EPiC Series in Built Environment

Volume 2, 2021, Pages 644–652

ASC 2021. 57th Annual Associated Schools
of Construction International Conference

Effects of Pervious Concrete Thickness on Leachate Water Temperature during Simulated Rain Events

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As construction continues to alter the horizon and cities continue to expand, increased emphasis has been placed on construction materials. Concrete, a widely used material in the construction industry continues to increase the temperature of urban environments in what is called heat island effect. Stored heat on a concrete surface can negatively impact the temperature of stormwater runoff by transferring heat to water running over the heated concrete. This research study showed that impervious concrete retained heat longer after simulated rainfall when compared to comparable pervious materials. Results from this study also indicated that pervious test cells with an infiltration rate above 3,000 in/hr offered greater transfer of heated water (as leachate) away from surface flows. Within this research both 4” and 6” thick pervious concrete test cells (12”x12”) were compared with respect to leachate water temperatures. Leachate water temperature from 6” pervious concrete was cooler than that from 4” pervious concrete due to the 6” cells having a larger thickness of concrete in which to absorb and retain more heat. The ability of pervious concrete to leach stormwater provide greater opportunity for site-specific, sustainable options comparable to comparable impervious materials.

Key Words: Impervious, Leachate, Pavement, Pervious, Stormwater

Introduction

Pervious concrete, also known as permeable or porous concrete, is known for its ability to allow water to pass through by gravity at rates in excess of 1000 inches/hr into the design media below it. Pervious concrete mix differs from traditional concrete mixtures in that it lacks fine aggregates. With little to no fine aggregates in a pervious concrete mix, surface water is able to move through open voids (approximately 18% porosity) quickly, unimpeded by capillary forces. Pervious concrete, although not commonly used in commercial construction, is commonly used for flatwork applications such as driveways and parking lots. These types of low-load areas can nevertheless receive a high volume of urban stormwater with runoff that can cause negative downstream effects such as flooding and accompanying property damage. Stormwater runoff occurs in almost every region of the United States, with more severe runoff events resulting from locally heavy rainfall. According to Tennis et al. (2004), the use of pervious concrete is recommended for the management of stormwater runoff on both a regional and local basis. The use of pervious concrete in the built environment has sparked

T. Leathem, A. Perrenoud and W. Collins (eds.), ASC 2021 (EPiC Series in Built Environment, vol. 2), pp. 644–652

interest in related research such as the role pervious concrete may play in urban stormwater heat mitigation.

As construction in the United States continues to expand the urban footprint laterally, landscapes that were natural are now home to large cities with impervious buildings and accompanying hardscape such as sidewalks, parking lots, and interconnected roads. This change, though beneficial to those who call these cities home, also has negative environmental consequences such as increased pollution in runoff and increased risk of flooding in downstream communities. The built environment affects the ability of the now urban surface to store heat. This phenomenon is known as the heat island effect and is common in most cities across the United States. According to the EPA (2019), the annual mean air temperature of a city with 1 million people or more can be 1.8-5.4 °F (1-3 °C) warmer than its surroundings. This temperature increase can negatively affect vegetation within the city as well as require increased in energy consumption for cooling in homes, businesses, and institutions. During a summer time storm in an urban area, as stormwater flows across heated urban surfaces the temperature of the runoff tends to increase as it absorbs and accumulates heat. This rise in temperature can be simulated and measured in a laboratory as a thermal ‘spike’ that may have adverse effects on downstream environments including aquatic flora and fauna.

Research Aims

The aim of this research was to evaluate the thermal properties and runoff temperature of 4” thick impervious concrete versus leachate from two pervious concretes (4” and 6” thick) and observe differences in the ability of each to transfer and/or absorb heat from urban runoff.

Research Objectives

1. To evaluate and record leachate water temperatures in two thicknesses of pervious concrete (4” and 6”) using temperature sensors placed on the surface, mid-section, and leachate outflow, while conducting simulated rain events.

2. To evaluate and record runoff water temperatures on 4” thick impervious concrete using temperature sensors placed on the surface, mid-section, and outflow, while conducting simulated rain events.

3. To compare data collected from pervious concrete studies to data collected in impervious concrete studies and evaluate the ability of each to transfer and/or absorb heat from urban runoff.

Literature Review

When reviewing literature pertaining to the thermal properties of concrete, there are several related topics of interest, including urban heat island effect, economics of pervious concrete versus traditional concrete, sustainable design, and low impact or green infrastructure design. These topics indicate that there is wide interest in the built environment to mitigate the negative impacts of our increasingly urban footprint. On the topic of concrete thickness and its thermal relationship to runoff temperature, there was no previous literature found regarding this subject. As the heat island effect increases within cities in the United States and worldwide, pervious concrete research such as the current research provide data to help us better understand the thermal impacts of our pavement designs.

Lorenzi et al. (2018) at the University of the Rio Grande in Brazil conducted a study of an existing pervious parking lot instrumented to monitor and collect surface temperatures and evaporation rates to determine subsequent heat transfer. Readings recorded included temperatures taken at the surface, mid-section and collected leachate outflow points from the pervious concrete. Water used to simulate a rainfall event was placed in a container outside to warm and poured over the pervious concrete once it reached ambient temperature. Data reported that initially, the temperature spiked due to the temperature difference at the concrete surface (Figure 1) as the water leached through the pervious concrete. As a result, outflow temperature was reduced due to heat transfer within the pervious concrete. As the water continued to exit, the pervious concrete temperature continued to decrease, further minimizing the negative effects of the heated stormwater. Results reported from this study indicate the potential for pervious concrete to mitigate temperature spikes in stormwater. Additional findings by these researchers noted that within the pores of the pervious pavement during leaching, evaporation occurs and this evaporative cooling effect is itself significant.

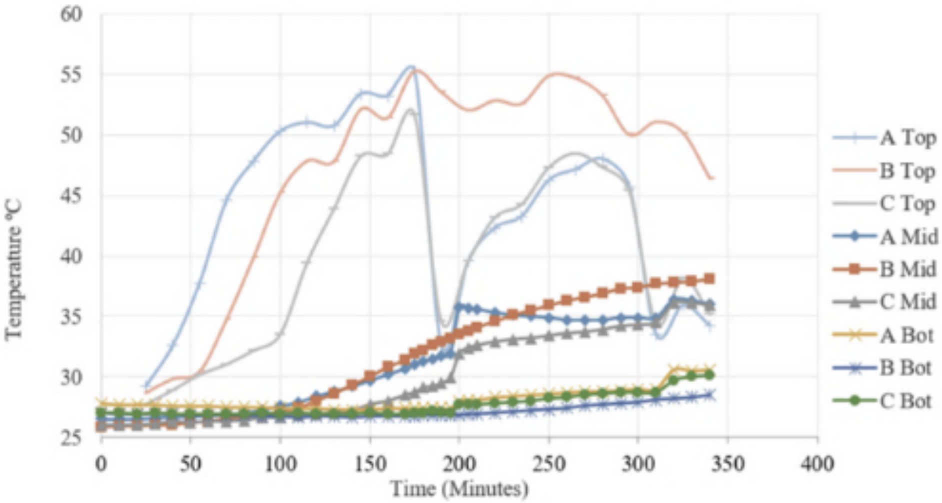


Figure 1: Temperature spike due to heat difference at the concretes surface. (Lorenzi et al., 2018)

Lu et al. (2019) in China studied an alternate concrete mix thought to be more environmentally friendly compared to traditional mix. Recycled concrete, commonly seen in landfills across the world, was used as aggregate in their mix. Since pervious concrete has very few fine aggregates, researchers chose to use waste glass cullet (WGC) to replace traditional fine aggregate and tested its structural properties, permeability, and thermal conductivity. While studying the thermal conductivity of this mix, researchers expected the created mixture to have a lower thermal conductivity compared to traditional mix because glass has a lower thermal conductivity rate compared to rock. Results below in Figure 2 indicated that without glass in the mix, the thermal conductivity of the mixture is increased.

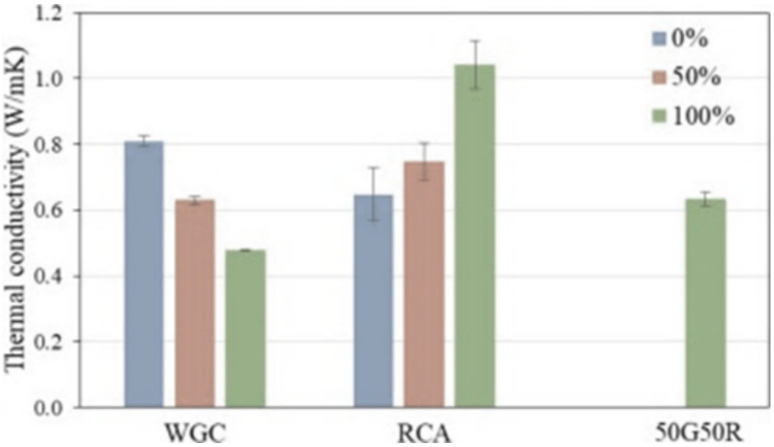


Figure 2: Results showing that glass has a lower thermal conductivity rate compared to rock (Lu et al., 2019).

Pervious concrete can be a sustainable alternative to a pavement building material where surface infiltration is desirable and where harmful stormwater runoff characteristics such as specific pollutants and/or temperature may be a concern. Additionally, pervious concrete has a life cycle that is comparable to traditional concrete (Concrete Network, 2018).

Methodology

This research methodology is primarily data-driven, with experimental data collection conducted in the Green Infrastructure Lab at the Center for Advanced Science, Innovation, and Commerce (CASIC) building at Auburn University. Researchers evaluated impervious versus pervious test cells to evaluate the ability of 4” and 6” thick pervious test cells to transfer heat via leachate water. All test cells measured 12”x12” and included replicated 4” pervious concrete, 6” pervious concrete, and 4” impervious concrete cells. Within the experimental setup, surface temperatures and runoff temperature from 4” impervious concrete served as a control against comparable surface temperatures and leachate temperature from pervious test cells.

All concrete test cells (Figure 3) were heated uniformly for approximately 5 hours to reach steady-state temperature and replicate maximum summertime pavement temperatures immediately before a storm event. Water sprinklers simulated rainfall onto all concrete test cells for approximately 1 hour. During rainfall simulation, temperature sensors recorded concrete temperature at the surface, concrete mid-section, and water outflow at each test cell. The continuous temperature record (10 second interval) began when the heat lamps were turned on and concluded 1 hour and 45 minutes after the sprinklers were turned off.

Lab Setup

The lab design and configuration provided sufficient space for replicated pervious concrete test cell observations. Fabricated test cell racks provided for 16 independent observations, only 12 of which were used in this study. Per Figure 3, below, pavers and gravel test cell locations were left empty and reserved for future studies.

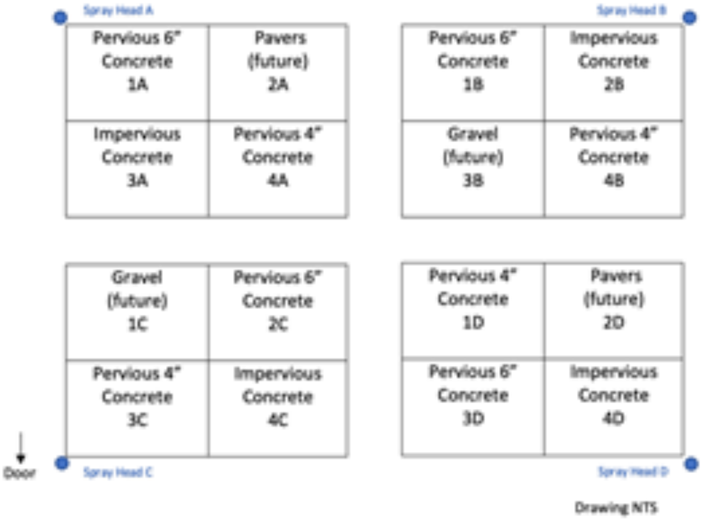


Figure 3: Plan View of Green Infrastructure Lab pavement test layout. Note: gravel and paver test cells (2A, 3B, 1C, and 2D) are reserved for future study and were not included in this research study.

Figure 4: Photo of the Green infrastructure Lab Layout with empty test cells before concrete was placed. Note heat lamps positioned above each rack of three concrete test cells and PVC sprinkler risers positioned at each corner of the test area for rainfall simulation.

In this research, 12 individual test cell boxes were designed to allow for uninterrupted water flow through each pervious test cell box into underdrain containers. Impervious test cells were fitted with runoff collection containers on the side to collect flow from sloped impervious surfaces. Test cell boxes were constructed of pressure-treated 2” x 12” lumber with inside dimensions of 13” x 13”. Each boxes was treated with water sealer to prevent water penetration in the wood. To support the weight of the gravel and concrete 3 - 3/8” rods were placed horizontally at the bottom of each box. To provide support as well as uninterrupted water flow through the box, a 12” x 12” rack of expanded metal was placed on top of the rods to contain concrete cells with underlying gravel.

Sprinkler Layout

As previously stated, the objective of this research is to test and compare impervious and pervious concrete performance with respect to runoff temperature mitigation under heating followed by simulated rain events. To achieve uniform precipitation across all test cells, four Hunter MP1000 Plastic Rotary Nozzles manufactured in the United States were attached to Rainbird Model 1806 spray bodies and operated at a water pressure of approximately 30 PSI to provide a 100% overlapping 8ft radius of throw from each corner sprinkler to cover the test area.

Heat Lamps

Heat lamps used in this experiment were Solaira Alpha 120V- 1500 Watt Weatherproof Infrared Heaters (Mississauga, Ontario, Canada). A total of 4 heat lamps were suspended above the experimental area and used to heat the concrete test cells (Figure 4). Heat lamps were suspended 24 iches above concrete test cells to provide uniform heat intensity. Each test cell was heated for approximately 5-6 hours or until surface temperature readings within the concrete reached equilibrium.

Concrete Test Cells

Concrete test cells were pre-cast prior to installing the concrete in cell boxes (Figure 4). A RocTest® TH-T 3 Kohm temperature sensor (Quebec, Canada) was embedded in the mid-section of each concrete form prior to pouring the concrete (Figure 5).

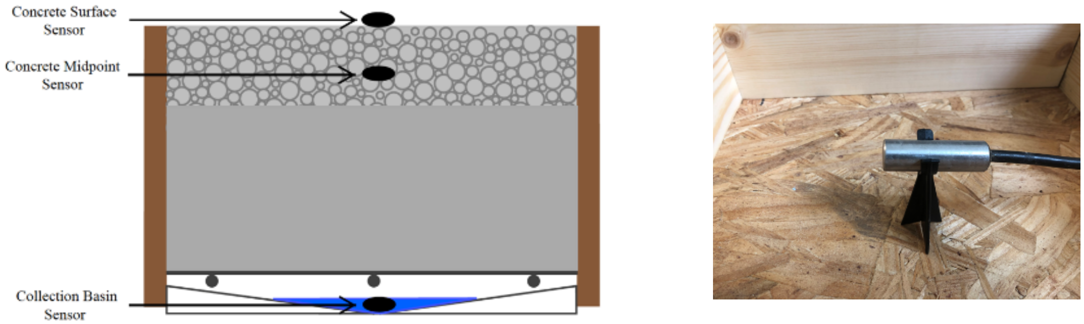
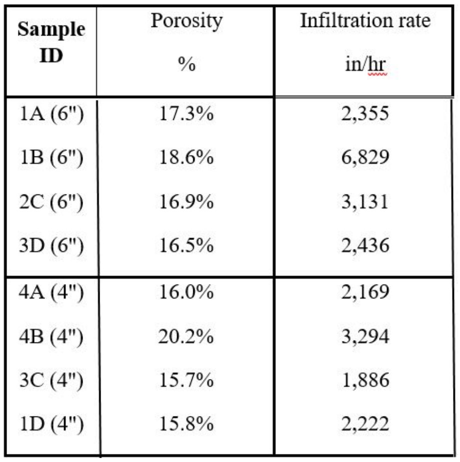


Figure 5 Temperature Sensor Diagram (pervious) and mid-point sensor in concrete form.

Pervious Concrete Mix Specifications and Resulting Porosity and Infiltration Rate

This experiment evaluated pervious concrete to achieve an optimal infiltration rate while still maintaining structural integrity that can be used in commercial applications. American Concrete Institutes (ACI) guidelines for pervious concrete were followed in this study. The pervious concrete mixture will be designed to meet the National Ready-Mix Association specifications. Pervious concrete test cells were hand-mixed, poured, covered with plastic, and allowed to cure for 7 days before being removed from forms.

A porosity test of resulting pervious concrete cells was determined for each pervious test cell used in this experiment. Porosity was calculated as the percent of open voids in the pervious concrete. The process used to calculate porosity in this study was the water displacement method. Infiltration rate was determined by 8” single-ring infiltrometer constructed by Auburn University researchers. Results of porosity and infiltration tests are shown in Figure 6, below.



Sample ID	Porosity %	Infiltration rate in/hr
1A (6")	17.3%	2,355
1B (6")	18.6%	6,829
2C (6")	16.9%	3,131
3D (6")	16.5%	2,436
4A (4")	16.0%	2,169
4B (4")	20.2%	3,294
3C (4")	15.7%	1,886
1D (4")	15.8%	2,222

Figure 6. Porosity and Infiltration Results for Pervious Pavement Test Cells (average porosity of pervious cells = 17.1%, average infiltration rate = 3,040 in/hr).

Temperature Testing Results

Three simulations were conducted in this study. The testing was divided into three phases that lasted approximately 7 hours and 15 minutes, including a heating cycle of five consecutive hours followed by a cooling cycle in which simulated rainfall was introduced for one hour. Sprinklers were turned on immediately after heat lamps were shut down with post-study “cool-down” temperature monitoring continuing for an additional 1 hour and 15 minutes after the sprinklers were turned off (in order to observe any difference in cooling trends created in the three study materials). Temperature results are shown below in Tables 2-4.

Table 2: Test Simulation #1 Results (all temperatures in degrees Celsius).

4” vs 6” Pervious Concrete						
	Surface Sensor		Midpoint Sensor		Outflow Sensor	
	4”	6”	4”	6”	4”	6”
Average Temperature	35.33	35.03	33.40	28.66	23.89	23.46
High Temperature	44.43	43.44	43.04	35.21	26.16	25.40
Low Temperature	20.54	20.90	20.04	20.02	19.95	19.67
Standard Deviation	8.29	7.87	6.48	4.59	1.51	1.28
Median Temperature	39.18	38.90	33.73	29.67	24.31	23.94

Table 3. Test Simulation #2 Results (all temperatures in degrees Celsius).

Pervious 6" Concrete			
	Surface Sensor	Midpoint Sensor	Outflow Sensor
Average Temperature	34.84	28.45	23.34
High Temperature	43.57	35.32	25.27
Low Temperature	20.58	19.49	19.05
Standard Deviation	8.14	4.71	1.74
Median Temperature	38.76	29.39	24.06

Pervious 4" Concrete			
	Surface Sensor	Midpoint Sensor	Outflow Sensor
Average Temperature	35.16	33.50	23.31
High Temperature	44.57	43.60	25.62
Low Temperature	20.25	19.71	19.42
Standard Deviation	8.68	6.73	1.71
Median Temperature	39.23	33.79	23.79

Table 4. Test Simulation #3 Results (all temperatures in degrees Celsius).

Pervious 6" Concrete			
	Surface Sensor	Midpoint Sensor	Outflow Sensor
Average Temperature	34.59	28.65	23.82
High Temperature	43.29	35.50	25.48
Low Temperature	20.70	19.70	19.37
Standard Deviation	7.72	4.71	1.62
Median Temperature	38.12	29.63	24.47

Pervious 4" Concrete			
	Surface Sensor	Midpoint Sensor	Outflow Sensor
Average Temperature	35.45	33.67	23.67
High Temperature	44.92	43.75	25.90
Low Temperature	20.33	19.86	19.61
Standard Deviation	8.42	6.64	1.61
Median Temperature	39.24	33.89	24.14

Conclusions

Pervious and impervious concrete test cells were evaluated in this study to assess the effects of heat mitigation on urban stormwater from different pavement materials and thicknesses. The study focused on a comparison of 4” and 6” pervious concrete against impervious test cells as control. Although both the 4” and 6” pervious test cells behaved similarly in this study with respect to thermal impact on stormwater leachate, there were several areas where the two surfaces deviated slightly. All three surfaces underwent a heating cycle to simulate solar heating from natural sunlight. During the heating cycles, both pervious concrete surfaces heated quickly due to the change in heat brought on by the heat lamps. The greatest increases in temperature were observed from the start of the heating cycle to the 30-minute mark. Throughout the remainder of the study, the 4” pervious test cells were observed to reach a higher surface temperature compared to the 6” pervious test cells. The cause of this faster rise in temperature was directly related to test cell thickness. The 4” pervious test cells with less volume (and mass) heated quicker under the heat lamps. When the cooling cycle began with water was applied, the results were reversed. During cooling, the larger volume and mass of concrete associated with the 6” pervious test cells resulted in a slower cooling rate compared to the 4” pervious test cells. Thus, the 4” pervious test cells more quickly dropped in temperature, eventually falling below the 6” pervious test cells in temperature.

When compared to the impervious test cells, both pervious test cells heated quicker which contradicts the often held opinion that pervious concrete is ‘cooler’ than impervious concrete. During the cooling cycle, however, pores associated with the pervious concrete appeared to allow all pervious test cells to cool much faster than the impervious test cells.

When evaluating the results from this study it is clear that varying concrete thickness changes its thermal properties due mainly to the difference in mass. Pervious concrete is unique in that surface water can flow through its pores vertically by gravity unlike impervious concrete, which requires the water to runoff horizontally. In this study, 6” pervious concrete had slightly cooler temperatures than the 4” impervious concrete, but in heating conditions both 4” and 6” pervious concretes had warmer surface temperatures than the impervious concrete.

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