The Contribution of Pavements to Urban Heat Islands

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This paper presents results from a study of temperature changes in stormwater through a variety of common pavement systems. The study was conducted at a specially constructed field pavements lab consisting of eight sample pervious and impervious pavement systems and grass and gravel control surfaces. Measurable results of slabs exposed to summer sun indicate a range of pavement surface temperatures based on color and porosity. A time-based study of stormwater from simulated rainfall events illustrates changes in thermal absorption of stormwater runoff and leachate. Impervious pavements are gradually cooled by stormwater runoff while pervious pavements add more heat to stormwater leachate. All pavements indicates a thermal spike in stormwater within the first five minutes of simulated rainfall. Researchers conclude that impervious pavements are likely to increase thermal pollution of water bodies and to contribute to Urban Heat Island. Pervious pavements, though storing more heat, are likely to contribute little to Urban Heat Island.

Keywords: Stormwater runoff, Urban Heat Island, Pervious pavements, Thermal spike

Introduction

Environmental awareness in the United States has increased the demand for construction products and practices having low environmental impact (Dietz 2007). For over thirty years, the negative hydrologic effects of increased impervious surface have been presented by numerous authors (Laenen 1983; Booth and Reinelt 1993; Schueler 1994; Arnold and Gibbons 1996; Dougherty et al. 2007). Many research studies have documented the impact of intense storm events and urban land use practices on nonpoint source pollutant fluxes (Omernik 1976; Jordan et al. 1986; Haith and Shoemaker 1987; Osborne and Wiley 1988; Kronvang 1992; Correll et al. 1999; Dougherty et al. 2006a, b). As a consequence, pervious pavements have been increasingly promoted as an urban storm water management practice (Burton and Pitt 2001) and have been recognized by US EPA as a Best Management Practice for treating storm water runoff (US EPA 2013).

This study investigates the temperature change of stormwater runoff from impervious pavements and leachate from pervious pavements of the same material. Pavement surface temperatures and resulting water temperatures were compared for a variety of pervious and impervious pavements representative of commercially available paving and landscape surface materials.

Literature Review

Thermal impacts of impervious pavements on the urban environment are acknowledged but have been less intensely studied than related hydrologic effects. An urban heat island effect was described but not named as such in Howard's nineteenth century climatological observations of London (1818-1820). Nearly two centuries later, Abu Eusuf and Asaeda (1996) confirmed that surface temperatures of porous and nonporous pavements were 17°C higher than air temperature. They used numerical modeling to reveal that pore size is important for the transport of water vapor in the pavement. Stempihar et. al (2011) used diurnal temperature observations in Arizona to complete one-dimensional pavement temperature modeling that included pervious and impervious surfaces. They found that in general, porous asphalt exhibited higher daytime surface temperatures than comparable impervious asphalt because of reduced thermal energy transfer from the surface to subsurface. Porous asphalt also showed lower nighttime temperatures related in a complex way to its high air void content and unique insulating properties (Stempihar et. al 2011). In 2010, Barbis and Welker reported the effect of 12 storms on the temperature of water in infiltration beds beneath porous pavements as a form of temperature mitigation through conduction of warm stormwater. They found that the subsurface infiltration bed served as an effective sink transferring heat energy from the surface. A 2009 study by Kevern, Haselbach and Schafer focused on temperatures reading from embedded sensors at the mid-level for both pervious and impervious pavements using traditional concrete. Results of the study found that the temperature at mid-level of pervious concrete averaged 5^{0}C (9^{0}F) higher than impervious concrete during the hottest time of day.

The US EPA (2013) currently defines "heat island" as built up (urban) areas that are hotter than nearby rural areas, both on the surface and in the atmosphere. US EPA recommends several strategies to mitigate the heat island effect, including increased tree and vegetative cover, green roofs, cool or reflective roofs, and cool pavements. Cool pavements according to US EPA (2013) are designed to reflect more solar energy, enhance water evaporation, or are otherwise modified to remain cooler than conventional pavements. Currently, there is no standard or labeling program to identify or rate cool paving materials. The Transportation Research Board formed a subcommittee on Paving Materials and the Urban Climate to address design, testing, standards development, and policy considerations related to the urban heat island (TRB, 2009). In 2013, the Transportation Research Board cited numerous health, environmental, and economic justifications to curb the urban heat island (UHI) effect in major cities. Their report documents that urban centers are typically made up of 30-45% paved surface (TRB, 2013).

Objectives of Study

This study compares six pervious pavements (porous asphalt, light and dark pervious concrete, light and dark concrete pavers, and gravel) with three conventional pavement materials (impervious asphalt and light and dark concrete) and a grass cover.

The objectives of this study were to:

1. Compare the summer daytime surface temperatures of nine different pavement surfaces and a grass cover.
2. Compare continuous temperature changes in summer daytime runoff, leachate, and pavement surface of nine different pavement surfaces and a grass cover during and after simulated rainfall.

Methodology

In 2012, faculty members and students of Auburn University Building Science, Architecture, and Biosystems Engineering collaborated with facilities workers at the University on the design and construction of a field lab for comparative testing of selected pavement systems. The first experiment, which shaped the initial lab design, compared the temperature of stormwater heated by ten different pavement systems exposed to summer insolation. Results of that study (unpublished) demonstrated the utility of replicated test plots for evaluation of thermal pollution potential. In 2013, additional pavement cells were installed and extensive testing was conducted during the summer, which included data collected using thermal probes and imaging recordings of water and surface temperatures.

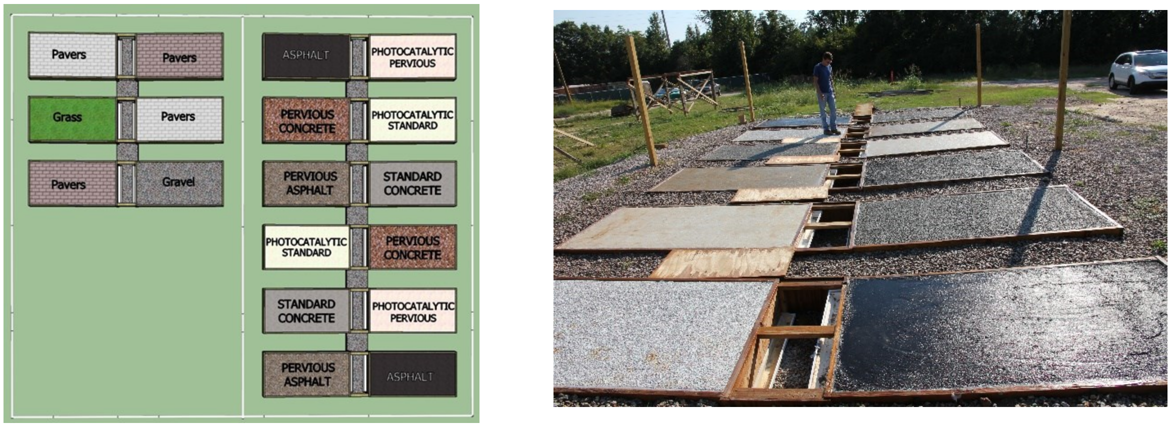

Figure 1: Field laboratory layout

The field lab layout (Figure 1) includes eighteen 4 ft. x 8 ft. duplicated test sections of the following materials: conventional and pervious concrete, conventional and pervious asphalt, conventional and pervious photocatalytic concrete, dark and light porous integrated concrete pavers, and control surfaces of gravel and asphalt (Figure 1). Each test section is cast within a 4 ft. x 8 ft. wood frame of treated 2x12's. A 6 in. thick slab is cast over a 6 in. thick subbase of drainable #57 graded limestone. The gravel bed provides a uniform subbase for all pavements as well as a stormwater reservoir typical of porous pavement systems.

Each 12 in. deep section is lined with 6 mil polyethylene plastic sheet to intercept leachate from the porous treatments. An irrigation system was installed to provide simulated rainfall onto each of the test surfaces and calibrated. Irrigation system was calibrated, an infiltration test (ASTM C1701) was conducted on each of the porous systems to determine surface infiltration rate.

Thermocouple recording

In the summer of 2013 data loggers were installed to record pavement temperatures on all test plots simultaneously using thermocouple probes (USB 501-TC, Measurement Computing, Norton, MA). Temperatures are recorded every 30 seconds beginning approximately 15 minutes before rainfall simulation with data loggers housed in waterproof containers during each test. Surface thermocouples are located at the center of each slab. Thermocouples in water are located in the center of water collection gutters at the base of each slab with trench openings covered by plywood to prevent solar gain on collected water (Figure 2). Thermocouples continuously tracked temperature changes during the 75-minute test period (15 min. full sun + 60 min. rainfall simulation).

Figure 2: Collection gutters with plywood cover to protect from heat gain.

Thermal probes with data loggers are effective to continuously record water temperatures, but have two recognized limitations when used for recording surface temperatures. Surface thermal probes can only read temperatures at one discrete location, which is not representative of the entire area. To further complicate surface temperature measurement, sensor contact at the surface of a pavement may be uneven allowing a large part of the sensor to be exposed to air circulation. To remedy deficiencies in thermocouple surface temperature measurement a more sophisticated but temporally discrete measurement thermal measurement and recording was used.

Thermal Image Recording

Thermal imaging was utilized to record and evaluate test plot surface temperatures before and after simulated rainfall events. The thermal imaging camera used was a Fluke® Ti32 (Everett, Washington – USA) selected for its accuracy, durability, portability, capability in both visible and infrared wavelengths, and on-screen emissivity correction and reflected background temperature compensation.

Thermal imaging used reflective light within thermal wavebands (7.5 µm to 14 µm (long wave)) to capture tens of thousands of temperature points across a field of vision. Excluding plot thermal edge effects, shadows, or obstructions to line-of-sight camera vision, thermal imagery offers a more comprehensive estimate of surface temperature than discrete temperature probes. Consequently, this study uses temperature probes for continuous measurement of surface and water temperature before and during rainfall events, and uses thermal imagery to capture and compare average plot surface temperatures both before and after simulated rainfall events. Imaged data was analyzed by using the Fluke SmartView® 3.5 software.

Thermal Camera Image Capture

Standing approximately two feet away from the edge of the slab, the thermal camera was pointed at the center of the slab. Upon gaining focus of the camera, the image was recorded. For each day of testing, consecutive thermal images were taken in succession with minimal delay between each data capture.

Temperature Logging and Analysis

Incoming city water temperature was also monitored and recorded throughout the test using a separate thermocouple. Weather data was recorded for each test date using digital weather station at the field lab. Temperature, humidity, and wind conditions were recorded between approximately 15 minutes prior and 15 minutes after each test.

Runoff, leachate, and surface temperature readings from duplicated pavement sections were recorded with the exception of grass and gravel plots, which were equipped with only one surface and one gutter thermocouple. Each test produced 36 sets of continuous temperature data, including 18 pavement surface temperature values and 18 gutter temperature values. Two thermal images per test plot were analyzed and recorded as pre- and post- rainfall average plot temperatures. All replicated data were averaged by treatment and pavement and color for more meaningful comparison.

Data Analysis

Average initial temperature of pavements in full summer sun during the 9-week study (Table 1) indicate that pervious pavements attained higher daytime temperatures than comparable impervious pavements. This observation confirms previously reported research about the higher daytime temperature of pervious compared to impervious pavements and questions the appropriate use of the term “cool pavement” when describing porous concrete and asphalt in hot urban centers during full sun.

Table 1: Surface Temperature Data Selected Materials (Thermal Imaging Camera) °F

Material	Average Start Temperature ^{0}F	Average End Temperature ^{0}F	Delta T ^{0}F	n =
Pervious Asphalt	133.5	102.6	30.9	30
Asphalt	128.3	105.6	22.7	28
Dark PICP Pavers	126.0	97.8	28.2	30
Gravel	122.0	90.6	31.4	15
Pervious Concrete	121.8	95.5	25.8	30
Pervious Photocatalytic Concrete	107.6	92.4	15.2	28
Concrete	107.3	96.5	10.8	30
Photocatalytic Concrete	101.2	92.0	9.2	28
Light PICP Pavers	113.0	92.1	20.9	30
Grass	99.9	89.9	10.0	14

*average end temperatures after 60 minutes of simulated rainfall

Gravel surfaces, the most porous of all material surfaces evaluated, had the highest observed infiltration rate, and was among the surfaces with the highest observed pre-test (122°F) surface temperatures. All pervious materials regardless of color and material type (asphalt, concrete, and photocatalytic concrete) when averaged together had nearly the same pre-test, full sun surface temperature (121.5 °F). Differences among porous pavements themselves became a function of color, with the darkest and most porous material (pervious asphalt 133.5°F) having the highest pre-test surface temperature. Light and dark pavers, considered hybrid pavement having both pervious and impervious properties were found on average (119.5°F) to be cooler than pervious asphalt and concrete (avg. 128.3°F) and hotter than impervious asphalt and concrete (avg. 117.9 °F). All surfaces evaluated in full sun, were observed to be hotter than grass (99.9 F), which in this study best captured the description "cool surface."

Average thermal camera temperature values were compared by correlation with corresponding discrete thermocouple temperatures to validate thermal image temperature estimates. Correlation of all recorded surface thermocouple results with corresponding average thermal image temperatures was 0.83. Authors are satisfied that this high correlation (Figure 3) validates thermal imaging temperature estimation used in this study.

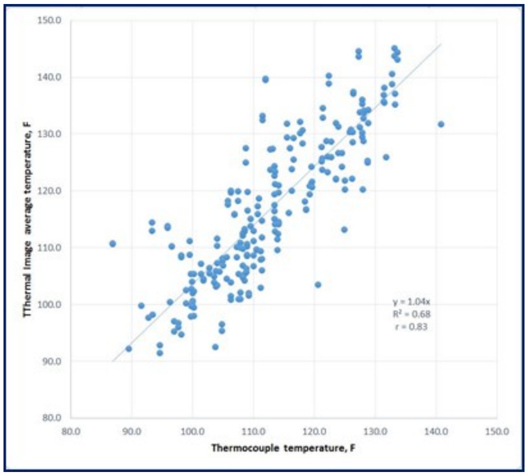

Figure 3: Average surface temperature correlation (all surface materials): average thermal image temperature vs. surface thermocouple temperature.

Figure 4 plots slab surface temperatures (solid lines) and water runoff temperatures (dashed lines) from impervious test slabs. Temperatures were obtained from a thermal probe taped to each slab surface and one in the runoff collection gutter for each slab. All graphs show a gradual cooling of the surfaces over the hour-long precipitation. A rapid temperature increase (thermal spike) in runoff temperatures typically occurred within the first five minutes after a rain event.

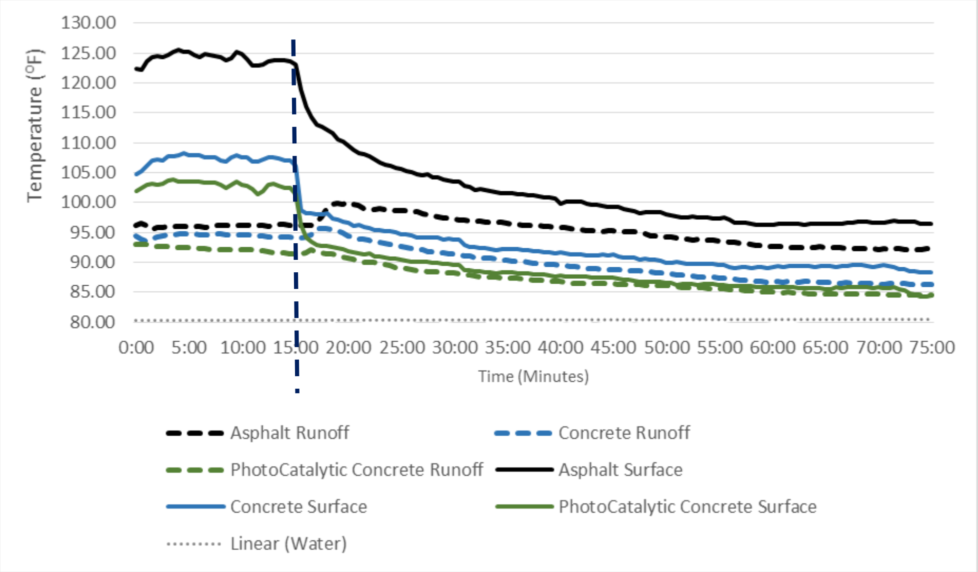

Figure 4: Impervious Surface and Water Temperatures by Thermal Probe

Figure 5 plots pervious surface and leachate water temperatures verses time. At the beginning of the test pervious asphalt is the hottest surface at 120°F, followed by pervious concrete at 110°F, then pervious concrete at 105°F. All surfaces are cooled by the rainfall dropping to 91°F, 87°F, and 82°F respectively. Interestingly, a gradual rise occurred in leachate temperatures from 85°F to 95°F for pervious asphalt, 91°F for pervious concrete, and 86°F for pervious photocatalytic concrete. All leachate temperatures rise above and cross pervious surface temperatures before reaching equilibrium temperature, as opposed to impervious surfaces (Figure 4) which tracked and cooled consistently. A more subtle thermal spike occurred in the leachate collected from the pervious pavements. This spike is indicated by a steepening of curve slope followed by a flatter slope, occurring within 5 minutes following the start of rainfall. Note that leachate water temperatures continue to rise after the spike, but at a slower rate.

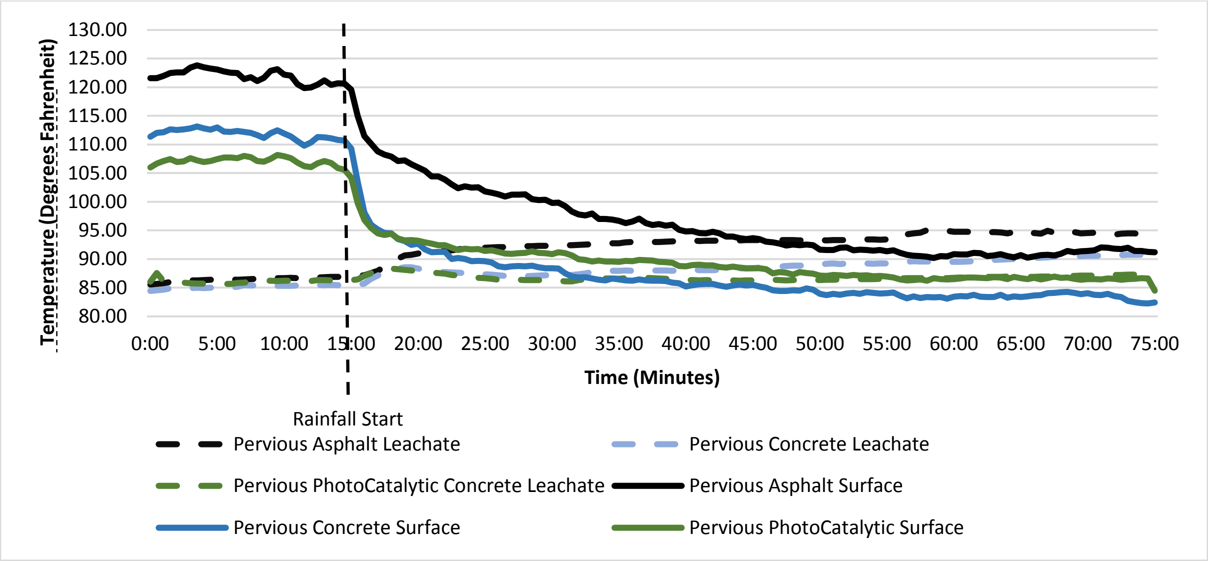

Figure 5: Pervious Surface and Water Temperatures by Thermal Probe

Discussion and Conclusions

Environmental benefits of pervious pavements include the treatment of stormwater runoff surges within the first 15 minutes, often called the "first flush," and immediate storage and potential recharge of a portion of precipitation events. Because of increased environmental concern regarding the urban heat island effect this study examines the surface, runoff, and leachate temperatures of various pervious and impervious pavement surfaces compared to grass. Pervious pavements in this study appear to be effective heat exchangers compared to impervious surfaces of the same material. This thermodynamic feature may be considered both an advantage and a disadvantage as water from rains can quickly dissipate heat from pervious urban surfaces in the daytime, but charge receiving waters with a slug of heated leachate. Of course, due to the detention/retention stormwater capability offered by properly designed and installed pervious pavement systems, heated leachate will likely be cooled by the time it reaches potential receiving waters. Research has shown that as much as 93% of stormwater captured by pervious pavements is infiltrated into subgrade soils and therefore will not reach any receiving waters (Estes 2009). Impervious pavements in full sun do not on average attain such high surface temperatures and tend to reach a temperature equilibrium with falling rainfall more quickly than pervious pavements. Implications of the dynamic heat exchange mechanisms of conduction and insolation during daytime and nighttime were not investigated in this study, but provide opportunities to further quantify thermal properties of urban pavements across day and nighttime conditions. Clearly, both impervious and pervious surfaces sustain a large initial temperature rise (shock) due to the conduction of water hitting a hot surface. Comparative thermal storage within the pervious pavement during day and night conditions requires more quantitative investigation to estimate heat transfer to water.

Pervious pavements observed in this study appear to provide better conduction and transfer of heat from surfaces exposed to solar radiation. The lighter color of the pavement surface has a reflective effect on both pervious and impervious to reduce heat. Lighter colors have a greater impact on reducing impervious surface temperatures due to their irregular surfaces. Pervious surface leachate temperatures are observed to rise steadily throughout the experiment to a temperature higher than impervious runoff. This result is unexpected and indicates that pervious pavements under full summer sunlight have higher capacity to transfer sustained solar heat gains than impervious surfaces, all other conditions being equal. Impervious surface runoff temperatures, although initially high under full insolation, cool more steadily than pervious surfaces, approaching steady-state temperature conditions that approach incoming water temperature. This result is expected, similar to water on a hot pan conducting heat away from the surface. What that means for the urban heat island (UHI) effect and downstream water quality will require further study under more controlled conditions than available in the current study.

In Summary, this research project compared the summer daytime surface temperatures of nine different pavement surfaces and a grass cover over a 9 week period in the hottest part of an Alabama summer. Results indicate that darker pavements were hotter, while more reflective lighter pavements were cooler. Pervious pavements in full sun were observed to be hotter than impervious pavements of the same material. Hybrid paver system pavements were somewhere in between. Grass was the coolest of all surfaces tested. Researchers suggest that grass surfaces might be used as a reference by which to measure all so called “cool pavements”.

The research also compared continuous temperature changes in summer daytime runoff, leachate, and pavement surface of nine different pavement surfaces and a grass cover during and after simulated rainfall. The impervious pavements provided more rapid temperature rise in rainfall runoff than pervious surfaces. Stormwater runoff temperatures along with impervious pavement surface temperatures steadily decreased by continuous rainfall over the 60 minute test period. However, although impervious pavement surfaces were cooled by rainfall, stormwater leachate temperatures gradually increased over the course of the test, indicating accumulating heat within the leachate due to 1) deeper penetration of solar heating within the pervious pavements and 2) greater heated surface contact area available to the leachate trickling through the pervious slabs.

A thermal spike was identified in all stormwater runoff from the impervious pavements. This spike occurred within the first 5 minutes of exposure to rainfall. It is this spike that could be the most threatening to nearby bodies of water and the aquatic life they support.

In spite of higher surface temperatures of porous vs. nonporous pavement, the stormwater thermal pollution impacts of using impervious surfaces is a net positive effect due to detention and retention of stormwater captured in these pavements, since all stormwater in properly designed, installed, and maintained pervious pavement systems is detained or retained within the system and rarely has an opportunity to come in contact with water bodies (Estes 2009). One surprising result of this study is the apparent higher heat captured by pervious pavements compared with impervious ones. The implications for heat island effects on urban environments are important and should be studied further. The effects of landscaping vegetative cover provided by complementary natural systems could play an important role in cooling hot pavements.

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