007. Redevelopment Projects. New York State Stormwater Management Design Manual. Prepared for New York State Department of Environmental Conservation. Retrieved June 13, 2008, from <www.dec.ny.gov/docs/water_pdf/swdmredevelop.pdf>. 4) Bean, E.Z.,W.F. Hunt, D.A. Bidelspach, and J.T. Smith. 2004. Study on the Surface Infiltration Rate of Permeable Pavements. Prepared for Interlocking Concrete Pavement Institute. 5) Interlocking Concrete Pavement Institute. 2008. Permeable Interlocking Concrete Pavements: A Comparison Guide to Porous Asphalt and Pervious Concrete. 6) Pratt, C.J. 2004. Sustainable Drainage: A Review of Published Material on the Performance of Various SUDS Components. Prepared for The Environment Agency. Retrieved June 13, 2008, from <www.ciria.org/suds/pdf/suds_lit_review_04.pdf>. 7) NDS, Inc. Technical Specifications for Grass Pavers. Retrieved June 13, 2008, from <www.ndspro.com/cms/index.php/Engineers-and-Architects.html>. 8) Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

55 Federal Highway Administration. 2002. Life Cycle Cost Analysis Primer. FHWA-IF-02-047. Office of Asset Management. Washington DC. August. 25 pp. Accessible at http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm.

56 D. Walls, J., M. Smith. 1998. Life-Cycle Cost Analysis in Pavement Design —Interim Technical Bulletin. FHWA-SA-98-079. Federal Highway Administration. September. 107pp . Accessible at http://isddc.dot.gov/OLPFiles/FHWA/013017.pdf.

57 Federal Highway Administration. Real Cost. version 2.5. Accessible at http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm.

58 U.S. EPA. 2007. Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices. EPA 841-F-07-006. Retrieved April 2, 2008, from <www.epa.gov/owow/nps/lid/costs07/documents/reducingstormwatercosts.pdf>.

59 International Standards Organization. Documents can be purchased at http://www.iso.org/iso/catalogue_detail?csnumber=37456.

60 See the Building for Environmental and Economic Sustainability (BEES) software at <www.bfrl.nist.gov/oae/software/bees/>.

61 Information on the LCA for Pavements Workshop held in May, 2010 is available at www.ucprc.ucdavis.edu/p-lca.

62 National Center of Excellence on SMART Innovations at Arizona State University <http://asusmart.com/background.php>.

63 The National Asphalt Pavement Association conducts training and professional development (see <www.hotmix.org/>) and the National Ready Mixed Concrete Association has a research lab near College Park, Maryland, and conducts training and professional development (see <www.nrmca.org/> for details). For the Interlocking Concrete Pavement Institute seminars, see <www.ncsu.edu/picp/upcoming.html>. See also recent sponsored research efforts, such as:

Kevern, J., V.R. Schaefer, and K. Wong. 2008. Temperature Behavior of a Pervious Concrete System. Under review for the 2009 Transportation Research Board Annual Meeting.

Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

64 For the design guidelines, see <www.cityofevanston.org/departments/communitydevelopment/planning/pdf/DGs_Final_000.pdf>.

65 City of Chicago. Chicago Green Alley Handbook. Retrieved May 15, 2008, from <http://egov.cityofchicago.org/webportal/COCWebPortal/COC_EDITORIAL/GreenAlleyHandbook.pdf>.

66 See:

Claudio, L. 2008. Synthetic Turf: Health Debate Takes Root. Environmental Health Perspectives 116.3. Retrieved September 16, 2008, from <www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2265067>.

Aubrey, A. 2008. High Temps On Turf Fields Spark Safety Concerns. NPR Morning Edition, 7 Aug. Retrieved September 16, 2008, from <www.npr.org/templates/story/story.php?storyId=93364750>.