INFLUENCE OF PERMEABLE INTERLOCKING CONCRETE PAVER PERFORMANCE ON INFILTRATION AND TEMPERATURE IN AN URBAN WATERSHED

By

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ABSTRACT

Urbanization is a form of land use change that typically results in an expansion of impervious surfaces and increased soil compaction. These urban-induced changes in watershed hydrology can result in stream channel erosion, degraded water quality and stream aquatic habitat, increased ambient air temperatures, and increased peak flows, all of which pose challenges to stormwater management. Recent efforts to improve stormwater treatment have included the implementation of green stormwater infrastructure (GSI), which include a range of measures that use plant or soil systems, permeable surfaces or other features to store, infiltrate, or evapotranspire stormwater and reduce flows to storm sewer systems and surface waters. Permeable Interlocking Concrete Pavers (PICP) are one type of GSI implemented in urban settings to reduce runoff through infiltration of stormwater at its source. Over the past decade, East Carolina University has been implementing GSI on their Greenville, NC East Campus, and has installed approximately 0.3 hectares (3,000 square meters) of PICPs, to reduce flooding and ponding and urban stormwater impacts to local streams. Surface infiltration rates were measured at 18 PICP, 10 forested, 21 campus lawn, and 12 fractured asphalt locations to evaluate the effectiveness of PICPs on campus. Infiltration rates between the groups were significantly different ($p < 0.05$). The median infiltration rate of PICP sites was 587.41 cm/h and it was estimated that peak discharge to local streams may be reduced by approximately 11.47 cubic feet per second (cfs) with current PICP installations. Regular asphalt (RA) sites were tested for infiltration where fractures in the pavement intersected, with a median infiltration rate of 3.8 cm/h; however, there were not enough data to draw conclusions on the secondary permeability of fractured asphalt in this study. Forested and campus lawn soils had median infiltration rates of 5.46 cm/h and 0.95 cm/h, respectively. A total of 93 soil cone index values (kPa) were taken at campus lawn ($n = 63$) and forested ($n = 30$) sites to determine the effect of existing surface conditions on infiltration rates. There was a significant difference between infiltration rates ($p = 0.007$) and maximum compaction values ($p = 0.000$) for forested and campus lawn sites. Surface temperatures were taken at each PICP site and RA parking lots for comparison. Recorded surface temperatures for both asphalt and PICP were lowest between 9 pm and 6 am, with the median temperature of asphalt being 1.64 °C warmer. Data collected and analyzed from this study showed that fractured asphalt and campus lawns had significantly lower infiltration rates compared to forested soils and PICP installations. Moreover, relative to PICPs, asphalt displayed elevated surface temperatures for longer periods of time that contribute to local environmental warming. The results in this study indicate that PICPs are effective in sandy soils for the management of stormwater runoff in urban settings as an alternative or addition to traditional gray infrastructure (pipes, ditches, concrete curbs, and culverts), and PICPs have the potential to minimize effects of the UHI by maintaining lower nighttime temperatures and shorter periods of peak temperatures.

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LIST OF SYMBOLS AND ABBREVIATIONS

AgB – Alaga loamy sand

Bb – Bibb complex

BA – bioretention areas

BMP – best management practice

C – rational coefficient

Crb – Craven fine sandy loam

DRI – double-ring infiltrometer

DWT – depth to water table

EIA – effective impervious area

ExB – Exum fine sandy loam

GMR – Greens Mill Run

GSI – green stormwater infrastructure

IC – impervious cover

IDF – intensity-duration-frequency

ISA – impervious surface area

LID – low impact development

MDC – Minimum Design Criteria

OcB – Ocilla loamy fine sand

Pa – Pactolus loamy sand

PA – porous asphalt

PC – pervious concrete

PCC – Portland cement concrete

PICP – permeable interlocking concrete pavers

PP – porous pavement

RA – regular asphalt

RSC – regenerative stormwater conveyance

SCM – stormwater control measure

SCW – stormwater constructed wetland

SHWT – seasonal high-water table

SIR – surface infiltration rate

SLR – sea level rise

SRI – single-ring infiltrometer

TIA – total impervious area

UHI – urban heat island

WaB – Wagram loamy sand

WaC – Wagram loamy sand

INTRODUCTION

The transition from rural to urban communities in the U.S began in the 1920's (Tippett, 2016). In North Carolina, the migration from rural to urban areas did not cross the majority threshold until 1990, when 50.4% of residents lived in urban communities (Tippett, 2016). In addition to metropolitan centers, North Carolina is an attractive location for seasonal homes and retirees. North Carolina ranked ninth in the nation in 2018 for residents 65 and older, with approximately 42,000 over 60 that moved from other states and abroad (NCDHHS, 2018). With population growth and the expansion of suburban and urban areas, comes the increase in impervious surfaces. Projections of urbanization between 2009 and 2060 for the Southeastern U.S. show the largest land-use conversion is from agricultural to urban, resulting in 11% - 21% of farmland converted to urban development (Terando *et al.*, 2014).

Stream hydrology is altered as natural systems are converted to agricultural and urban environments in response to population increases; deforestation, channelization, and stream burial are common as land-use intensifies with urbanization (O'Driscoll *et al*, 2010a; Violin *et al*. 2011). The increase in impervious area is often followed by the impairment of stream function and alteration of stream hydrology and channel morphology, reducing low order streams to storm drainage systems (Kaushal and Belt, 2012; O'Driscoll *et al*, 2010a; Schueler *et al.*, 2009; Vietz *et al.*, 2016). The physical, chemical, and ecological impairments to streams caused by urbanization are collectively referred to as "Urban Stream Syndrome" (Askarizdeh *et al.*, 2015; Walsh *et al.*, 2005). In addition to impaired stream function, a higher density of impervious area contributes to higher environmental temperatures and the "Urban Heat Island" effect (Stempihar *et al*., 2012).

The effects of increasing temperatures in urban centers due to climate change pose public health concerns, particularly for the elderly and low-income communities (Kunkel *et al*., 2020). Impervious surfaces include buildings, parking lots, sidewalks, roads (total imperviousness) and formal drainage systems (effective imperviousness) that reduce infiltration of precipitation, increase surface runoff, and increase urban air temperatures.

Historically, watershed planning has primarily focused on the effective transport of surface runoff in urban areas to surface water bodies for protection against flooding and economic damages (Ellis and Marsalek, 1996). The portion of impervious area associated with direct transport is effective imperviousness (EIA), consisting of impervious surfaces that directly drain to piped storm sewer systems and discharge into local streams (Brabec *et al.*, 2002; Askarizadeh *et al.*, 2015). Headwater, or low order streams play a significant role in the exchange of material between upland areas and downstream coastal waters and are commonly buried in urban watersheds, reducing their capability to filter and soak up runoff (Elmore and Kaushal 2008). The process of stream burial ranges from directing water into concrete-lined ditches to covering streams in a concrete and brick culvert system, resulting in contaminant flow directly to streams. As a result of stream burial in the City of Greenville, NC, Hardison *et al.* (2009) found that drainage density decreased by approximately 40% compared to surrounding rural watersheds.

The destruction of natural channels can inhibit the function of streams and adjacent riparian zones to filter contaminants in runoff, absorb overland flow, recharge groundwater, and prevent erosion (O'Driscoll *et al*., 2010a; Rheinhardt *et al.*, 2007; Violin *et al*., 2011). Nutrient sensitive watersheds in the North Carolina Coastal Plain are particularly susceptible to excess nitrogen and phosphorus inputs from runoff associated with agricultural and urban wastewater and fertilizers, resulting in eutrophication and fish kills (U.S. EPA, 2013). Under natural conditions, floodplains and riparian buffers reduce surface temperatures and aid in the infiltration and percolation of overbank flow to recharge the groundwater system. In addition, these buffers act as filters to remove pollutants that would be transported downstream by sediment or in the water column (Rheinhardt *et al.*, 2007). While stormwater conveyance infrastructure is designed to prevent flooding, increase in impervious cover exacerbates the loss of stream function in urban settings (Brown *et al.*, 2010; Kaushal and Belt, 2012).

Impervious surfaces increase runoff and the frequency of flooding, creating streams that behave in a flashy manner by exhibiting decreased lag time between precipitation events and increased discharge (Vietz *et al*., 2016; Walsh *et al.*, 2005). Contaminant input is increased by point (industrial discharge) and nonpoint sources (leaking underground storage tanks, aging infrastructure, stormwater runoff), entering streams directly through stormwater infrastructure or by interacting with groundwater (Kaushal and Belt, 2012; O'Driscoll *et al.*, 2010a). Humphrey *et al.* (2018) found that 45% of baseflow and 80% of stormflow samples collected from an urban stream in Greenville, NC exceeded the EPA threshold for *E. coli* concentrations. Streams draining urban land respond by deepening and widening because of bank and channel erosion and exhibit a much simpler habitat than forested streams – less woody debris, disconnected or absent riparian zones, and disconnected floodplains (Koryto *et al.*, 2017; Vietz *et al.*, 2016). Previous studies conducted on rural and urban streams in the Inner Coastal Plain of NC found increased channel incision and decreased stream habitat in streams that drained watersheds with higher percentages of TIA (Hardison *et al*, 2009; Robbins, 2017; Soban, 2007). Based on previous work by Schueler *et al*. (2009), impacts of impervious cover on stream health are interrelated and range depending on the extent of development in an area, with streams exhibiting initial signs of impairment when watersheds contain > 10%-25% total impervious cover.

A high density of impervious area, including buildings and paved surfaces, contributes to higher environmental temperatures in the urban setting referred to as the urban heat island (UHI) effect (Stempihar *et al.*, 2012). Frequency and duration of warmer temperatures in urbanized areas, compared to rural surroundings, can negatively impact communities without access to adequate cooling (Kunkel *et al*., 2020). Heat generated from impervious surfaces not only increases ambient temperature but disrupts air circulation, resulting in urban induced rainfall (O'Driscoll *et al.*, 2010a). In addition to higher temperatures and more frequent precipitation events, runoff from impervious areas can increase stream temperatures and alter aquatic habitats (Wardynski *et al.*, 2013). Surface properties of pavements, such as their high infrared absorption, have been shown to increase runoff temperatures that affect biological processes (O'Driscoll *et al.*, 2010a; Wardynski *et al.*, 2013). In the Maryland Piedmont, Nelson and Palmer (2007) recorded a temperature surge over 7°C associated with runoff from asphalt, suggesting a negative impact on aquatic life.

Stormwater control measures (SCMs) are engineered or preventative techniques designed to manage the quality and quantity of runoff from impervious surfaces associated with urban development. Stormwater management approaches, such as Green Stormwater Infrastructure (GSI) and stream restoration projects, can improve stream health in nutrient-sensitive watersheds and in communities stressed for water resources. GSI is a type of SCM designed to mimic natural landscapes by intercepting, absorbing, and filtering stormwater runoff to lower peak discharge, treat stormwater quality, and facilitate the improvement of urban streams (Passeport *et al.*, 2013). Large structural SCMs include stormwater constructed wetlands (SCW), bioretention areas (BA), and regenerative stormwater conveyances (RSC) designed to capture and manage large volumes of storm flow in the urban setting, and reduce runoff by enhancing evapotranspiration, infiltration, and storage (Brown *et al.*, 2010; Carleton *et al.*, 2000; Carleton *et al.*, 2001; Cizek *et al.*, 2014). Stormwater runoff can also be reduced by a variety of Low Impact Development (LID) practices to support groundwater recharge (permeable pavement), increase evapotranspiration (green roofs, rain gardens, bioswales), and decrease discharge through redirection (cisterns, rain barrels, downspout disconnection) (Askarizadeh *et al.*, 2015).

Permeable pavement (PP) systems are a "green" alternative to traditional "gray" impermeable concrete pavement or asphalt, commonly used in parking lots, driveways, and walkways (Guo *et al.*, 2018). Surface material and design of PP vary and are typically grouped as porous asphalt (PA), pervious concrete (PC), or permeable interlocking concrete pavers (PICP) (NCDEQ 2017; Selbig and Buer, 2018; Weiss *et al.,* 2019). Regardless of the material and design, each system has permeable layers that mimic the hydrologic characteristics of soils to reduce overall discharge to receiving waters and attenuate first flush concentrations by allowing stormwater runoff to infiltrate into a subsurface reservoir or exfiltrate to surrounding soils and recharge groundwater. Balades *et al.* (1995), measured a 59% reduction in suspended matter at a PP parking lot in a Bordeaux suburb of France. In the city of Reze, France, retentions of lead (84%), cadmium (77%), and zinc (73%) were higher in permeable pavement compared to traditional pavement (Atunes *et al.*, 2018). Deicing agents used in colder climates during winter months can also create environmental concerns for groundwater and surface waters (Dietz *et al.*, 2017; Drake *et al.*, 2013). A study conducted in Connecticut found Cl^- concentrations in groundwater to be significantly less ($p < 0.01$) downgradient of a PA parking lot, indicating that permeable pavements could improve shallow groundwater quality in urban areas (Dietz *et al.*, 2017).

PA and PC differ from traditional pavements, in that fine aggregate is reduced or eliminated from the mix to allow the formation of voids during curing; however, an increase in permeability diminishes pavement strength (NCDEQ, 2017; Weiss *et al.*, 2019). PICPs are concrete brick pavers varying in geometry, that when installed, allow water to drain through the joints between pavers. According to the NCDEQ *Stormwater Design Manual* (2017), PICP has the highest initial material and installation cost when compared to PA and PC but is easier and less expensive to replace if significant clogging occurs. In addition to infiltration and retention, PP systems have been shown to reduce noise, improve icy conditions in winter, and improve traffic safety when roads are wet (Bäckström, 2000; Chu and Fwa, 2019; Selbig and Buer, 2018). Due to fine particle clogging of these systems, periodic monitoring and maintenance is recommended to sustain infiltration rates (Balades *et al.*, 1995; Bean *et al.*, 2007; Weiss *et al.*, 2019). In a 7-year PP laboratory experiment conducted by Kamali *et al.* (2017), a zero-runoff coefficient was observed for the first five years, then increased to 15% and 35% the sixth and seventh years, respectively. However, previous studies have concluded that all types of PP perform significantly better with respect to runoff reduction and pollutant removal than traditional asphalt and concrete (Brattebo and Booth, 2003; Collins *et al.*, 2008; Pratt *et al*., 1995). In Kinston, N.C., Collins *et al.* (2008) observed mean runoff reductions >99% in two PICP parking stalls.

The design of PICPs allows for stormwater or precipitation to infiltrate the void spaces between pavers. Void/joint material typically consists of highly permeable aggregates that can have infiltration rates greater than 5080 cm/h (Weiss *et al.*, 2019). Pratt *et al.* (1989) observed peak flow reductions in four experimental PICP sections underlain with different sub-base stone, noting some 5-10 min delays compared to 2-3 min delays for asphalt. However, fine particle clogging and soil compaction can significantly reduce infiltration capacity and increase surface runoff. In a field study conducted in Maryland, North Carolina, Virginia, and Delaware by Bean *et al.* (2007), the median infiltration rate for all sites without fines was 2000 cm/h, with the highest average rates at 4000 cm/h. Infiltration significantly decreased more than 99% with fine sediment accumulation (e.g., windblown, vehicular traffic, construction) (Bean *et al.*, 2007). Maintenance practices, such as pressure washing, sweeping, suction, milling, or any combination are significant factors in maintaining infiltration rates of PP over time (Balades *et al.*, 1995; Weiss *et al.*, 2019). Soil compaction affects the physical properties of soil (usually within the top 30 cm), decreasing infiltration as the result of an increase in strength and bulk density (Alaoui *et al.*, 2018; Bean *et al.*, 2015; Gregory *et al.*, 2006). Land use changes from natural vegetation to agricultural lands, and then to urban development are associated with soil degradation (Alaoui *et al.*, 2018). Sandy topsoils can become compacted by recurrent wet and dry cycles during flood irrigation (Kozlowski, 1999). In north central Florida, Gregory *et al.* (2006) reported a decrease in infiltration rates from 733 mm/h to 178 mm/h due to compaction associated with construction activities. When considering installation sites for PICP, on-site investigations to determine soil characteristics should be performed to ensure proper function of the systems (NCDEQ *Stormwater Design Manual*, 2017).

In addition to runoff reduction, permeable pavement studies have reported lower surface and ground temperatures during warmer months. For example, a study conducted in Taipei City, Taiwan documented lower surface temperatures of PICPs over a 15-month period compared to regular asphalt, showing the greatest difference of 14.3°C during high-temperature months of the summer and fall (Cheng *et al.*, 2019). The Taipei City results indicate that permeable pavements may reduce Urban Heat Island (UHI) effects associated with higher percentages of buildings and paved areas (Cheng *et al.*, 2019; Stempihar *et al.*, 2012). In the North Carolina Mountains, Wardynski *et al.* (2013) found that daily temperatures in the subbase stone layer of constructed paver cells were on average 4.4-5.2°C cooler than just below the pavers, suggesting a reduction in thermal loads to cold water streams.

Logistical challenges, costs of monitoring and maintenance, and project failures contribute to the lack of research available, but standard guidelines and evaluation results are imperative to the success of future projects (Al-Rubaei *et al.*, 2015; Kondolf and Micheli, 1995; Passeport *et al.*, 2013). As cities strive to confront stream impairment and localized flooding associated with excess urban runoff, it is critical that GSI projects be evaluated so that communities can implement the most effective mitigation strategies in local watersheds (Kondolf and Micheli, 1995). Limited PP studies have been conducted in the North Carolina Coastal Plain (Bean *et al.*, 2005; Bean *et al.*, 2007; Collins *et al.*, 2008), an area that faces many stormwater challenges (population growth, sea-level rise, climate change) and typically has shallow water tables (< 10 ft. depth) (Eimers *et al.*, 2001). The Coastal Plain consists of a generally flat, low elevation landscape subject to frequent flooding, with stream gradients ranging between 0.5% and less than 0.01% (Sweet and Geratz, 2003). Climate change and sea level rise (SLR) may increase flooding and the frequency of tropical storms in this region. NOAA (2014) reported values of greater than 20 days for nuisance floods, associated with SLR, along the U.S. East Coast and an acceleration along the Southeast Atlantic Coast (North Carolina, South Carolina, Georgia) since the 1980s. The danger to nutrient sensitive waters at the coast is a direct consequence of high frequency flood events. North Carolina's Albemarle-Pamlico estuary system is the second largest in the U.S., draining nearly half of North Carolina's watersheds (DeBusk *et al.*, 2010). The estuary system is critical in water quality maintenance by trapping and storing sediment and nutrients, but an increase in runoff-derived nutrients causes low-oxygen levels and eutrophication (Debusk *et al.*, 2010; Hupp, 2000). This study aims to help fill knowledge gaps and improve understanding of PICP as a form of GSI that can mitigate some of the stormwater challenges of Coastal Plain settings. Although it may be assumed that Coastal Plain regions with shallow water tables may have limitations for PICP implementation, limited studies (Bean *et al.*, 2007) have quantified the effectiveness of PICPs in Coastal Plain settings and compared those with PICPs in settings with deeper water tables.

The goals of this study were to evaluate how urban land cover affects infiltration rates and quantify how PICPs in a Coastal Plain watershed reduce the impacts of urbanization on infiltration capacity and ambient temperatures. Specific objectives were identified and accomplished to achieve the study goals and included:

(1) determination of surface infiltration rates of PICP and effects on peak discharge of receiving waters; (2) comparison of PICP infiltration rates to those of campus lawns, forested soils, and impervious surfaces; (3) determination of secondary permeability of fractured asphalt as a pathway for infiltration; (4) comparison of surface temperatures of PICP and regular asphalt.

STUDY AREA AND METHODS

The hydrology and morphology of watersheds vary according to vegetation, soils, climate, geology, and topographic conditions. Compared to the Piedmont and Mountain streams of North Carolina, Coastal Plain streams exhibit low-gradients and broad floodplains that experience frequent flooding and prolonged inundation (Hupp, 2000). Bankfull flood events occur more frequently in the Coastal Plain (0.19-year) relative to Mountain and Piedmont (1.5-year) settings and are attributed to a high mean annual precipitation (48-58 inches) and a shallow groundwater table (Sweet and Geratz, 2003). Soils commonly consist of coarse fluvial, aeolian, and riverine sediments that thicken and dip to the east, deposited during cycles of eustatic sea level fluctuations (Hupp, 2000; O'Driscoll *et al.*, 2010b). Unconsolidated surficial deposits change from sand in the Inner Coastal Plain to poorly drained, loamy soils toward the coast (Sweet and Geratz, 2003).

The conversion of natural landscapes to agricultural and urban environments in the Coastal Plain over the last few hundred years has resulted in upland erosion, with marked aggradation of floodplains following deforestation in the 18th and 19th centuries (Hardison *et al.* 2009). Channelization and widespread drainage of coastal wetlands for agricultural use further altered stream hydrology and contributed to watershed impairment. While the benefits of drainage networks improve crop production by lowering the water table, drainage tiles bypass riparian buffers and route agricultural runoff into stream channels. In addition to drainage for cropland, stream channelization for flood control and navigation has also been documented as altering watersheds in the region (Hardison *et al.*, 2009).

In the City of Greenville, agriculture and industry (cotton, tobacco, livestock) dominated in the late 1800's, but land-use practices transitioned from agricultural to urban as Greenville became a center for education (Copeland, 1982). The land area used by the City of Greenville more than doubled between the 1980s and early 2000s, to match the population doubling to approximately 72,000 people (Hardison *et al.*, 2009). Between 2000 and 2010, the population of Greenville increased by approximately 24,000 residents (U.S. Census Bureau). Figure 1 shows a 29% increase in land development between 1996 and 2016.

Located adjacent to Greenville's downtown area, East Carolina University's (ECU) East Campus lies within two sub-watersheds, Town Creek and Greens Mill Run, that drain into the Tar River (Tar-Pamlico watershed), and ultimately the Pamlico Sound. The campus is flood-prone due to the presence of the larger sub-watershed, Greens Mill Run (GMR), and its floodplain. In 2011, the impervious surface area (ISA) of Town Creek and GMR were 59% and 23.9%, respectively (USGS *Streamstats*, 2016). Figure 2 and Table 1 show the ISA of ECU's East Campus is approximately 50% of the land area. To reduce stormwater runoff generation on campus, ECU began replacing impervious areas with PICPs in several locations across campus in 2010. Currently, there are six areas on the ECU main campus with PICPs covering a combined area of approximately 0.3 hectares (3,000 square meters), with plans to expand in the future (Figure 3).

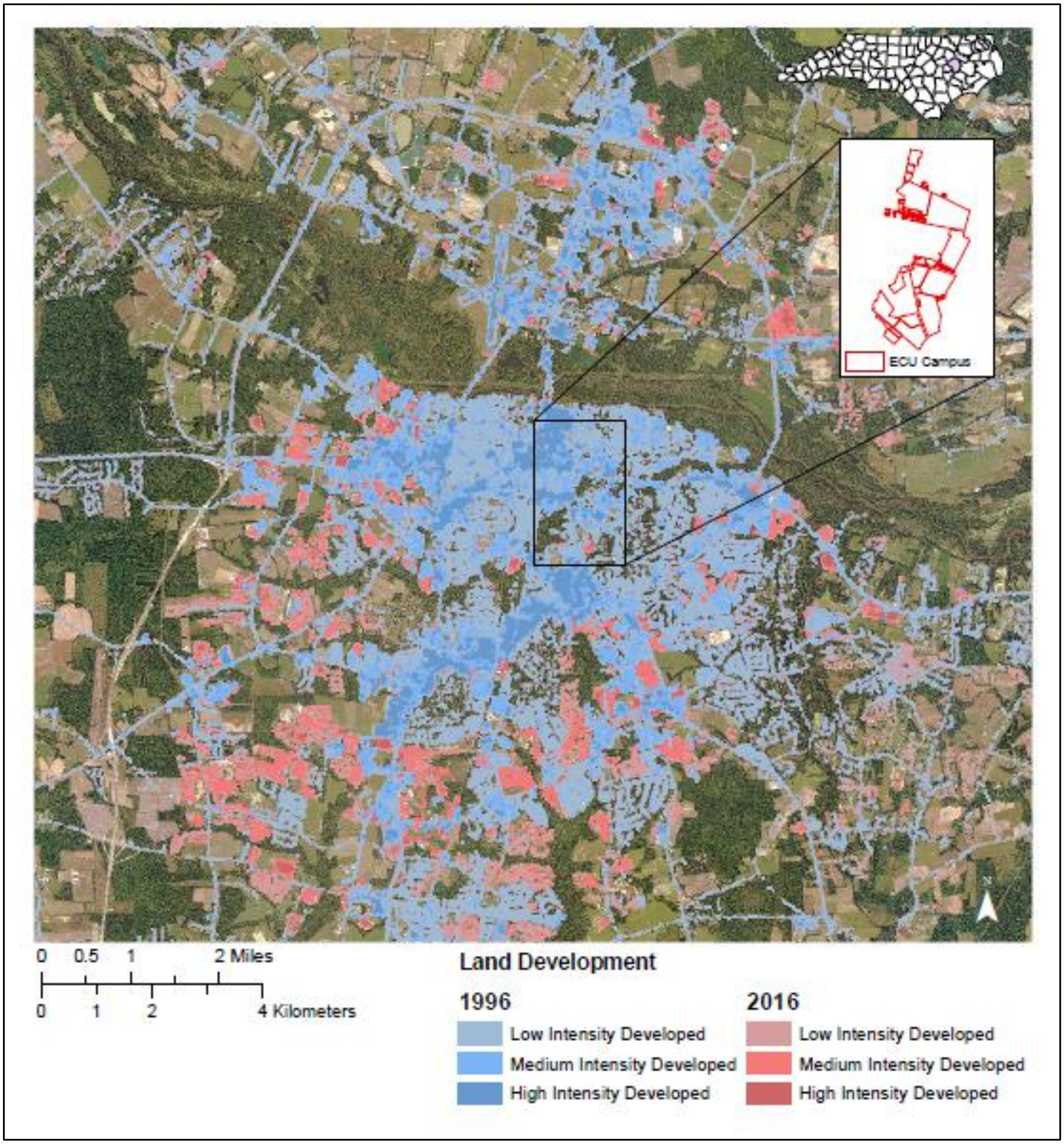


Figure 1. Land development increase in Greenville, NC from 1996 to 2016 (NOAA C-CAP Regional Land Cover Data 1996 and 2015-2017).

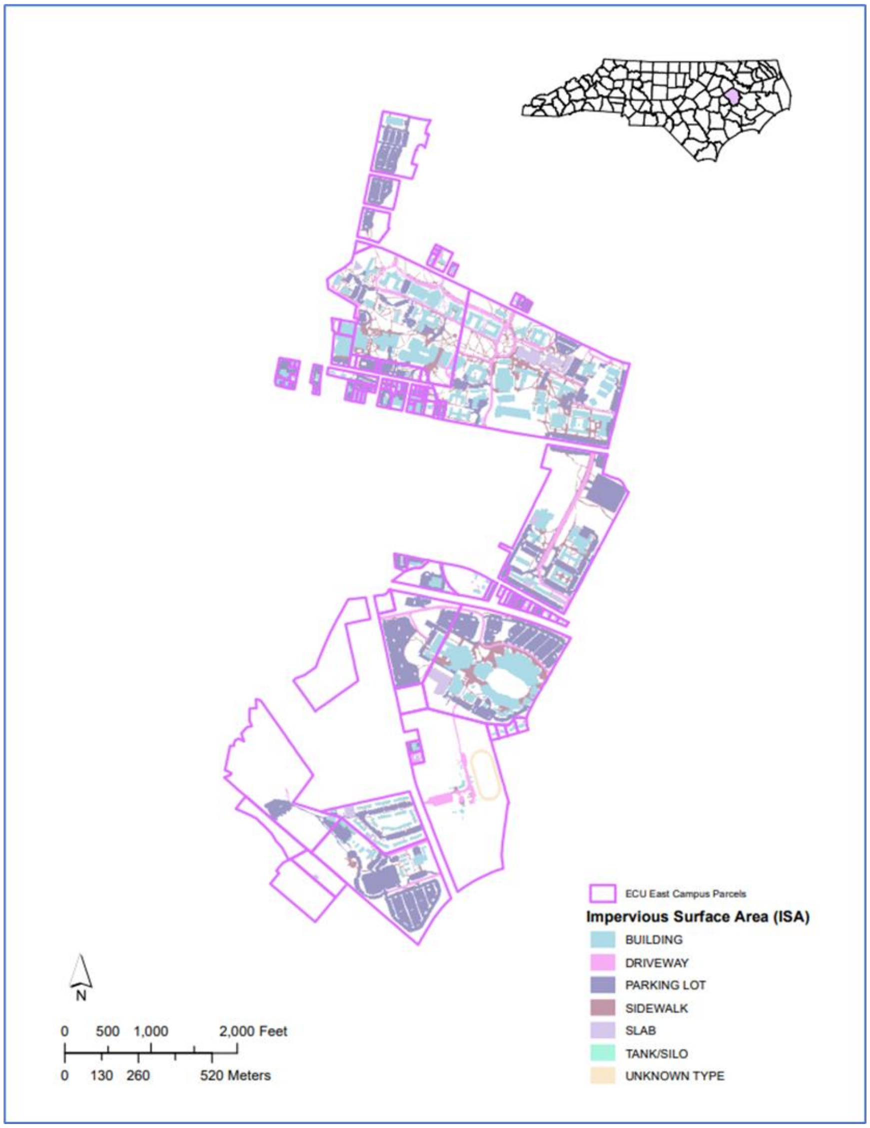


Figure 2. Impervious surface area map of ECU's East Campus (modified from S. Thieme, 2010).

Table 1. Impervious surface type and percentages of total study area (ECU East Campus).

Feature Type	Area (m²)	% Total ISA	% Total Area
Building	185702.05	28.54	13.01
Driveway/Road	56629.33	8.70	3.97
Parking Lot	285379.43	43.86	19.99
Sidewalk	95225.40	14.64	6.67
Slab	22992.76	3.53	1.61
Tank/Silo	186.79	0.03	0.01
Unknown	4479.35	0.69	0.31
% ISA of Total Parcel Area			**45.58**

Site Selection

PICP, campus lawn, forested, and asphalt sites were selected to represent a range of infiltration rates, compaction values, and surface temperatures across the study area to evaluate the potential benefits of PICP as a stormwater management tool (Figure 3 and Table 2). All campus lawn sites tested in this study were chosen to represent disturbed soils associated with development, landscaping maintenance practices, and foot traffic. An urban forest was chosen because it is a relatively undisturbed area that has not been cleared for development. Infiltration and compaction measurements for the forested and campus lawn sites were taken in winter and early spring, and all tests were preceded by at least a 24-hour dry period, with no heavy rain at least three days prior to testing. Air temperatures ranged from 12 °C (54 °F) to 24 °C (76 °F). A total of 61 infiltration measurements were taken across the study area: PICP (n = 18), campus lawns (n = 21), forested (n = 10), and fractured asphalt (n = 12). A total of 93 cone index measurements, used to determine the degree of compaction in soils, were taken at campus lawn (n = 63) and forested (n = 30) sites, and 72 thermal measurements were taken at PICP (n = 36) and asphalt (n = 36) sites. PICP and asphalt sites were mapped based on existing installations across ECU's main campus. All asphalt sites selected for secondary permeability were in some degree of disrepair and fractures used for measurements had not been patched. When considering the addition of GSI, such as PICPs, soil properties (e.g., soil type and depth to water table) can limit infiltration rates, and in-situ soils should be well-drained with a water table at least 60 cm (2 ft.) below the bottom of the paver subgrade. Campus lawn and forested sites were mapped using the USDA Web Soil Survey (2020) and selected based on similar hydrologic soil groups (Group A), depth to water table (DWT) (> 60 cm), and susceptibility to compaction (low) to determine the impact of soil compaction on infiltration rates (Appendix A). Soils are assigned to hydrologic groups according to the rate of infiltration for a bare soil, based on runoff estimates (USDA Web Soil Survey, 2020). Hydric soils, such as the Bibb Complex (Group D), were not considered for sample sites because they typically occur in floodplains and wetlands on campus and these areas are not generally available for development; Group D soils in their natural condition are assigned two classes indicating drained and undrained areas, respectively. Sixteen sites consisted of Group A, well-drained sands with high infiltration rates when thoroughly wet (USDA Web Soil Survey, 2020). 1900 Charles Boulevard consisted of Group A, Group A/D, and Group D soils. However, all measurements at this location were taken in Group A soils. The Starbucks mobile PICP site consisted of Group C soils, with a low infiltration rate related to an impermeable layer or fine texture (USDA Web Soil Survey, 2020).

Additional cone index data were included to increase the sample size for campus lawn and forested areas; a total of 78 measurements were used to compare soil conditions across campus. The previous data were collected by a group of students over a three-week period during the summer of 2009, and a total of 47 maximum cone index values were recorded for campus lawn (n = 26) and forested (n = 21) areas. For comparison, only maximum compaction values were used from the 2020 data for campus lawn (n = 21) and forested (n = 10) sites. Previous sample sites were at or near those selected in this study. Sites from both studies are grouped into four USDA soil classifications: 1) Alaga loamy sand (AgB); 2) Exum fine sandy loam (ExB); 3) Wagram loamy sand (WaB/WaC). WaB is the predominant soil in the study area (52%), consisting of 77.7% sand, 16.3% silt, and 6% clay (USDA Web Soil Survey, 2020).

Discharge estimates were calculated using the rational method outlined in the City of Greenville's *Manual of Standard Designs and Details* (2011), based on a 10-year rainfall return frequency. It should be noted that the equation is primarily used for determining runoff in small drainage areas and minor stormwater design systems. To apply the rational method to a larger study area, sub-basins were selected using the USGS *StreamStats* program for the estimation of time of concentration (Tc). Time of concentration is the time it takes water to flow from the most remote point in the basin to the basin outlet, which is reduced in urbanized watersheds. Because there are multiple land-use types across the study area, a weighted runoff coefficient was estimated by subdividing the drainage area based on land-use conditions.

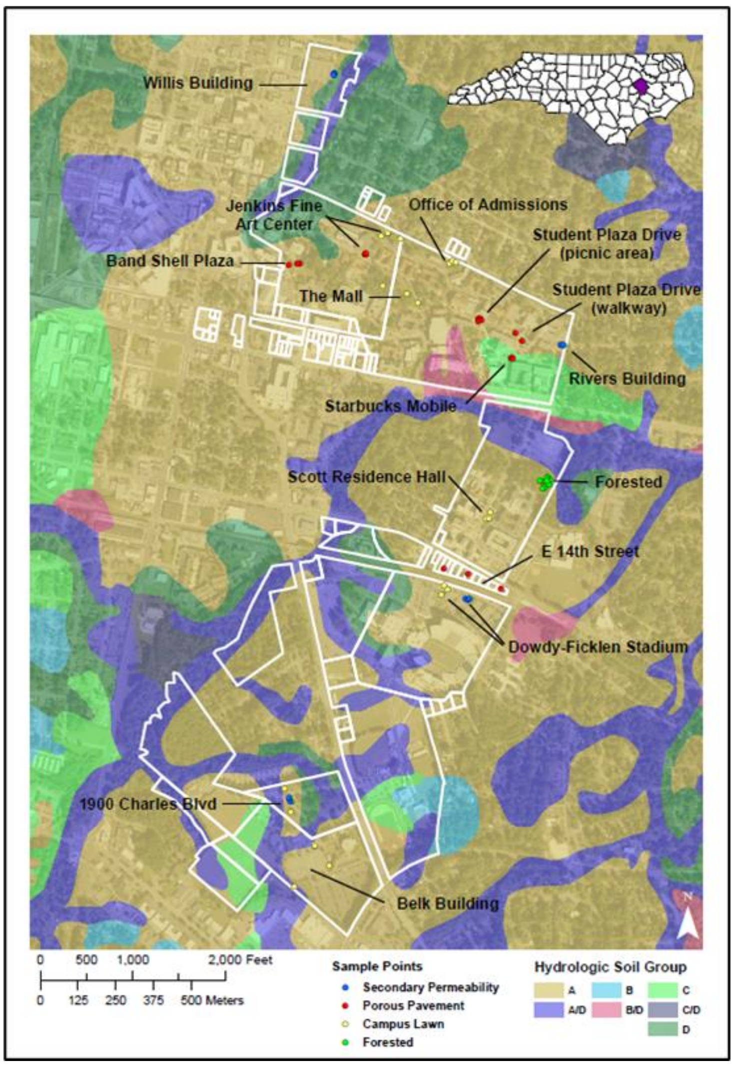


Figure 3. ECU East Campus sample point locations and soil map (USDA SSURGO Data, 2020).

Table 2. Sample sites and number of samples collected (2020).

	Infiltration		Compaction		Temperature	
Site	# of Sites Sampled	n	# of Sites Sampled	n	# of Sites Sampled	n
PICP	6	18			4	36
Forested	1	10	1	30		
Campus Lawn	7	21	7	63		
Asphalt	4	12			4	36

Infiltration Rates of PICP

Six PICP (n = 18) sites were tested to determine surface infiltration rates (Figure 4). A Turf-Tec® Double-Ring Infiltrometer was used to measure surface infiltration rates at each site (Figure 5). At each PICP site, three tests were conducted at different locations to determine variability in infiltration rates of permeable pavers based on existing surface conditions (Bean, 2005; Bean *et al.*, 2005; Bean *et al*., 2007). Tests were performed between November 2019 and February 2020, and all tests were preceded by at least a 24-hour dry period (Appendix B). The test used for this study modified some of the methods and materials in ATSM D 3385 (ASTM, 2003) and ASTM C1781/C1781M (ASTM, 2014); the "Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer" and the "Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems", respectively. The methods and materials as modified by Bean, were adapted to operate with a limited water supply (Bean, 2005; Bean *et al*., 2005; Bean *et al*., 2007). A volume of 19 L (5 gal) was transported at a time for each location.

To modify the ATSM D 3385 for a hard surface, the inner ring of the infiltrometer was sealed to the surface using a thin ring of plumber's putty according to Bean *et al.*, 2005 and the ATSM C1718/C1781M (2014). Water was added to the inner ring to determine if any leakage to the outer ring existed, to prevent leakage both the inner and outer rings were sealed with putty

(Bean, 2005; Bean *et al*., 2005; Bean *et al*., 2007). Prior to measurements both rings were filled 3 times to saturate the voids and underlying aggregate/soil (Turf-Tec® International, 2020). After saturation, a falling head test was conducted to determine infiltration rates by measuring the time that the water level takes to fall in the inner ring (Gregory *et al.*, 2005; Nichols *et al.*, 2014; Turf-Tec® International, 2020). The initial water level in the inner ring and time were recorded. Both parameters were measured and recorded every 30 seconds; however, if complete infiltration occurred in less than 30 seconds, the time for complete infiltration was recorded (Bean, 2005; Bean *et al*., 2005; Bean *et al*., 2007). A test was complete when 10.16 cm (4 in) of water completely infiltrated the pavement.

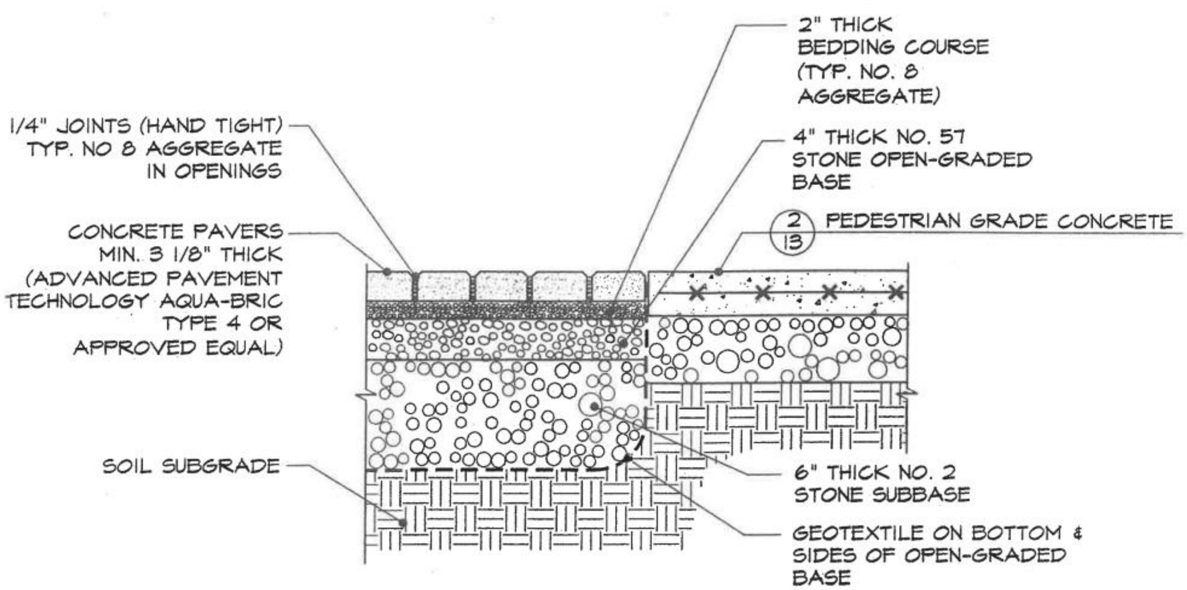


Figure 4. Cross section of PICP design provided for Student Plaza Drive location (Fred Adams Paving Co., Inc. 2016)

Figure 5. Typical setup of double-ring infiltrometer at PICP test sites.

Infiltration Rates of Campus Lawns and Forested Soil

Seven campus lawn sites and one forested site were tested to determine surface infiltration rates of disturbed and undisturbed soils, respectively. A Turf-Tec® Double-Ring Infiltrometer was used to measure surface infiltration rates at each site (Figure 6). At each campus lawn site, three tests were conducted at different locations to determine variability in infiltration based on existing surface conditions (Bean, 2005; Bean *et al*., 2005; Bean *et al*., 2007). A total of ten tests were conducted at the forested site. Tests were performed between February 2020 and April 2020, and all tests were preceded by at least a 24-hour dry period. The test used for this study modified some of the methods and materials in ATSM D 3385 (ASTM, 2003), the "Standard Test Method for

Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer". The methods and materials as modified by Bean, were adapted to operate with a limited water supply (19 L) (Bean *et al*., 2005; Bean *et al*., 2007).

The double ring cutting blades were placed on the area to be tested and driven 2 inches into the ground until the Saturn ring was flush with the ground surface. The ground was saturated by filling the inner and outer rings 3 times, allowing infiltration between fillings and enough time for the soil to swell (EPA, 1980; Turf-Tec® International, 2020). After saturation, the initial water level in the inner ring and time were recorded. Both parameters were measured and recorded every 5 minutes. A test was considered complete when the water level drop stabilized, generally around 30 minutes.

Figure 6. Typical Setup of double-ring infiltrometer at campus lawn (left) and forested test sites (right).

Infiltration Rates of Fractured Asphalt for Secondary Permeability

Most impervious surface literature assumes asphalt is totally impervious and focuses on quantifying components of urbanization that affect water quality, but little work has been done to consider the infiltration capacity of urban pavement through joints and fractures (Wiles and Sharp, 2008). Four sites were selected to measure the secondary permeability of fractured asphalt (Figure 3). Sites were mapped using the USDA Web Soil Survey (2020) and selected based on the hydrologic soil group and susceptibility to compaction of underlying soils. Soils are assigned to hydrologic groups according to the rate of infiltration, based on estimates of runoff potential (USDA Web Soil Survey, 2020). The USDA (2020) soil classification for three sample locations is Wagram loamy sand (WaB) and is 77.7% sand, 16.3% silt, and 6% clay. WaB is a well-drained soil (Group A) with high infiltration rates when thoroughly wet (USDA Web Soil Survey, 2020). 1900 Charles Boulevard consists of four USDA soil classifications; Bb, CrB2, OcB, and WaB. However, WaB is the underlying soil for all sample points at this location.

Four fractured asphalt sites were tested to determine surface infiltration rates. A Turf-Tec® Double-Ring Infiltrometer was used to measure surface infiltration rates (Figure 7). At each site, three tests were conducted at different locations to determine secondary permeability of impervious cover based on existing surface conditions. Measurements were taken where two or more fractures intersected and were contained within the footprint of the inner ring. A width measurement was recorded for each fracture. Tests were performed in April 2020, and all tests were preceded by at least a 24-hour dry period. The test used for this study modified some of the methods and materials in ATSM D 3385 (ASTM, 2003) and ATSM C 1718 (ASTM, 2014); the "Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer" and the "Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems", respectively. The methods and materials as modified by Bean, were adapted to operate with a limited water supply (19 L) (Bean, 2005; Bean *et al*., 2005; Bean *et al*., 2007).

To modify the ASTM D 3385 for a hard surface, the inner ring of the infiltrometer was sealed to the pavement at a fracture intersection using a thin ring of plumber's putty (Wiles and Sharp, 2008; ASTM, 2014). The methods used are similar to those in the earlier section (Infiltration Rates of PICP). A test was considered complete around 5 minutes; however, if complete infiltration occurred in less than 5 minutes, the time for complete infiltration was recorded. Wiles and Sharp (2008) noted that infiltration rates generally decrease and level out within 5 minutes of infiltration on pavement surfaces.

Figure 7. Typical setup of double-ring infiltrometer at asphalt sites.

Soil Compaction Measurements

Soil compaction was measured at the forested (n = 30) and campus lawn (n = 63) site locations using a Spectrum™ FieldScout SC 900 cone penetrometer (Spectrum Technologies, Inc. Plainfield, Illinois) (Figure 8). Penetrometers measure soil strength on a cone index scale of 0-7,000 kPa (0-1,000 PSI) (±103 kPa; Spectrum 2009). The tip of the penetrometer is placed on the soil surface and force is applied to push the probe deeper into the soil profile, for a depth up to 45 cm (18 in) (Spectrum 2009). As soil compaction values increase, bioturbation, plant root growth, and infiltration decrease. Based on the degree to which plant roots can penetrate soils, 2068 kPa (300 psi) is a commonly cited threshold for soil compaction at a depth of 7.62 cm (3 in) (Mangiafico, 2009; Pitt *et al.*, 1999). Three cone index measurements (kPa) were taken at each site where infiltration measurements were collected. Cone index measurements were recorded in increments of 2.5 cm (1 in) up to 15.2 cm (6 in).

Figure 8. Spectrum™ FieldScout SC 900 cone penetrometer (Spectrum Technologies, Inc. Plainfield, Illinois 2009).

Surface Temperature Measurements of PICP and Asphalt

Eight sites were selected to compare surface temperatures of traditional asphalt and PICP and determine if PICP is an effective solution to mitigate effects of the UHI. PICP and asphalt sites were mapped based on existing installations and parking lots across the ECU campus (Figure 9). Four PICP (n = 36) and four asphalt (n = 36) sites were paired to determine and compare surface temperatures. A FLIR® E5 infrared camera (FLIR Technologies, Inc.) was used to measure surface temperatures across the study area (Figure 10). A total of 72 measurements were performed between the months of June and July 2020, from 11 am to 2 pm. Observed air temperatures during sampling times were between 28-33 °C. All tests were preceded by at least a 24-hour dry period. Additionally, two HOBO® U20L-04 Data Loggers monitored pavement temperature at 5-min intervals between July 23rd and July 27th, 2020. Data loggers were secured onto pavement surfaces at the PICP Starbucks Mobile location and Willis Building parking lot (Figure 11).

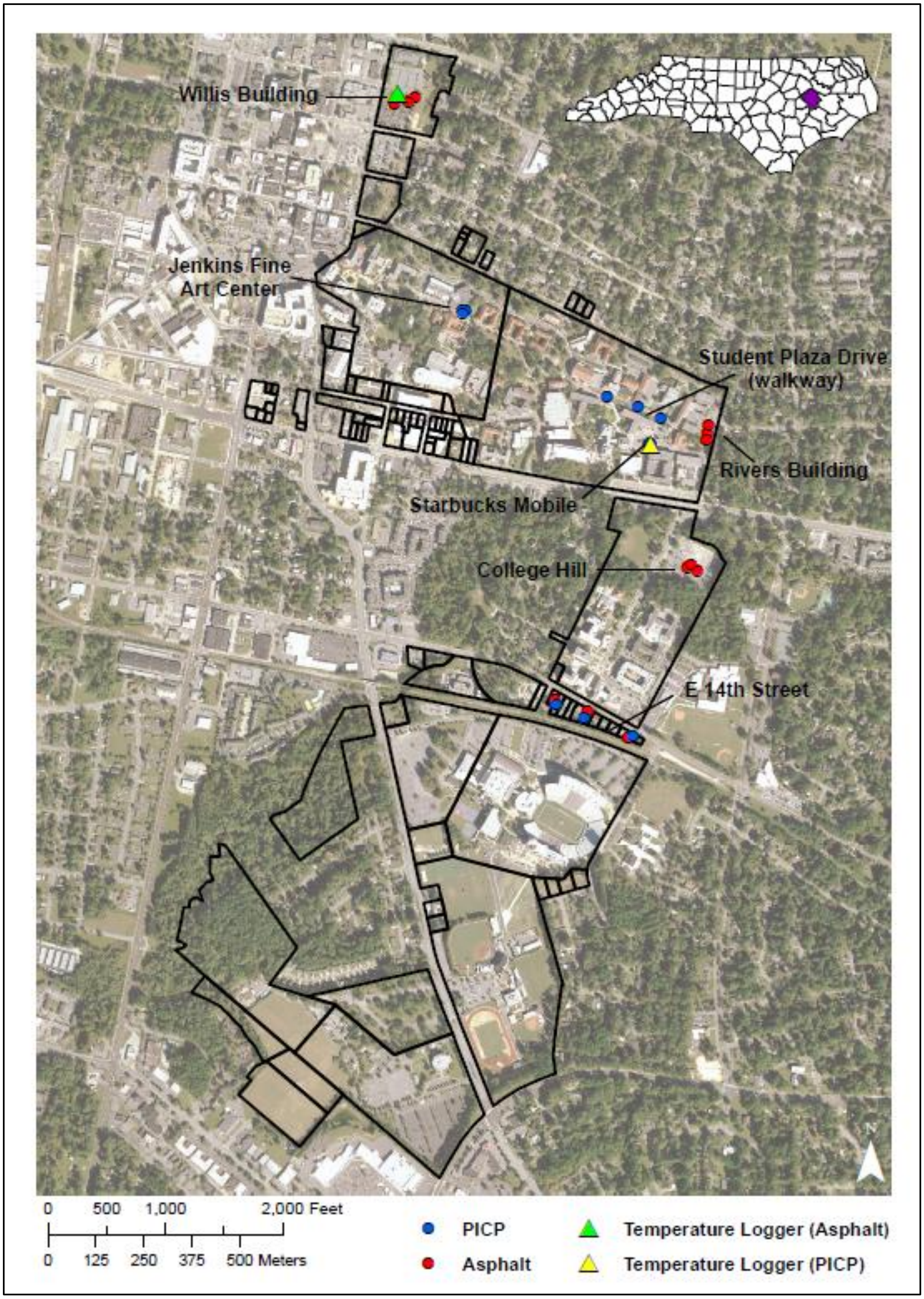


Figure 9. Thermal measurement sample locations.

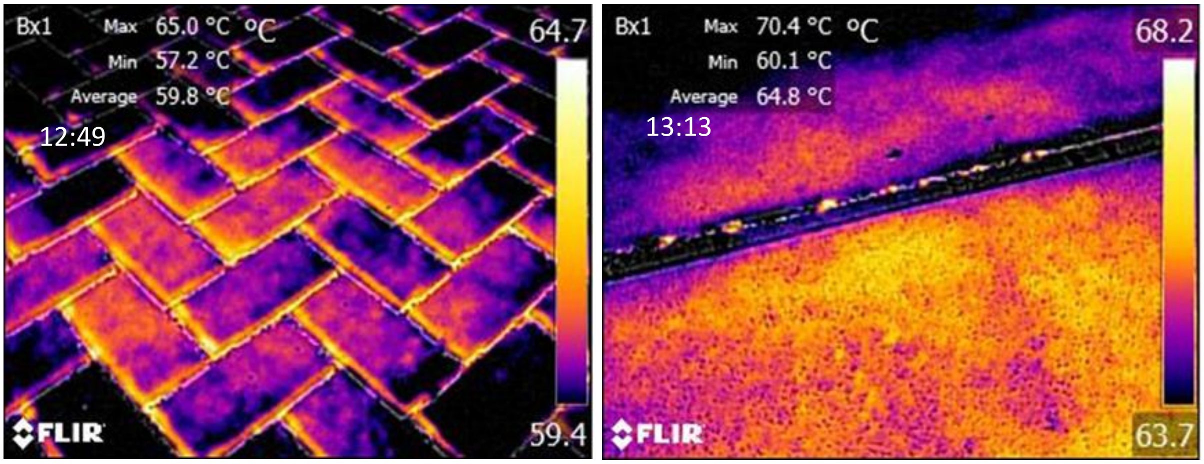


Figure 10. Infrared images of Jenkins Fine Art Center PICP site (left) and Willis Building parking lot asphalt site (right), taken on June 6, 2020.

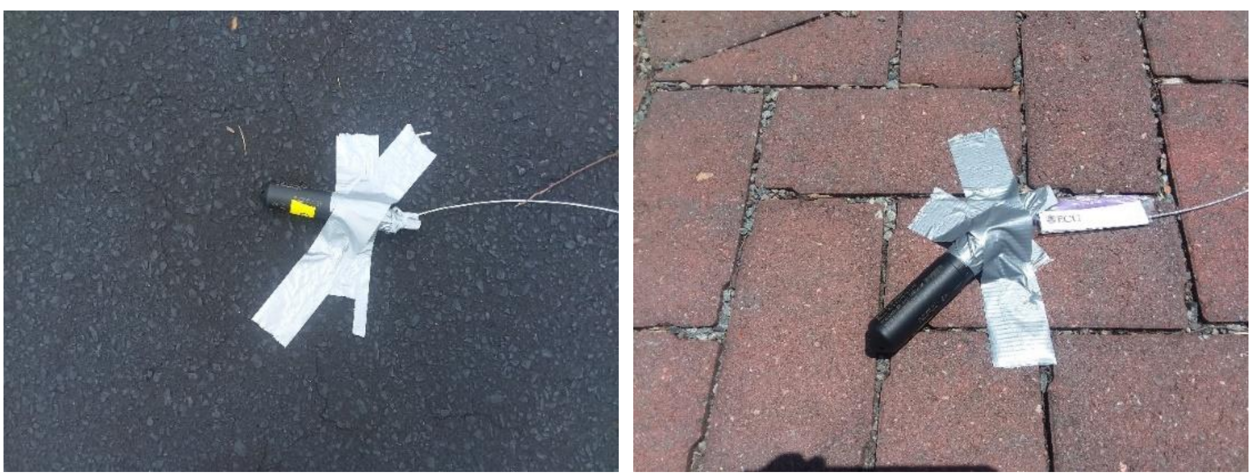


Figure 11. Setup of data loggers for surface temperature measurements at the Willis Building parking lot (left) and Starbucks Mobile PICP (right) sites.

RESULTS

Infiltration Rates of PICP, Campus Lawns, and Forested Soils

Surface infiltration rates (SIR) were tested for six PICP, one forested soil, seven campus lawn, and four fractured asphalt sites across the ECU Main Campus using a Turf-Tec® Double-Ring Infiltrometer and falling head test. Three tests were performed at each site to determine the variability in infiltration rates based on existing conditions, and water levels were plotted as functions of time (Appendix C). Infiltration rates are typically highest at the beginning of a storm and decrease over time as soils swell and the storage capacity is depleted (Pitt *et al.*, 1999). SIRs were calculated by recording water level change in the inner ring over time until infiltration rates became stable ($I = \Delta H/t$) (Figure 12) (Appendix D). Figure 14 shows the land cover type for campus lawns (left) and forested soils (right).

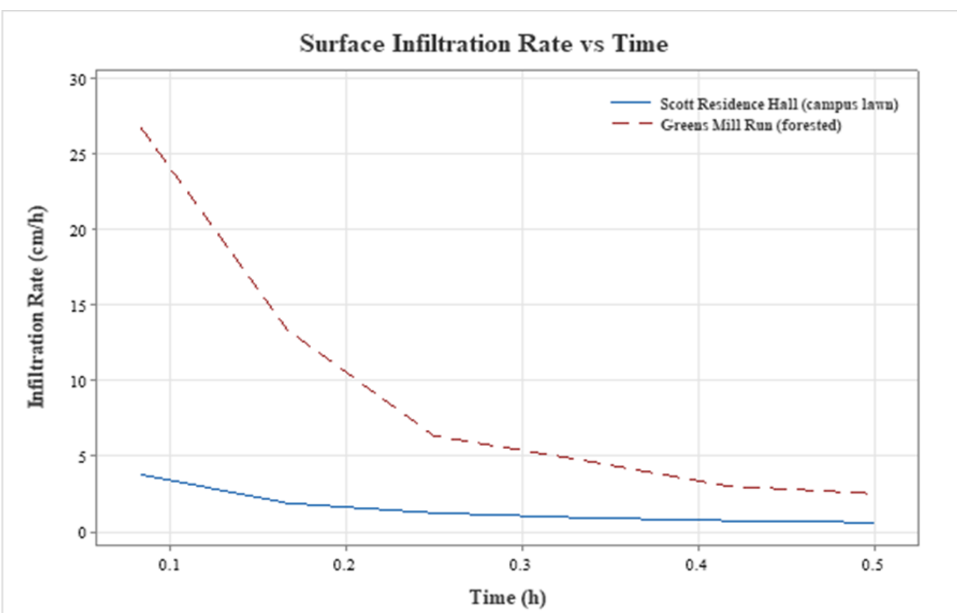


Figure 12. Typical graph of surface infiltration rates versus time for one test at the forested site (Greens Mill Run) and one test at a campus lawn site (Scott Residence Hall).

Figure 13. Images of land cover type for campus lawns (left) and forested soils (right). Scott Residence Hall (left) has lawn areas covered by well-maintained turfgrass. Greens Mill Run (right) is an urban forest covered with leaf litter.

The infiltration rates of the groups were significantly different ($p < 0.05$) (Figure 14). Table 3 lists average surface infiltration rates and R^2 values for PICP, Forested, and Campus Lawn sites. The median surface infiltration rate for PICPs was three orders of magnitude greater than campus lawns. Generally, it is assumed that impervious surfaces have infiltration rates close to 0, but SIR for asphalt were taken where fractures in the pavement intersected and do not represent effective infiltration for the entire pavement surface. Some data at the fractured asphalt sites were eliminated due to leakage around the base of the infiltrometer. The Willis building parking lot site was not used in analyses, and one measurement taken at 1900 Charles Blvd and two measurements take at Dowdy-Ficklen Stadium were eliminated from the data set (Table 4). Surface infiltration rates of PICP varied across each location; however, most R^2 values for water level versus time relationships were greater than 0.9. Average SIRs for PICPs were compared to the year of installation to determine if infiltration decreased over time. Although, sites installed after 2015 had slightly higher infiltration rates, there was not a strong pattern in performance versus age for sites sampled (Figure 15).

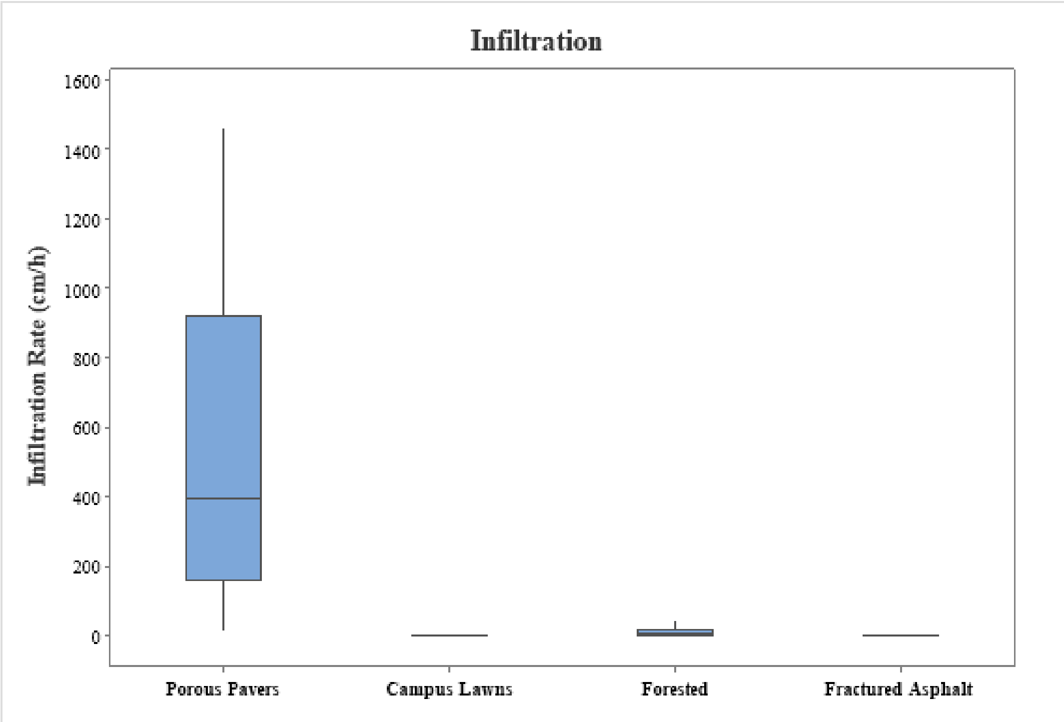


Figure 14. Comparison among surface infiltration rates of PICP, campus lawn, forested, and fractured asphalt sites.

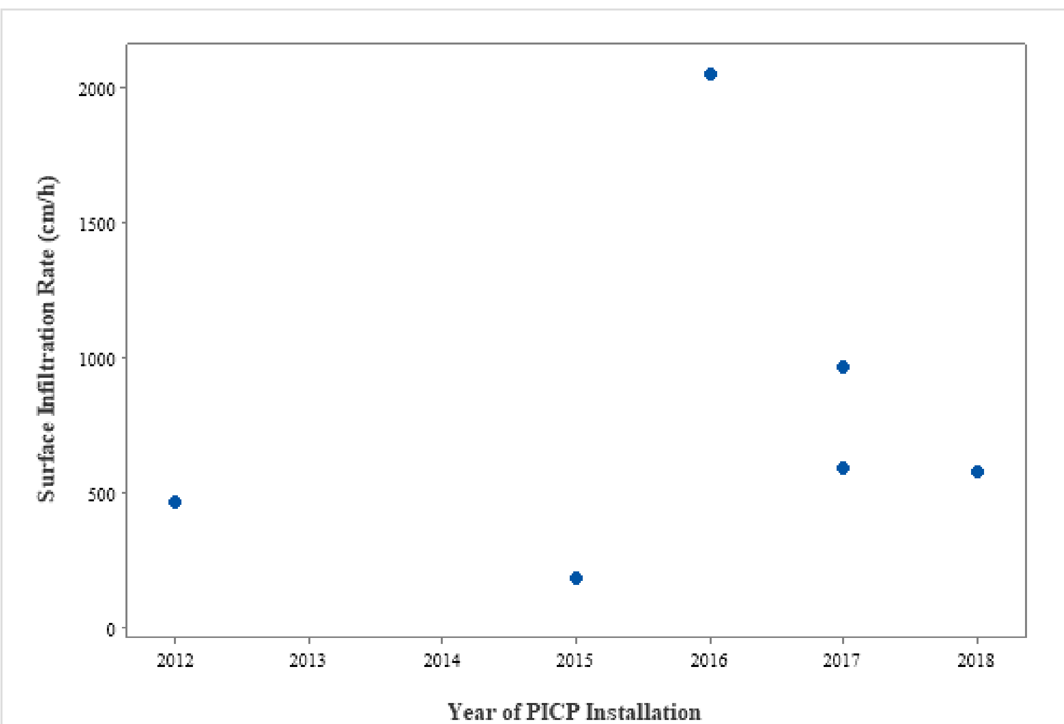


Figure 15. Average surface infiltration rate for each PICP site and year of installation.

Table 3. Average surface infiltration rates and average R^2 values at each test site.

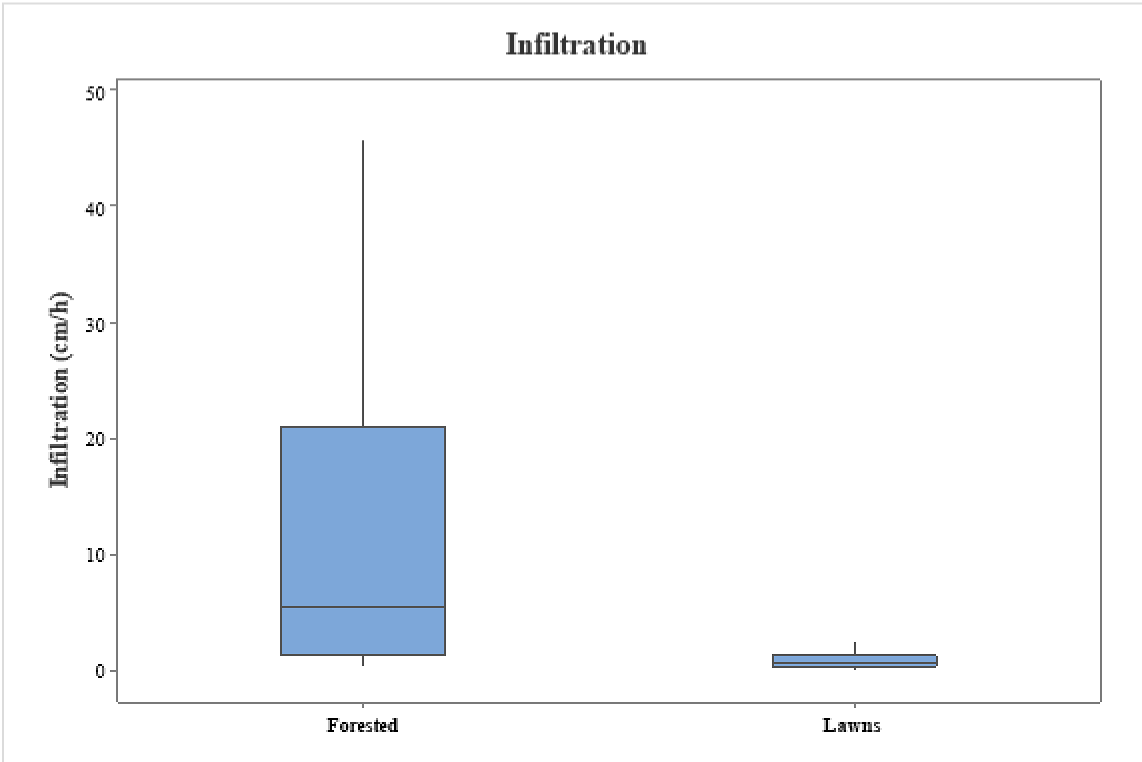
Site Name	Average SIR (cm/h)	Average R^2
PICP		
Jenkins Fine Art Center	2044.70	0.97
Student Plaza Drive (picnic area)	965.20	0.97
Student Plaza Drive (walkway)	594.36	0.98
Band Shell Plaza	580.45	0.96
E 14th Street Parking Lot	463.55	0.84
Starbucks Mobile	182.64	0.98
Median	**587.41**	
Forested		
Greens Mill Run Greenway	14.29	0.95
Median	**5.46**	
Campus Lawn		
1900 Charles Blvd	1.69	0.99
Jenkins Fine Art Center	1.48	0.99
Belk Building	1.06	0.99
Office of Admissions	0.95	0.99
Scott Residence Hall	0.45	0.98
Dowdy-Ficklen Stadium	0.32	NA
The Mall	0.26	NA
Median	**0.95**	

Table 4. Surface infiltration rates at fractured asphalt sites.

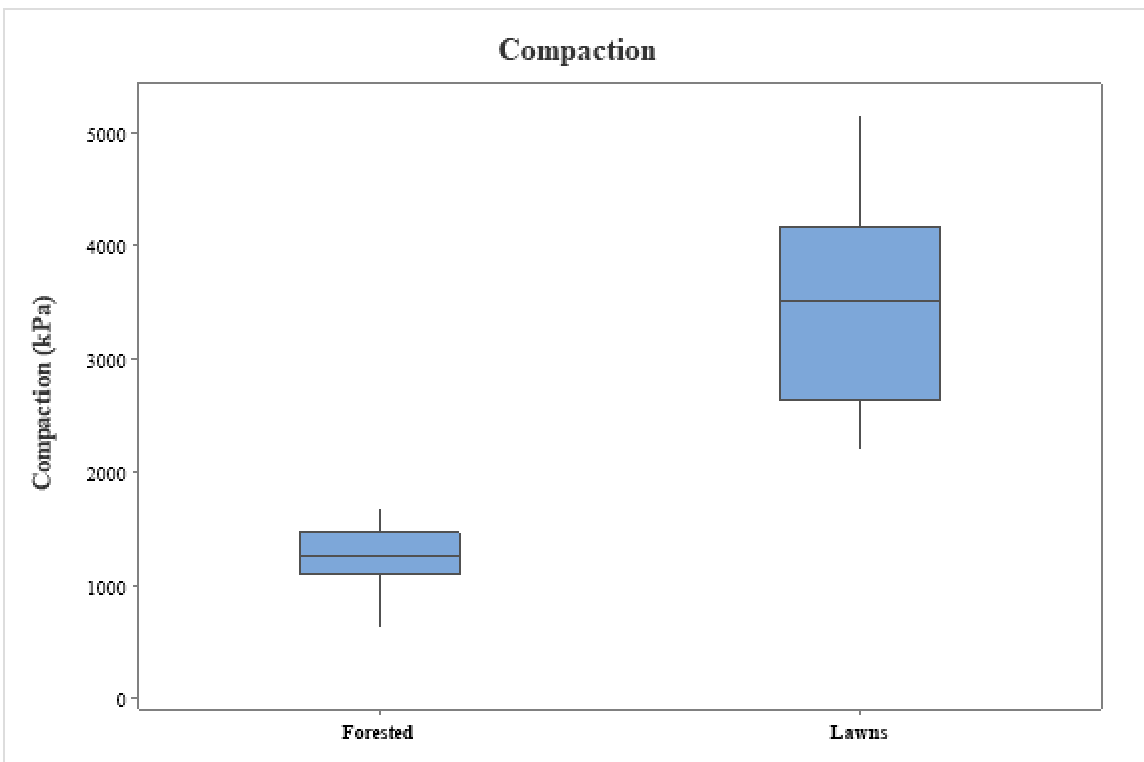
Fractured Asphalt (secondary permeability)	SIR (cm/h)
1900 Charles Blvd	2.4
1901 Charles Blvd	3.8
Dowdy-Ficklen Stadium	3.82
Rivers Building	3.8
Rivers Building	3.82
Rivers Building	0.64
Median	**3.8**

Three cone index measurements were taken at each infiltration measurement location to compare existing soil conditions across the study area (Appendix E). Figures 16a and 16b show SIR and maximum compaction values from each set of measurements, respectively. Table 5 summarizes SIRs of campus lawns and forested soils in this study. The infiltration rates measured for soils at the forested site were variable. However, 50% of infiltration rates for forested soils were higher than observed values for campus lawn soils. The maximum measured infiltration rate at the forested site was 57.14 cm/h and the minimum measured infiltration rate was 0.32 cm/h. Maxium measured compaction at the forested site was 1,682 kPa (244 psi) at a depth of 10.16 cm (4 in), with a measured infiltration rate of 2.54 cm/h. The minimum measured compaction value was 455 kPa (66 psi), which corresponds to the minimum measured infiltration rate of 0.32 cm/h and may be due to a shallow water table or impermeable layer. Forested site cone index values taken at a depth up to 15.2 cm (6 in) did not exceed 2,068 kPa (300 psi).

The average infiltration rate measured for soils at campus lawn sites is lower than the average rate of residential lawns (6.4 cm/h) reported by Pitt *et al.*, 1999, and 54% of cone index values exceeded the threshold of 2,068 kPa (300 psi) at a depth of 7.62 cm (3 in). The maximum measured infiltration rate was 2.54 cm/h and the minimum measured infiltration rate was 0.32 cm/h. The maximum measured compaction at campus lawn sites was 5,157 kPa (748 psi), with an infiltration rate of 0.32 cm/h; minimum measured compaction was 1,579 kPa (229 psi), with an infiltration rate of 0.32 cm/h. Two campus lawn sites, the Mall and Dowdy-Ficklen Stadium, had no measured infiltration rates for 1 out of 3 tests each; this does not mean that the soils have no permeability, but that it was too low to measure using the test method in this study. There was a significant difference between infiltration rates ($p = 0.007$) and maximum compaction values ($p = 0.000$) between forested and campus lawn sites.



a.



b.

Figure 16. Infiltration rates (a) and maximum compaction values (b) at the forested and campus lawn sites (n = 10 for the forested site; n = 21 for campus lawn sites).

Table 5. Summary of infiltration rates for campus lawns and forested soils.

Site	**Campus Lawn**	**Forested**
	Infiltration rate (cm/h)	
Average	0.89	14.29
Median	0.95	5.46
Maximum	2.54	57.15
Minimum	0	0.32
Standard Deviation	0.79	20.3

Average cone index profiles in Figure 17 show relative compaction with soil depth up to 10.16 cm (4 inches). Nine cone index measurements were taken at each campus lawn site; however, four of the sites (1900 Charles Blvd., Belk Building, Office of Admissions, Dowdy-Ficklen Stadium) included at least one set of measurements that did not exceed a depth of 10.16 cm (4 in), and values greater than a depth of 10.16 cm were eliminated for averaging. Factors inhibiting cone penetrometer depth include the degree of compaction from foot traffic and maintenance vehicles, and plant roots. For the forested site (Greens Mill Run Greenway), the greatest compaction occurred within the top 3 cm (1.18 in) of soil, then remained relatively consistent with depth. Compaction continued to increase with depth for the campus lawn sites, with the greatest compaction occurring shallower than 10 cm (3.9 in). Campus lawn sites sampled in the current study are adjacent to highly trafficked walkways and recreation areas and may not represent all lawn space across campus.

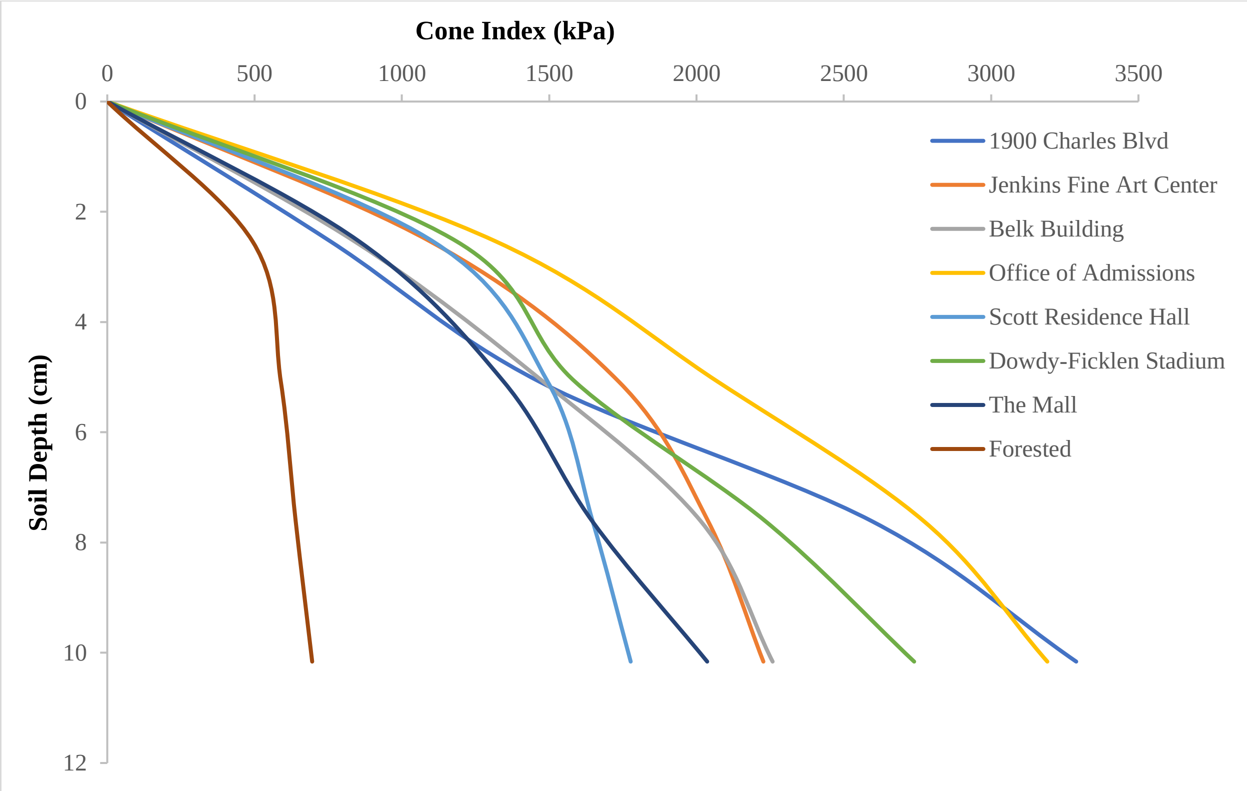


Figure 137. Average cone index values for the forested site (n = 30) and campus lawn sites (n = 9 at each site) (1 in = 2.54 cm).

Additional data collected in 2009 were included to increase the sample size for forested soils and campus lawns; only maximum compaction values from each set of measurements were used for comparison (n = 31 for forested sites; n = 47 for campus lawn sites) (Appendix F). The maximum compaction values for the two groups were significantly different ($p < 0.05$). The median compaction values for forested and campus lawn soils were 1,613 kPa (234 psi) and 4,702 kPa (682 psi), respectively (Figure 18). The median cone index value for campus lawn soils was nearly three times greater than forested soils, which may be due to a degree of compaction from foot traffic and maintenance vehicles.

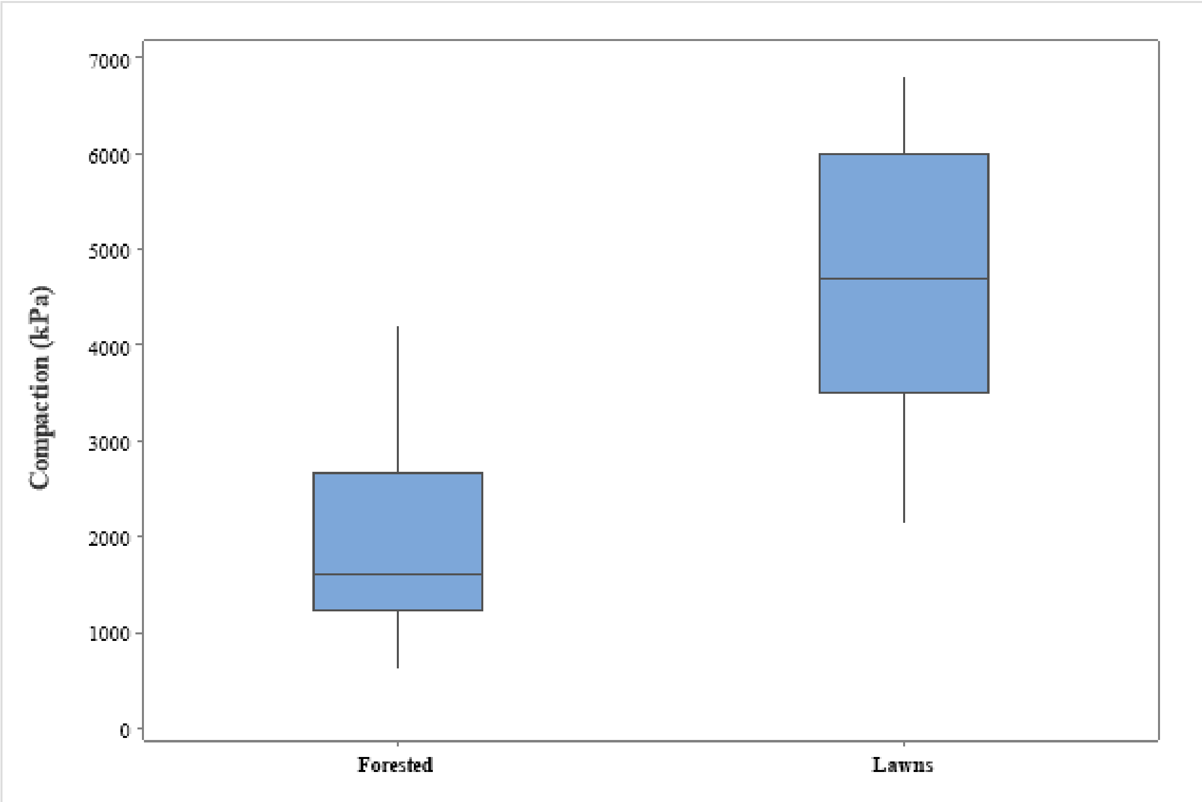


Figure 18. Comparison between forested soils and campus lawns across the study area (2009 and 2020 data).

Secondary Permeability of Fractured Asphalt

Surface infiltration rates (SIR) were tested for four fractured asphalt sites using a Turf-Tec® Double-Ring Infiltrometer and falling head test. At each site, three tests were conducted at different locations to determine secondary permeability of impervious cover based on existing surface conditions. All tests were performed on asphalt at locations where more than one fracture, or multi-fractures, were present and had not been patched (Wiles and Sharp, 2008). Width measurements were recorded for each fracture contained within the footprint of the inner ring.

Due to leakage around the base of the infiltrometer, data from the Willis Building parking lot were not included in analyses. In addition, Dowdy-Ficklen Stadium had two out of three tests and 1900 Charles Blvd had one out of three tests that were eliminated from analyses because the measurements were compromised by leakage. There was no correlation between SIR and average fracture width in asphalt across sample sites (Figure 19). The median SIR for fractured asphalt pavements was 3.8 cm/h. The minimum SIR was 0.64 cm/h and the maximum SIR was 3.82 cm/h; the minimum fracture width was 0.5 cm and the maximum fracture width was 2.5 cm (Table 6). Because asphalt without cracks is assumed to have close to 0 infiltration, the effective infiltration for the entire asphalt area at each site is expected to be lower than what was measured at the fractures.

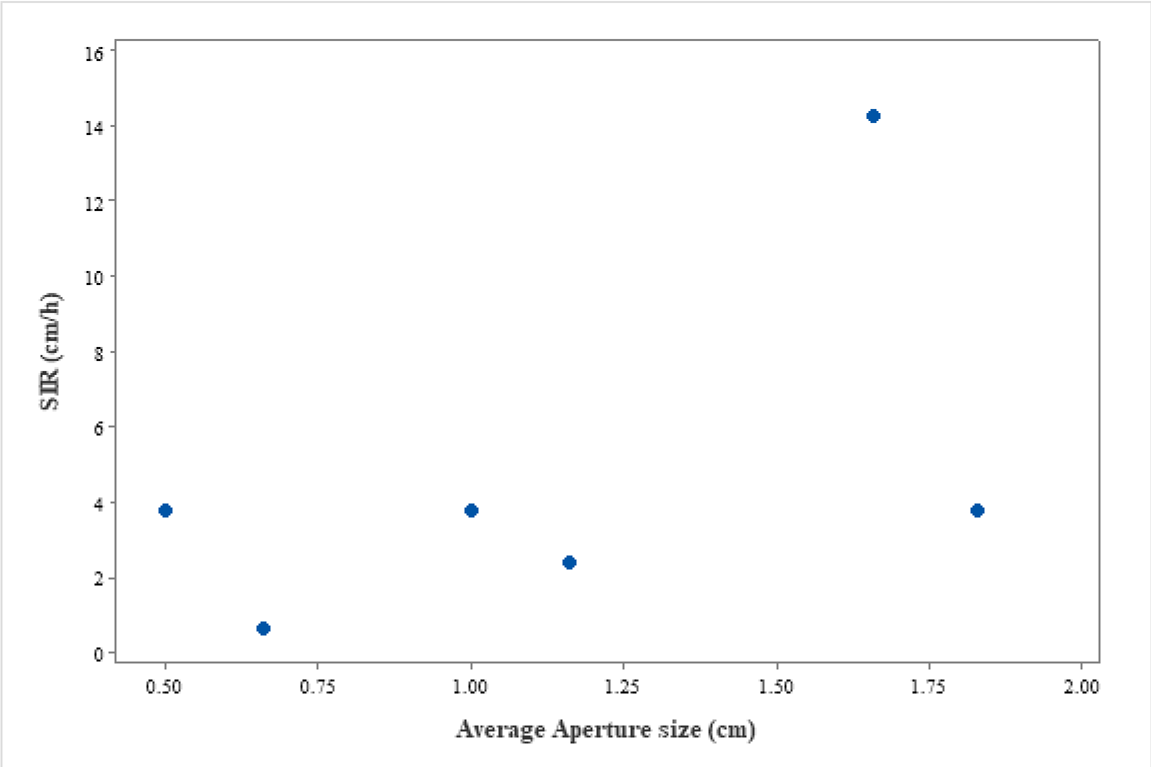


Figure 19. Surface infiltration rates are plotted against average fracture width in asphalt and demonstrate that there was no significant correlation across the sites sampled.

Table 6. Summary of sample point characteristics (6 multi-fractures).

Site Name	SIR Range (cm/hr)	Aperture Range (cm)
Rivers Building	0.64 - 3.82	0.5 - 1.0
1900 Charles Blvd	2.40 - 3.80	0.5 - 2.5
Dowdy-Ficklen Stadium	3.82	0.5 - 2.0

Effects of PICP on Peak Discharge

Impermeable surfaces greatly increase runoff and the primary role of permeable pavement is to reduce the amount of runoff entering surface waters. Estimating peak runoff and runoff volume can be determined using various methods; the rational method and the Natural Resources Conservation Service (NRCS) method are widely accepted (NC DEQ, 2013). Stormwater calculations for the City of Greenville are outlined in the *Manual of Standard Designs and Details* (2011) using the Rational Method (Equations 1 and 2).

$$Q = CIA \qquad \text{(Equation 1)}$$

Where: Q = Peak discharge, in cubic feet per second (cfs)

C = "Runoff Coefficient", unitless

I = Intensity of rainfall inches per hour, for a storm duration equal to the time of concentration, Tc

A = Drainage basin area, acres

$$T_C = \frac{\left(\frac{L^3}{H}\right)^{0.385}}{128}$$

(Equation 2)

Where: L = Maximum length of travel time of water (feet)

H = Difference in elevation between the most remote point on the basin and the outlet (feet)

Rational, or runoff, coefficients (*C*) relate the amount of runoff to the amount of rainfall received, with standard tables widely available for *C* values. Runoff coefficients are empirically derived based on basin characteristics such as land-use, soil type, and watershed slope (Hayes and Young, 2006). Larger values correspond to areas with low infiltration rates (impermeable surfaces, compacted soils), and lower values indicate higher permeability surfaces, therefore, less runoff (forests, lawns, permeable pavements) (Table 6). Because land use is not homogenous over the drainage area, the area was subdivided based on land use type and a weighted average was calculated to determine runoff coefficients for land cover conditions (NC DEQ, 2013) (Appendix G). Rainfall intensity in Equation 1 was determined by first calculating Tc for sub-basins within the study area. Time of concentrations for sub-basins were found through an iterative process and a graphical solution was then used to determine rainfall intensity, *I*, based on 10-year return frequency. The USGS *StreamStats* program was used to select sub-basins within the parcel area for length of travel time and elevation difference in Equation 2. Time of concentration is often defined as the time it takes water to flow from the most hydraulically distant point of the basin to the basin outlet (Hayes and Young, 2006). Tc is reduced in urbanized watersheds, therefore, Tc for each sub-basin was multiplied by a surface coefficient based on surface type (mowed channel, concrete channel, asphalt); time of concentrations for all sub-basins were summed and applied to an IDF curve to derive rainfall intensity for the City of Greenville (Appendix H). Table 7 summarizes discharge estimates for the study area based on undisturbed woodlands, existing conditions, conditions prior to PICP installations, and replacing impermeable surfaces with PICP. Previous studies and industry standards have stated a range of PICP runoff coefficients based on existing surface conditions (Bean, 2005; ICPI, 2008; Pratt *et al.*, 1995). Under certain environmental and maintenance conditions PICP can have runoff coefficients as low as 0.0, meaning that no runoff is expected and all water will infiltrate into the voids. Because there is a range of PICP *C* values based on empirical data but no runoff was observed in the current study, a runoff coefficient of 0 was chosen to estimate discharge for PICP conditions in the study area.

Table 7. Standard Rational Coefficients for wooded, recreational, commercial, and PICP land use type.

Land Use	Runoff Coefficient (C)
*Wooded	0.2
*Recreational	0.3
*Commercial	0.95
**PICP	0.0-0.44

*Taken from the City of Greenville's *Manual of Standard Designs and Details* (2011).

**Taken from Bean (2005), ICPI (2008), and Pratt *et al.* (1995).

Table 8. Peak discharge for land use conditions estimated using the Rational Method.

Land Cover	Weighted Runoff Coefficient	Q (cfs)
*Wooded (pre-development)	0.20	56.48
Current Conditions	0.59	676.88
Prior to PICP campus retrofits	0.60	688.35
****Implementing additional PICPs across campus**	**Range of weighted *C* values**	**Range of Q**
Retrofitting only RA parking lots with PICP	0.42 - 0.50	481.85 - 573.63
Retrofitting RA parking lots, drives, and walkways with PICP	0.30 - 0.44	344.18 - 504.79

* The wooded runoff coefficient used from Table 6 to estimate peak flows for the study area falls within the range of runoff coefficients (0.05-0.25) cited in the literature for wooded areas (NC DEQ, 2013).

** A range of retrofit discharge estimates are shown based on the range of *C* values from Table 7 used to calculate weighted runoff coefficients.

Although some sediment accumulation was observed during testing, all PICP sites maintained high infiltration rates that exceeded the forested, campus lawn, and fractured asphalt site surface infiltration rates. Current conditions in Table 8 include approximately 0.3 hectares (3,000 m^2) of PICPs installed across ECU's main campus, which reduce stormwater discharge to local streams by approximately 11.47 cubic feet per second (cfs) when compared to previous conditions prior to PICP retrofits. However, infiltration tests are snapshots of infiltration at one point and SIR for PICPs may vary during a rain event when precipitation rates are variable across the surface and runoff from adjacent areas flows to PICPs. The weighted runoff coefficient for current conditions suggests that approximately 60% of rainfall, based on a 10-year storm intensity, is surface runoff but may be reduced to 30% if there are additional PICP installations across campus. Retrofitting all parking lots, drives, and walkways with PICPs would reduce runoff by approximately 50%, and if all impervious surfaces except rooftops were converted runoff could be reduced by 53% for the study area.

Influence of PICP on Surface Temperatures

Four PICP and four asphalt sites were paired to determine and compare surface temperatures using a FLIR® E5 infrared camera (FLIR Technologies, Inc.). Infrared images recorded maximum, minimum, and average surface temperatures, with the aggregate-filled voids displaying the highest temperatures during testing (Figure 20) (Appendix I). Three thermal measurements were performed at each site on June 4, July 6, July 14, and July 15 between 11 am and 2 pm. The observed air temperature during testing was between 28 °C (82 °F) and 33 °C (91

°F). Asphalt and PICP sites were grouped by proximity, and measurements were taken to determine if the time of day influenced surface temperatures (Table 9). On June 4, the median asphalt temperature was 54.4 °C (130 °F) and the median PICP temperature was 55.1 °C (131 °F); asphalt temperatures were recorded between 11:36 am and 12:38 pm and PICP temperatures were recorded between 12:32 pm and 1:25 pm. The July 6, 2020 median asphalt temperature was 59.55 °C (139 °F) and the median PICP temperature was 57.25 °C (135 °F); PICP temperatures were recorded between 12:38 pm and 1:06 pm and asphalt temperatures were recorded between 1:13 pm and 2:05 pm. July 14 and 15, 2020 measurements were spread over two days to ensure readings were taken within the same time frame. Thermal measurements were recorded between 11:54 am and 12:27 pm. The median asphalt temperature was 57.7 °C (136 °F) and the median PICP temperature was 54.9 °C (131 °F). Although the median temperature was greater for asphalt (using and infrared camera), a Mann-Whitney U test was performed and there was no significant difference between surface type temperatures during testing ($p = 0.22$) (Figure 21).

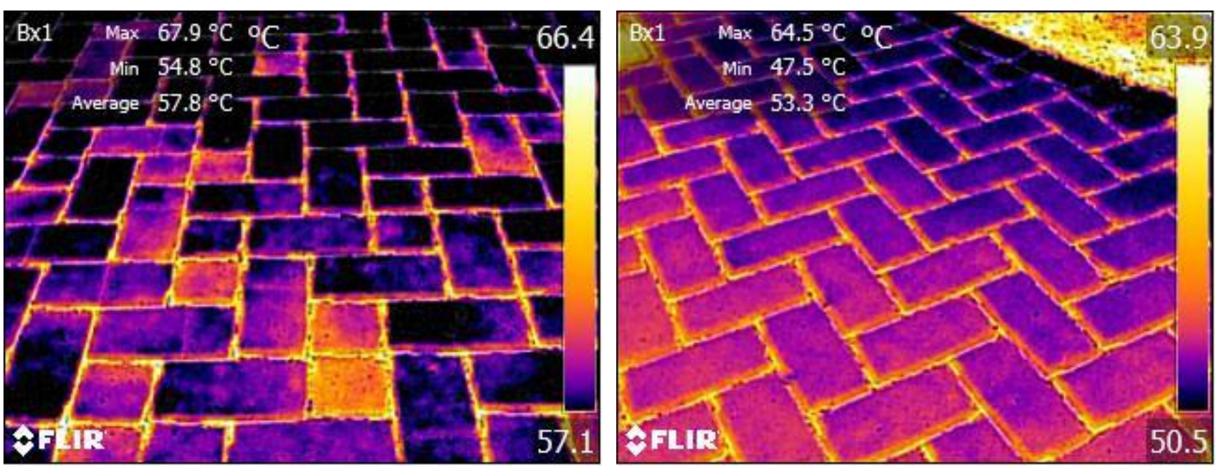


Figure 20. Infrared images of Student Plaza Drive (left) and Starbucks Mobile (right) PICP sites showing maximum, minimum, and average temperatures. The highest temperatures can be seen in the aggregate-filled voids.

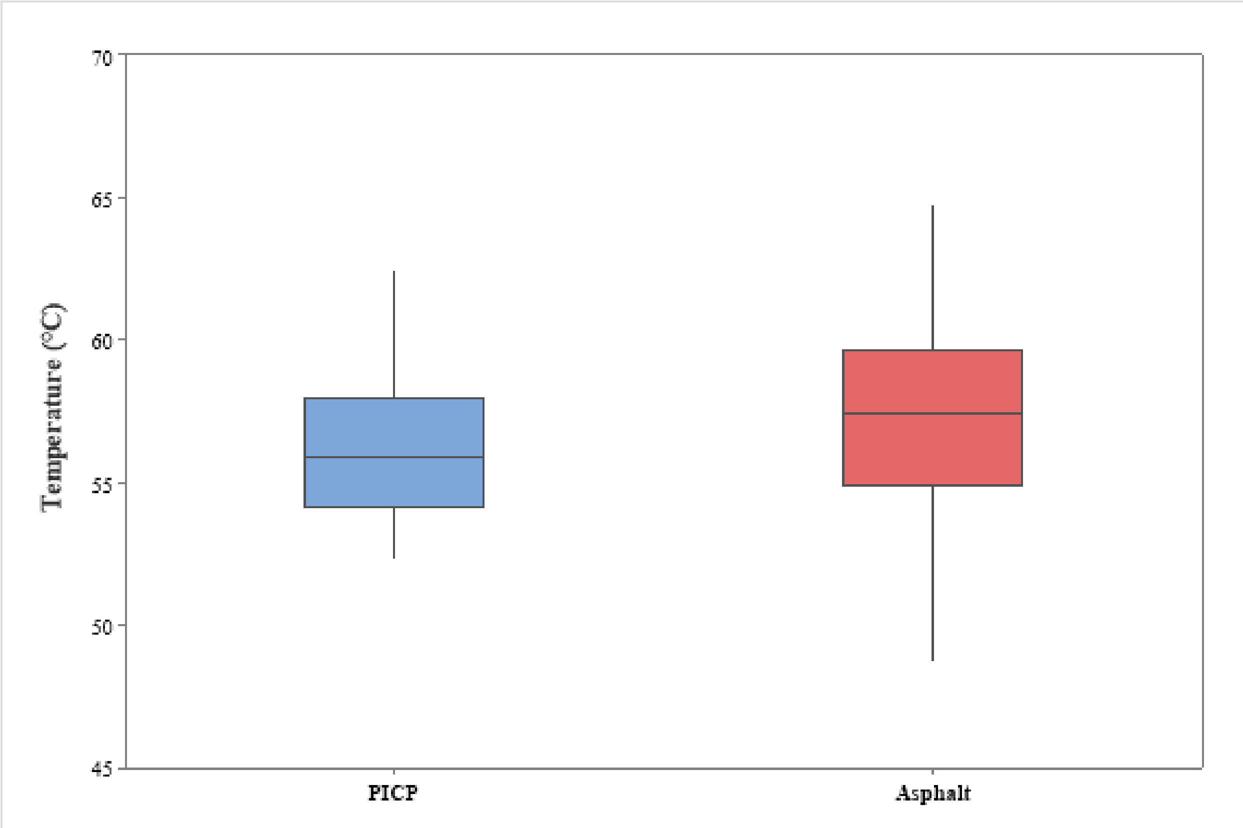


Figure 21. Infrared temperature comparison between PICP and asphalt pairs . There was a greater median temperature and wider temperature range for asphalt, however the difference between surface temperatures during the testing period was not significant based on a Mann-Whitney test ($p = 0.22$).

Table 9. Hourly air temperatures and surface material type during infrared testing (NCSU, 2021).

Date	Surface Material	Time	Temperature (°C)
6/4/2020	RA	11:00	28
6/4/2020	RA	12:00	30
6/4/2020	PP	13:00	31
6/4/2020	PP	14:00	31
7/6/2020	PP	12:00	32
7/6/2020	PP/RA	13:00	32
7/6/2020	RA	14:00	33
7/15/2020	PP/RA	12:00	32
7/15/2020	PP/RA	13:00	33

*Missing values for July 14, 2020.

Additionally, two HOBO® U20L-04 Data Loggers monitored pavement temperature at 5-min intervals between 3:00 pm on July 23rd and 5:55 pm on July 27th, 2020 (Figure 22). The average daily air temperatures during the monitoring period were between 25 °C (77 °F) and 30 °C (86 °F) (NCSU, 2021). The maximum surface temperature for the asphalt site during the monitoring period was 56.2 °C at 3:00 pm on July 26, 2020. The maximum surface temperature for the PICP site was 55.6 °C at 3:55 pm on July 26, 2020. The time series data show lower nighttime temperatures for PICP, and a general trend that PICP is slower to reach maximum temperatures compared to asphalt. Recorded surface temperatures for both asphalt and PICP were lowest between 9 pm and 6 am. Table 10 shows average nighttime temperatures of each surface type, with a median difference of 1.64 degrees C . The median temperatures for asphalt and PICP over the monitoring period were 34.2 °C and 29.7 °C, respectively. There was a significant difference in surface temperatures during monitoring of full diurnal cycles ($p < 0.05$), with asphalt having significantly higher temperatures relative to PICP. The greatest difference in peak and minimum temperatures occurred on July 25, 2020, with asphalt displaying a 0.91° higher daytime temperature and a 2.33° higher nighttime temperature than PICP. Over the monitoring period, asphalt temperatures were an average of 0.69° higher than PICP during the daytime and an average of 1.81° higher than PICP during the nighttime.

Average daily air temperatures during the logger monitoring period were comparable to those during infrared testing (Table 11). Both surface types followed the trend of ambient air temperature, but maximum daily surface temperatures recorded for PICP were lower than RA four out of five monitoring days (Table 12). Although PICP and RA maximum daily temperatures were within 1°, PICP exhibited overall lower nighttime temperatures and were generally slower to warm than RA.

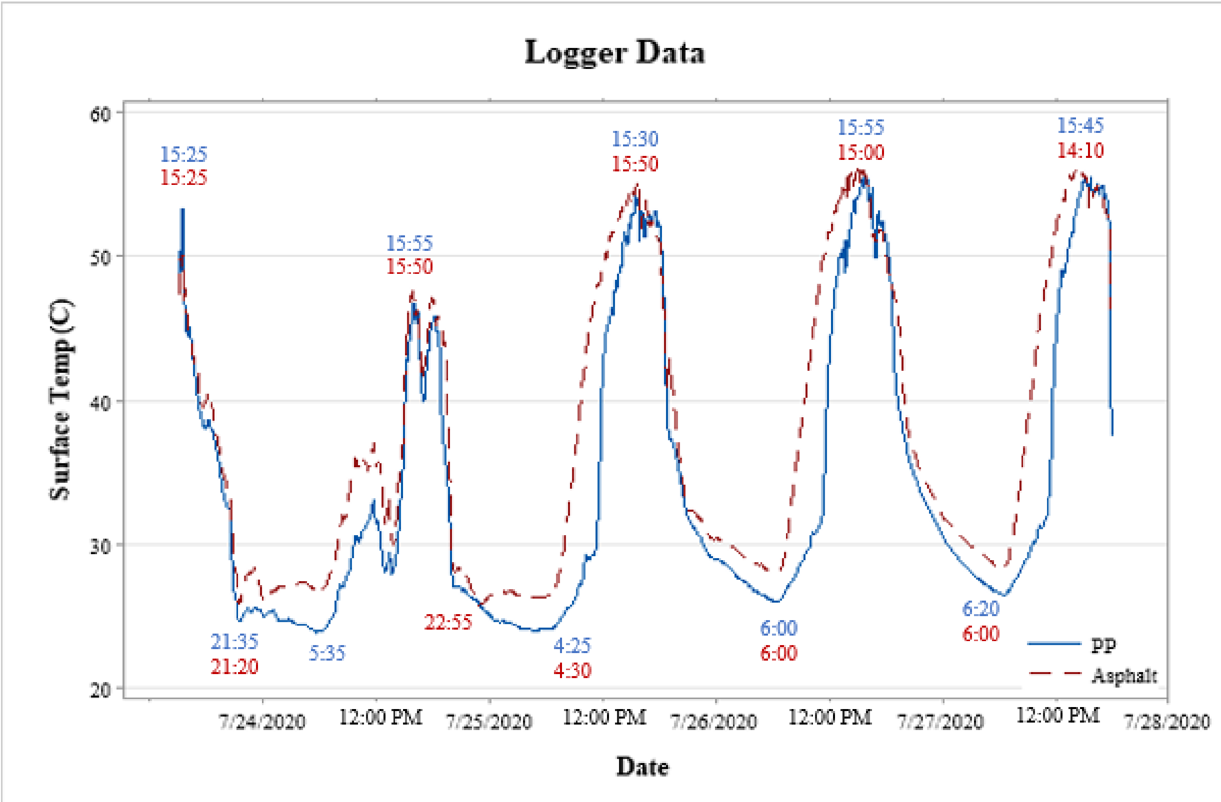


Figure 22. Time series plot of asphalt and PICP temperature data. Peak and minimum times Observed and labeled in blue (PICP) and red (asphalt). There was a significant difference in surface temperatures during the automatic monitoring period ($p < 0.05$).

Table 10. Average surface temperatures of PICP and asphalt between 9 pm and 6 am.

Date	PP (°C)	Asphalt (°C)	Difference (°C)
7/23/2020-7/24/2020	24.83	27.09	2.26
7/24/2020-7/25/2020	24.90	26.55	1.65
7/25/2020-7/26/2020	28.36	29.96	1.60
7/26/2020-7/27/2020	29.68	31.31	1.63
Median	**26.63**	**28.53**	**1.64**

Table 11. Average daily air temperatures during testing and monitoring periods (NCSU, 2021).

Infrared Testing		**Logger Monitoring**	
Date	Temperature (°C)	Date	Temperature (°C)
6/4/2020	27	7/23/2020	28
7/6/2020	27	7/24/2020	25
7/14/2020	27	7/25/2020	27
7/15/2020	28	7/26/2020	29
		7/27/2020	30

Table 12. Maximum surface temperatures during logger monitoring period.

PICP			**Regular Asphalt**		
Date	Time	Temperature (°C)	Date	Time	Temperature (°C)
7/23/2020	15:25	53.31	7/23/2020	15:25	50.04
7/24/2020	15:55	46.72	7/24/2020	15:50	47.50
7/25/2020	15:30	54.21	7/25/2020	15:50	55.12
7/26/2020	15:55	55.58	7/26/2020	15:00	56.20
7/27/2020	15:45	55.43	7/27/2020	14:10	55.89

DISCUSSION

Infiltration Rates of PICP and Influence of PICP on Peak Discharge

Previous studies have shown a decrease in PICP infiltration rates over time due to particle clogging (Balades *et al.*, 1995; Bean *et al.*, 2007; Kamali *et* al., 2017; Selbig and Buer, 2018; Weiss *et al.*, 2019). There were no earlier infiltration data to compare against the measurements taken during the current study. At ECU PICP sites are in areas that receive wind-blown or stormwater transported particles from nearby greenspace and campus landscaping, or particle deposition from vehicular traffic. However, regular surface maintenance of PICP using the combination of a sweeper truck and backpack blowers occurs two or three times per week to remove surface debris; backpack blowers are used twice per year (fall and spring) to remove fines within the voids (John Gill, personal communication, March 26, 2020). Surface infiltration rates were variable at each test site, and average infiltration rates in this study were compared to the year of installation to determine if new PICP installations performed better with respect to infiltration than older sites. There was no pattern to suggest that older sites had lower infiltration rates; instead, the type and amount of use each PICP area receives may be contributing to overall performance.

No substantial clogging was noticed during PICP infiltration tests. However, Student Plaza Drive walkway and Jenkins Fine Art Center had one out of three tests that exceeded 60 seconds with SIR one and two orders of magnitude lower than the other two tests performed at each site. These findings suggest that infiltration rates can vary over the PICP area and may indicate the presence of some sediment accumulation. The highest PICP infiltration rates measured at Jenkins

Fine Art Center and the Student Plaza Drive picnic area could have resulted from routine surface maintenance and low foot/vehicular traffic. The Student Plaza Drive picnic area provides additional outdoor seating for students and may experience daily upkeep, in addition to periodic PICP maintenance, for the removal of trash and debris associated with ECU Dining Services in Wright Plaza. These PICP sites cover a small area adjacent to highly trafficked walkways, possibly allowing each site to receive less traffic. Student Plaza Drive walkway, Band Shell Plaza, and E 14th Street Parking lot sites are subject to continual foot and vehicular traffic (parking and maintenance vehicles). Because they were installed in the same year (2017), the amount of traffic at the Student Plaza Drive sites could account for the difference in infiltration rates. The lowest infiltration rate, measured at the Starbucks Mobile site, could have resulted from several factors, including: soil type, maintenance, frequent foot traffic, and compaction associated with parking of the mobile food truck.

Soils are susceptible to compaction from development and heavy equipment that move particles closer together at the expense of pore space (Bean *et al*., 2015; Gregory *et al*., 2006). Using USDA Web Soil Survey (2020) ratings, five PICP sites consist of Group A soils and rated low for compaction; the soils underlying the Starbucks mobile PICP site rated high for compaction due to the increase in clay content of Exum fine sandy loams. Additionally, wood mulch, mixed into the stone subgrade to improve water quality by removing nitrogen, may be contributing to a decrease in infiltration at the Starbucks Mobile site (John Gill, personal communication, March 29, 2021).

Infiltration tests varied at each PICP site, but average SIR at each PICP site met the Minimum Design Criteria (MDC) requirement for infiltration of at least 127 cm/h (50 in/h) (NCDEQ 2017). Each of the three tests used to average PICP SIRs, were greater than 15 cm/h

(5.9 in/h). These rates exceed infiltration rates of hydrologic groups A (> 0.3 in/h) and C (0.05-0.15 in/h) soils (USDA 1986). The lowest SIR of PICPs (15.24 cm/h) exceeded 80% of infiltration rates measured at the forested site in this study. Therefore, some clogging that may occur does not cause PICP to have surface infiltration rates lower than naturally vegetated areas. Referring to precipitation frequency estimates taken from NOAA's *Precipitation Frequency Data Server (PFDS)*, PICPs may be able to accommodate the volume of large storm events (e.g., 100-yr storm) with a 1-hour duration (9.65 cm/h; Table 13). Periodic observations during rainfall events did not reveal runoff generation at PICP sites (Figure 23), however in some cases stormwater runoff generated from adjacent areas may flow to PICP areas. Using similar test methods, average SIRs were comparable to results found by Bean *et al*. (2007), Collins *et al*. (2008), Selbig and Buer (2018), and Vaillancourt *et al*. (2019) (Table 14).

Table 13. Precipitation frequency estimates (cm/h) (NOAA 2017).

Duration	Average recurrence interval (years)			
	2y	10y	25y	100y
60-min	4.57	6.53	7.67	9.65

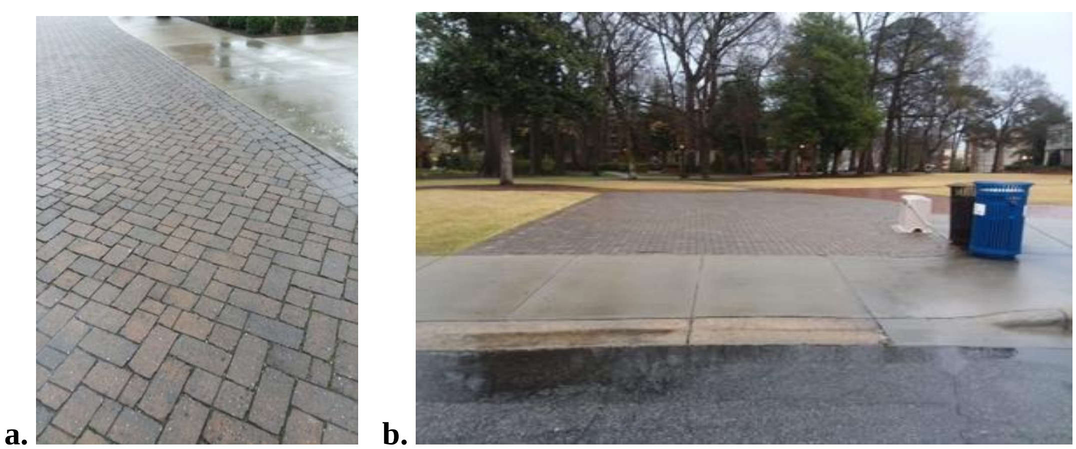


Figure 23. PICP sites show no runoff generation during rainfall events; (a) Student Plaza Drive on February 6, 2020 and (b) Band Shell Plaza on March 3, 2020.

Table 14. Features of selected test methods for infiltration and range of average surface infiltration rates (SIR).

Reference	Test Material	Test Description Summary	Test Result	Average SIR (cm/h)	
				Low	High
Bean *et al.* (2007) North Carolina, USA Maryland, USA Virginia, USA Delaware, USA	PICP	Modified version of ASTM D 3385 using a DRI and SRI, and falling head test; for DRIT begin timing when water reaches predetermined depth, stop timing when all water has infiltrated surface; for SRIT measure the time it takes a known volume of water to infiltrate surface.	Average rate of fall in water head, reported as cm/h.	53	2000
Collins *et al.* (2008) North Carolina, USA	PICP	Modified version of ASTM D 3385 using a DRI and falling head test; begin timing when water reaches predetermined depth, stop timing when all water has infiltrated surface.	Average rate of fall in water head, reported as cm/h.	171	1536
Selbig and Buer (2018) Wisconsin, USA	PICP	Modified version of ASTM C 1701/1701 M using SRI with a constant head test; measure the time it takes for a known volume of water to infiltrate surface.	Average rate of fall in water head, reported as in/h (converted to cm/h for comparison).	61	2070
Vaillancourt *et al.* (2019) Quebec, Canada	PICP	ASTM C 1781/1781 M using a SRI and constant head test; measure the time it takes a known mass of water to infiltrate surface.	Average rate of fall in water head, reported as mm/h (converted to cm/h for comparison).	164	941
Current study (2020) North Carolina, USA	PICP	Modified version of ASTM D 3385 and ASTM C 1718 using a DRI and falling head test; begin timing when water reaches predetermined depth, stop timing when all water has infiltrated surface.	Average rate of fall in water head, reported as cm/h.	183	2045

Like many states, North Carolina awards credit for implementing SCMs in new development or retrofits. Shallow infiltration systems, such as PP, are used to slow and filter stormwater entering surface waters to reduce flooding and improve water quality. USDA ratings for these systems are based on soil properties such as, depth to water table, soil type, or other factors that can limit infiltration (USDA Web Soil Survey, 2020). Permeable pavements receive SCM credit when appropriately sized and may be considered 100% pervious if used in conjunction with other SCMs, or as an addition to existing projects (e.g., patio, driveway, walkway, parking pad/lot) (NCDEQ 2017). According to the NCDEQ *Stormwater Design Manual* (2017) for PP systems, the minimum separation between the bottom of the subgrade and the seasonal high-water table (SHWT) should be two feet (60.96 cm), but no less than one foot (30.48 cm). Three of the fractured asphalt sites met the minimum requirement for depth to water table (>60 cm) and may be ideal candidates for PICP installations to replace the aging infrastructure. Six campus lawn sites also met the minimum requirement and consisted of well-drained soils, suggesting that adjacent impervious surfaces (sidewalks and drives) in these areas could be considered for PICP retrofits in the future. The addition of PICPs adjacent to disturbed soils can mitigate some of the negative impacts associated with urbanization. Because 1900 Charles Boulevard consists of hydrologic soil groups that have slow infiltration rates, this site would not be ideal for PICP installation. While the Belk building site consists of Group A soils, a portion of the site is underlain by Pactolus loamy sand, which is considered limiting for shallow infiltrations systems due to its wetness and may require additional drainage.

Figure 24 shows drives, sidewalks, and parking lots across campus that have the potential to be retrofitted with permeable pavers. The dark blue shaded areas are considered severely limited due to construction and maintenance practices, public safety concerns, or soil properties that affect infiltration (USDA Web Soil Survey, 2020). One observation from the map and previous runoff estimates is that parking lots contribute significantly to surface runoff, making up approximately 20% of the study area IC. Parking lots that are not ideal for installation due to limiting soils were omitted from the map. Using the rational method for discharge estimates, peak flow could be reduced up to 29% by replacing existing asphalt with PICP and up to an additional 20% by replacing concrete sidewalks and drives. Based on parking lot size and well-draining hydrologic Group A soils, it is recommended that the Willis Building, Dowdy-Ficklen Stadium, and Belk Building lots be considered for PICP retrofits. To ensure soil properties are conducive to SCM installations, site-specific data should be obtained.

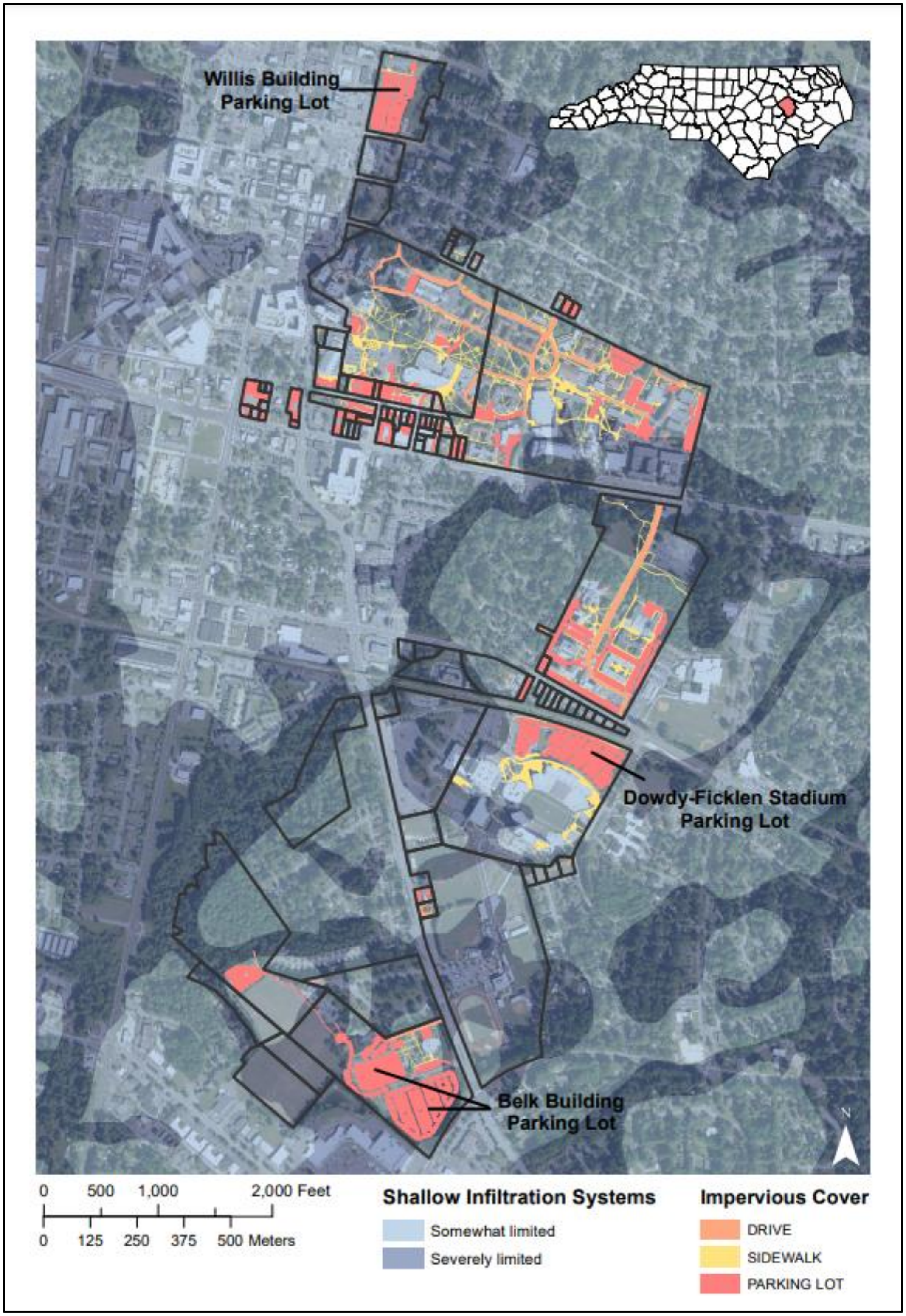


Figure 24. Shallow infiltration systems soil map and potential IC sites for PICP retrofits (USDA SSURGO Data, 2020).

Infiltration Rates of Campus Lawns and Forested Soils

Urban soils are assumed to be compacted to some degree from construction and maintenance activities associated with development, and hydrologic group classifications may no longer apply (USDA, 1986). The negative effects include limiting plant root growth, poor aeration, and poor drainage, causing compacted soils to behave as partially impervious surfaces (Mangiafico, 2009; USDA Web Soil Survey, 2020) that can reduce groundwater recharge and increase stormwater runoff. While heavy equipment can compact soils up to 1 m deep, surface compaction typically occurs within the top 10 cm of soil and the greatest impacts can be measured at depths of 30 cm and shallower (Alaoui *et al.*, 2018; Bean *et al.*, 2015; Kozlowski, 1999). For example, there was no measurable infiltration rate for 1 out of 3 tests at The Mall and Dowdy-Ficklen Stadium sites. Both areas consist of well-maintained turf grasses and receive considerable student and public recreational use, as well as lawnmowing. Many factors affect soil porosity, and infiltration rates may vary in a single soil type depending on macropores in the soil (e.g., plant roots, animal boroughs, earthworm holes) (Mangiafico, 2009; Pitt *et* al., 1999; USDA, 2008). Infiltration rates at the Office of Undergraduate Admissions site ranged from 0.32 cm/h (0.13 in/h) to 2.22 cm/h (0.87 in/h); SIR at Jenkins Fine Art Center and Scott Residence Hall ranged from 0.63 cm/h (0.25 in/h) to 2.54 cm/h (1 in/h). Heavy foot traffic and routine maintenance of campus lawn areas, such as mowing, may contribute to soil compaction, bare soils, and low infiltration rates. The average infiltration rate of all campus lawn sites [0.89 cm/h] in this study is lower than the average rate of 6.4 cm/h for compacted residential lawns reported by Pitt *et al.* (1999). However, Gregory et *al.* (2006) estimated 2.3 cm/h for compacted pasture areas in sandy soils in Florida. Four of the campus lawn sites had average infiltration rates comparable to or greater than hydrologic soil group A (> 0.76 cm/h), indicating those soils do not have infiltration rates lower than bare soils, but the highest average infiltration rate of 1.69 cm/h at campus lawn sites is less than the 2-year, 1-hour storm event (4.57 cm/h), therefore runoff can be expected for smaller storms. Campus turfgrasses are typically aerated once per year to help reduce compaction by loosening soil (John Gill, personal communication, March 26, 2020).

Ten infiltration tests were performed at the forested site. The two highest infiltration rates were comparable to undisturbed infiltration rates reported in the literature for similar conditions of sandy soils in forested areas with leaf litter (Gregory *et al.*, 2006; Kays, 1980). Generally, infiltration rates decrease as compaction increases in soils, however some of the low infiltration rates at the forested site were associated with low compaction values. For example, the two lowest infiltration rates (0.32 cm/h) corresponded with low median compaction values of 365 kPa (53 psi) and 593 kPa (86 psi). Because the forested site is located adjacent to a local stream, Greens Mill Run, some of the low infiltration rates could have resulted from a shallow water table or hydric soil layer that was not delineated on the USDA soil map. However, the average infiltration rate at the forested site was greater than the 100-year, 1-hour storm intensity of 9.6 cm/h (3.78 in/h) for Greenville, NC (NOAA PFDS, 2017), suggesting that no runoff is expected. In contrast, the highest measured infiltration rate at campus lawn sites was 2.54 cm/h (1.0 in/h).

Secondary Permeability of Fractured Asphalt

Effects of urbanization on surface waters are typically described in terms of runoff quality and quantity, relating an increase in impervious surfaces to increased contaminant input, decreased infiltration, and increased flooding. The City of Greenville, like many urbanized communities, implemented a Stormwater Utility Fee (effective in 2003) based on the amount of impervious cover on a property as part of its stormwater management program to comply with state and federal water quality regulations (City of Greenville, 2021). As previously mentioned, the ISA of ECU's East Campus is approximately 50% of the land area. However, the secondary permeability of impervious surfaces cannot be ignored as an infiltration pathway and possible component of urban groundwater recharge (Wiles and Sharp, 2008).

The process of groundwater recharge occurs when water enters the saturated zone but can be complicated to quantify in an urban setting due to multiple land uses, and research in urban groundwater recharge is limited (Lerner, 2002). *Direct recharge* takes place in the soil profile directly below where precipitation falls, which differs from *localized recharge,* where rainfall moves laterally short distances on the ground surface before infiltration and can occur at fractures in impervious surfaces (Lerner, 2002; Wiles and Sharp, 2008). For example, the observed surface infiltration rates for fractured asphalt parking lots in this study ranged from 0.64 cm/h to 3.82 cm/h. Wiles and Sharp (2008) summarized and compared results from their study with previous studies, listing a range of SIR from 0.18 cm/h to 2.7 cm/h for various impervious surfaces. These findings suggest that while impervious cover may decrease direct recharge, there is potential for localized recharge. The Wiles and Sharp (2008) study and the current study recorded width measurements of fractures but found no significant correlation between SIR and fracture width in sampled sites. Fractures in pavement are often filled with sediment or debris, and the lack of correlation is expected; therefore, fracture fill and asphalt subgrade are possible controls of infiltration rates (Wiles and Sharp, 2008). Tests at three of the four sites (1900 Charles Blvd, Dowdy-Ficklen Stadium, and Willis Building) were compromised by leakage around the base of the infiltrometer and the data were eliminated from analyses. The small size of the infiltrometer could also have contributed to inaccurate data, and infiltration testing would need to be repeated for comparison using a larger instrument to include a broader area without fractures. A more accurate collection method and analyses might include using scan lines to determine the density of fractures and ultimately, how pavements behave with respect to infiltration over a larger area instead of at selective points where infiltration might be expected. Based on the range of infiltration rates of impervious cover reported in the literature and measured infiltration rates in the current study, it is likely that areas with fractured asphalt are not entirely impermeable, suggesting that some infiltration can be expected. Lerner (2002) suggested that some localized recharge may occur and approximately 50% of all ISA (surface infrastructure and storm drainage systems) should be treated as permeable. However, infiltration rates at fractured asphalt sites in this study were significantly lower than PICP and forested site infiltration rates, and more accurate data would need to be collected to draw conclusions about the effect of fractured asphalt on localized recharge and runoff reduction on the ECU campus. It is likely that fractures are a small percentage of the area, and future work could address infiltration rates across entire parking lots to determine if asphalt infiltration plays an appreciable role in reducing overall stormwater runoff.

With the exception of PICPs, the results in this study show how human activities have decreased infiltration rates and increased runoff generation. Rational coefficients (C) relate the amount of rainfall to runoff in a drainage area, ranging between 0 and 1.0, where a value of 0 indicates that no rainfall with become runoff, and a value of 1.0 indicates that all rainfall will become runoff (Hayes and Young, 2005). Generally, as rational coefficients increase, infiltration decreases. Table 15 summarizes infiltration rates measured in this study by land use type with corresponding C values taken from NC DEQ *Erosion and Sediment Control Planning and Design Manual* (2013).

Table 15. Summary table of surface type, land use cover, average surface infiltration rates, and rational coefficients.

Surface Type	Land Use	Average SIR cm/h	Average SIR in/h	Rational *C*
PICP	Shallow Infiltration System	805.15	317	0
Forested	Woodlands	14.49	5.7	0.05-0.25
Campus Lawn	Recreational	0.89	0.35	0.10-0.35
Fractured Asphalt	Streets	3.05	1.2	0.70-0.95
*Unfractured Asphalt	Streets	0	0	0.70-0.95

*Infiltration rates of unfractured asphalt were not measured in this study but are assumed to be 0.

Surface Temperatures of PICP and Asphalt

Climate change is felt globally as the result of human activity, and the effect of increasing temperatures creates public health concerns for vulnerable communities. Under a rapid emissions scenario, North Carolina temperatures are projected to increase 6°-10°F by 2100 and the last decade (2009-2018) was the warmest decade recorded in North Carolina history (Kunkel *et al.*, 2020). Due to their high heat absorption and retention impervious surfaces cause urban centers to be warmer than surrounding rural areas, referred to as the Urban Heat Island effect (Dello *et al.*, 2020; Stempihar *et al.*, 2012). To combat elevated temperatures, cities can increase the use of vegetation and consider replacing dark, low-albedo materials, such as asphalt, with light-colored surfaces (Rosenfeld *et al.*, 1995). PICP are constructed according to ASTM C936, typically made of Portland cement concrete (PCC) or similar materials with higher albedo (0.25) than regular asphalt (0.05-0.15), that may help mitigate effects of the UHI (ICPI, 2008; Stempihar *et al.*, 2012).

Because most PICP temperature studies have focused on stormwater runoff in paver cell layers and data for surface temperature variations is limited (Novo *et al.*, 2013; Wardynski *et al.*, 2013), one goal of this study was to collect surface temperature information using two methods. Previous studies have shown that PC (porous concrete) and PICP may reach daytime temperatures of RA but are slower to warm than traditional asphalt (Selbig and Buer, 2018; Stempihar *et al.*, 2012). Under dry summer conditions, Selbig and Buer (2018) found that permeable pavers were slower to adjust to ambient air temperatures by approximately 60 minutes. Observations during high temperature months in Taipei City, Taiwan showed a faster temperature drop and lower nighttime temperatures for PICP compared to RA (Cheng *et al.*, 2019). Using short interval automatic monitoring, PICP data obtained in this study showed a similar trend. For example, PICP was slower to reach maximum temperatures, with approximately 20- to 60-minute delays compared to RA for three out of five monitoring days. In addition, surface temperatures for PICP were lowest between 9 pm and 6 am, with a median difference of 1.64 degrees C. The benefits of slower warming, faster cooling, and generally lower temperatures of PICP should be considered as an alternative to asphalt in urban areas to help reduce surface temperatures, especially during summer months when air temperatures can create hazardous outdoor conditions. An additional benefit is reduced high temperatures spikes in streams during runoff events in summer months (Wardynski *et al.*, 2013).

Infrared images were also taken to determine if the time of day influenced surface temperatures, but the infrared data in this study is inconclusive. Because of the variability in measurements associated with time of day, moisture, shading, and vegetation, long-term automatic monitoring would provide a better picture of how PICP behaves seasonally. Additionally, remote sensing may offer more spatially extensive results when comparing the thermal behavior of surface materials. For example, two studies conducted in China were able to analyze land cover types using Landsat images and quantify their impact on the UHI (Liu *et al.*, 2015; Zhang *et al.*, 2017).

CONCLUSIONS

Six PICP sites were measured for surface infiltration rates and compared to campus lawn and forested sites. All PICP sites performed significantly better than forested and campus lawn sites. Therefore, some observed fines did not cause PICP sites to have infiltration rates lower than hydrologic group A soils (loamy sand, sandy loams), indicating the addition of PICP would produce less runoff and play a key role in stormwater management. However, this study did not address the ability of maintenance practices to maintain infiltration rates over time, or the impact of siting and construction practices on infiltration. Infiltration rates of asphalt are assumed to be close to 0, but data collected in this study showed that joints and fractures provided a pathway for infiltration of rainfall. However, there were not enough data to draw conclusions on the role fractures play in reducing runoff. Future work could be targeted to look at the broader influence of fractures on infiltration by measuring the density, extent, and width of fractures on various pavement conditions. Evaluating the secondary permeability of impervious cover can allow city planners to better understand the effects of aging infrastructure on local hydrology and assist in guidance for the siting of GSI installations and retrofits.

Infiltration rates and runoff estimates in this study showed that PICP can considerably reduce the impact of stormwater. While no substantial clogging was noted during testing, regular maintenance is recommended to maintain infiltration rates of PICP over time. Problems with fine sediment accumulation should be addressed before fines migrate further into voids where they are harder to dislodge. As mentioned previously, a range of Rational Coefficients has been stated in the literature for PICP and a value of 0.0 was selected to represent the study area, since no runoff was observed during rain events. Ideally, all PICP rational coefficients would be close to zero but in-situ soils, subbase construction, and sediment accumulation are limiting factors in infiltration rates. Because DRI and SRI tests are instantaneous, long-term data collection of outflow volumes during storm events would allow for a more thorough analysis of PICP installations and comparison among published rational coefficient values to determine how well these systems function in different soils and with various maintenance practices.

Previous research has shown that soil compaction has a negative impact on infiltration rates and increases surface runoff in sandy soils, and similar results were found in the current study. Combining previously collected data with data from the current study, the median compaction value of campus lawn sites was nearly three times that of forested sites. However, the sites measured in this study may not represent all lawns across campus. Campus lawns are aerated annually to reduce compaction by loosening soil and enhancing the flow of water, air, and nutrients to plant roots. The Campus Mall, where the greatest foot traffic occurs, generally had low infiltration rates compared to sites with less foot traffic, such as the Belk Building or 1900 Charles Blvd. Future work could evaluate the relationship between foot traffic and maintenance activities (lawnmowing) on compaction and infiltration. To minimize runoff and flood potential in urban areas where soils have been disturbed, compaction could be offset by employing a combination of SCMs, maximizing greenspace, incorporating native plant species into the landscape, and planting trees. A number of best management practices (BMP) can also be considered at initial project design and during construction to reduce or mitigate soil compaction associated with development such as, minimizing site disturbance, protecting disturbed soils from further compaction, and tillage of previously compacted soils.

In addition to reducing stormwater runoff, this study showed that PICP can reduce surface temperatures relative to asphalt and may have the ability to reduce the overall effect of the UHI.

PICP surface temperatures generally followed changes in air temperatures and were slower to warm and faster to cool than traditional asphalt. Although PICP surface temperatures during the daytime were within one degree of regular asphalt, PICP exhibited overall lower nighttime temperatures. Because infrared data in this study was limited, long-term automatic monitoring would provide a more detailed understanding of how PICP behaves seasonally. Further evaluation would require monitoring of temperature differentials in paver cell layers and surface runoff from asphalt parking lots to determine if there is a significant difference in thermal loads to local streams.

PICP systems are a beneficial type of LID that can be implemented in existing areas, such as parking lots, driveways, patios, and sidewalks. Without necessarily requiring additional land area, PICPs can reduce the need for larger SCMs and reduce runoff volumes to existing stormwater infrastructure, this is often beneficial in urban areas where additional space for SCMs may be limited due to existing infrastructure. These systems also help communities meet state and federal water quality regulations by capturing rainwater at the point of impact and treating a portion of runoff from adjacent areas. While initial installation costs may be high, repair and maintenance of PICPs can be more cost effective than other types of porous pavement. Brick pavers can be replaced if cracked or damaged and a combination of backpack blowers, pressure washing, and sweeper trucks can be used to maintain infiltration rates. Pavers typically consist of lighter colored materials compared to traditional asphalt. The high reflective quality of PICP and ability to manage and treat stormwater runoff allow urban centers to mitigate the effects of the Urban Heat Island and combat water quality and quantity issues associated with urbanization. Additionally, because PICPs readily drain, ponding is reduced or eliminated and pavers are more resistant to freezing. The ground below PICPs remains above freezing and the open voids allow snowmelt to infiltrate, which can prevent degradation of the pavers and improve overall safety and aesthetics. Results from this study showed benefits of implementing PICPs in urbanized communities, and previous studies have shown that all PP systems perform better with respect to surface runoff and pollutant removal than traditional asphalt. Future work should focus on long-term monitoring and maintenance of PP systems to guide future projects and foster a wider acceptance of LID as a stormwater management strategy.

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APPENDIX A: Site Coordinates and Soil Characteristics (USDA Web Soil Survey, 2020)

Table 1a. Site coordinates and soil characteristics.

Latitutde	Longitude	Type of Surface	Soil Unit	Soil Type	HSG	Drainage Class	DWT (cm)	Suseptibility to Compaction
35.601664	-77.361222	Forested	WaC	Wagram loamy sand	A	well drained	192	low
35.592579	-77.371087	Maintained grass	WaB	Wagram loamy sand	A	well drained	192	low
35.609102	-77.367005	Maintained grass	WaB	Wagram loamy sand	A	well drained	192	low
35.590272	-77.369516	Maintained grass	AgB	Alga loamy sand	A	excessively drained	>200	low
35.608161	-77.364767	Maintained grass	WaB	Wagram loamy sand	A	well drained	192	low
35.600533	-77.363595	Maintained grass	WaB	Wagram loamy sand	A	well drained	192	low
35.598425	-77.365023	Maintained grass	WaB	Wagram loamy sand	A	well drained	192	low
35.607002	-77.365938	Maintained grass	WaB	Wagram loamy sand	A	well drained	192	low
35.608468	-77.367834	PICP	WaB	Wagram loamy sand	A	well drained	192	low
35.606506	-77.363738	PICP	WaB	Wagram loamy sand	A	well drained	192	low
35.605823	-77.362159	PICP	WaB	Wagram loamy sand	A	well drained	192	low
35.608226	-77.370228	PICP	WaB	Wagram loamy sand	A	well drained	192	low
35.598423	-77.363071	PICP	WaB	Wagram loamy sand	A	well drained	192	low
35.605293	-77.362562	PICP	ExB	Exum fine loamy sand	C	moderately well drained	61	high

APPENDIX B: PICP Surface Infiltration Rate Site Summaries

Table 1b. Surface Infiltration Rate Test Sites and Appendices.

Site	**Appendix**
E 14th Street	B1
Jenkins Fine Art Center	B2
Student Plaza Drive (walkway)	B3
Student Plaza Drive (picnic area)	B4
Band Shell Plaza	B5
Starbucks Mobile	B6

Appendix B 1

Site: E 14th Street Parking Lot

Use: Campus parking lot

Approximate Pervious Area: 2008 m^2
21600 ft^2

Approximate Drainage Area: 2008 m^2
21600 ft^2

Construction Year: 2012

Test Date: November 21, 2019

Visual Assessment: No major clogging, but some sand accumulation near concrete barrier that separates PP and RA.

Maintenance Practice: Sweeper truck and backpack blowers 2-3 times per week for surface debris; backpack blowers twice per year to remove fines within voids.

Existing Conditions Tests:

Test #1	Test #2	Test #3	Average (cm/h)
476.25	742.95	171.45	463.55

Appendix B 2

Site:	Jenkins Fine Art Center
Use:	Walking and Tree Box Filter
Approximate Pervious Area:	60 m^2 650 ft^2
Approximate Drainage Area:	60 m^2 650 ft^2
Construction Year:	2016
Test Date:	February 3, 2020
Visual Assessment:	Voids look clear of debris and fines.
Maintenance Practice:	Sweeper truck and backpack blowers 2-3 times per week for surface debris; backpack blowers twice per year to remove fines within voids.

Existing Conditions Tests:

Test #1	Test #2	Test #3	Average (cm/h)
38.1	2438.4	3657.6	2044.7

Appendix B 3

Site: Student Plaza Drive (walkway)

Use: Walking and light vehicular traffic (maintenance vehicles)

Approximate Pervious Area: 1050 m^2
11300 ft^2

Approximate Drainage Area: 1050 m^2
11300 ft^2

Construction Year: 2017

Test Date: February 3, 2020

Visual Assessment: Voids mostly clear of debris and fines; most fines noticed at southeast end of walkway near Rivers building.

Maintenance Practice: Sweeper truck and backpack blowers 2-3 times per week for surface debris; backpack blowers twice per year to remove fines within voids.

Existing Conditions Tests:

Test #1	Test #2	Test #3	Average (cm/h)
15.24	1463.04	304.8	594.36

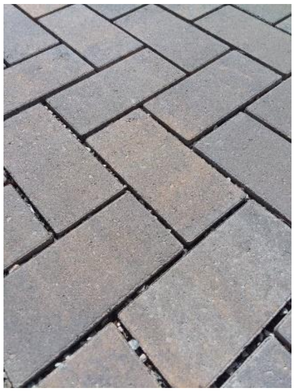
Appendix B 4

Site:	Student Plaza Drive (picnic area)
Use:	Outdoor seating and light foot traffic.
Approximate Pervious Area:	59 m^2 630 ft^2
Approximate Drainage Area:	59 m^2 630 ft^2
Construction Year:	2017
Test Date:	February 3, 2020
Visual Assessment:	Voids mostly clear of debris and fines; some mulch from adjacent landscaping in voids.
Maintenance Practice:	Sweeper truck and backpack blowers 2-3 times per week for surface debris; backpack blowers twice per year to remove fines within voids.

Existing Conditions Tests:

Test #1	Test #2	Test #3	Average (cm/h)
2438.4	320.04	137.16	965.2

Appendix B 5



Site: Band Shell Plaza

Use: Walking and light vehicle traffic.

Approximate Pervious Area: 93 m^2
1000 ft^2

Approximate Drainage Area: 93 m^2
1000 ft^2

Construction Year: 2018

Test Date: February 16, 2020

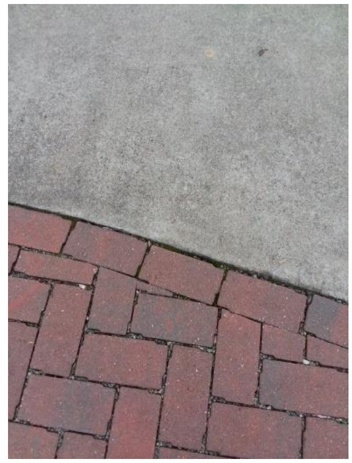
Visual Assessment: Voids clear of debris and fines.

Maintenance Practice: Sweeper truck and backpack blowers 2-3 times per week for surface debris; backpack blowers twice per year to remove fines within voids.

Existing Conditions Tests:

Test #1	Test #2	Test #3	Average (cm/h)
548.64	596.35	596.35	580.45

Appendix B 6



Site: Starbucks Mobile

Use: Mobile food truck parking pad.

Approximate Pervious Area: 79 m^2
850 ft^2

Approximate Drainage Area: 79 m^2
850 ft^2

Construction Year: 2015

Test Date: February 16, 2020

Visual Assessment: Voids mostly clear of debris and fines; some mulch from adjacent landscaping in voids.

Maintenance Practice: Sweeper truck and backpack blowers 2-3 times per week for surface debris; backpack blowers twice per year to remove fines within voids.

Existing Conditions Tests:

Test #1	Test #2	Test #3	Average (cm/h)
65.31	228.6	254	182.64

APPENDIX C: Double-Ring Infiltrometer Test Data

Table 1c. Double-ring infiltrometer inner ring water levels with corresponding times and R^2 values from three tests at one site.

Site	Figure
Jenkins Fine Art Center PICP	C1
Student Plaza Drive (picnic area) PICP	C2
Student Plaza Drive (walkway) PICP	C3
Band Shell Plaza PICP	C4
14th Street Parking Lot PICP	C5
Starbucks Mobile PICP	C6
Greens Mill Run (forested)	C7
1900 Charles BLVD (campus lawn)	C8
Jenkins Fine Art Center (campus lawn)	C9
Belk Building (campus lawn)	C10
Office of Admissions (campus lawn)	C11
Scott Residence Hall (campus lawn)	C12
Dowdy-Ficklen Stadium (campus lawn)	C13
The Mall (campus lawn)	C14
Willis Building Parking Lot (secondary permeability)	C15
1900 Charles BLVD Parking Lot (secondary permeability)	C16
Dowdy-Ficklen Stadium Parking Lot (secondary permeability)	C17
Rivers Building Parking Lot (secondary permeability)	C18

APPENDIX C: Double-Ring Infiltrometer Test Data

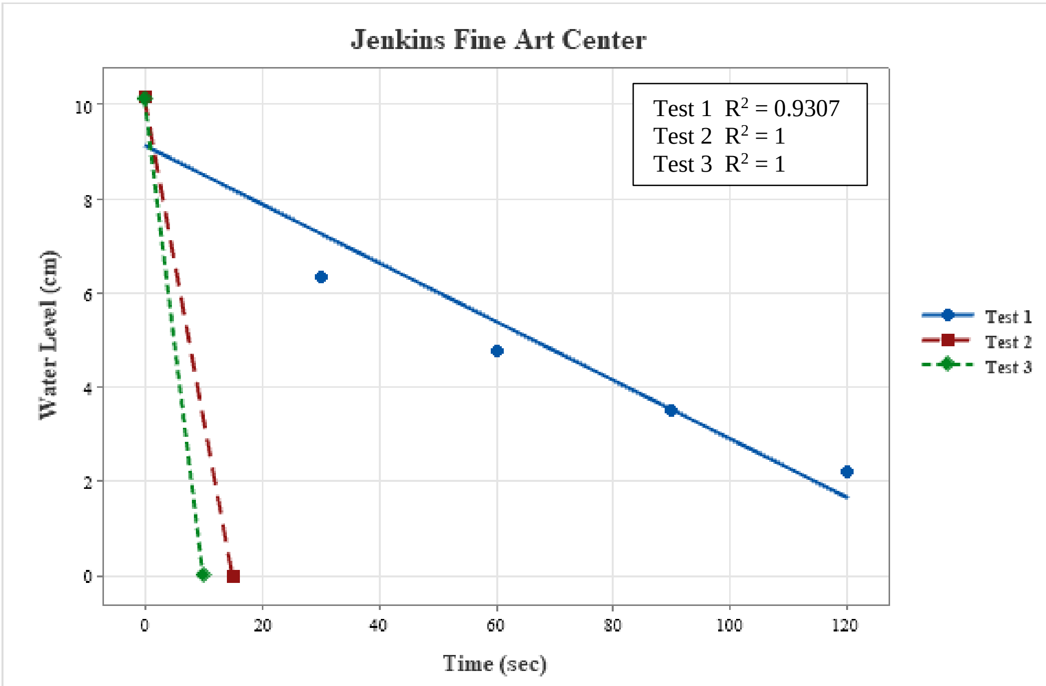


Figure C1.

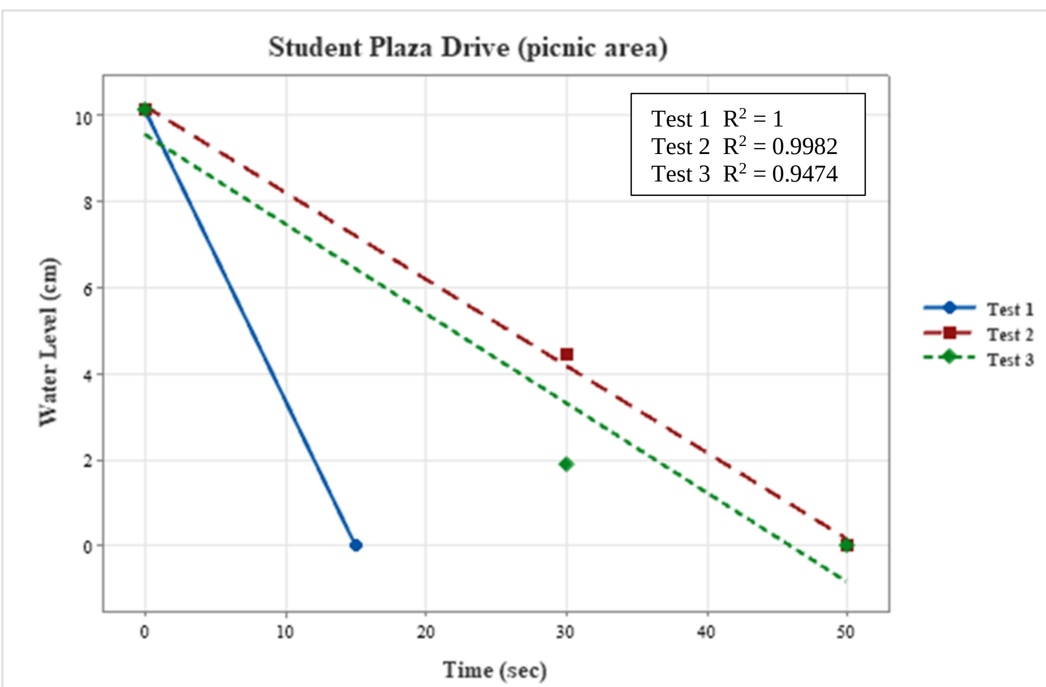


Figure C2.

APPENDIX C: Double-Ring Infiltrometer Test Data

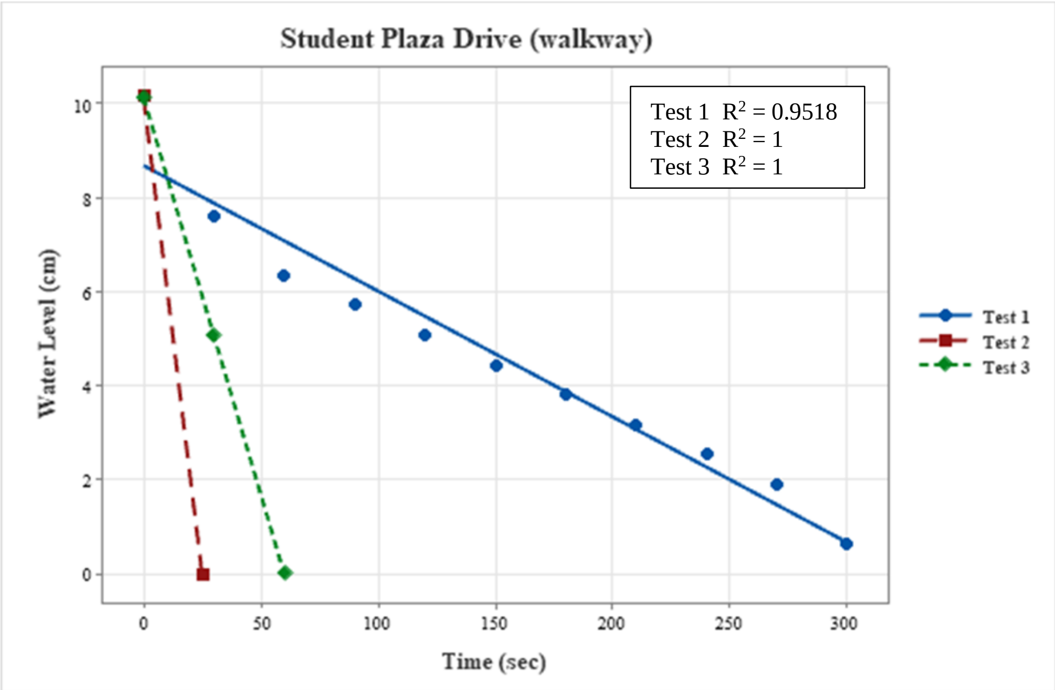


Figure C3.

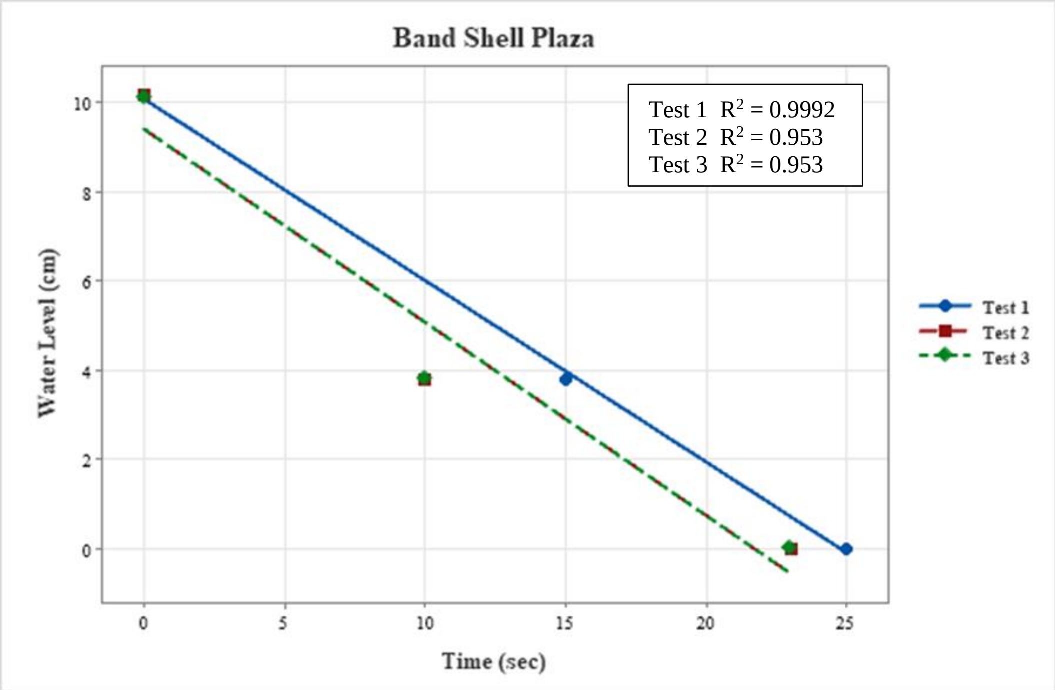


Figure C4.

APPENDIX C: Double-Ring Infiltrometer Test Data

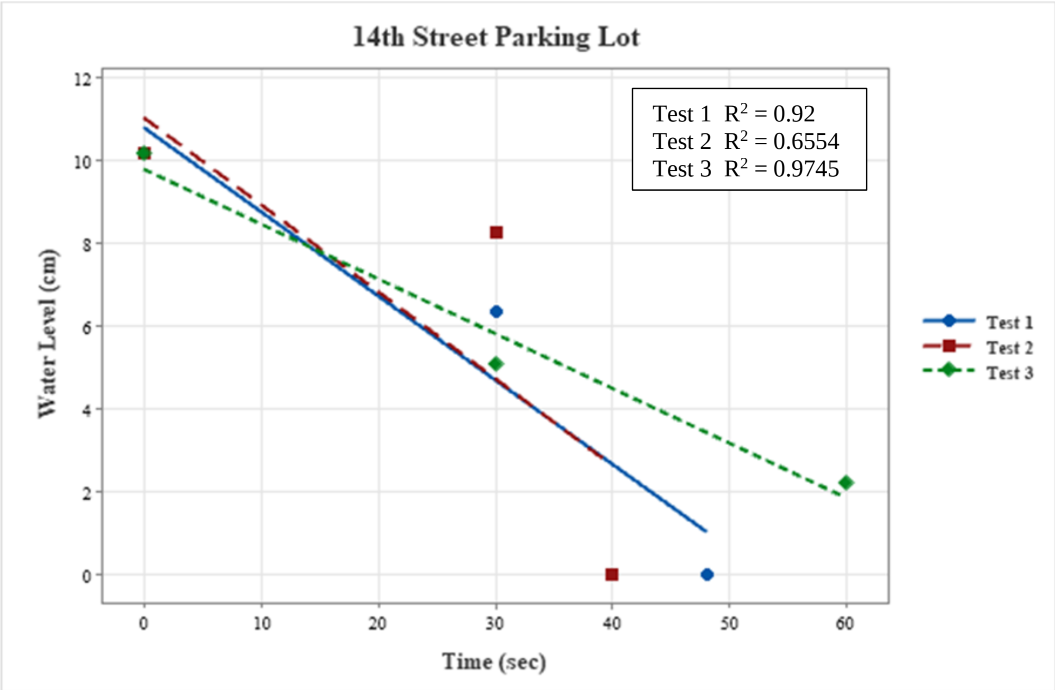


Figure C5.

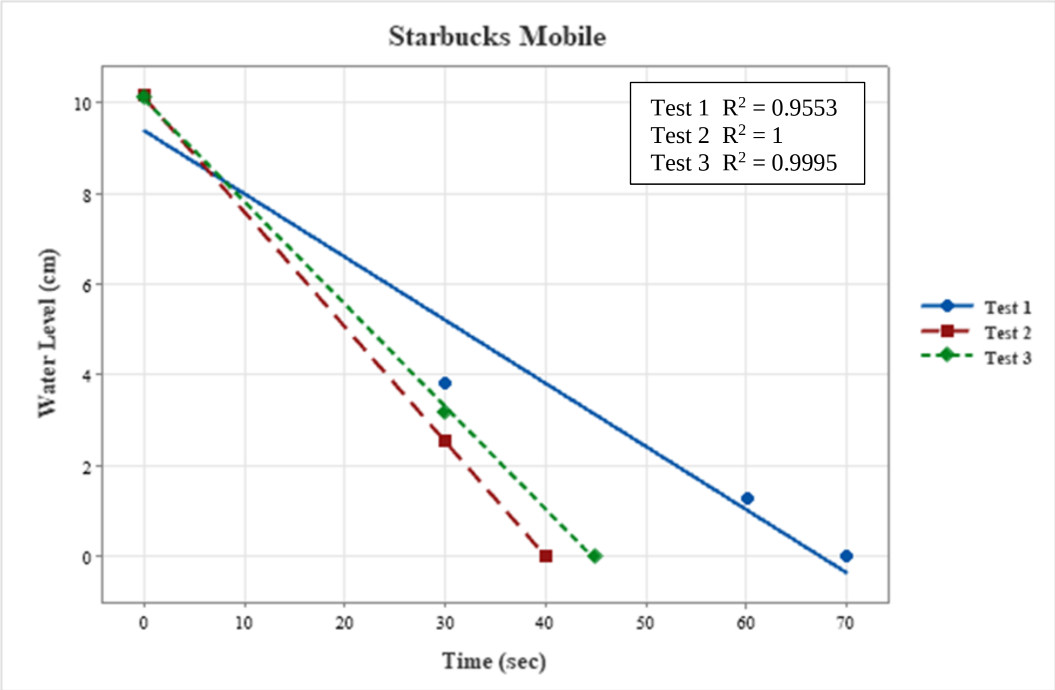


Figure C6.

APPENDIX C: Double-Ring Infiltrometer Test Data

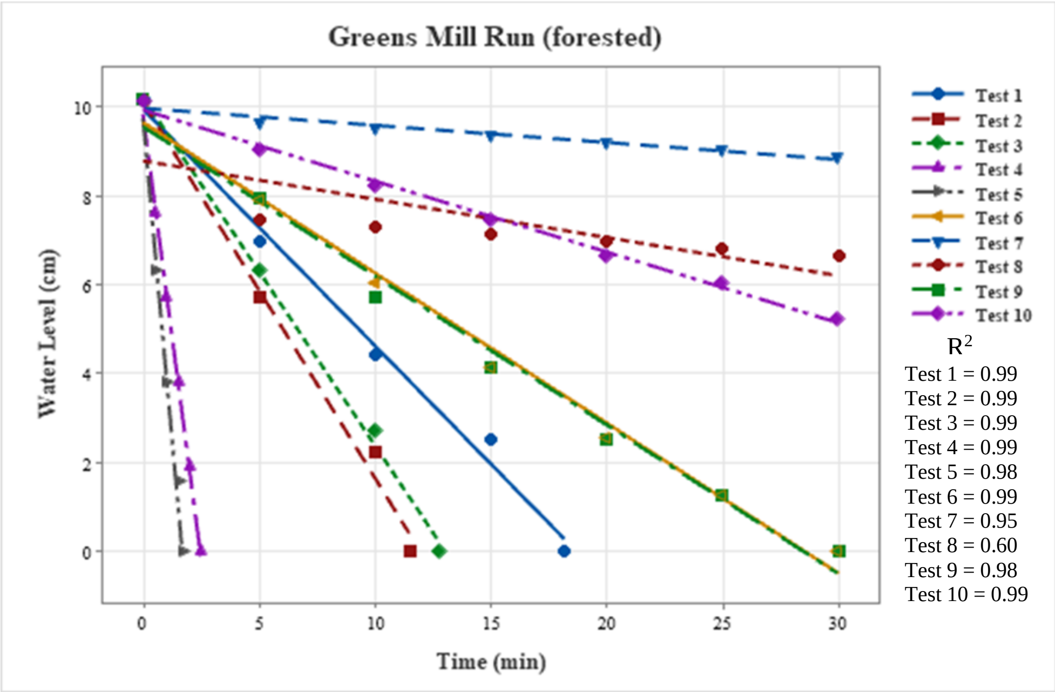


Figure C7.

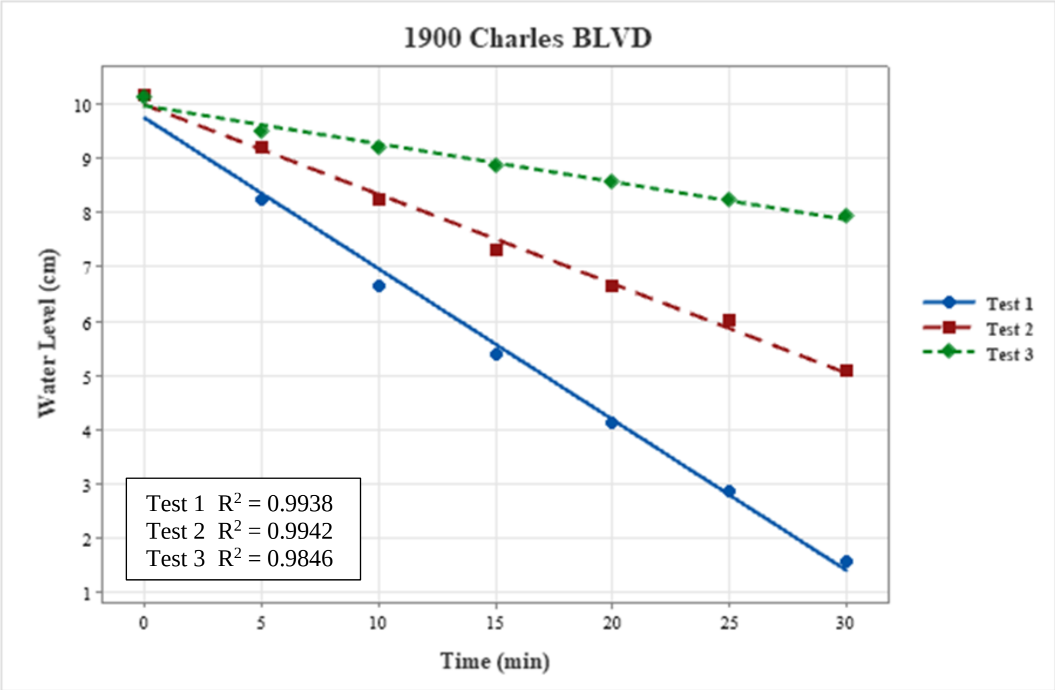


Figure C8.

APPENDIX C: Double-Ring Infiltrometer Test Data

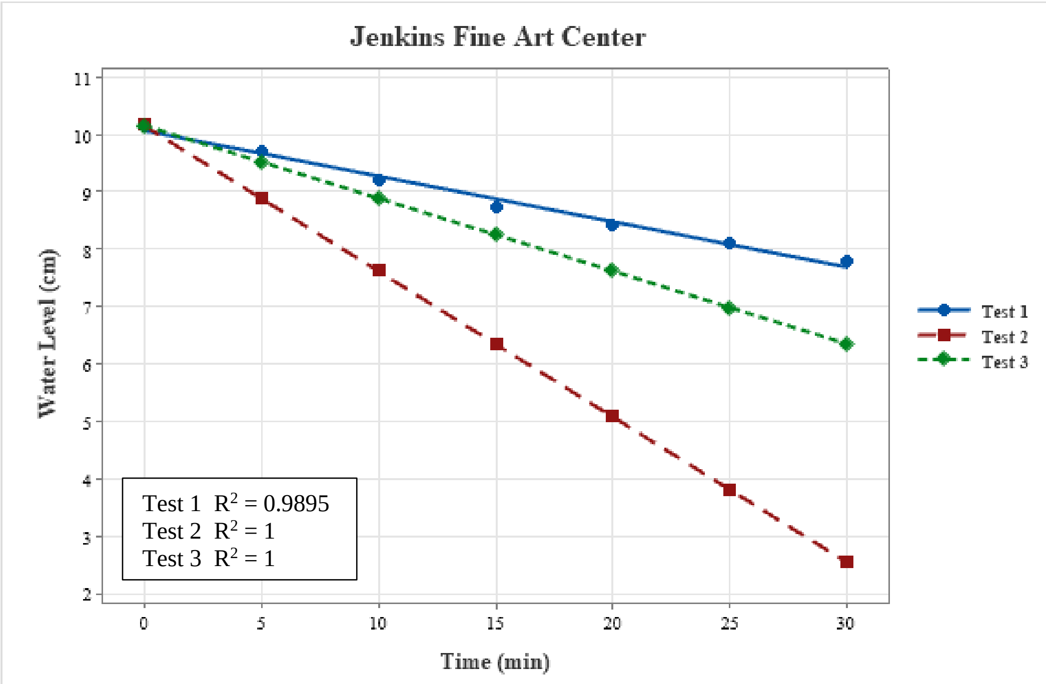


Figure C9.

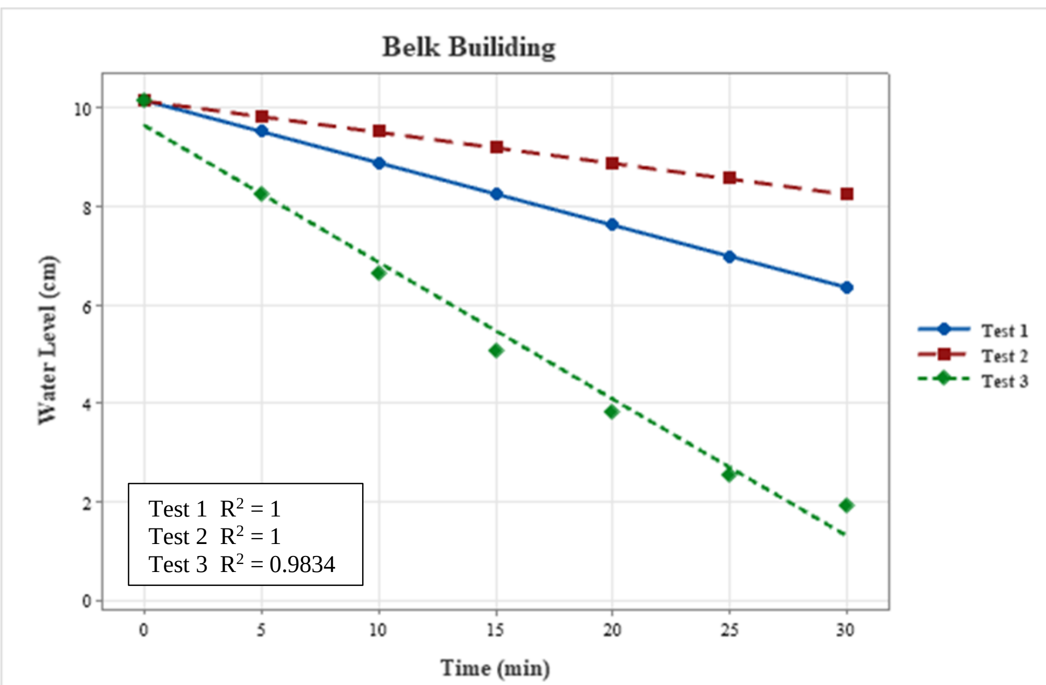


Figure C10.

APPENDIX C: Double-Ring Infiltrometer Test Data

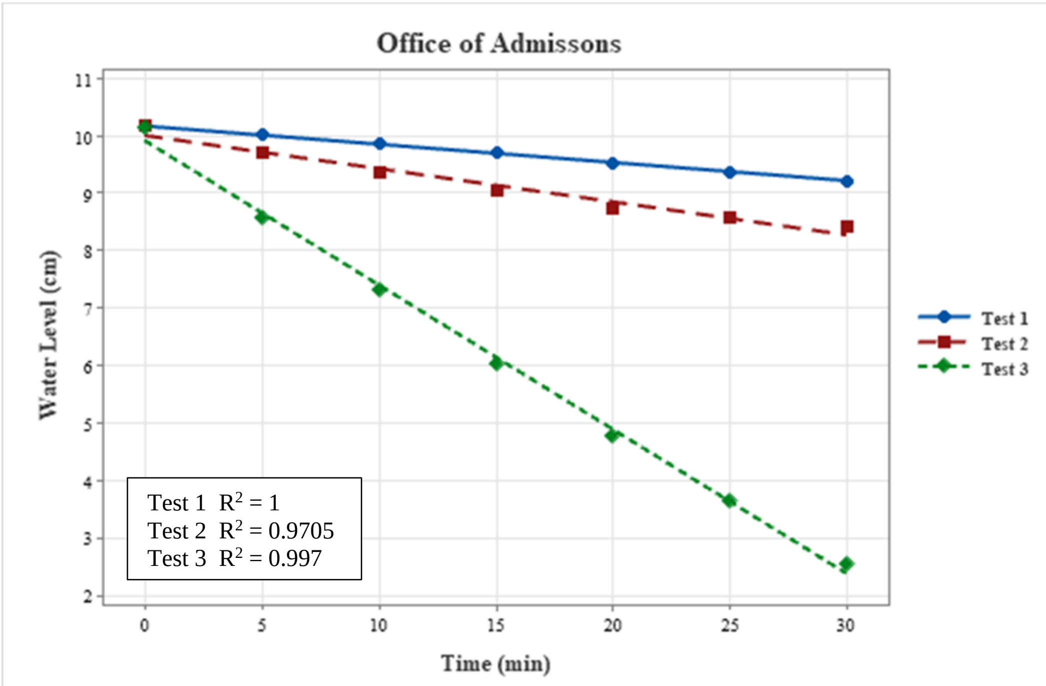


Figure C11.

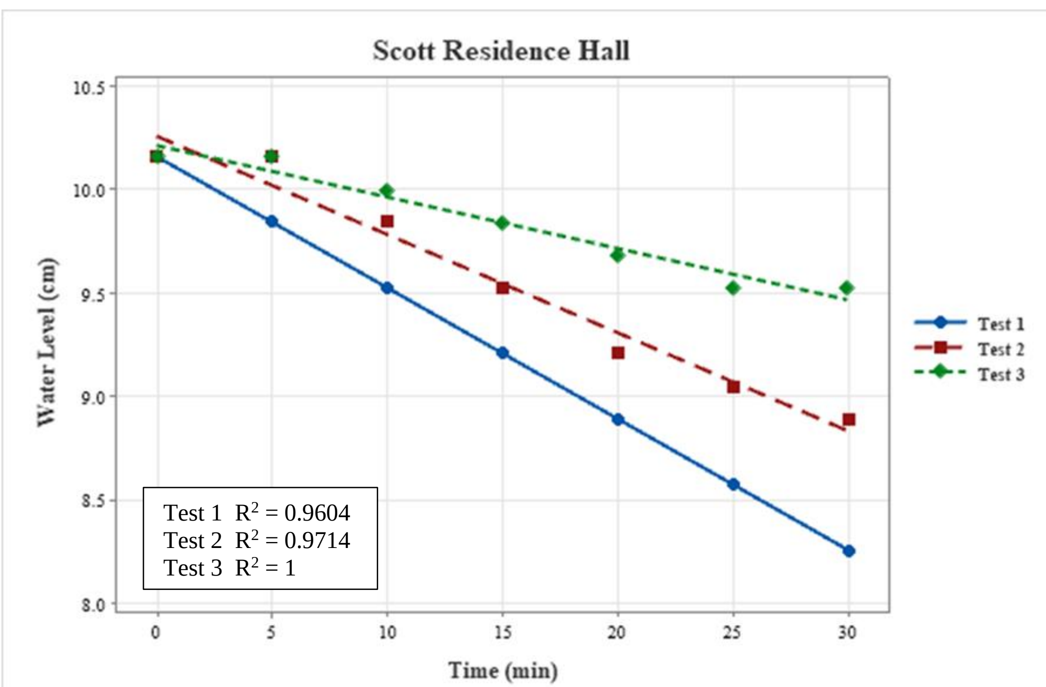


Figure C12.

APPENDIX C: Double-Ring Infiltrometer Test Data

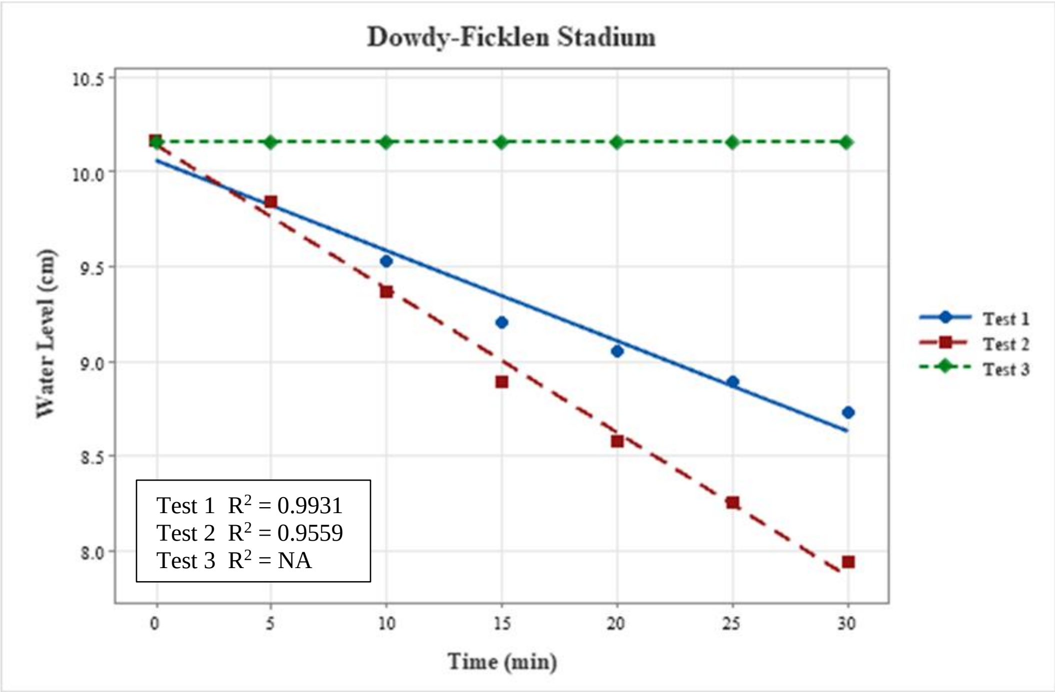


Figure C13.

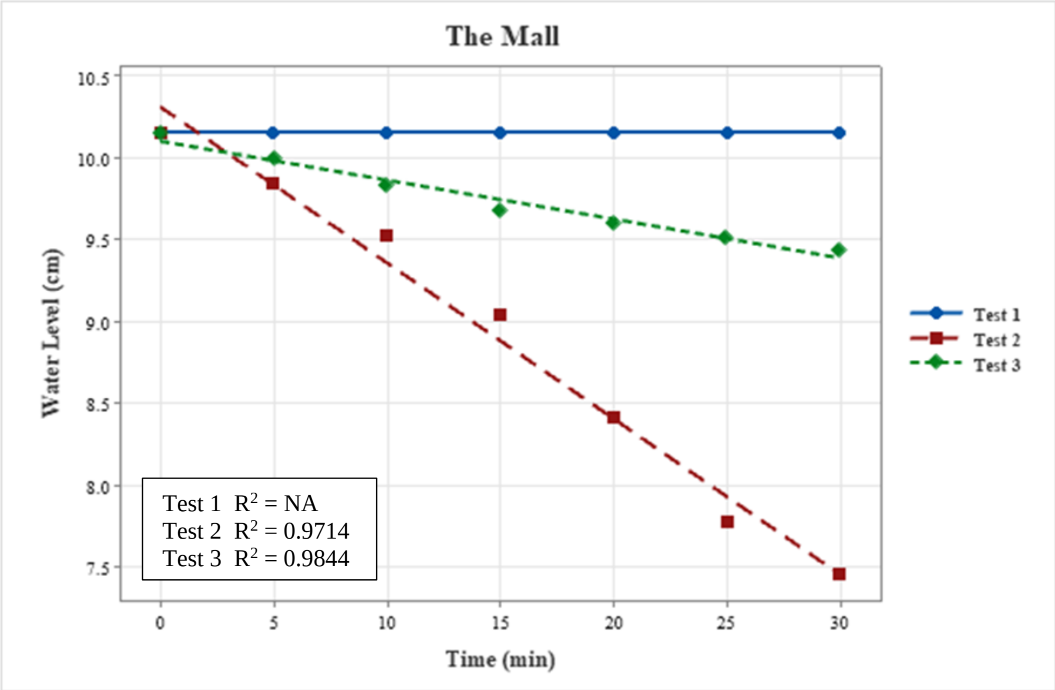


Figure C14.

APPENDIX C: Double-Ring Infiltrometer Test Data

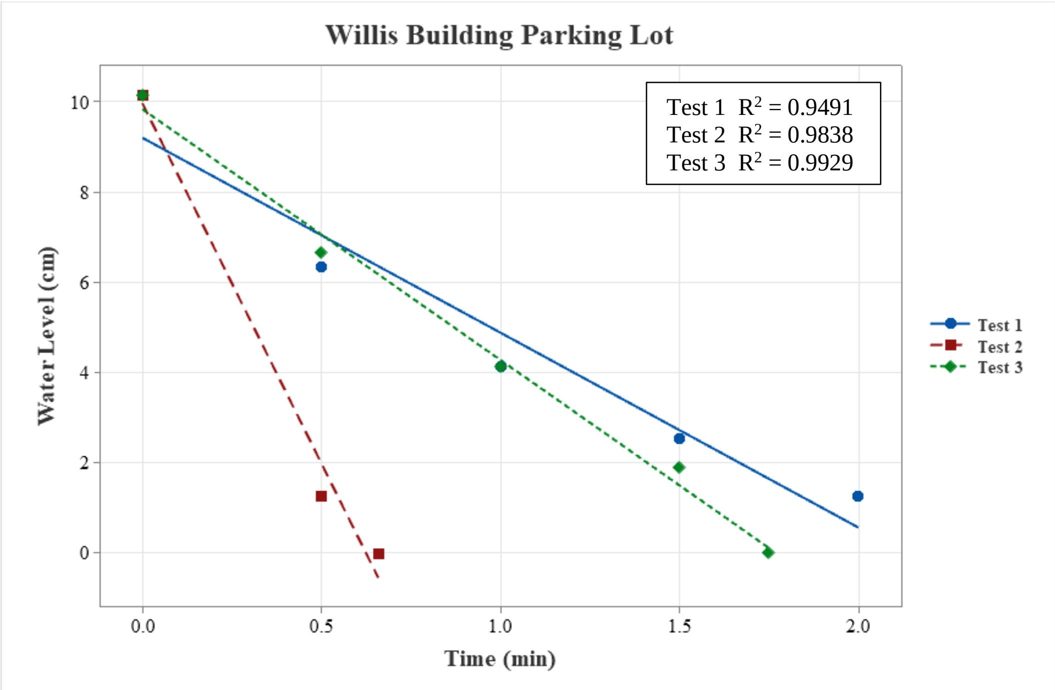


Figure C15.

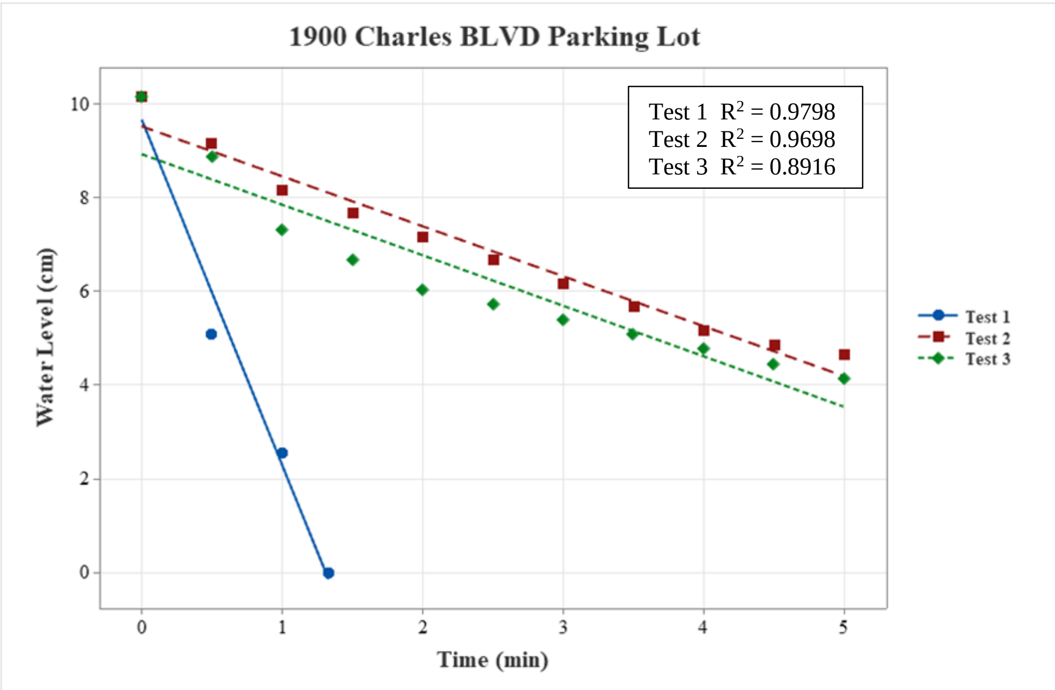


Figure C16.

APPENDIX C: Double-Ring Infiltrometer Test Data

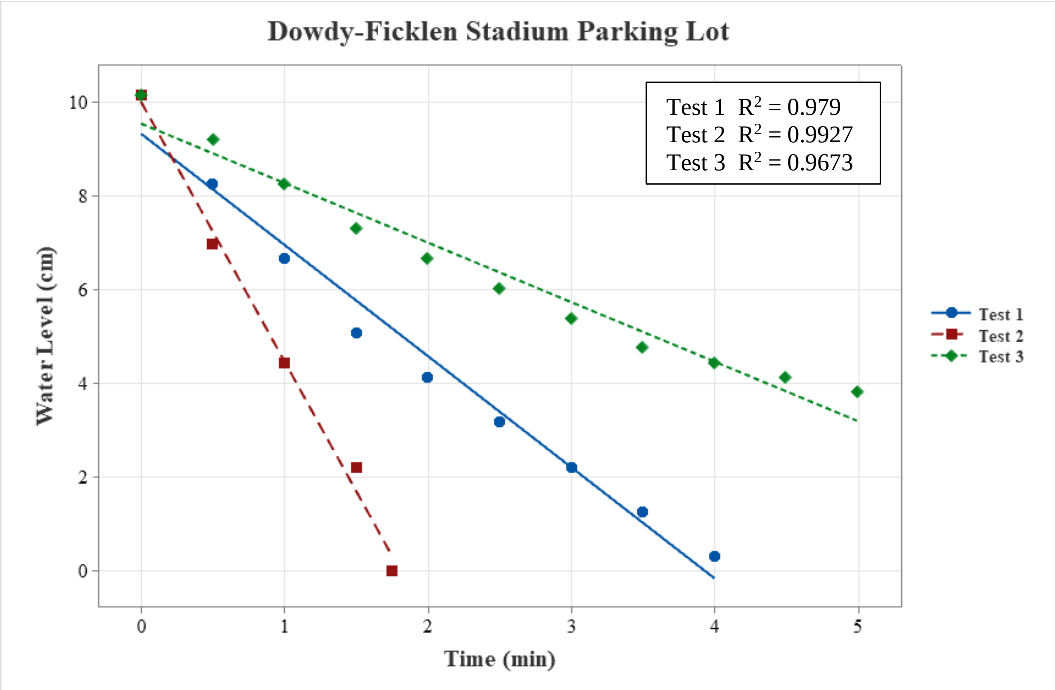


Figure C17.

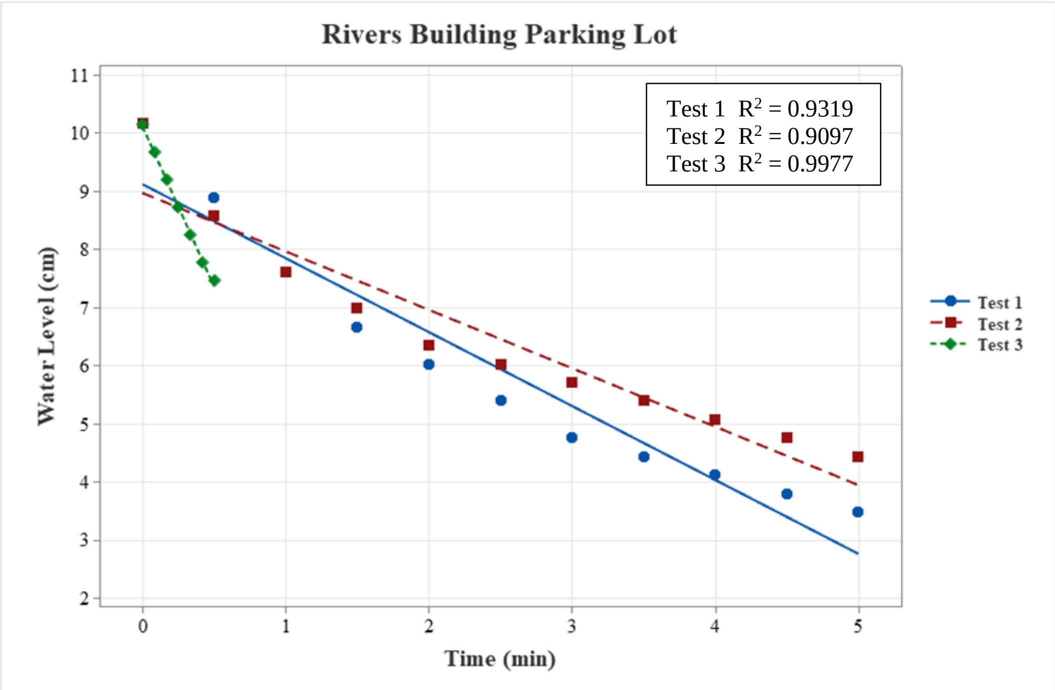


Figure C18.

APPENDIX D: Surface Infiltration Rates

Table 1d. Surface infiltration rates for forested, campus lawn, and asphalt secondary permeability sites.

Site											
Forested	**Test #1**	**Test #2**	**Test #3**	**Test #4**	**Test #5**	**Test #6**	**Test #7**	**Test #8**	**Test #9**	**Test #10**	**AVG (cm/h)**
Greens Mill Run	8.39	11.59	12.7	45.72	57.15	2.54	0.32	0.32	2.54	1.59	14.29
Campus Lawn											
1900 Charles Blvd	2.54	1.91	0.63								1.69
Jenkins Fine Art Center	0.64	2.54	1.27								1.48
Belk Building	1.27	0.63	1.27								1.06
Office of Admissions	0.32	0.32	2.22								0.95
Scott Residence Hall	0.64	0.32	0.38								0.45
Dowdy-Ficklen Stadium	0.32	0.63	0								0.32
The Mall	0	0.64	0.16								0.27
Secondary Permeability											
Willis Building	38.10	114.30	65.31								72.57
1900 Charles Blvd	114.30	2.40	3.80								40.17
Dowdy-Ficklen Stadium	14.28	76.22	3.82								31.44
Rivers Building	3.80	3.82	0.64								2.75

APPENDIX E: 2020 Cone Penetrometer Data

Table 1e. 2020 forested site cone index values (kPa).

Forested Site		Depth (cm)					
	Sample	**2.54**	**5.08**	**7.62**	**10.16**	**12.7**	**15.24**
Location 1	**1**	344.75	772.24	1013.57	944.615	1158.36	944.615
	2	137.9	310.275	524.02	455.07	455.07	661.92
	3	206.85	455.07	696.40	910.14	875.665	696.395
Location 2	**1**	68.95	1468.64	875.67	344.75	558.50	344.75
	2	208.65	310.28	344.75	455.07	524.02	627.45
	3	386.12	1158.36	1082.52	1048.04	1296.26	1296.26
Location 3	**1**	455.07	420.6	592.97	696.4	696.4	661.92
	2	841.19	806.72	1116.99	841.19	1082.52	1116.99
	3	0	103.43	420.6	386.12	344.75	558.5
Location 4	**1**	137.9	386.12	386.12	1082.52	696.4	806.72
	2	772.24	558.5	524.02	841.19	1013.57	1048.04
	3	172.38	344.75	627.45	455.07	592.97	696.4
Location 5	**1**	661.92	558.5	524.02	661.92	772.24	772.24
	2	1227.31	772.24	627.45	696.4	910.14	1399.69
	3	661.92	696.4	592.97	455.07	661.92	696.4
Location 6	**1**	910.14	627.45	661.92	696.4	806.72	696.4
	2	558.5	558.5	558.5	661.92	1048.04	1048.04
	3	420.6	420.6	386.12	772.24	944.62	1227.31
Location 7	**1**	275.8	344.75	310.28	310.28	558.5	558.5
	2	172.38	206.85	275.8	310.28	455.07	455.07
	3	592.97	275.8	627.45	386.12	420.6	420.6
Location 8	**1**	310.28	275.8	627.45	627.45	661.92	627.45
	2	1296.26	806.72	558.5	627.45	627.45	627.45
	3	344.75	275.8	310.28	420.6	420.6	455.07
Location 9	**1**	696.4	910.14	1048.04	1682.38	1082.52	1399.69
	2	772.24	592.97	420.6	524.02	1082.52	1227.31
	3	68.95	524.02	592.97	772.24	875.67	310.28
Location 10	**1**	806.72	1330.74	1468.64	1192.84	1116.99	1116.99
	2	386.12	386.12	344.75	310.28	558.5	455.07
	3	910.14	1013.57	1048.04	1296.26	1227.31	1158.36

APPENDIX E: 2020 Cone Penetrometer Data

Table 2e. 2020 campus lawn site cone index values (kPa).

Campus Lawn Site		Depth (cm)					
	Sample	**2.54**	**5.08**	**7.62**	**10.16**	**12.7**	**15.24**
1900 Charles Blvd.	1	558.50	2137.45	3647.46	4523.12	1578.96	1544.48
	2	103.43	1082.52	2702.84	4281.80	*	*
	3	1192.84	1434.16	2702.84	2840.74	*	*
	4	910.14	1227.31	1820.28	2627.00	*	*
	5	68.95	772.24	1399.69	2420.15	3716.41	*
	6	1330.74	2240.88	2592.52	2737.32	3047.59	1785.81
	7	68.95	206.85	2489.10	3330.29	4350.75	4137.00
	8	1647.91	2240.88	2978.64	3509.56	3964.63	*
	9	944.62	1854.76	3047.59	3330.29	4247.32	4633.44
Jenkins Fine Art Center	1	910.14	1544.48	1889.23	2592.52	3226.86	3509.56
	2	772.24	1082.52	1854.76	1889.23	2240.88	2558.05
	3	696.40	1889.23	2454.62	2909.69	3330.29	3047.59
	4	1365.21	2171.93	2420.15	2420.15	2385.67	2592.52
	5	1048.04	2240.88	2489.10	2420.15	2068.50	1854.76
	6	1578.96	1647.91	1682.38	1854.76	1716.86	1578.96
	7	1613.43	1930.60	2171.93	2171.93	2171.93	2558.05
	8	1365.21	2034.03	2240.88	2316.72	2240.88	2206.40
	9	524.02	1082.52	1158.36	1468.64	1227.31	1716.86
Belk Building	1	68.95	68.95	1785.81	2171.93	2806.27	3047.59
	2	627.45	1889.23	2316.72	2240.88	3509.56	*
	3	1192.84	2102.98	2206.40	2137.45	1930.60	2034.03
	4	1227.31	1965.08	3413.03	4068.05	*	*
	5	68.95	875.67	910.14	1854.76	1116.99	*
	6	2034.03	2351.20	2420.15	2240.88	3192.39	*
	7	696.40	875.67	1227.31	1613.43	2385.67	2351.20
	8	1578.96	1716.86	1930.60	1965.08	1930.60	2240.88
	9	68.95	1468.64	1930.60	2034.03	2351.20	2702.84
Office of Admissions	1	910.14	1365.21	2240.88	2840.74	2909.69	3612.98
	2	1158.36	1716.86	2489.10	2944.17	3509.56	3819.83
	3	455.07	1013.57	1820.28	2592.52	2978.64	4171.48
	4	2454.62	4633.44	4633.44	3475.08	*	*
	5	1048.04	2068.50	3861.20	5157.46	*	*
	6	558.50	1082.52	3047.59	3750.88	4771.34	*
	7	2737.32	3364.76	2944.17	3226.86	3330.29	3399.24
	8	841.19	1854.76	2558.05	2909.69	2806.27	3861.20
	9	1716.86	1544.48	1365.21	1820.28	2454.62	3433.71
Scott Residence Hall	1	68.95	661.92	1296.26	1578.96	2206.40	2420.15
	2	420.60	1192.84	1296.26	1578.96	1682.38	1365.21
	3	910.14	1227.31	1227.31	1158.36	1192.84	2137.45
	4	841.19	1082.52	1227.31	1399.69	1399.69	1578.96
	5	1192.84	1544.48	1468.64	1716.86	1647.91	1399.69
	6	3475.08	3612.98	3123.44	2702.84	2489.10	2420.15
	7	1365.21	1365.21	1578.96	1889.23	1716.86	2137.45
	8	386.12	1399.69	1965.08	2034.03	2171.93	2206.40
	9	1296.26	1365.21	1647.91	1930.60	2137.45	2034.03
Dowdy-Ficklen Stadium	1	841.19	1854.76	2558.05	2978.64	2737.32	2702.84
	2	2385.67	2385.67	2316.72	2171.93	2454.62	1082.52
	3	1013.57	1227.31	2351.20	2978.64	2489.10	2316.72
	4	1192.84	1468.64	2102.98	2385.67	2420.15	2702.84
	5	1399.69	1785.81	2558.05	4419.70	*	*
	6	1082.52	1647.91	3647.46	4247.32	4702.39	*
	7	1048.04	1434.16	1296.26	1434.16	2351.20	2420.15
	8	1647.91	1116.99	1082.52	1192.84	1820.28	2240.88
	9	68.95	1365.21	2206.40	2840.74	2978.64	3123.44
The Mall	1	772.24	1082.52	1399.69	1330.74	1399.69	2351.20
	2	696.40	806.72	910.14	1820.28	1854.76	1578.96
	3	68.95	1013.57	1578.96	1716.86	2068.50	1716.86
	4	2068.50	2420.15	2489.10	2702.84	3261.34	2137.45
	5	34.48	592.97	592.97	1013.57	1930.60	2171.93
	6	34.48	1116.99	1227.31	1820.28	2592.52	3192.39
	7	1158.36	1468.64	1578.96	1785.81	2737.32	3399.24
	8	1399.69	1785.81	2385.67	2978.64	3819.83	1227.31
	9	1468.64	1820.28	2661.47	3157.91	4171.48	806.72

*No data

APPENDIX F: 2009 and 2020 Cone Penetrometer Data

Table 1f. 2009 and 2020 maximum cone index values (kPa).

	2009		2020	
Site	**Forested**	**Campus Lawn**	**Forested**	**Camus Lawn**
	1117	6530	1158	3510
	1227	4702	1469	4068
	2137	6212	1117	2703
	1613	2875	1083	3510
	3820	5192	1400	2593
	2661	6564	1227	2558
	2317	5999	627	2351
	4213	2137	1296	3261
	2593	5226	1682	4171
	1613	5371	1469	4171
	2386	6805		5157
	910	6212		3861
	2213	6033		2420
	2806	5999		3613
	1227	6771		2206
	2944	3999		2979
	1469	4840		4702
	2351	6102		3123
	3510	6137		4523
	3330	6564		3716
	3399	5999		4633
		5750		
		4909		
		4351		
		5020		
		5647		
Median	2351	5875	1262	3510

APPENDIX G: Stormwater Calculations for Peak Discharge Estimates

Table 1g. Summary of subdivided areas based on land use with corresponding weighted coefficients.

Rational Method for Flow (Q=CIA)	Wooded	Current Conditions	Prior to PICP retrofits	Retrofitting RA parking lots with PICP	Retrofitting parking lots, drives, and walkways with PICP
Total Drainage Area (campus parcels in acres)	353	353	353	353	353
Subarea A (acres) ISA		161	161.84	90.5	53.84
Subarea A (runoff coefficient)		0.95	0.95	0.95	0.95
Subarea B (acres) Wooded		1.6	1.6	1.6	1.6
Subarea B (runoff coefficient)		0.2	0.2	0.2	0.2
Subarea C (acres) Recreational/grassed		189.56	189.56	189.56	189.56
Subarea C (runoff coefficient)		0.3	0.3	0.3	0.3
Subarea D (acres) PP		0.84	0	71.34	108
Subarea D (runoff coefficient)		0.44	0.44	0.44	0.44
Weighted Runoff Coeffiecient	0.2	0.60	0.60	0.42-0.50	0.30-0.44
10-yr rainfall intensity (graphical solution in inches)	0.8	3.25	3.25	3.25	3.25

Table 2g. Watershed sub-basin flow lengths and elevations within campus parcels for the determination of Tc.

	Flowpath	Elevation Profile	
Drainage Areas	**L (length of travel time of water in feet)**	**Most Remote Point on Basin**	**Basin Outlet**
Town Creek (TC)			
portion of stream buried	800	35.03	30.64
portion of stream daylighted	1998	32.56	6.9
Green Mill Run (GMR) sub-basins			
1	1700	62.55	31.58
2	1370	77.18	54.03
3	2177	66.95	54.13
4	1048	48.2	26.62
5	2620	74.22	30.36
6	2036	66.66	25.61
7	1808	61.21	27.94
8	2260	54.6	27.93
9	1431	65.4	21.02

APPENDIX G: Stormwater Calculations for Peak Discharge Estimates

Table 3g. Total time of concentration for each sub-basin within campus parcels.

Drainage Areas	L^3 (feet)	H (difference in elevation in feet)	Tc (time of concentration in minutes)	Surface type	Multiplier	Final Tc
Town Creek (TC)						
portion of stream buried	512000000	4.39	9.97	concrete channel	0.2	2
portion of stream daylighted	7976023992	25.66	14.53	mowed channel	none	15
Green Mill Run (GMR) sub-basins					**Total Tc for TC**	**17**
1	4913000000	30.97	11.22	concrete channel	0.2	2
2	2571353000	23.15	9.78	concrete channel	0.2	2
3	10317519233	12.82	20.96	concrete channel	0.2	4
4	1151022592	21.58	7.37	asphalt	0.4	3
5	17984728000	43.86	16.17	concrete channel	0.2	3
6	8439822656	41.05	12.40	concrete channel	0.2	2
7	5910106112	33.27	11.72	concrete channel	0.2	2
8	11543176000	26.67	16.51	concrete channel	0.2	3
9	2930345991	44.38	8.01	concrete channel	0.2	2
					Total Tc for GMR	**24**

APPENDIX H: ***Manual of Standard Designs and Details*, City of Greenville, NC (2011)**

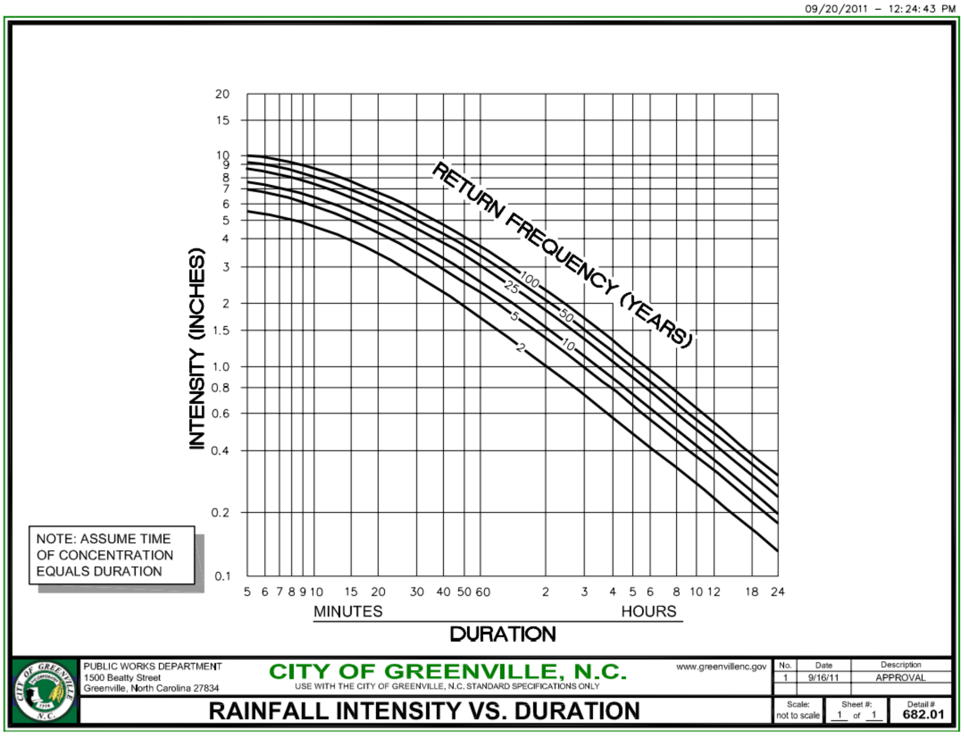


Figure H1. Rainfall intensity vs. duration graphical solution.

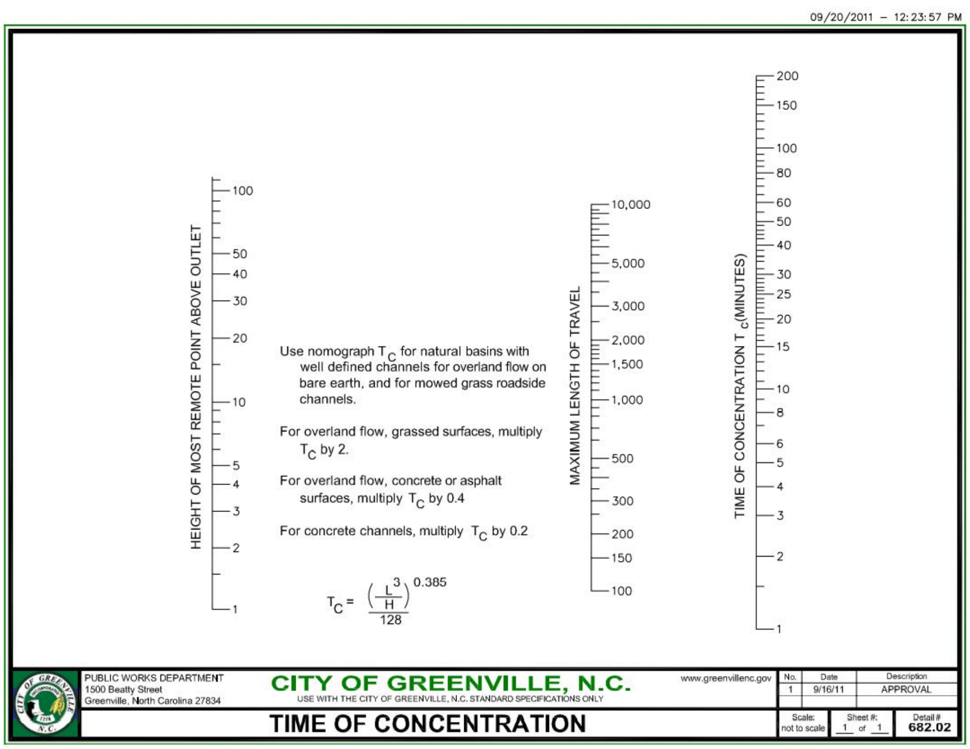


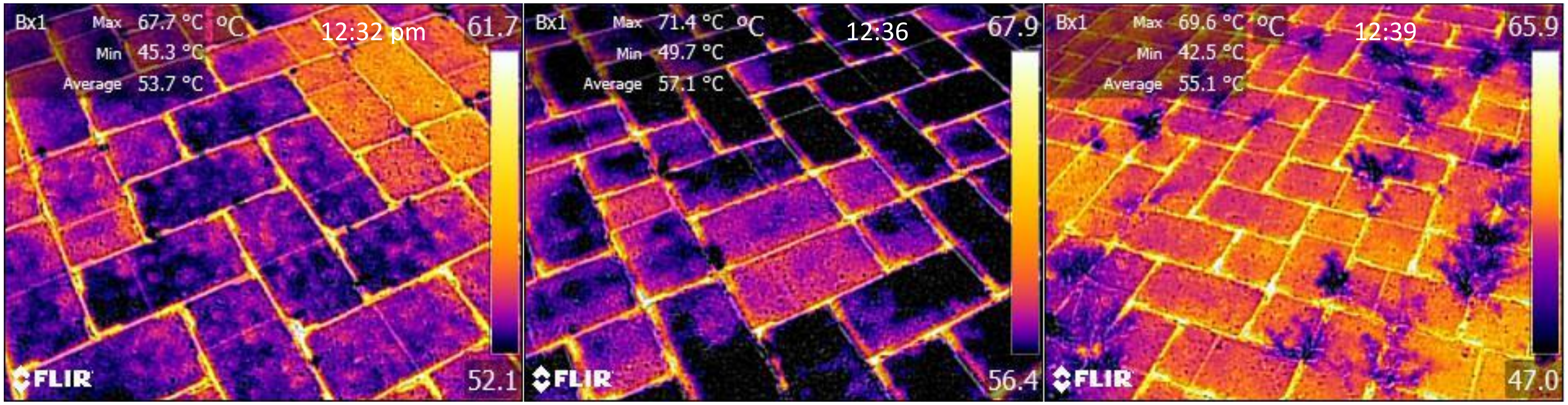
Figure H2. Time of concentration equation and nomograph.

APPENDIX I: Thermal Measurement Site Infrared Images

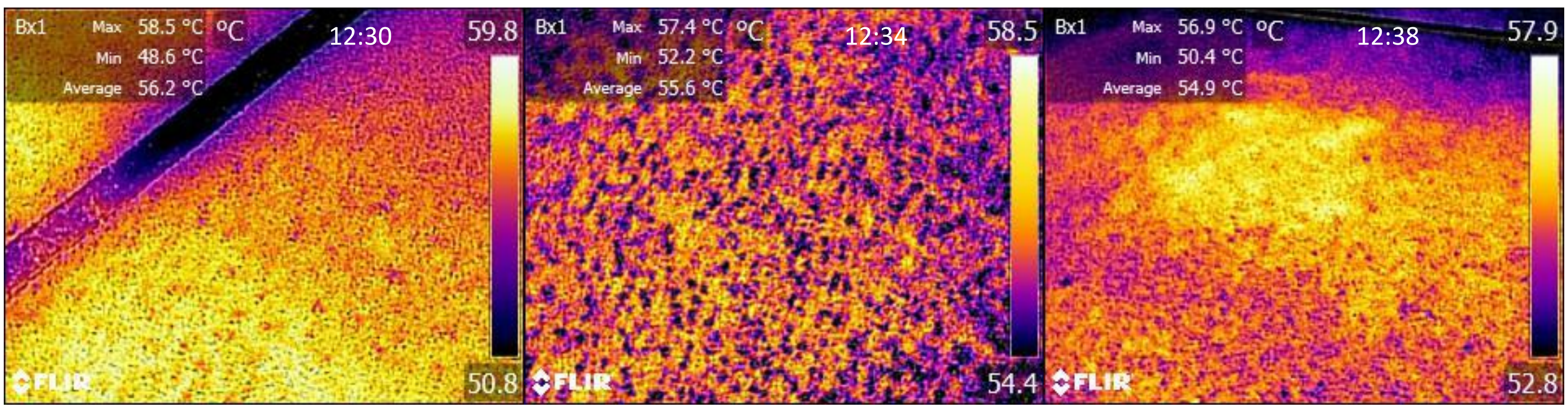
Table 1i. PICP and asphalt paired test site infrared images and appendices.

June 4, 2020	**Appendix**
14th Street PICP/14th St Parking Lot	I1
Student Plaza Walkway PICP/Rivers Building Parking Lot	I2
Jenkins Fine Art Center PICP/Willis Building Parking Lot	I3
Starbucks Mobile PICP/College Hill Parking Lot	I4
July 6, 2020	
14th Street PICP/14th St Parking Lot	I5
Student Plaza Walkway PICP/Rivers Building Parking Lot	I6
Jenkins Fine Art Center PICP/Willis Building Parking Lot	I7
Starbucks Mobile PICP/College Hill Parking Lot	I8
July 14 & 15, 2020	
14th Street PICP/14th St Parking Lot	I9
Student Plaza Walkway PICP/Rivers Building Parking Lot	I10
Jenkins Fine Art Center PICP/Willis Building Parking Lot	I11
Starbucks Mobile PICP/College Hill Parking Lot	I12

Appendix I 1**:** 14th Street Parking Lot (June 4, 2020)

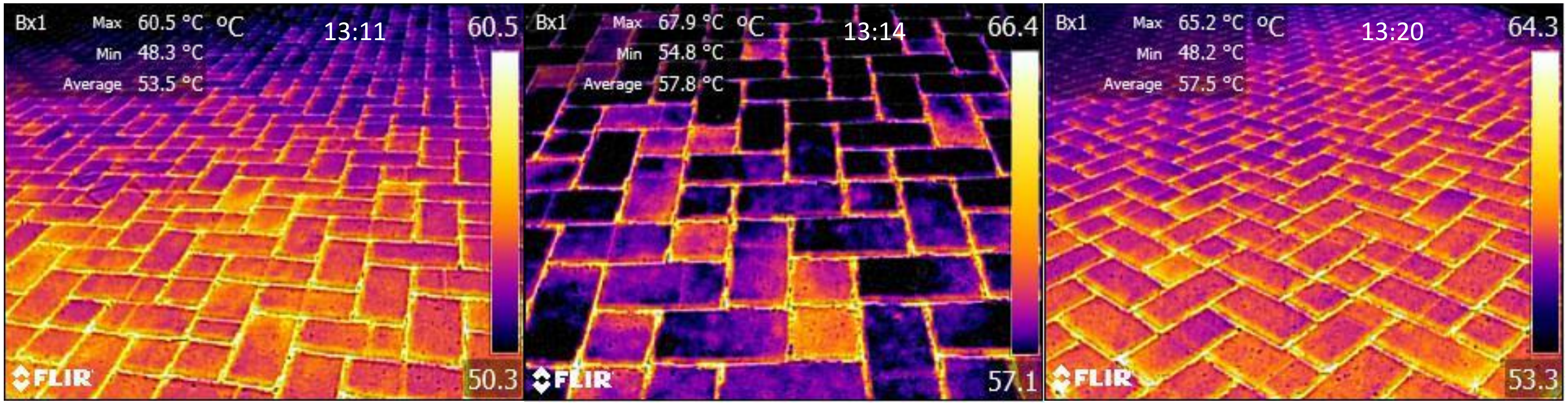


Site Coordinates: 35.598423, -77.363071

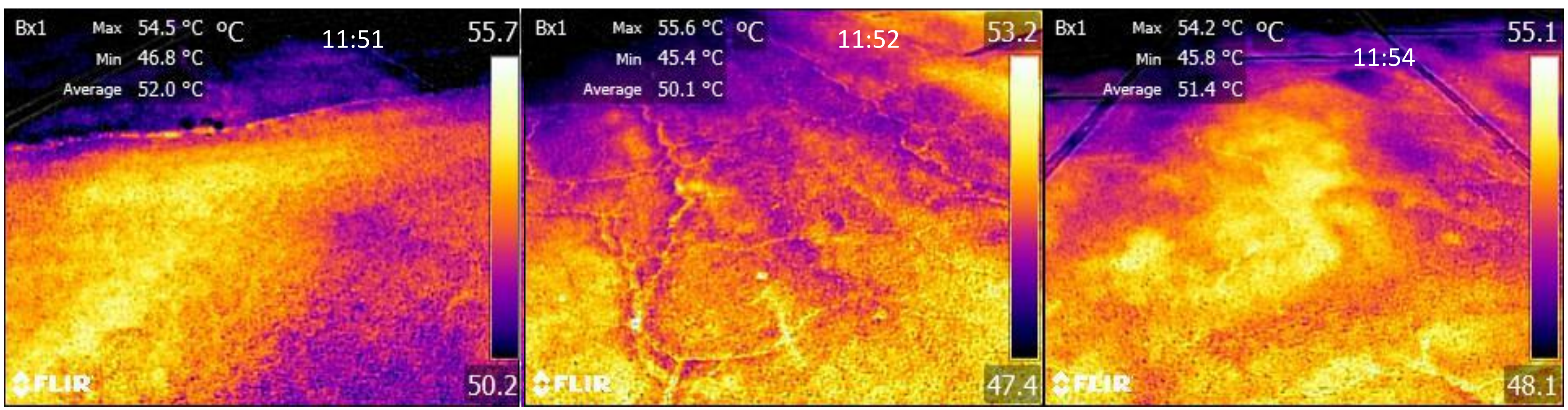


Site Coordinates: 35.598423, -77.363071

Appendix I 2: Student Plaza Walkway and Rivers Building Parking Lot (June 4, 2020)

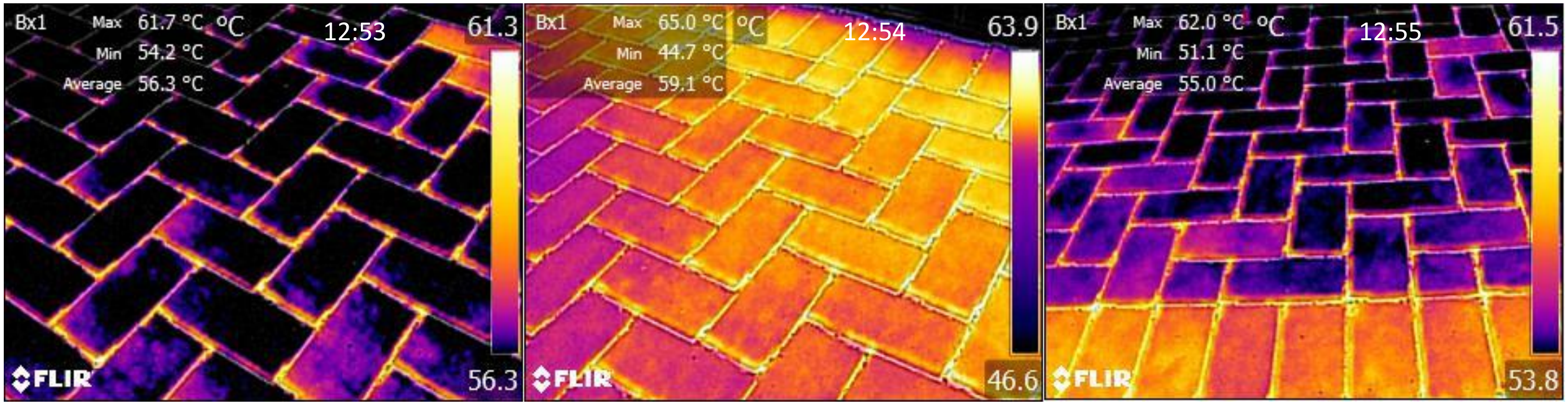


Site Coordinates: 35.605823, -77.362159

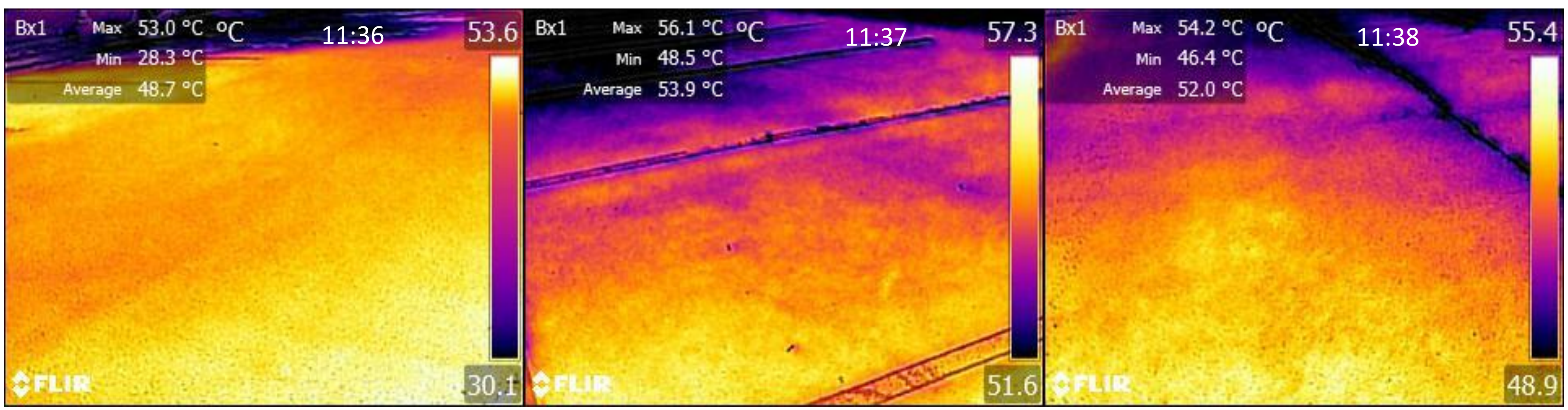


Site Coordinates: 35.605673, -77.360751

Appendix I 3: Jenkins Fine Art Center and Willis Building Parking Lot (June 4, 2020)

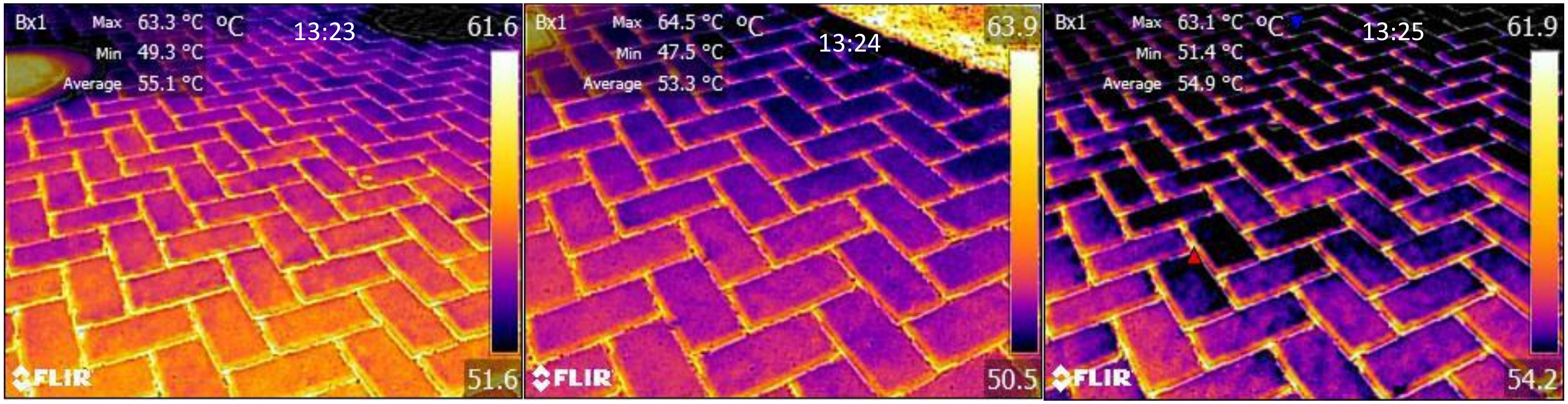


Site Coordinates: 35.608468, -77.367834

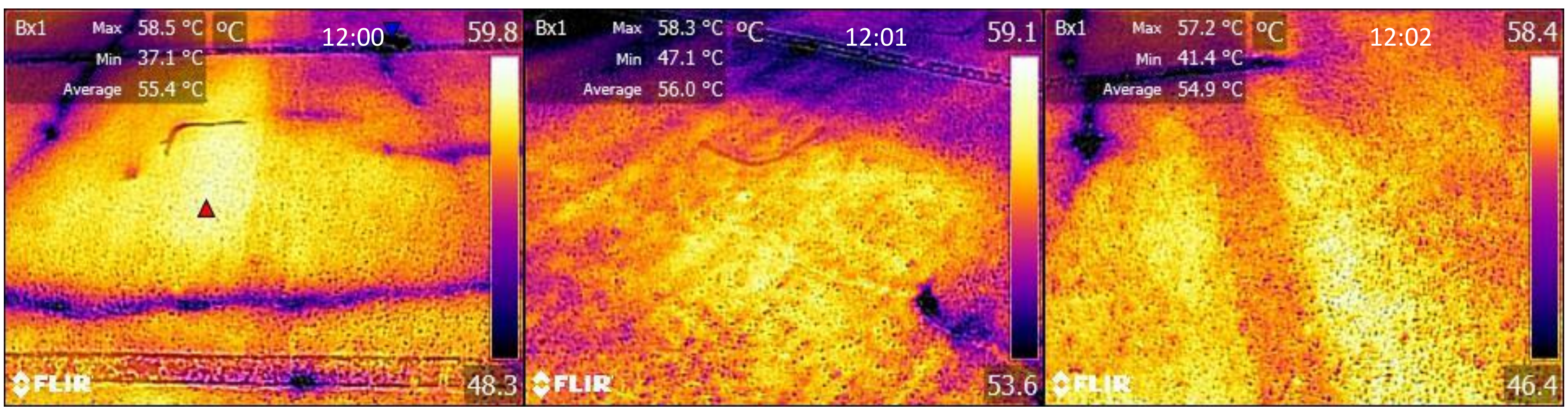


Site Coordinates: 35.613882, -77.368844

Appendix I 4: Starbucks Mobile Parking Pad and College Hill Parking Lot (June 4, 2020)

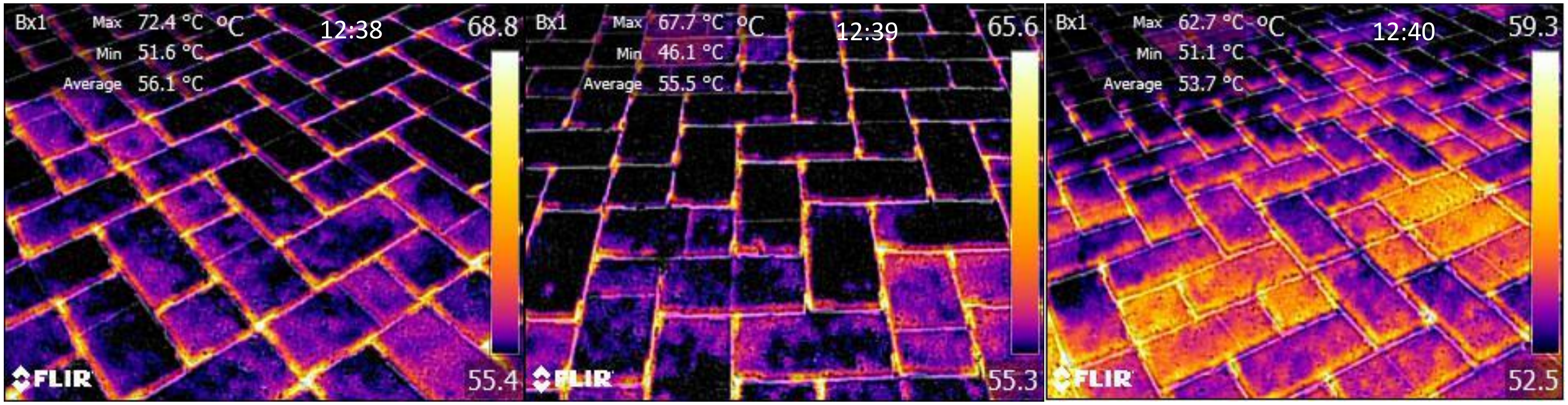


Site Coordinates: 35.605293, -77.362562

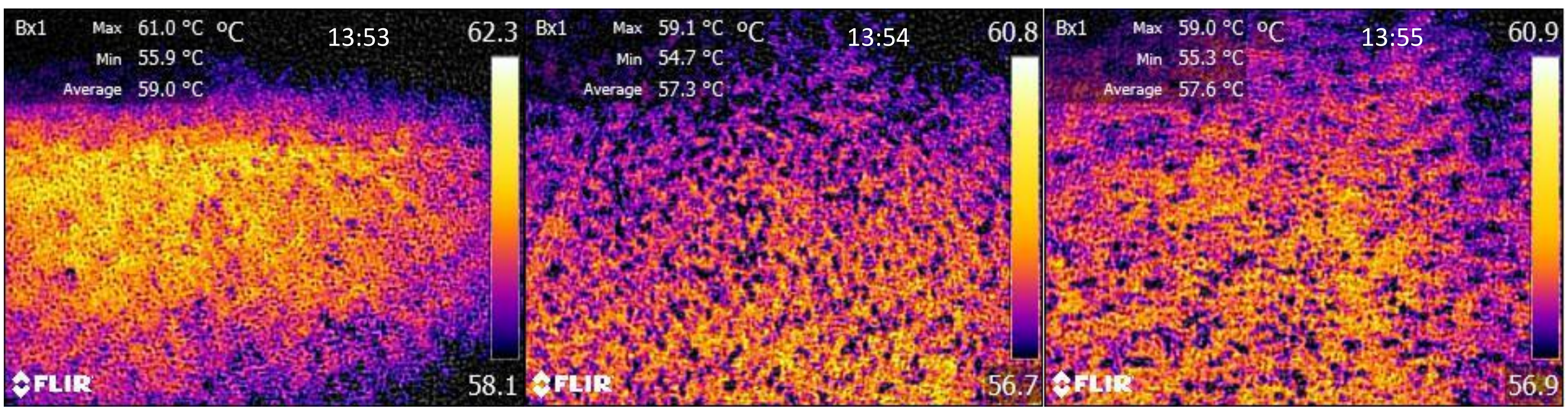


Site Coordinates: 35.602222, -77361111

Appendix I 5: 14th Street Parking Lot (July 6, 2020)

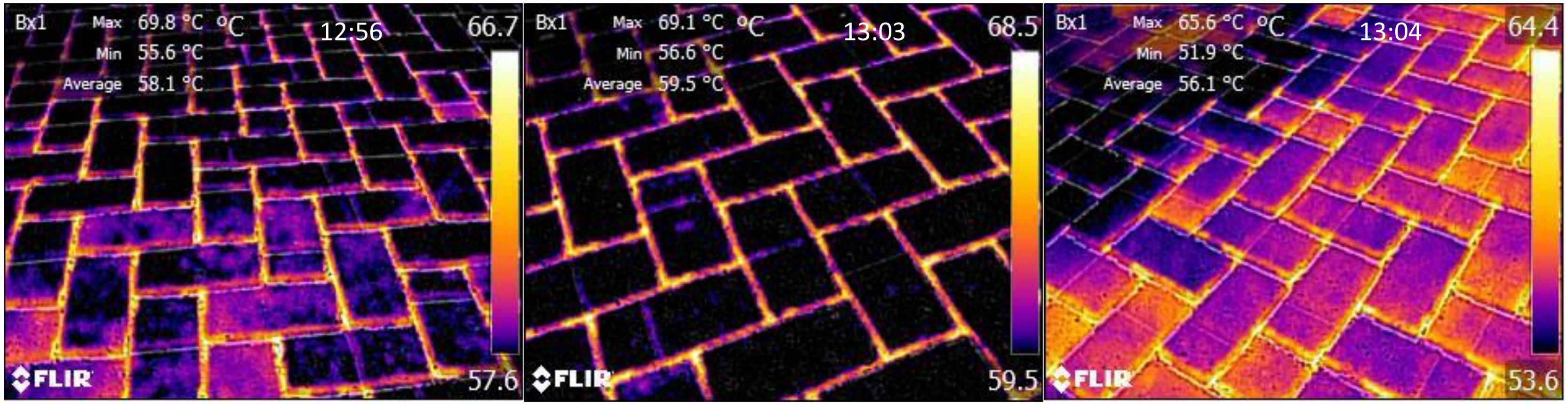


Site Coordinates: 35.598423, -77.363071

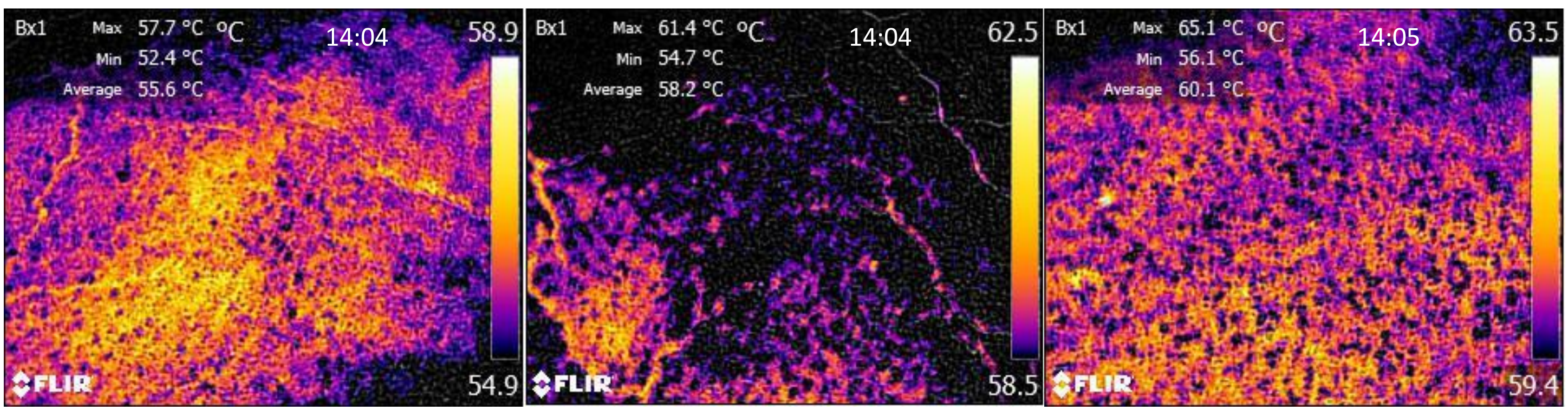


Site Coordinates: 35.598423, -77.363071

Appendix I 6: Student Plaza Walkway and Rivers Building Parking Lot (July 6, 2020)

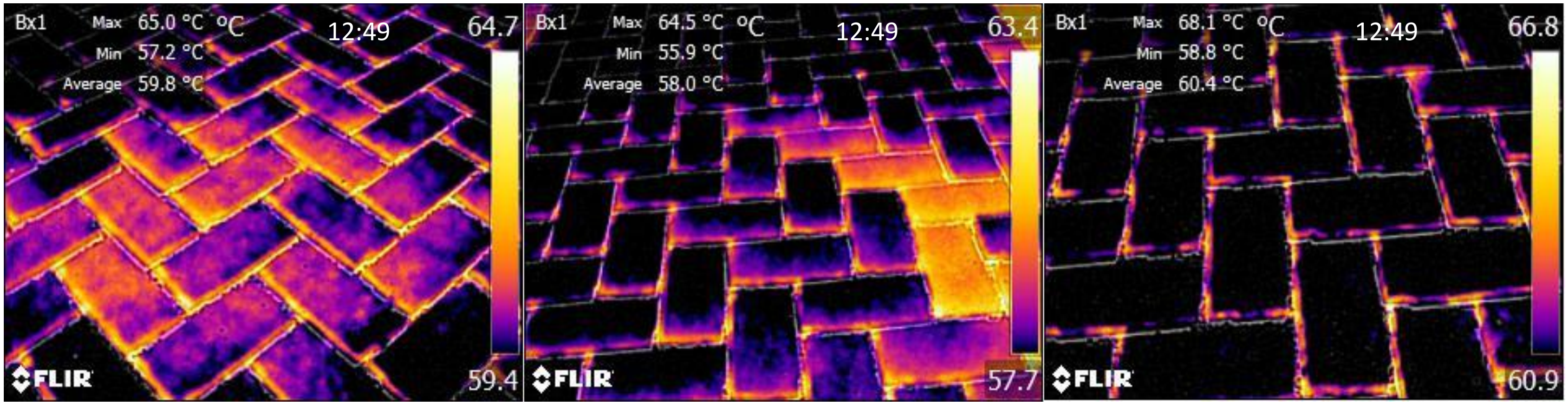


Site Coordinates: 35.605823, -77.362159

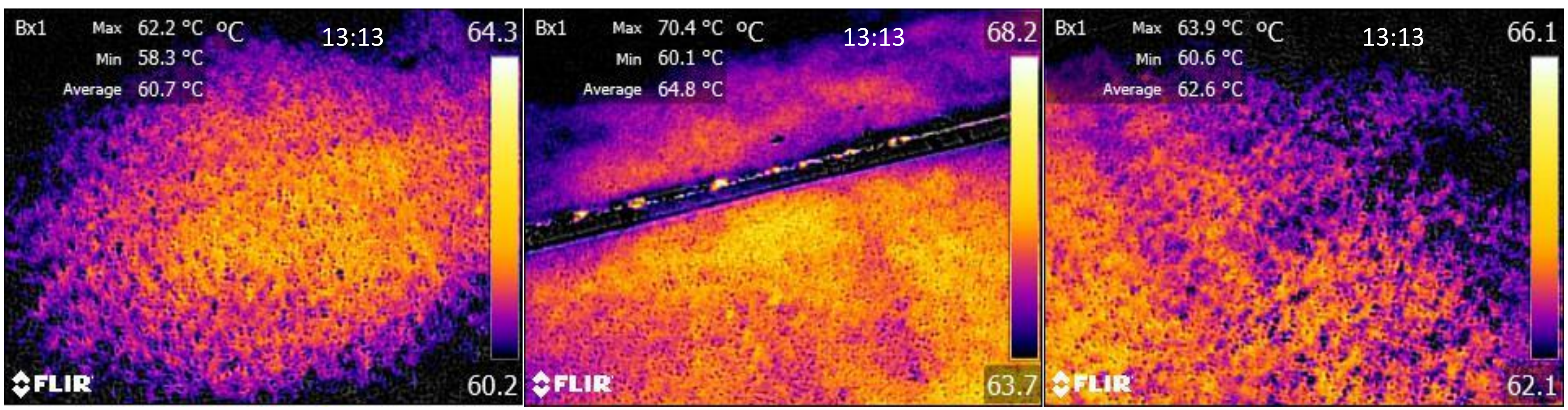


Site Coordinates: 35.605673, -77.360751

Appendix I 7: Jenkins Fine Art Center and Willis Building Parking Lot (July 6, 2020)

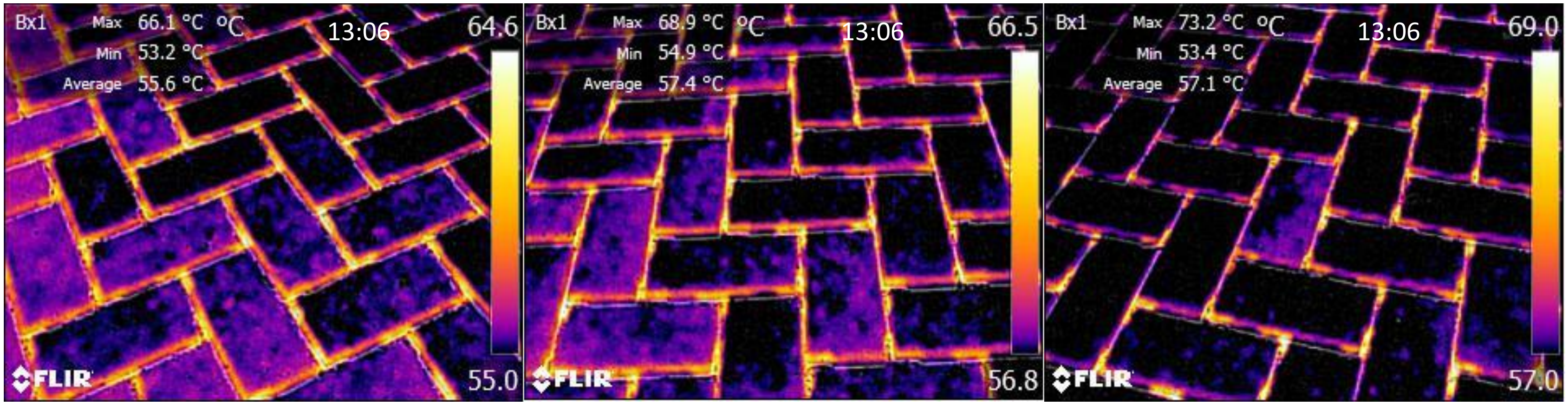


Site Coordinates: 35.608468, -77.367834

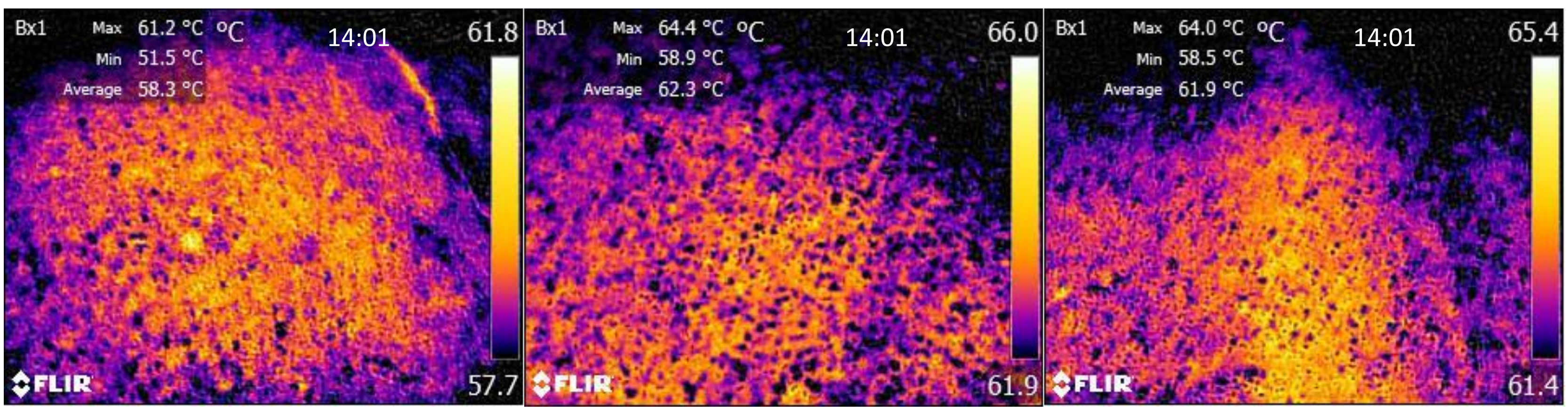


Site Coordinates: 35.613882, -77.368844

Appendix I 8: Starbucks Mobile Parking Pad and College Hill Parking Lot (July 6, 2020)

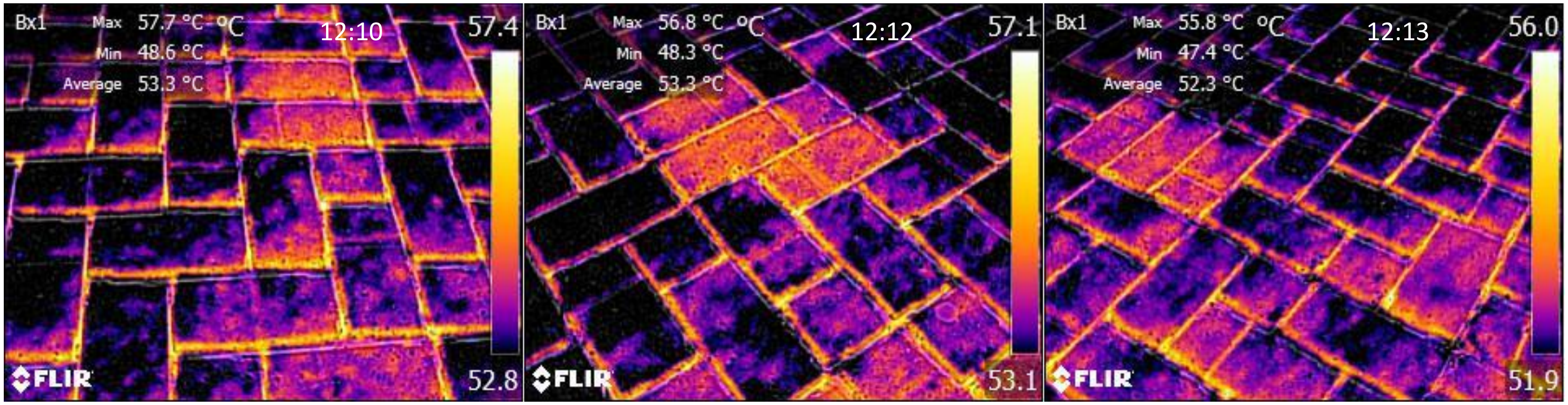


Site Coordinates: 35.605293, -77.362562

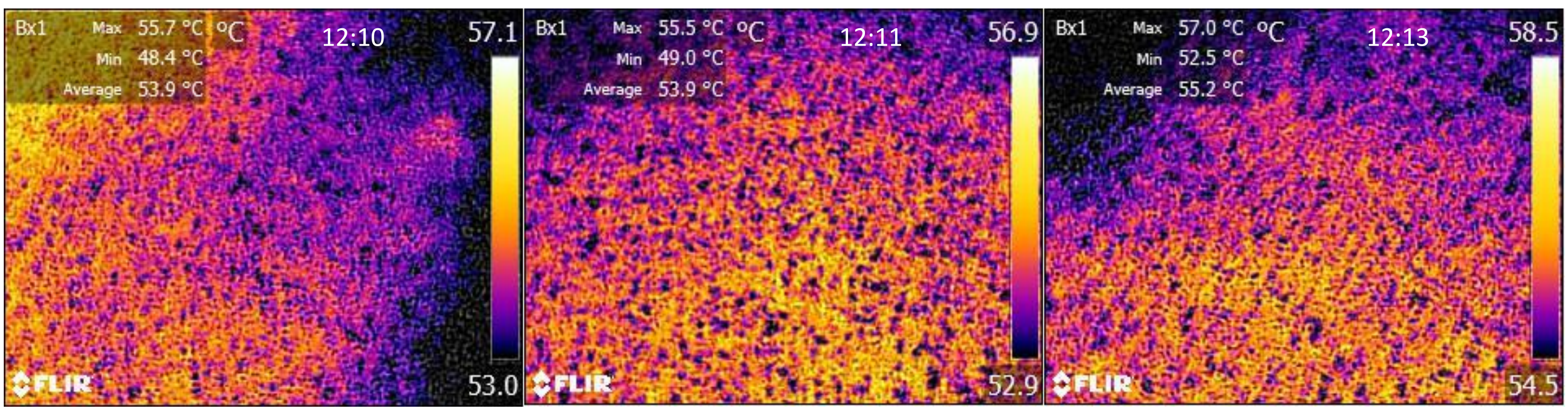


Site Coordinates: 35.602222, -7736111

Appendix I 9: 14th Street Parking Lot (July 15, 2020)

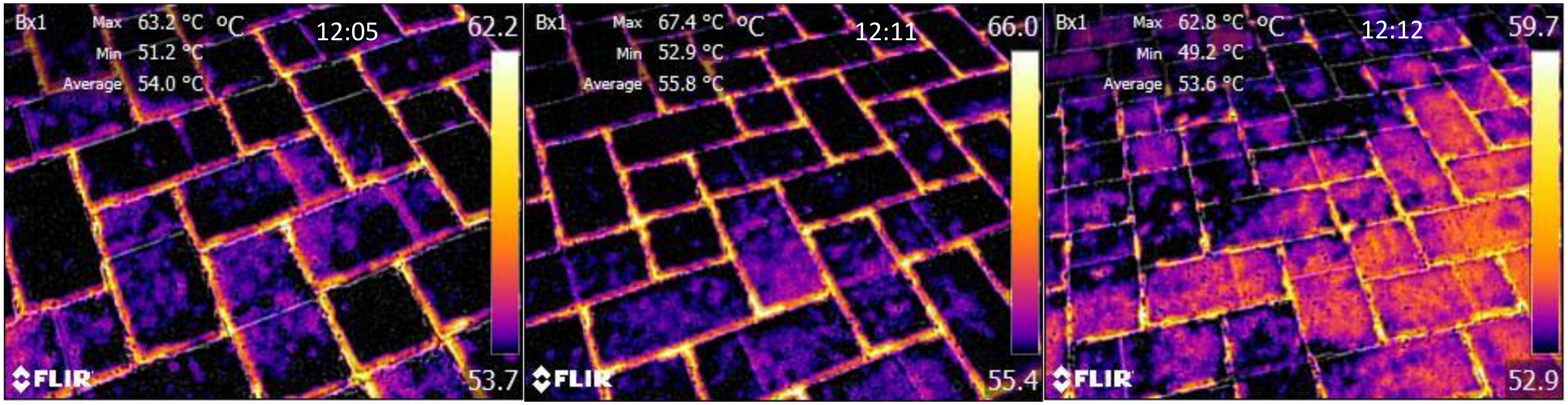


Site Coordinates: 35.598423, -77.363071

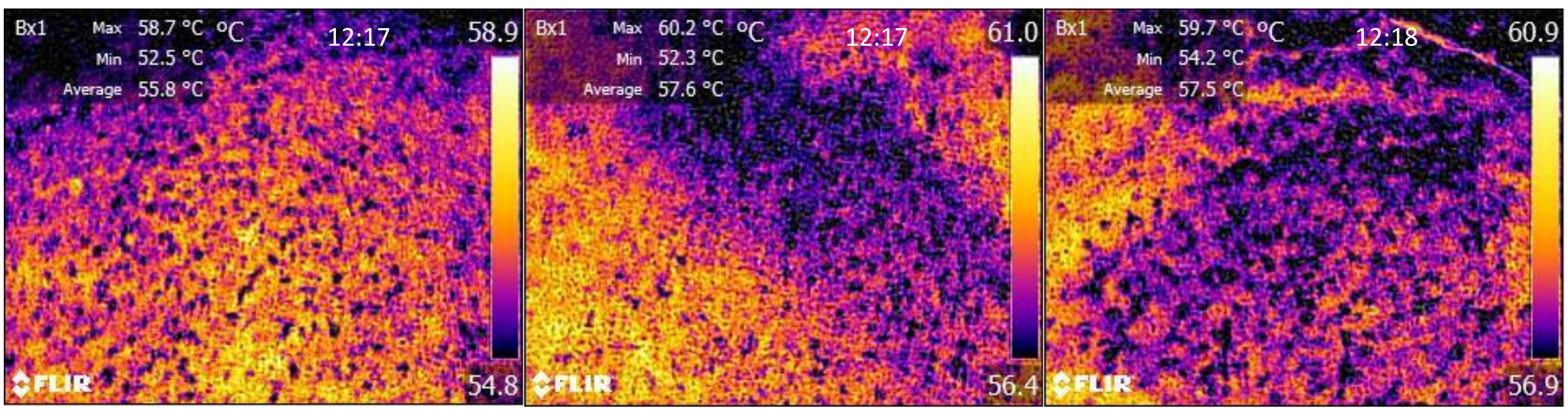


Site Coordinates: 35.598423, -77.363071

Appendix I 10: Student Plaza Walkway and Rivers Building Parking Lot (July 14, 2020)

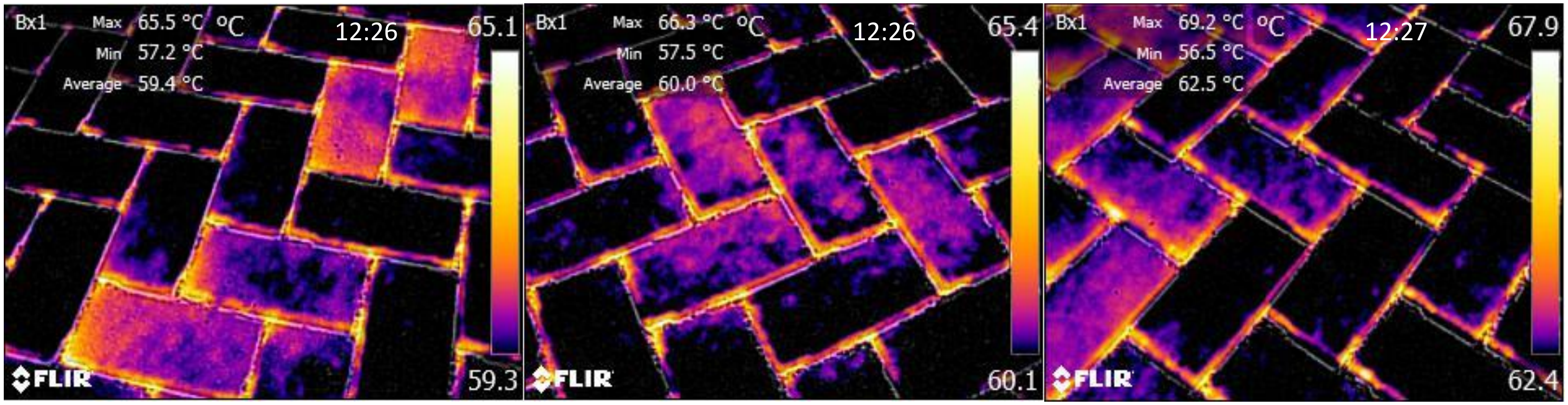


Site Coordinates: 35.605823, -77.362159

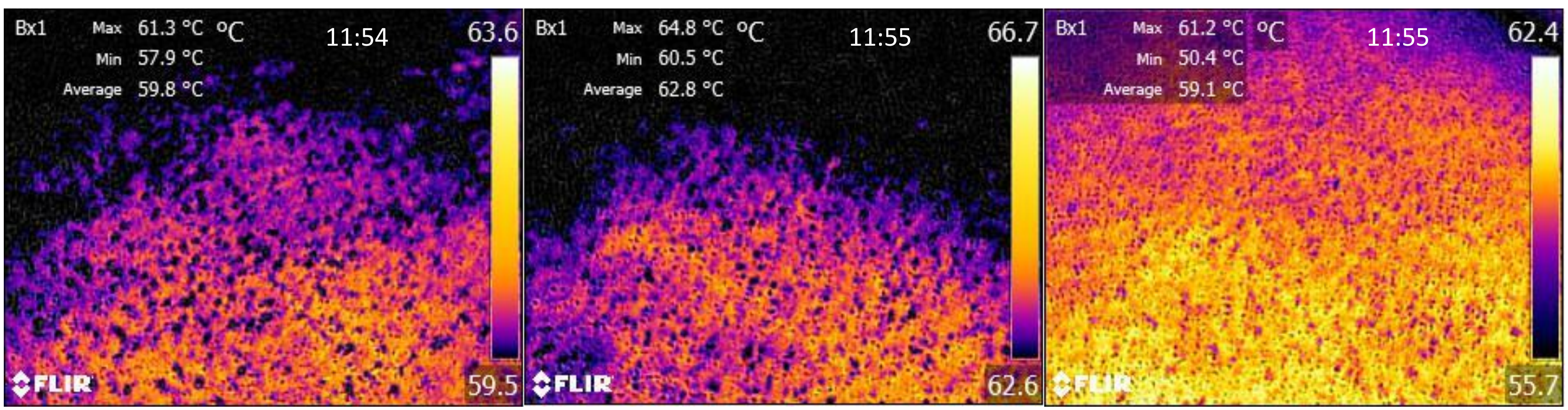


Site Coordinates: 35.605673, -77.360751

Appendix I 11: Jenkins Fine Art Center (July 14, 2020) and Willis Building Parking Lot (July 15, 2020)

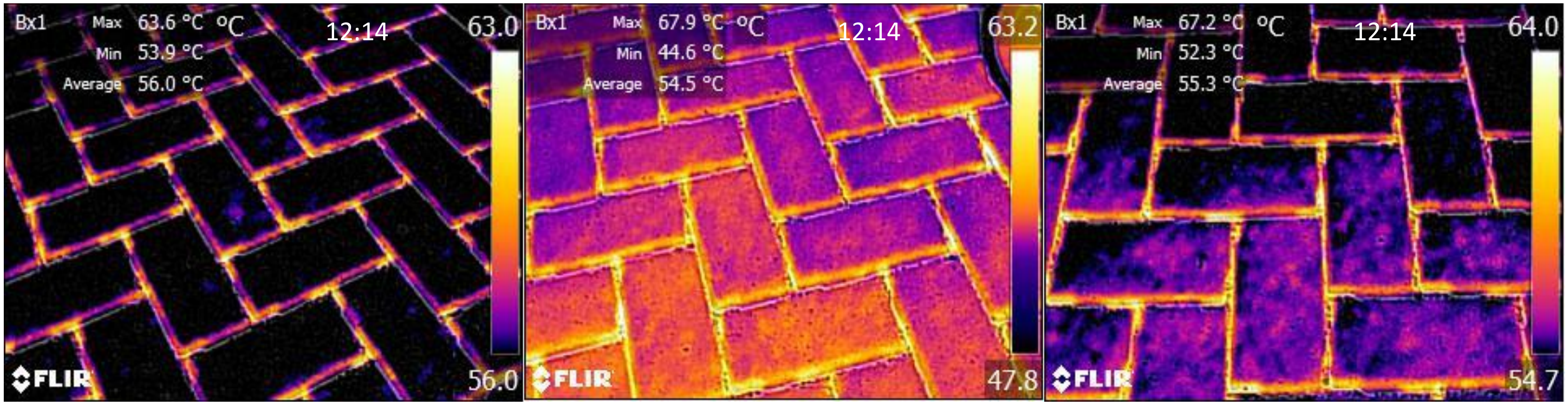


Site Coordinates: 35.608468, -77.367834

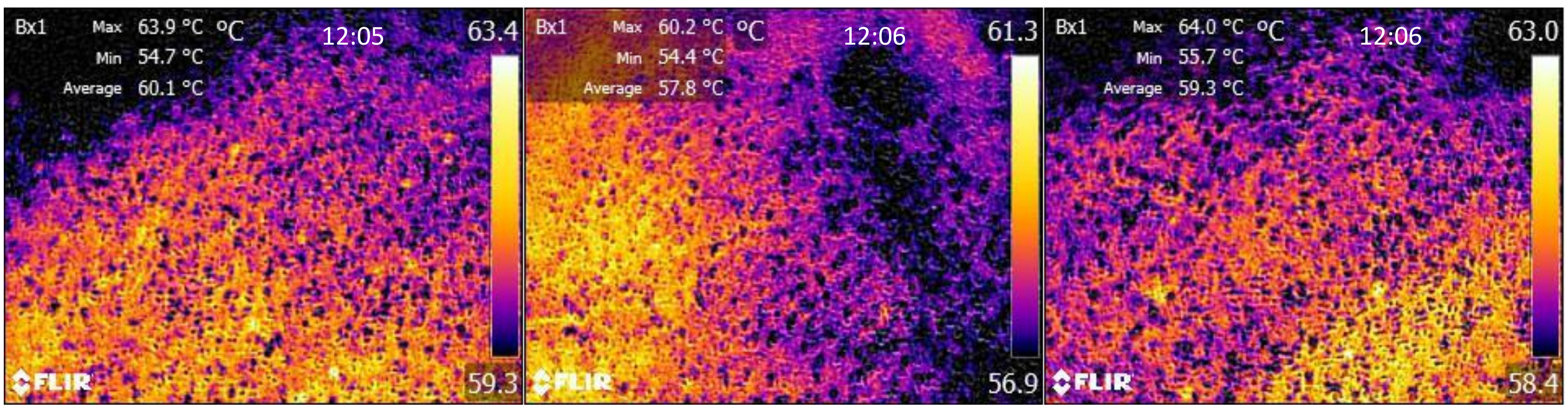


Site Coordinates: 35.613882, -77.368844

Appendix I 12: Starbucks Mobile Parking Pad (July 14, 2020) and College Hill Parking Lot (July 15, 2020)



Site Coordinates: 35.605293, -77.362562



Site Coordinates: 35.602222, -7736111