Evaluating the Urban Heat Mitigation Potential of the San Antonio Cool Pavement Pilot Program

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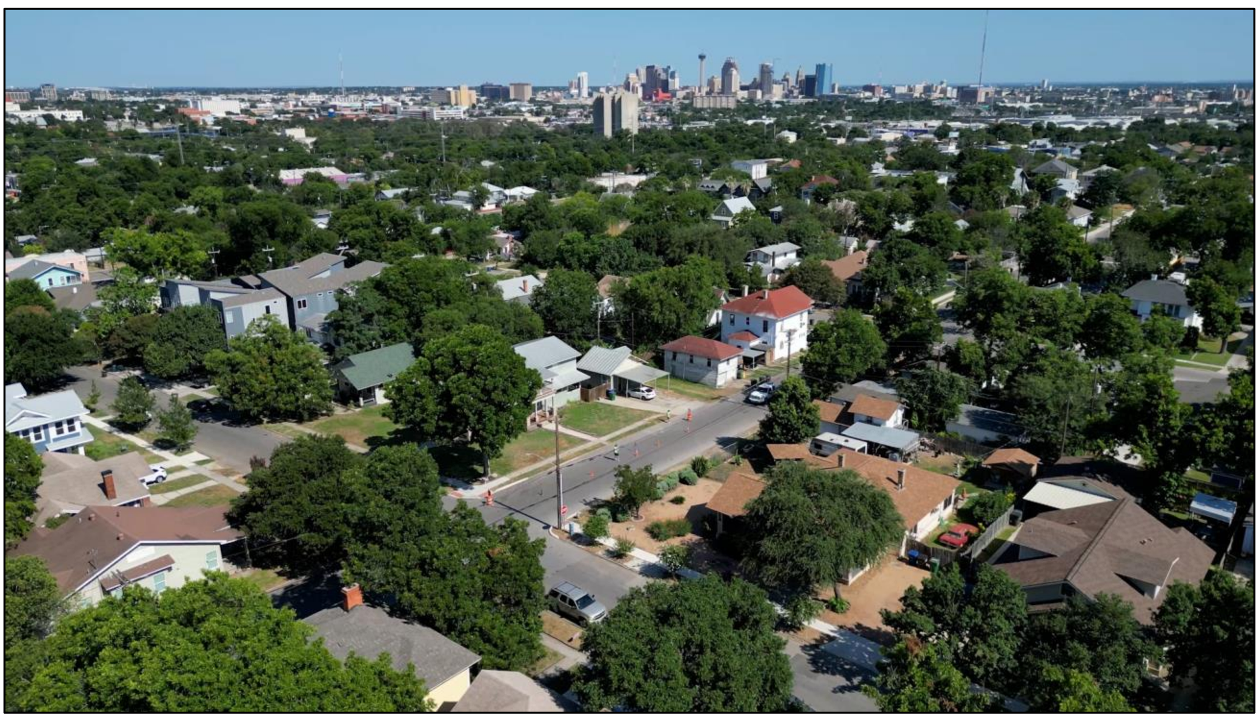
EXECUTIVE SUMMARY

Extreme heat is one of the most pressing climate hazards that urban areas face. Elevated temperatures threaten public health, the environment, and urban infrastructure. One mitigation strategy that has gained increasing popularity across cities is the usage of cool pavement. The City of San Antonio, Texas, as part of its broader climate action and adaptation plan, conducted a cool pavement pilot program in 2023 in collaboration with the University of Texas at San Antonio.



Drone photo looking southeast with downtown San Antonio in the background and the Grant Avenue cool pavement installation in the foreground (Image Credit: AccuWeather).

The pilot program evaluated the effectiveness of three different cool pavement treatments at six test plots across San Antonio during the summer of 2023. The products included PlusTi produced by Pave Tech, Durashield produced by GAF Streetbond, and

SolarPave produced by SealMaster. A fourth cool pavement product produced by GuardTop was not evaluated since the final installation occurred after the fieldwork began. For each site, meteorological measurements were collected across the cool pavement installation as well as a representative control site in the neighborhood. Specifically, data was collected to assess the surface temperature, air temperature, wet bulb globe temperature, albedo, and components of the net radiation budget over the cool pavement and control sites. Statistical tests were applied to determine the differences in the various meteorological variables between the cool pavement sites and the control sites.

The findings indicated that the performance of the cool pavement installations varied across the products tested. The SealMaster product displayed the most consistent and statistically significant reductions in surface temperatures with an average reduction of 3.58°F during the afternoon testing period. The maximum surface temperature reduction observed relative to fresh asphalt was 18°F.

The differences in air temperature were modest and less statistically significant across the different sites, products, and testing periods. The overall average difference in the mean air temperature between the cool pavement sites and control sites was 0.07°F (i.e., the cool pavement sites were marginally warmer). The maximum reduction in the average air temperature was 1.4°F, but this was one of only two (out of 72) cool pavement samples that demonstrated air temperature reductions greater than 1°F.

Similar findings were observed for the wet bulb globe temperature as only small differences were typically observed between the cool pavement sites and control sites. The average difference in the mean wet bulb globe temperature during the daytime was -0.13°F, indicating that heat stress at the cool pavement sites was marginally lower. However, given the accuracy of the instrument, this small difference should be considered largely inconclusive.

The albedo measurements suggested that the SealMaster product produced the most substantial increase in albedo from 0.22 to 0.28. Generally, the control sites exhibited relatively high albedos due to the worn nature of a typical street surface. The albedo alterations were also observed when analyzing the individual shortwave components of the net radiation budget.

Overall, the results generally aligned with studies conducted in Phoenix and Los Angeles that also documented cool pavement's clear potential to reduce surface temperature while simultaneously highlighting its more modest impact on air temperature.

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San Antonio skyline seen at night from the Hays Street Bridge. The first cool pavement installation in San Antonio was installed in 2021 on Hays Street east of the bridge terminus.

THE UNIVERSITY OF TEXAS AT SAN ANTONIO RESEARCH TEAM

The University of Texas at San Antonio research team at the Mountain Star cool pavement installation. Standing row (from left to right): Ryun Jung Lee, Matt Kenney, Tabytha Clearwater, Jasmine Renteria, Wei Zhai, Samuel Rueda, and Neil Debbage. Kneeling row (from left to right): Tyler Pursch, Emma Jones, Allison Pineda, and Esteban López-Ochoa.

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1. INTRODUCTION

Urban areas experience more extreme heat than surrounding rural areas. The built environment combined with concentrated anthropogenic activity results in a phenomenon known as the urban heat island effect.[1] The urban heat island effect has many consequences that impact environmental, social, and economic systems. Benefits of reducing high temperatures within urban areas include fewer heat related deaths and illnesses, lower energy consumption during the summer, reduced infrastructure maintenance costs, and increased climate resilience within the context of broader global climatic changes. Additionally, addressing urban heat inequities through the lens of environmental justice can help address long term disparities where certain communities face disproportionate heat burdens. Purposeful, meaningful, and effective actions that mitigate the impacts of the urban heat island effect can help protect the future livability and economic vitality of cities.

This study examines the efficacy of cool pavement, which is one strategy that cities are exploring to address the urban heat island effect. Cool pavement has been installed in a variety of municipalities within the United States including Los Angeles, CA and Phoenix, AZ. Cool pavement has traditionally referred to paving materials that have a higher albedo and reflect more incoming solar radiation, which lowers the surface temperature and the quantity of heat absorbed into the surface.[2] Due to technological advancements, the cool pavement definition has expanded to include surfaces that encourage evaporative cooling (e.g., permeable pavers), materials that alter the surface emissivity, and other technologies that can be applied to the surface to help it remain cooler than traditional asphalt. Regardless of the specific mechanism, cool pavements aim to reduce temperatures within urban environments and alleviate the urban heat island effect.

To assess the performance of cool pavement in San Antonio, a team of researchers at the University of Texas at San Antonio (UTSA) partnered with the City of San Antonio (COSA) to collect various meteorological measurements at each cool pavement installation and a control site during the summer of 2023. This report provides an overview of the COSA cool pavement pilot program, outlines the methods used by the UTSA research team to collect and analyze the field data, and presents the major findings regarding cool pavement performance.

2. CITY OF SAN ANTONIO COOL PAVEMENT PILOT PROGRAM

San Antonio's extreme summer temperatures make the city an ideal location to pilot innovative technologies, such as cool pavement, that potentially mitigate excessive urban heat. Summertime high temperatures in San Antonio regularly surpass 90ºF and prolonged heatwaves can occur where high temperatures remain above 100ºF for weeks. Due to the relative proximity of the Gulf of Mexico, southeasterly flow can contribute to high humidity levels, which increase the heat index and effectively make the city feel even hotter.

San Antonio became the first city in Texas to test cool pavement with an installation on Hays Street in 2021.[3] After record setting warmth in 2022 where the city observed the third highest number of 100-degree days on record, COSA decided to conduct a full pilot program of cool pavement technology. The pilot was supported by COSA's Resiliency, Energy Efficiency and Sustainability Fund and helps address the goals outlined in COSA's Climate Action and Adaptation Plan.

To select the specific locations for the cool pavement products, COSA consulted heat and equity data to identify census tracts with high scores for temperature, poverty, and percentage of people of color. Within the candidate census tracts, COSA selected roads that were in adequate condition and had minimal shading. Finally, each City Council District Office decided the final locations from the candidate list. The plots of different cool pavement treatments were installed across COSA's ten city council districts beginning in April and ending in July of 2023.

2.1 COOL PAVEMENT PRODUCTS

Three of the four types of cool pavement included in the pilot were assessed in this study. Unfortunately, issues were encountered during the original installation of the GuardTop product, and the final installation did not occur until mid-July after fieldwork was well underway. The three products evaluated included PlusTi produced by Pave Tech, Durashield produced by GAF Streetbond, and SolarPave produced by SealMaster. Each cool pavement product has a different appearance and utilizes various physical mechanisms to reduce temperature. The three products were installed at two different locations for a total of six field sites dispersed throughout the city (**Figure 1**).

2.1.1 GAF Streetbond: Durashield

The Durashield product from GAF Streetbond is a spray-on, epoxy-modified waterborne acrylic coating that was installed on May 17th and 18th at Carol Crest and Spiral Creek, respectively. The product is designed for application on asphalt pavements. The color of the material is solar gray, which has a darker appearance than other cool pavement products (**Figure 2a**). Durashield has a minimum Solar Reflective Index (SRI), which accounts for both albedo and emissivity alterations, of 33. The product not only has the potential to mitigate urban heat but may extend the life of the roadway.

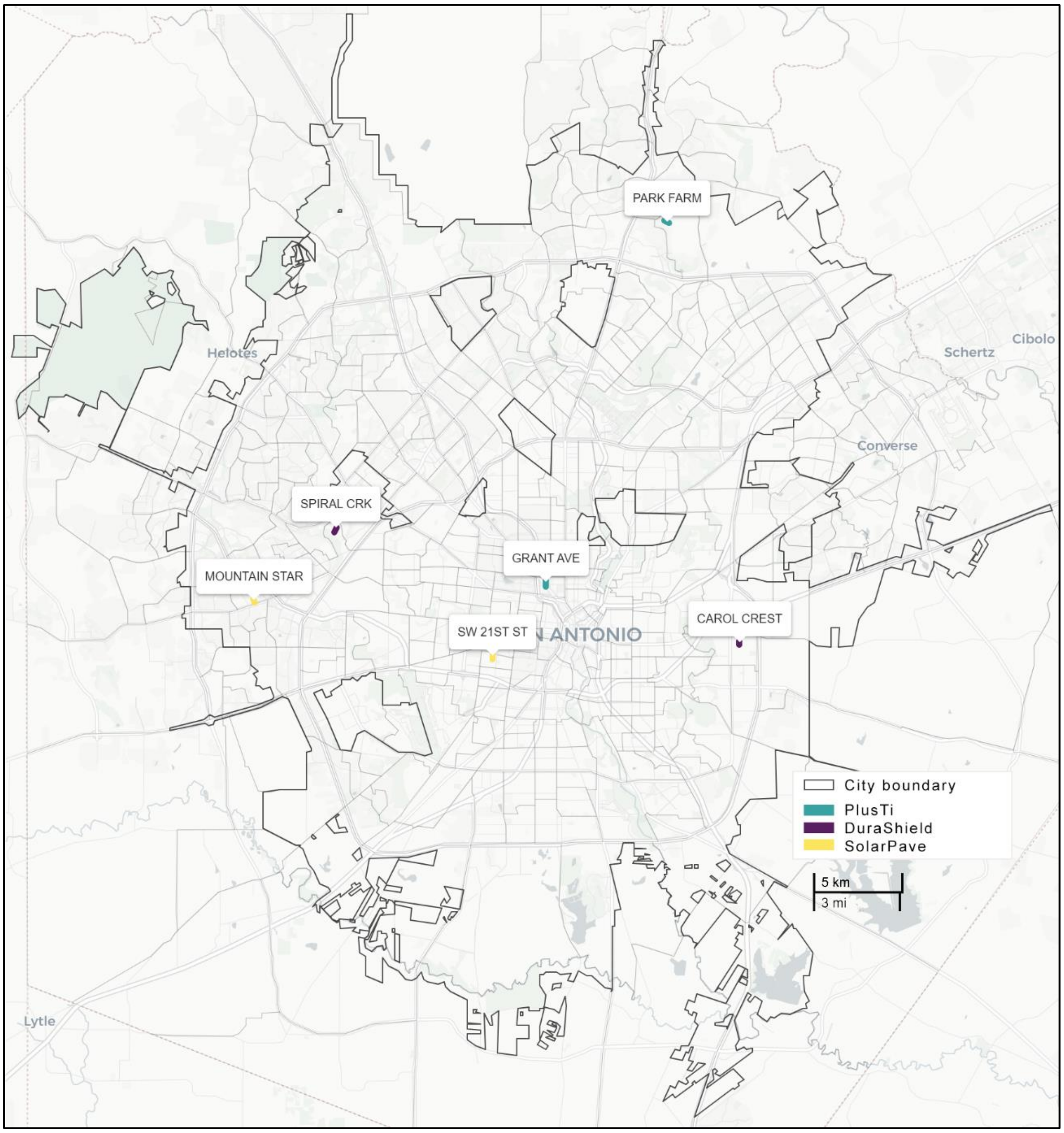

Figure 1. Location of the six cool pavement study sites in San Antonio by product type.

2.1.2 SealMaster: SolarPave

The SolarPave product from SealMaster is a spray-on acrylic polymer emulsion coating that was installed on May 1st and 2nd at SW 21st St. and Mountain Star, respectively. The material is light-colored and has a minimum SRI of 33 (**Figure 2b**). The product is recommended for coating asphalt streets and parking lots but not concrete surfaces. The product has the potential to mitigate the urban heat island effect, enhance road durability, and increase nighttime road visibility due to its lighter color.

2.1.3 Pave Tech: PlusTi

The PlusTi product from Pave Tech is a titanium dioxide-based spray-on material that was installed on April 24th and 25th at Grant Ave. and Park Farm, respectively. Unlike the previous two materials, PlusTi is a penetrant rather than a coating, meaning it is absorbed into the pavement matrix and does not fundamentally alter the appearance of the road surface (**Figure 2c**). The product also focuses primarily on altering the emissivity of the surface rather than the albedo. The SRI of the product is approximately 40. The product has the potential to mitigate urban heat, extend the life of the roadway since it is an asphalt rejuvenator, and reduce vehicle related pollution.

Figure 2. Examples of the cool pavement products evaluated in the study: A) Durashield at Carol Crest (cool pavement in the background with untreated road in the foreground), B) SolarPave at Mountain Star (cool pavement on the right with untreated road on the left), and C) PlusTi at Grant Avenue (cool pavement on the right with untreated road on the left).

3. METHODS

The basic design of this study was based largely on recent research conducted for the Phoenix, AZ cool pavement program by Arizona State University.[4] The data collection period spanned from June 27th to September 1st of 2023, which was the hottest summer on record in San Antonio. The study period was selected to evaluate the performance of the cool pavement products during the hottest portion of the year.

3.1 STUDY SITES

For each of the study sites (**Figure 1**), a specific portion of the cool pavement installation was identified for collecting the meteorological measurements. The study plot locations were selected to minimize the amount of shadowing from adjacent trees and houses so that solar exposure was maximized. The plot locations were also selected to maintain neighborhood accessibility (i.e., minimize the number of blocked driveways) and avoid road segments with large numbers of parked cars.

Untreated control plots were selected for each cool pavement installation to provide a baseline against which the cool pavement performance would be evaluated. The control plots were located either on an untreated segment of the same street or within one block of the cool pavement. The control plots were located on road segments with similar surrounding urban morphologies and shared the same orientation as the cool pavement installations so they would experience similar wind flow regimes and sun angles. The selected sites are described in **Table 1** and the specific plot locations are mapped in Appendix A.

Table 1. Characteristics of the study sites including the cool pavement treatment and control plots.

	Location			Cool Pavement Characteristics				Data Collection Dates (2023)	
Site	District	Control	Treatment	Manufacturer	Product	Installer	Installation Date (2023)	Phase I	Phase II
Grant Ave.	1	98.511927 W 29.451801 N	98.509958 W 29.451834 N	Pave Tech	PlusTi (oil based)	Pavement Restoration	24-Apr	28-Jun 12-Jul 26-Jul	24-Aug 25-Aug
Park Farm	9	98.442672 W 29.627592 N	98.442349 W 29.628417 N	Pave Tech	PlusTi (oil based)	Pavement Restoration	25-Apr	27-Jun 11-Jul 25-Jul	-
Carol Crest	2	98.403685 W 29.419381 N	98.400169 W 29.420087 N	GAF Streetbond	Durashield (water/acrylic based)	Creative Paving	17-May	27-Jun 11-Jul 25-Jul	17-Aug 18-Aug
Spiral Creek	6	98.630526 W 29.474777 N	98.629696 W 29.476078 N	GAF Streetbond	Durashield (water/acrylic based)	Creative Paving	18-May	29-Jun 13-Jul 27-Jul	-
Mountain Star	4	98.675183 W 29.440883 N	98.676013 W 29.440502 N	SealMaster	SolarPave (water/acrylic + polymer based)	Gallo Paving	2-May	29-Jun 13-Jul 27-Jul	31-Aug 1-Sep
SW 21st St.	5	98.540192 W 29.414403 N	98.53995 W 29.415892 N	SealMaster	SolarPave (water/acrylic + polymer based)	Gallo Paving	1-May	28-Jun 12-Jul 26-Jul	-

3.1.1 Carol Crest

The Carol Crest site was located southwest of the IH-10 and IH-410 interchange in District 2. The cool pavement installation incorporated the entire span of Carol Crest from Argonne Dr. to Kay Ann Dr. The individual cool pavement testing plot ran south from Belinda Lee St. (**Figure A1**). The southern portion of the cool pavement was selected to avoid taller trees that were more proximate to the road in the northern block. The control plot was located in the analogous block of Susanwood Dr. and had a similar north-south orientation.

3.1.2 Grant Ave.

The Grant Ave. site was located southeast of the IH-10 and Woodlawn Ave. intersection in District 1. The cool pavement installation on Grant Ave. ran from W Craig Pl. to Cincinnati Ave. Constraints regarding the location of the most appropriate control plot largely dictated the location of the cool pavement testing site. Blanco Rd. to the east was a major four-lane thoroughfare, so Michigan Ave. to the west was the most appropriate residential control road. Due to the orientation of Fredericksburg Rd., the southern portion of Michigan Ave. had a more urban character than much of the cool pavement installation. Therefore, the northern edge of the cool pavement was selected for measurements along with the same segment of Michigan Ave. (**Figure A2**). The two testing sites ran parallel to each other in a north-south direction, and both had similar xeriscaped yards to the west.

3.1.3 Mountain Star

The Mountain Star site was located west of the TX-151 and Potranco Rd. intersection in District 4. The cool pavement installation spanned the entire length of Mountain Star. The specific cool pavement test plot extended southwest from Wildhorse Run to the alley in order to avoid blocking additional traffic (**Figure A3**). Since Rebeccas Trail was also selected for a cool pavement installation, the most appropriate control site was Wormack Way. The control plot ran from Sage Ter. to Fall Pass St. The cool pavement installation on Mountain Star was selected for study rather than Rebeccas Trail since more cars were generally parked on Rebeccas Trail, and it was at a higher elevation than the control.

3.1.4 Park Farm

The Park Farm site was located northeast of the TX-1604 and US-281 interchange in District 9. The cool pavement installation covered the majority of Park Farm. The cool pavement test plot was near the middle of Park Farm in an area that minimized shade. Since Park Ranch was wider than Park Farm, Park Cir. was selected as the control (**Figure A4**). The two streets were parallel to each other with a northwest-southeast orientation. Encino Ridge St., the other cool pavement installation in District 9, was not selected for study due to its largely north-south orientation and tree canopy, which resulted in pronounced shadowing.

3.1.5 Spiral Creek

The Spiral Creek site was located west of the IH-410 and TX-16 interchange in District 6. The cool pavement installation ran from Creek Ridge to Ribbon Creek. The cool pavement testing site incorporated the portion of Spiral Creek between Hidden Creek and Sparrow Creek (**Figure A5**). Identifying a suitable control location was challenging since the other roads in the subdivision did not have the same orientation as Spiral Creek. Ultimately, a portion of Spiral Creek to the southwest of the cool pavement installation was selected as the control site since there was a notable curve in Spiral Creek to the northeast. The control site was also smaller than the cool pavement test plot to minimize issues with shadowing.

3.1.6 SW 21st St.

The SW 21st St. site was located northwest of the US-90 and IH-10 interchange in District 5. The cool pavement installation ran south from S. Laredo St. to Saltillo Rd. The open field to the west of SW 21st St. associated with Jeremiah Rhodes Middle School influenced the locations of both the cool pavement and control testing sites (**Figure A6**). The northern portion of the cool pavement adjacent to the open field was selected for testing since this enabled an analogous portion of SW 21st St. between Hidalgo St. and Potosi St. that also bordered the field to be used as the control plot.

3.2 INSTRUMENTS

Several different instruments were deployed at each field site to capture various meteorological variables including the surface temperature, air temperature, and wet bulb globe temperature (WBGT) (**Table 2**).

3.2.1 FLUKE 572-2 Infrared Thermometer

To measure the surface temperature at the cool pavement sites and control sites, FLUKE 572-2 infrared thermometers were used (**Figure 3a**). The surface temperature is the temperature of the street surface itself rather than the air above it. For temperatures above freezing, the thermometer accuracy is ± 2°F or ± 1% of the reading, whichever is greater. The emissivity was set to 0.95 for all the FLUKE measurements, which followed the methodology from the Phoenix, AZ cool pavement study.[4]

Table 2. Summary of the instruments used to collect meteorological data.

Instrument	Meteorological Variable	Units
FLUKE 572-2	Surface Temperature	ºF
FLIR E4	Surface Temperature	ºF
Kestrel 5400 WBGT HST	Air Temperature	ºF
	Globe Temperature	ºF
	Wet Bulb Globe Temperature	ºF
	Relative Humidity	%
	Wind Speed	mph
	Pressure	hPa
NR01 4-Component Net Radiometer	Longwave Radiation (Incoming & Outgoing)	W/m^2
	Shortwave Radiation (Incoming & Outgoing)	W/m^2
	Albedo	Unitless
	Net Radiation	W/m^2

3.2.2 FLIR E4

To complement the surface temperature measurements from the FLUKE infrared thermometer, a forward looking infrared (FLIR) camera was also used to capture images of the surface temperature. These images helped identify the localized surface temperature differences on either side of the seam formed where the cool pavement treatment meets the untreated street. The FLIR E4 has an infrared resolution of 80 x 60 (4,800 pixels) and an accuracy of ±2% or ±3.6°F depending on the ambient and object temperature.

3.2.3 Kestrel 5400 Heat Stress Tracker

Kestrel 5400 Heat Stress Trackers were used to measure additional meteorological variables. The primary variables included wind speed, air temperature, relative humidity, globe temperature, pressure, and the WBGT. The WBGT is a heat stress metric that considers air temperature, relative humidity, wind speed and incident sunlight. The sensor is most accurate when it is oriented directly into the wind since this enables ventilation and ensures the impeller captures the entire wind strength. Therefore, the sensor was attached to a vane mount that pivots with the wind direction. The sensor and vane mount were then connected to a collapsible tripod to ensure a level and standardized measurement height (**Figure 3b**). The air temperature accuracy is 0.9°F, the relative humidity accuracy is 2%, the globe temperature accuracy is 2.5°F, and the WBGT accuracy is 1.3°F.

3.2.4 NR01 4-Component Net Radiometer

A Hukseflux NR01 4-component net radiometer was used to measure the net radiation budget for the cool pavement and control sites. The NR01 includes two pyranometers, one facing up and one facing down, to measure the incoming shortwave (energy from the sun) and outgoing shortwave (sunlight reflected by the surface) radiation fluxes. It also includes two pyrgeometers, one facing up and one facing down, to measure the incoming longwave (downwelling from the atmosphere and clouds) and outgoing longwave (energy emitted by the surface) radiation fluxes. From these variables, the albedo (shortwave out/shortwave in) and net radiation budget can be calculated (shortwave in - shortwave out + longwave in - longwave out). The NR01 was attached to a six-foot metal tripod using a four-foot metal cross arm. The sensor was positioned four feet above the ground and three feet from the main mast of the tripod (**Figure 3c**). The NR01 was wired, using a four-wire bridge module, to a Campbell Scientific CR1000X datalogger for data storage.

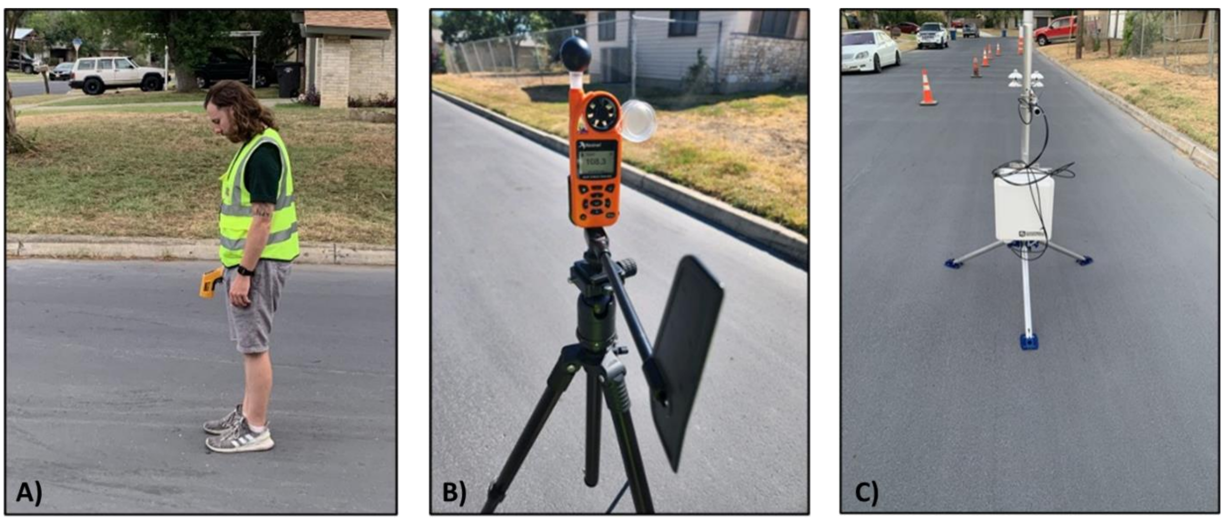

Figure 3. The a) FLUKE 572-2 infrared thermometer, b) Kestrel 5400 Heat Stress Tracker, and c) Hukseflux NR01 4-component net radiometer deployed in the field.

3.3 FIELD CAMPAIGNS

The fieldwork was conducted from June 26th to September 1st in 2023. A total of 15 days of fieldwork were performed, excluding the initial site visits for planning. For each field day, traffic cones and barrels were laid out the evening prior to close one lane of the street at both the cool pavement and control testing plots (**Figures A1-A6**). The detailed schematics used to guide the data collection process within the lane closures are provided in Appendix B.

Two separate phases of fieldwork were performed. Phase I focused on capturing air temperature, WBGT, and surface temperature data while Phase II was designed to evaluate the net radiation budgets. For each day of fieldwork, data was collected from the San Antonio International Airport weather station (KSAT ASOS) to help characterize the broader meteorological characteristics and contextualize our site-specific observations.

3.3.1 Phase I

Phase I consisted of three fieldwork sessions (Session 1: June 27th - 29th, Session 2: July 11th - 13th, and Session 3: July 25th - 27th). During each three-day session, all six sites were visited. Therefore, each site was characterized by three days of data after the completion of Phase I (**Table 1**). During each field day, data was collected simultaneously at the cool pavement testing site and control testing site to enable meaningful comparisons. The data collection occurred in four one-hour increments between 6:00 am - 7:00 am, Noon - 1:00 pm, 4:00 pm - 5:00 pm, and 9:00 pm - 10:00 pm. The morning session was designed to capture the low temperature, the noon session aligned with the highest sun angle, the afternoon session included the hottest portion of the day, and the evening session was after sunset and enabled an evaluation of how the surfaces were cooling.

The surface temperature data was collected every five minutes throughout each one-hour period using the FLUKE 572-2 infrared thermometer. A 4 row by 3 column grid was used to define the specific points where surface temperatures were measured. The grid spanned from the middle of the road to the curb and the entire length of the road closure (**Figure 4**). Every grid point was visited once during each hour period resulting in 12 surface temperature measurements. Point 1,1 was the first point collected followed by 1,2 and 1,3 after which the same order was repeated on each subsequent row. The specific grid structure at each site is provided in Appendix B. In addition to storing the surface temperature readings on the FLUKE 572-2, a survey was completed with each measurement to note if the point was in shadow or if any abnormal surface characteristics were present (e.g., damage, dirt, debris).

The air temperature and WBGT were collected using the Kestrel 5400 Heat Stress Tracker. The instrument was positioned in a portion of the test plots that avoided shadows since direct sunlight was required for the WBGT calculations. The sensor was also located closer to the middle of the road than the curb to maximize the impact of the road surface on the measurements. The specific locations of the Kestrels at each site are provided in Appendix B. The Kestrels were programmed to take and record measurements every 5 seconds. Since direct sunlight on the temperature sensor during low wind conditions reduces the sensor accuracy, the Kestrel was repositioned if calm conditions occurred where the sensor was in direct sunlight for 30 seconds. This involved spinning the wind vane slightly, so the temperature sensor was shaded by its own enclosure. A survey was also completed to note any considerable shadowing from clouds, if and when any repositioning was required, and the wind direction.

Figure 4. Diagram of the grid used to collect surface temperature measurements.

In addition to visiting all the cool pavement and control plots, one additional road segment was included as an alternative surface temperature control. On July 13th and July 27th, surface temperature data was collected on a segment of Sparrow Creek, which was repaved with fresh asphalt at the end of June. This data was collected using a more compact version of the sampling grid (**Figure 4**) and with minimal time elapsing between measurements since it was outside the formal road closure. Finally, the FLIR E4 thermal imagery and surface temperature measurements were gathered at every site during Session 3.

3.3.2 Phase II

Phase II also consisted of three fieldwork sessions (Session 1: August 17th & 18th; Session 2: August 24th & 25th, and Session 3: August 31st & September 1st). Since one NR01 net radiometer was available, only three sites were included in Phase II. Carol Crest, Grant Ave., and Mountain Star were selected so each cool pavement product was evaluated (**Table 1**). During each two-day field session, data was collected at the cool pavement testing site on the first day and the control testing site on the second day. Unlike Phase I, the data collection occurred continuously from 6:00 am to 10:00 pm.

The radiation fluxes and albedo were evaluated using the Hukseflux NR01 4-component net radiometer. The net radiometer was positioned facing southward within the lane closure in an area designed to minimize shadowing throughout the day. The specific placement of the net radiometer is mapped in Appendix B. The datalogger was programmed to record minute and hourly averages of the radiation measurements.

To complement the net radiometer data, a Kestrel recording measurements every 20 seconds was also deployed each day and positioned in an area to minimize shadowing. The same Kestrel repositioning protocols were followed, and the survey from Phase I was also completed. Finally, surface temperature measurements were collected every ten minutes at one point behind the net radiometer. Finally, during Session 1, Carol Crest was revisited with the FLIR E4 for additional thermal imagery collection.

3.4 STATISTICAL ANALYSIS

The data processing and statistical analyses were conducted using a combination of Microsoft Excel and R. For the surface temperature measurements collected during Phase I, the three sessions were combined into one dataset. This produced a potential maximum sample size of 36 for each one-hour observation period at each site (i.e., 12 observations during each hour window x 3 site visits). Points that were in shade were removed from the dataset to prevent the cooler temperatures from biasing the averages. Once the shadow observations were removed, the average surface temperatures were calculated for the cool pavement testing sites and control testing sites during each time period. A two-sample t-test was then performed to evaluate the statistical significance of the differences.

Since the air temperature and WBGT were collected every 5 seconds during Phase I, a data reduction algorithm was performed to reduce issues with temporal autocorrelation (i.e., observing the same temperature repeatedly, which creates statistical redundancy in the dataset). The Durbin-Watson test was performed and if the result was significant the data was reduced using every n^{th} observation (i.e., every other, every third, etc.). After each data reduction, the Durbin-Watson test was re-run and the process continued until the temporal autocorrelation was eliminated. This resulted in a variable sample size for every site and hour observation period, with smaller sample sizes generally occurring in the morning and night when the temperature fluctuations were minor. Boxplots using the reduced datasets were created to visualize the air temperature and WBGT differences between the cool pavement and control for each individual hour period. Two-sample t-tests were also performed to evaluate the statistical significance of the differences.

The radiation measurements collected during Phase II were used to calculate the albedo of each surface. The albedo differs throughout the day due to variations in the sun angle and the most reliable measurements are obtained in the afternoon. The hourly average incoming and outgoing shortwave radiation fluxes between noon and 4:00 pm were utilized in the albedo calculations. Temporal line graphs were also created to visualize the individual components of the net radiation budget.

3.5 GIS ANALYSIS

Since the surrounding environment can influence the temperature at the different cool pavement installations as well as each control plot, GIS was used to characterize the immediate surroundings. The GIS analysis incorporated land use information to quantify the general urban morphology (i.e., type and density of structures) at each site. Components of the natural environment, such as tree canopy coverage and land cover, were also considered since they can impact temperature as well. Finally, remotely sensed surface temperature was analyzed to help contextualize the in-situ observations obtained during the fieldwork. **Table 3** provides an overview of the specific datasets used during the GIS analysis. Due to data availability, the data sources for the GIS component predated the fieldwork.

Table 3. Data used in the GIS analysis to characterize the surrounding environment of the cool pavement installations and control sites.

Dataset	Source	Year
Land use	Bexar County Appraisal District	2022
Land cover	USGS NLCD (30m resolution)	2019
Tree canopy	LiDAR Texas A&M (1m resolution)	2017
Surface temperature	Landsat 8 (30m resolution)	2022 (August)

ArcGIS Pro and R were used to quantify the characteristics of the surrounding environments using two buffer distances (200ft and 500ft). The percentage of each land use and land cover category within the buffers, the percent of the buffer areas that were tree canopy, and the average surface temperature within the buffers were all calculated. This methodology was applied to the entire length of the six cool pavement installations as well as the specific cool pavement testing sites and control sites.

4. RESULTS

4.1 FIELD SITE CHARACTERISTICS

The GIS analysis of the field sites served two primary purposes. First, the cool pavement installations were compared to one another to contextualize the meteorological observations from the field data collection. Maps of the surrounding environmental characteristics of the cool pavement installations are provided in Appendix C. Second, the specific cool pavement testing sites and control testing sites were compared to ensure they were reasonably analogous.

4.1.1 Cool Pavement Installation Comparisons

In terms of land use, the cool pavement installations were generally surrounded by single-family residential properties. Over 65% of the 200ft buffer was characterized as single-family residential for Carol Crest, Mountain Star, Spiral Creek, and Park Farm since these installations were imbedded within traditional subdivisions (**Table 4**). Grant Ave. and SW 21st St. were more mixed in terms of land use. Grant Ave. included multi-family residential, primarily due to the subdivision of the existing housing stock into duplexes, and the high portion of commercial land use at SW 21st St. can be attributed to Jeremiah Rhodes Middle School bordering the road to the west.

All the areas surrounding the cool pavement were developed but to varying degrees according to the land cover data. Grant Ave., Mountain Star, SW 21st St., and Spiral Creek were all primarily characterized by medium intensity development whereas low intensity development was more abundant at Park Farm and Carol Crest (**Table 4**).

Table 4. Field site characteristics within the 200ft and 500ft buffer for each cool pavement installation.

	GRANT AVE.		CAROL CREST		MOUNTAIN STAR		SW 21ST ST.		SPIRAL CREEK		PARK FARM	
	200ft	500ft	200ft	500ft	200ft	500ft	200ft	500ft	200ft	500ft	200ft	500ft
LAND USE (%)												
Single-Family	45.13	44.79	67.66	58.80	79.28	74.20	46.20	43.81	66.04	58.77	86.69	71.27
Multi-Family	14.01	12.99	-	-	-	-	-	-	3.19	19.29	-	-
Commercial/Office	4.69	12.86	-	0.67	-	-	26.97	27.18	26.97	-	-	-
Vacant	5.74	3.34	3.47	15.91	-	0.39	4.96	12.65	4.96	1.09	-	-
Utilities/Industrial	-	0.39	-	0.34	-	-	-	-	-	-	-	-
Agriculture/Farm & Ranch	-	-	-	-	-	-	-	-	-	-	-	8.26
Road	30.43	25.62	28.87	24.28	20.72	25.41	21.87	16.37	30.77	20.85	13.31	20.47
LAND COVER (%)												
Developed, Open Space	-	0.91	4.44	16.56	-	1.20	17.02	22.42	-	5.82	8.51	25.61
Developed, Low Intensity	20.00	28.64	77.78	50.92	12.77	17.37	25.53	33.33	40.68	26.46	80.85	56.71
Developed, Med Intensity	60.00	53.18	17.78	29.45	76.60	72.46	48.94	37.58	59.32	63.49	10.64	10.37
Developed, High Intensity	20.00	17.27	-	3.07	10.64	8.38	8.51	6.67	-	4.23	-	1.22
Deciduous Forest	-	-	-	-	-	-	-	-	-	-	-	1.22
Evergreen Forest	-	-	-	-	-	-	-	-	-	-	-	2.44
Shrub/Scrub	-	-	-	-	-	0.60	-	-	-	-	-	2.44
TREE CANOPY (%)	33	35	25	26	22	23	26	29	42	39	44	52
LAND SURFACE TEMP. (°F)	109.1	109.1	110.9	110.9	112.7	110.9	109.1	107.3	107.3	107.3	103.7	103.7

The tree canopy percentage varied substantially between each cool pavement site. The Mountain Star location exhibited the least developed tree canopy, which may be attributable to it being a newer subdivision. Only 22% of the area within the 200ft buffer at Mountain Star was occupied by tree canopy (**Table 4**). The tree canopy for Carol Crest, SW 21st St., and Grant Ave. was slightly more expansive with values ranging from 25% to 33%. Park Farm and Spiral Creek both exhibited the most abundant tree canopy within the 200ft buffer as the coverage exceeded 40%.

Remotely sensed land surface temperatures varied by almost 10°F between the coolest location (Park Farm) and the warmest location (Mountain Star). This generally aligned with the differences in tree canopy coverage (**Table 4**). The majority of the temperatures ranged between 107°F and 110°F. There were also only marginal differences between the 200ft and 500ft buffer results, which highlights how the resolution of the remotely sensed imagery is largely insufficient to detect highly localized temperature variations.

4.1.2 Cool Pavement Testing Site and Control Site Comparisons

The comparison of the cool pavement testing sites (i.e., the specific portion of the cool pavement installation evaluated) and the control testing sites was limited to the 200ft buffer to characterize the most immediate surroundings (**Table 5**). The Grant Ave. cool pavement site and control site were very analogous, as both were characterized by a mix of single- and multi-family residential land use with predominately medium intensity development. The tree canopy coverage percentages were also identical.

Table 5. Built and natural environment characteristics within the 200ft buffer surrounding the cool pavement testing site (CP) and control site (CON) for each cool pavement installation.

	GRANT AVE.		CAROL CREST		MOUNTAIN STAR		SW 21ST ST.		SPIRAL CREEK		PARK FARM	
	CP	CON	CP	CON	CP	CON	CP	CON	CP	CON	CP	CON
LAND USE (%)												
Single-Family	58.92	58.85	71.63	71.30	76.87	80.20	32.72	37.10	65.57	67.82	89.72	83.29
Multi-Family	10.60	12.09	-	-	-	-	-	-	2.86	2.66	-	-
Commercial/Office	-	-	-	2.24	-	-	44.56	42.95	-	-	-	-
Vacant	-	-	-	0.18	-	-	3.16	0.94	-	0.04	-	-
Road	30.47	29.06	28.37	26.27	23.13	19.80	19.55	19.00	31.57	29.49	10.28	16.71
LAND COVER (%)												
Developed, Open Space	-		-	9.09	-	-	27.27	28.00	-	-	16.67	5.00
Developed, Low Intensity	16.67	10.53	81.82	40.91	5.00	28.00	27.27	28.00	46.15	38.10	70.83	75.00
Developed, Med Intensity	83.33	89.47	18.18	50.00	80.00	64.00	36.36	44.00	53.85	61.90	12.50	20.00
Developed, High Intensity	-		-	-	15.00	8.00	9.09	-	-	-	-	-
TREE CANOPY (%)	35	35	28	16	25	25	14	24	45	38	40	43
LAND SURFACE TEMP. (°F)	109.1	107.3	110.9	110.9	112.7	112.7	110.9	109.1	107.3	107.3	103.7	103.7

The cool pavement site and control site at Carol Crest also shared similarities in terms of land use but differed in terms of land cover and tree canopy. The cool pavement site contained more low intensity development and exhibited greater tree canopy coverage than the control site. This was primarily due to the 200ft buffer at the cool pavement site incorporating a small drainage culvert east of the cool pavement between Carol Crest and Sapphire Dr. Although this may have influenced the meteorological measurements, the impact was likely negligible since the cool pavement was separated from the culvert by the houses on the east side of Carol Crest. Additionally, it was not possible to mimic the proximity to the culvert with the control site since the cool pavement was installed along the entirety of Carol Crest.

The Mountain Star cool pavement and control sites were very similar. Both were predominately single-family residential with medium intensity development, and they shared the same tree canopy coverage. The sites located at SW 21st St. were also reasonably analogous in terms of land use, as both contained notable commercial development due to the middle school. The school's playing fields were reflected in the land cover percentages with each site consisting of over 25% developed open space. One difference was the tree canopy coverage, as the cool pavement percentage was ten points lower. This was primarily attributable to the vacant lot east of the cool pavement site and the more robust tree canopy associated with the properties east of the control segment on SW 21st St. Since the aim of the site selection was to ensure similar exposure to the open field, no other segment of the cool pavement was particularly suitable for evaluation.

The Spiral Creek testing sites exhibited similarities across all the metrics. The cool pavement and control were predominately single-family residential and surrounded by medium intensity development. The cool pavement test site and control site at Park Farm were also largely analogous, as their surroundings consisted of single-family residential land use and low intensity development. Overall, the results in **Table 5** suggest that the urban morphologies of the cool pavement testing sites and control sites were similar, particularly given the site selection constraints, which enabled meaningful comparisons.

4.2 METEOROLOGICAL CHARACTERISTICS OF THE FIELD DAYS

By many metrics, 2023 in San Antonio was record setting in terms of heat. The average high temperature from June to August was 100.2°F, which was the hottest on record. Throughout the year, the city also set records for the total number of 100°F days (75) and the number of consecutive 100°F days (23).

For the first field session of Phase I, the hourly maximum temperatures ranged from 104°F to 99°F with a modest cooling trend occurring throughout the week (**Figure 5**). Each day exhibited a similar diurnal pattern with regards to wind strength, as wind speeds gradually increased through the afternoon and the evening. The relative humidity patterns were also similar between each day. The second session of Phase I was notably warmer as afternoon hourly temperatures ranged from 102°F to 105°F (**Figure 6**). The wind speeds remained around 10mph each day until the evening when the wind speeds increased to

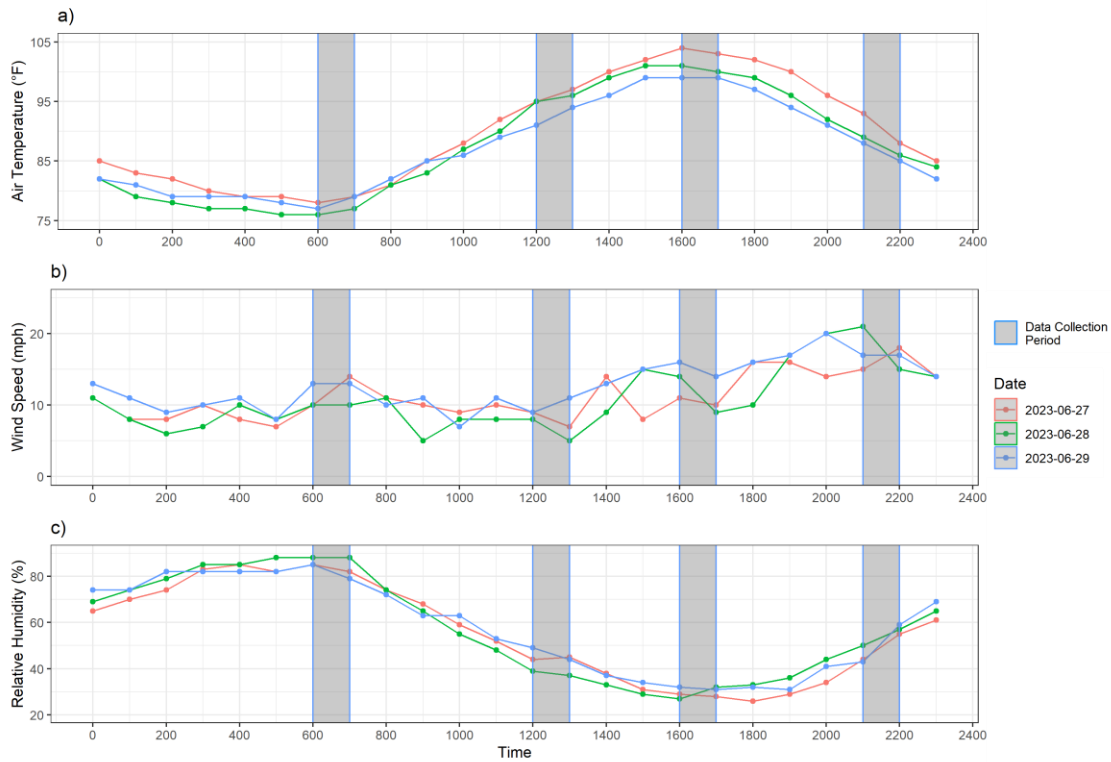

Figure 5. Meteorological characteristics at KSAT ASOS for field session one of Phase I.

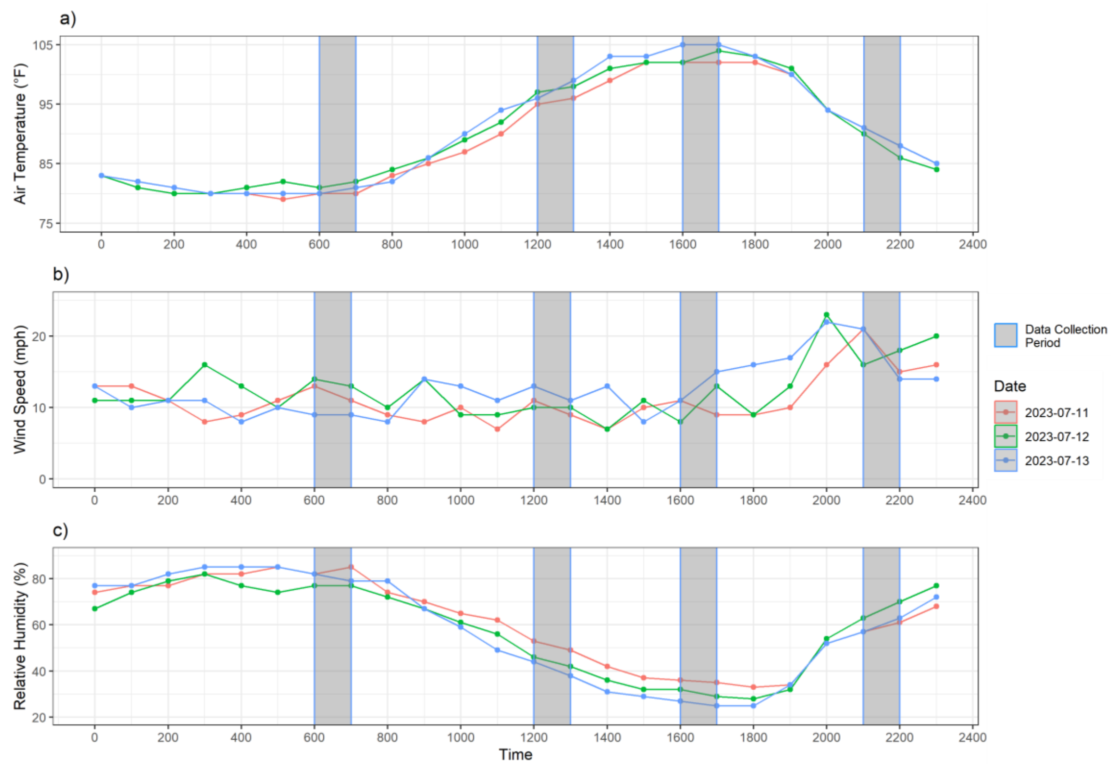

Figure 6. Meteorological characteristics at KSAT ASOS for field session two of Phase I.

20mph. The pronounced winds likely enhanced mixing, which could potentially minimize the impacts of cool pavement on air temperature. The third session of Phase I was the coolest with afternoon hourly temperatures not exceeding 100°F (**Figure 7**). The differences in the temperature profiles of the three individual days were minimal. Wind speeds were generally calmer throughout the day compared to session two, but stronger winds were again present in the evening. Overall, the differences between the three days within each session of Phase I were minor, which helped enable fair comparisons between the various cool pavement products since all sites were not visited on the same day. The weather plots also illustrated that the warmest and coolest portions of the day were generally captured by the sampling strategy.

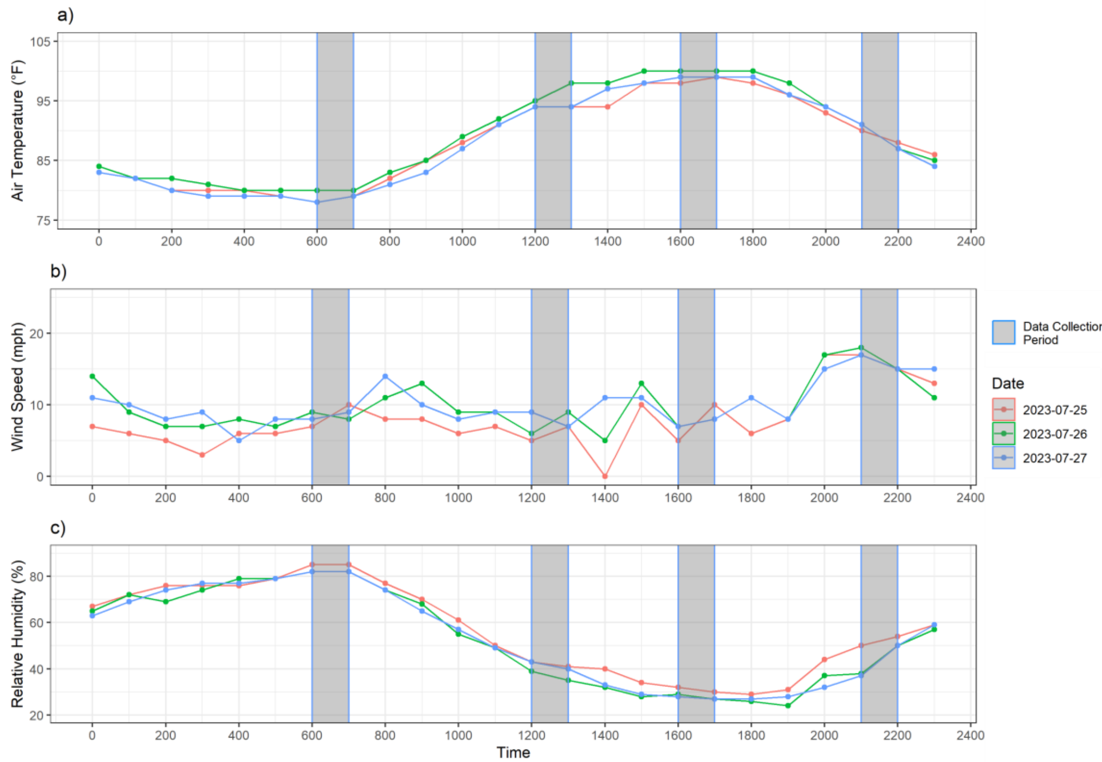

Figure 7. Meteorological characteristics at KSAT ASOS for field session three of Phase I.

The first session of Phase II, which occurred at Carol Crest, was characterized by similar temperatures at the cool pavement site (August 17th) and the control site (August 18th) (**Figure 8**). Specifically, there was only a 1°F difference for the hourly low and high temperature observations. The winds gradually increased throughout both days but were marginally stronger on the 18th, which perhaps contributed to the slightly cooler temperatures in the evening. The diurnal trends in relative humidity were reasonably analogous. For the second session of Phase II at Grant Ave., the temperature differences were more pronounced (**Figure 9**). The day (August 24th) data collection occurred at the cool pavement site was cooler, as hourly temperature observations did not exceed 100°F. The relative humidity was also higher to start the day although this could be partially due

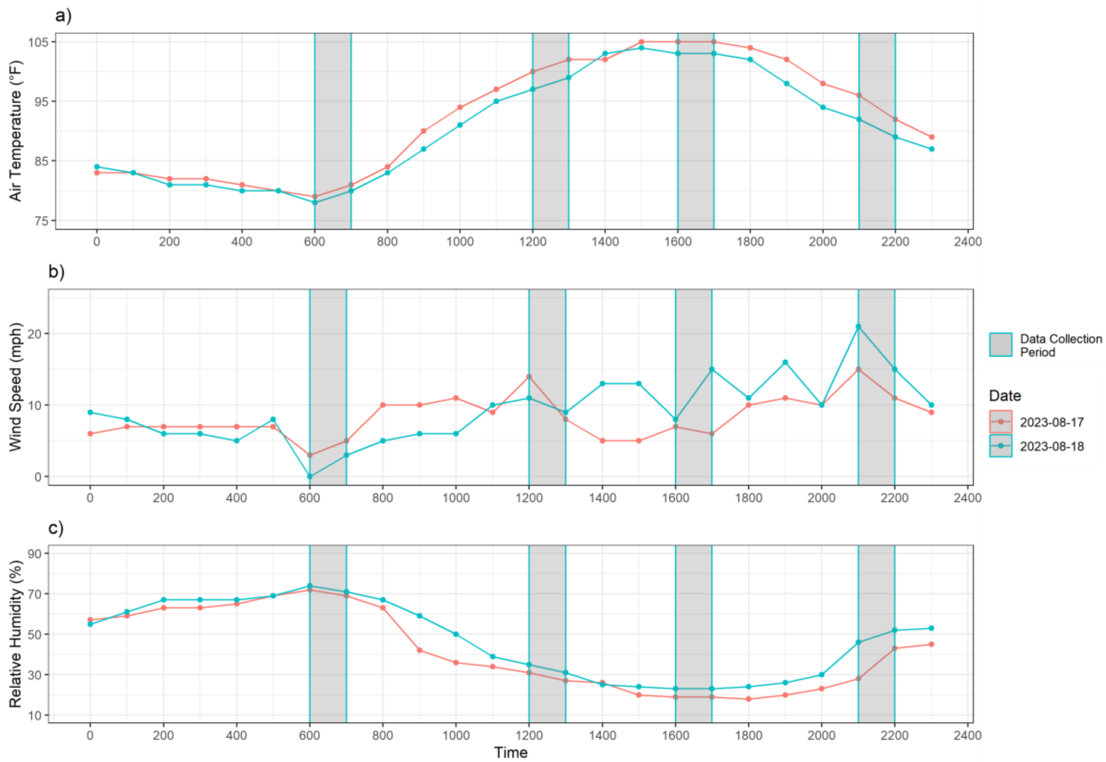

Figure 8. Meteorological characteristics at KSAT ASOS for field session one of Phase II.

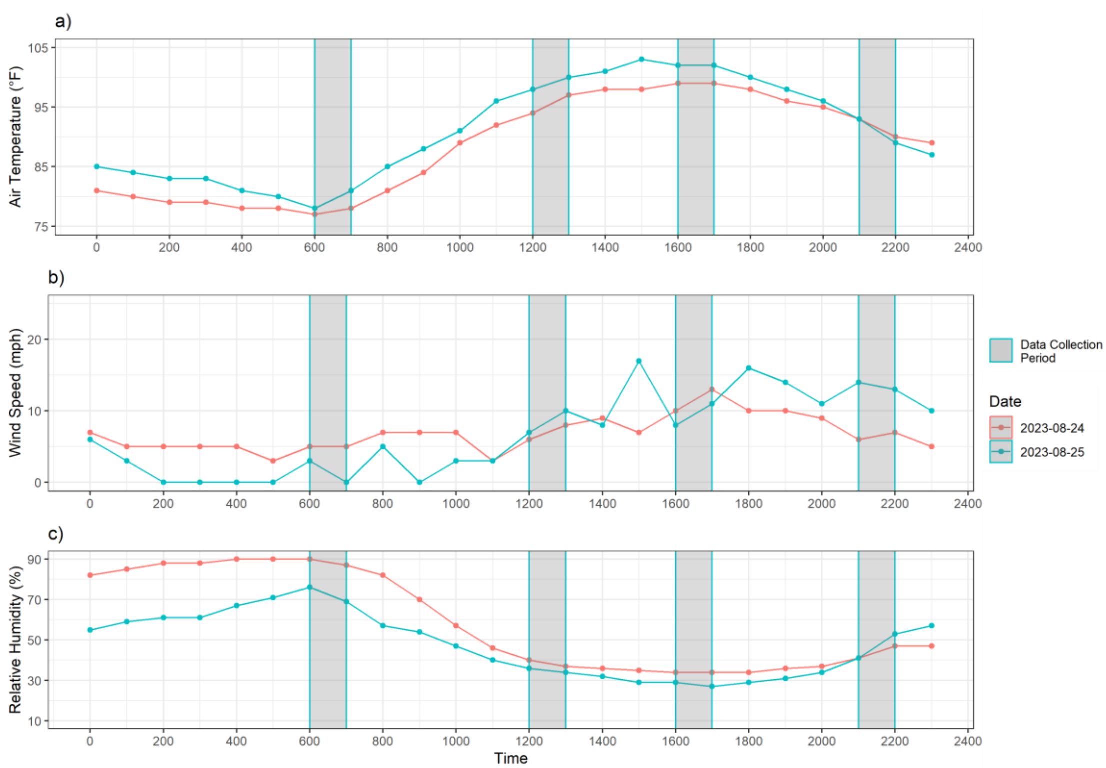

Figure 9. Meteorological characteristics at KSAT ASOS for field session two of Phase II.

to the lower air temperatures. The final session of Phase II occurred at Mountain Star. The air temperature profiles were very similar, and the wind speeds remained relatively calm throughout both days (**Figure 10**). The most notable difference was the elevated relative humidity on the control site day (September 1st). Overall, the conditions for the cool pavement site days and control site days were generally similar and understanding the minor differences that occurred helped contextualize the net radiation budget findings.

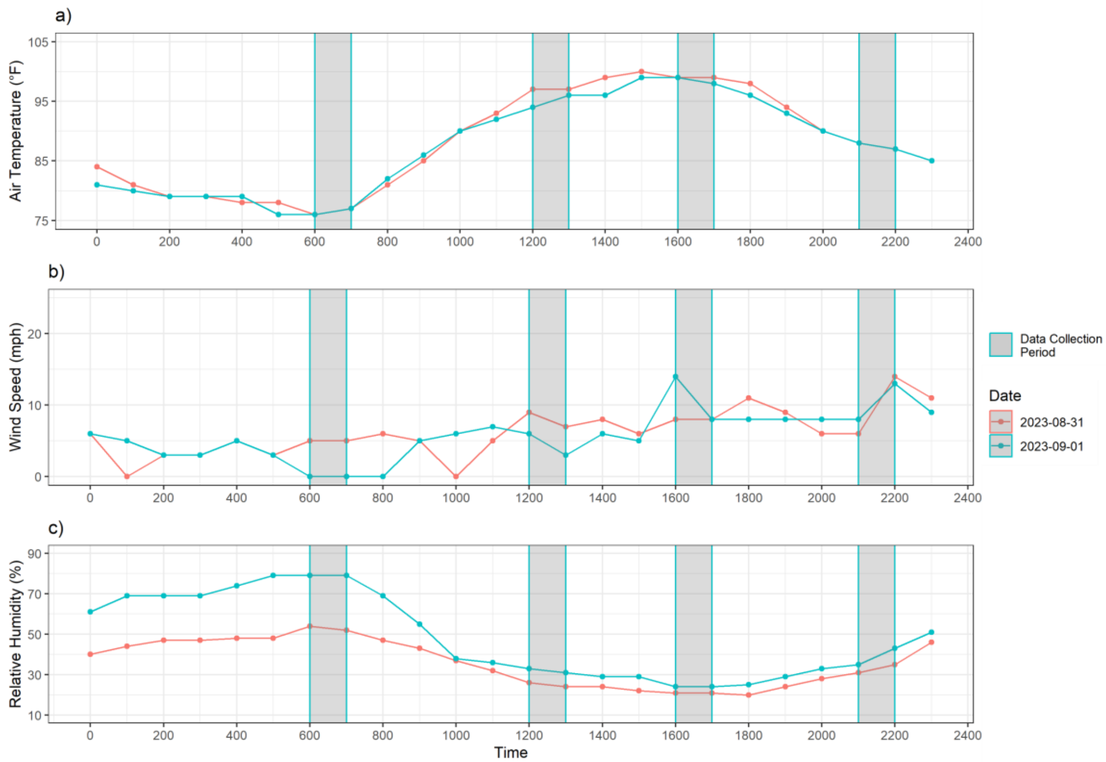

Figure 10. Meteorological characteristics at KSAT ASOS for field session three of Phase II.

4.3 SURFACE TEMPERATURE DIFFERENCES

The surface temperature differences between the cool pavement sites and control sites were modest in the morning and never exceeded +/- 1°F (**Table 6**). The small differences were also not statistically significant.

By noon, differences in the surface temperatures were more pronounced and all statistically significant. The largest negative difference occurred at Park Farm as the PlusTi product was 4°F cooler than the control site. The other PlusTi site at Grant Ave. was 12°F warmer than the control. This is potentially attributable to road surface differences between the Grant Ave. cool pavement installation and the control site. The PlusTi product was applied to a road that appeared to be resurfaced more recently than the control and the other roads in the neighborhood. This highlights a potential sensitivity of the PlusTi

Table 6. Differences in surface temperature between cool pavement (CP) sites and control (CON) sites by time of day. The sample size (N) is reported for both sites and varies due to the exclusion of points in shadows. Statistically significant differences are indicated by p-values in bold.

Site Name	Avg. CP Surface Temp. (°F)	CP N	Avg. CON Surface Temp. (°F)	CON N	Difference (°F)	T-Value	P-Value
Morning (6:00 am - 7:00 am)							
Carol Crest	87.00	36	86.33	36	0.67	1.18	0.24
Spiral Creek	89.14	36	88.30	36	0.84	1.42	0.16
Park Farm	88.02	35	88.83	36	-0.80	-1.61	0.11
Grant Ave.	89.00	36	89.72	36	-0.72	-1.31	0.20
Mountain Star	86.67	36	86.02	36	0.65	1.03	0.31
SW 21st St.	90.22	36	91.11	36	-0.88	-1.58	0.12
Noon (12:00 pm - 1:00 pm)							
Carol Crest	133.92	36	130.65	28	3.26	2.27	**0.03**
Spiral Creek	134.49	36	136.52	33	-2.04	-2.07	**0.04**
Park Farm	130.86	33	134.88	31	-4.02	-2.25	**0.03**
Grant Ave.	139.36	27	126.40	25	12.96	12.83	**0.00**
Mountain Star	125.14	35	128.64	36	-3.50	-4.11	**0.00**
SW 21st St.	131.51	36	133.79	36	-2.28	-3.56	**0.00**
Afternoon (4:00 pm - 5:00 pm)							
Carol Crest	143.92	32	144.11	31	-0.20	-0.18	0.86
Spiral Creek	146.42	32	146.90	25	-0.48	-0.57	0.57
Park Farm	146.20	36	149.78	35	-3.59	-3.26	**0.00**
Grant Ave.	146.53	36	140.61	36	5.92	4.68	**0.00**
Mountain Star	132.75	34	135.93	36	-3.18	-2.53	**0.01**
SW 21st St.	142.19	36	146.17	36	-3.97	-3.50	**0.00**
Night (9:00 pm - 10:00 pm)							
Carol Crest	103.59	36	103.82	36	-0.23	-0.33	0.74
Spiral Creek	104.73	36	102.68	36	2.05	2.71	**0.01**
Park Farm	107.88	36	108.11	36	-0.22	-0.35	0.73
Grant Ave.	104.37	36	103.90	36	0.47	0.73	0.47
Mountain Star	99.51	36	100.16	36	-0.66	-0.90	0.37
SW 21st St.	104.30	36	107.00	36	-2.70	-4.38	**0.00**

product to the underlying road surface since it is a penetrant rather than a coating. The Durashield product also displayed mixed results as the Carol Crest cool pavement was 3°F warmer than the control site while the Spiral Creek cool pavement was 2°F cooler. The SolarPave product exhibited a consistent cooling trend at both sites (Mountain Star and SW 21st St.) with an average surface temperature reduction of 2.9°F.

Reductions in surface temperatures were observed in the afternoon for the majority of sites. The SolarPave product again exhibited a consistent cooling trend at both locations

(Mountain Star and SW 21st St.) with surface temperatures on average 3.6°F cooler. Lower surface temperatures were also observed at both Durashield sites (Carol Crest and Spiral Creek), but this reduction was less than 1°F and not statistically significant. The results for the PlusTi product were again mixed, as the Park Farm cool pavement was 3.6°F cooler than the control site while the Grant Ave. installation was 5.9°F warmer.

The surface temperature differences at night were less pronounced and similar to the results from the morning as most sites displayed differences within +/- 1°F. This suggests that the cooling influence of cool pavements may be limited primarily to the daytime. Two notable exceptions occurred as the Spiral Creek cool pavement was significantly warmer and the SW 21st St. cool pavement was significantly cooler.

Although comparing the averages across the sampling grid provided a robust measure to evaluate the typical surface temperature changes, point samples were also taken via the FLIR E4 to determine potential maximum surface temperature differences (**Figure 11**). At the Spiral Creek Durashield site, a 5°F reduction was observed between the cool pavement and fresh asphalt on Sparrow Creek. A similar 6°F reduction was noted at SW 21st St. The

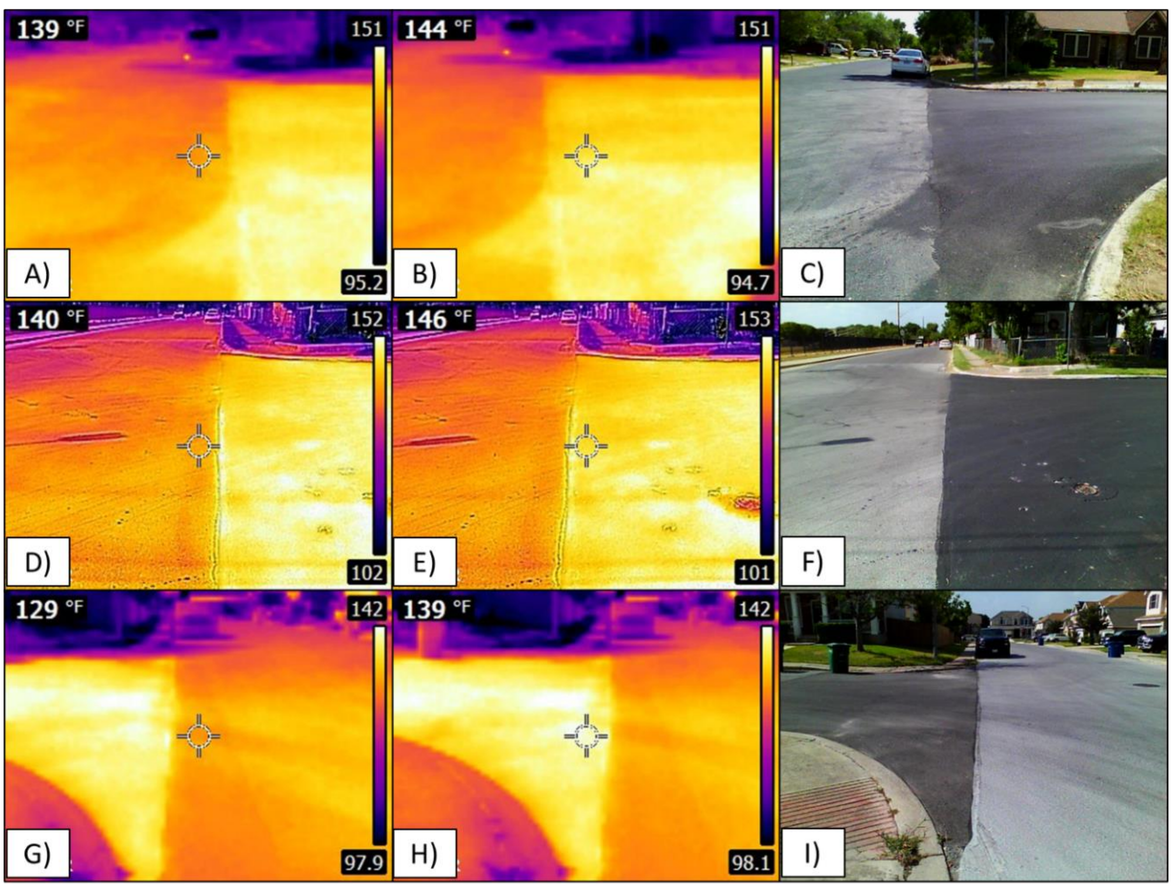

Figure 11. Surface temperature differences observed at Spiral Creek (A-C), SW 21st St. (D-F) and Mountain Star (G-I) during the afternoon sessions.

largest cooling influence occurred at Mountain Star, as the SolarPave product was 10°F cooler than a small portion of asphalt adjacent to the cool pavement. The PlusTi locations were not included in **Figure 11** because it was challenging to find clear seams for comparison since the product was largely invisible (**Figure 2c**).

The thermal imagery results highlighted the importance of the nature of the control surface. The statistics in **Table 6** were based on the control sites, which were typical neighborhood roads (i.e., not a freshly repaved surface) with similar surroundings. Since Sparrow Creek was repaved during the fieldwork, additional surface temperature measurements were gathered for the fresh asphalt on July 13th and 27th. The noon surface temperature average for the asphalt was 153.7°F while the afternoon average was 157.9°F. The Spiral Creek cool pavement surface temperature averages during the same two days and time periods were 135.5°F and 144.8°F, which was 18°F and 13°F cooler, respectively.

4.4 AIR TEMPERATURE DIFFERENCES

When considering all the sites and times collectively, the average difference in the mean air temperature between the cool pavement sites and control sites was 0.07°F (i.e., the cool pavement sites were marginally warmer). This suggests that the potential cooling influence of the cool pavements did not outweigh other environmental factors such as atmospheric mixing. The average difference in the mean air temperature was 0.24°F when only the noon and afternoon sessions were analyzed, again indicating that the cool pavement sites were marginally warmer. When combining the night and morning measurements, the mean air temperature difference was -0.11°F, which suggests that the cool pavement sites were slightly cooler. Given the accuracy of the Kestrel and the small magnitude of the differences, it is challenging to determine conclusively if there were notable overall differences in the air temperature between the cool pavement sites and control sites.

The analysis was disaggregated by day, time, and site to identify if any notable alterations in air temperature occurred for particular products during individual time periods. The results for the Durashield sites were mixed (**Figure 12**). In the morning, Carol Crest exhibited statistically significantly cooler air temperatures whereas the opposite occurred at Spiral Creek. It should be noted that statistical significance cannot necessarily be equated with the magnitude of the differences, since they were still modest (i.e., <0.5°F). The most notable difference during the noon sessions was observed at the Carol Crest cool pavement, which was 1.6°F warmer than the control during field session three. The most substantial reduction in air temperature occurred in the afternoon, as the Carol Crest cool pavement was 1°F cooler during field session one. This fluctuation between the Carol

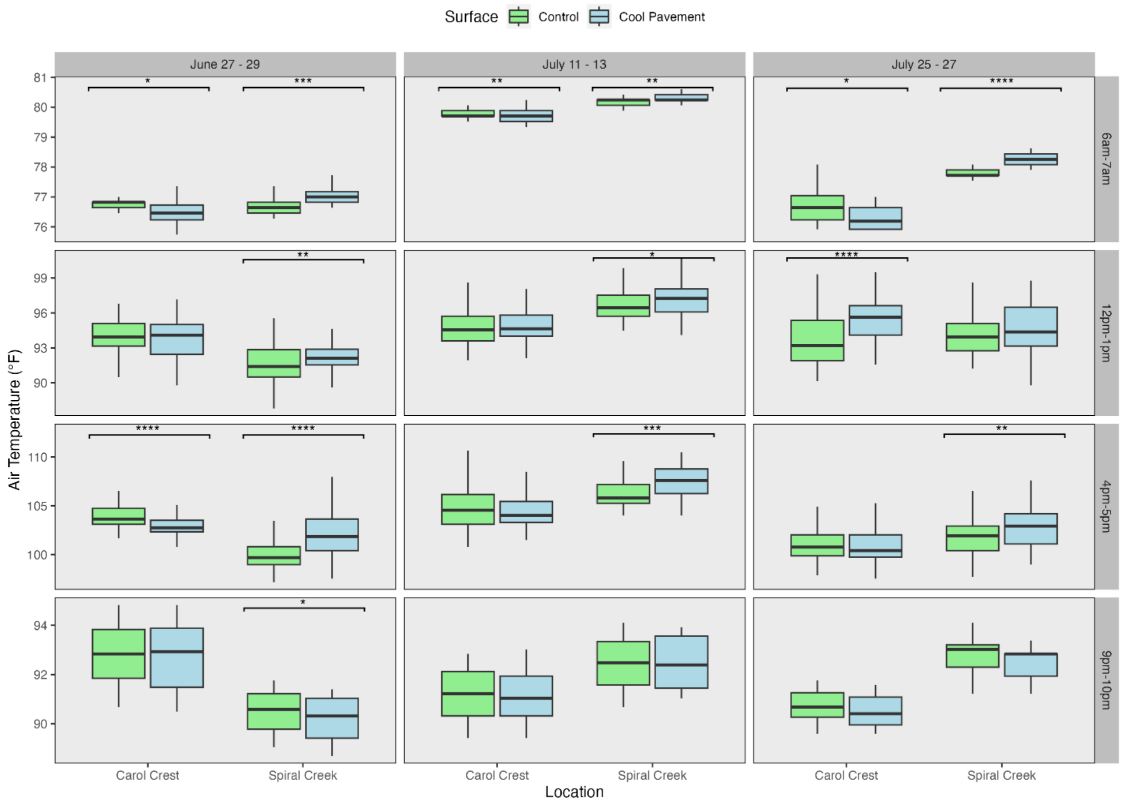

Figure 12. Air temperature differences for the Durashield sites by day and time. Level of statistical significance is indicated by the asterisks where: * p-value <= 0.05, ** p-value <= 0.01, *** p-value <= 0.001, and **** p-value <= 0.0001.

Crest cool pavement exhibiting warmer and cooler temperatures than the control site on different days may suggest that the cool pavement was not a primary driver of air temperature differences between the sites. A general lack of statistically significant differences in air temperature was observed at night for the Durashield sites.

The majority of the PlusTi samples exhibited statistically significant reductions in air temperature during the morning (**Figure 13**). This might be attributable to the PlusTi product focusing primarily on altering the emissivity of the surface rather than the albedo. Although the reductions were statistically significant, the average difference in the morning air temperature was 0.18°F. The largest air temperature contrast for the PlusTi product occurred at the Grant Ave. installation during the noon data collection period in mid-July, as the cool pavement site was 1.6°F warmer. This aligns with the notable surface temperature increases observed for the Grant Ave. cool pavement at midday. During the afternoon periods, the Park Farm cool pavement site displayed both significantly warmer and cooler air temperatures than the control. This lack of a robust and consistent signal potentially indicates that the influence of the cool pavement on air temperature was more of a secondary factor. The air temperature differences between the PlusTi cool pavement and control sites were similar in the evening with the exception of Park Farm in late July.

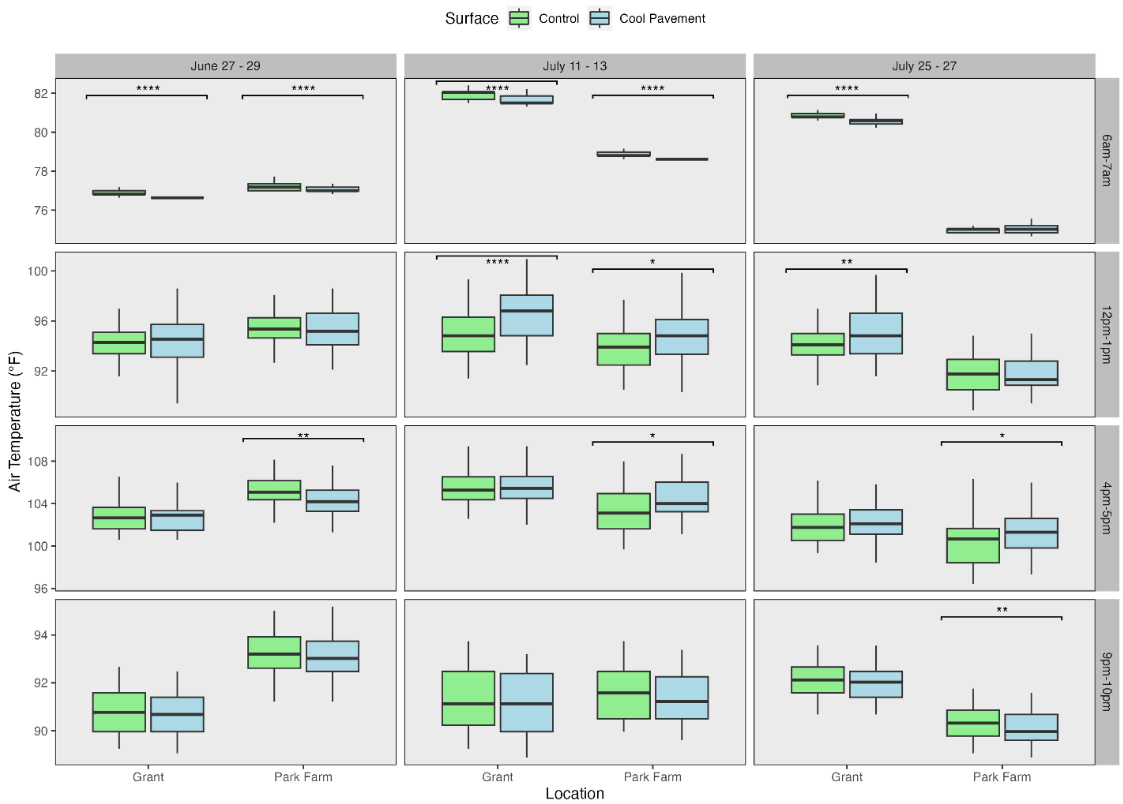

Figure 13. Air temperature differences for the PlusTi sites by day and time. Level of statistical significance is indicated by the asterisks where: * p-value <= 0.05, ** p-value <= 0.01, *** p-value <= 0.001, and **** p-value <= 0.0001.

Half of the SolarPave samples displayed statistically significant differences in air temperature during the morning, but the signal was mixed with the Mountain Star cool pavement exhibiting warmer temperatures and the SW 21st St. cool pavement registering lower temperatures (**Figure 14**). The magnitude of these statistically significant differences in the morning was also modest. No significant differences were observed during the noon to 1:00 pm sampling period for the SolarPave product. In the afternoon, the largest reduction in the average air temperature between any cool pavement and control site was observed at SW 21st St., as the cool pavement was 1.4°F cooler. On the other afternoon sampling days, the average air temperatures at the SW 21st St. cool pavement were 0.4°F and 0.6°F cooler. Although these differences were not statistically significant, it was one of the few sites that displayed a consistent cooling trend across each afternoon site visit. The SW 21st St. cool pavement also exhibited statistically significant cooling for two of the three night site visits. This aligned with the statistically significant reductions observed for surface temperature and might be attributable to the general openness of the site since it was bordered by a field. The magnitude of the average air temperature reduction at SW 21st St. across the three nights was 0.3°F.

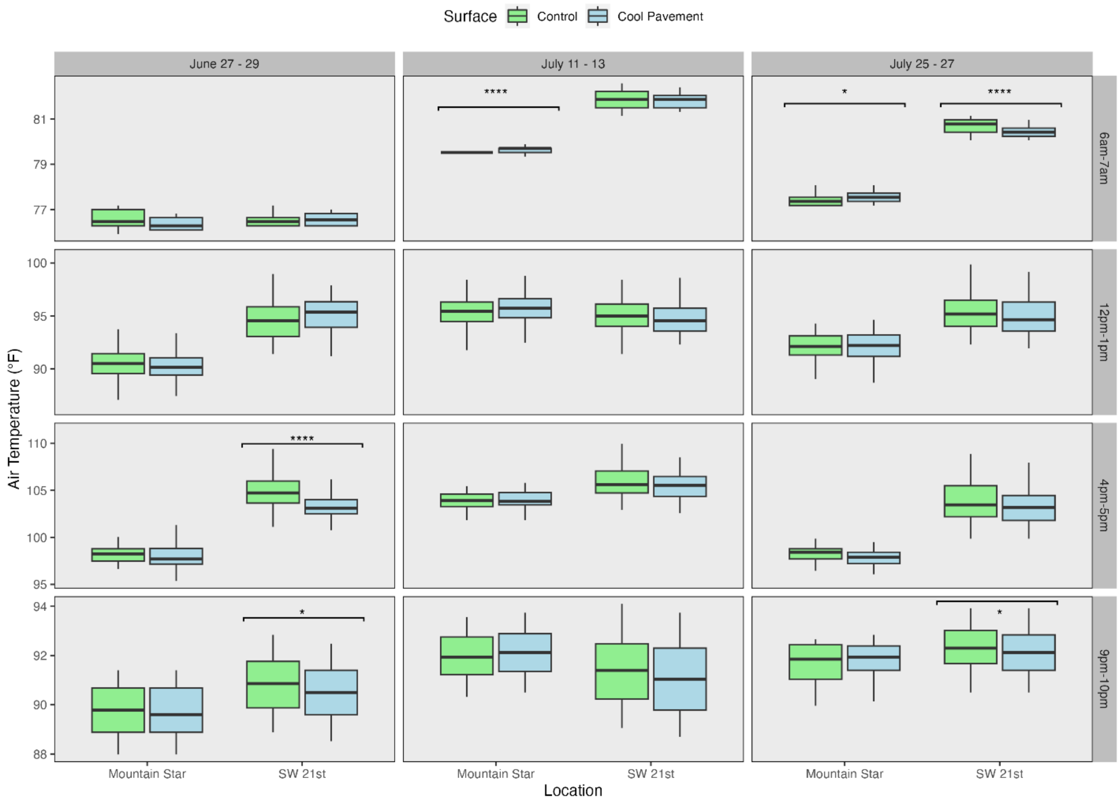

Figure 14. Air temperature differences for the SolarPave sites by day and time. Level of statistical significance is indicated by the asterisks where: * p-value <= 0.05, ** p-value <= 0.01, *** p-value <= 0.001, and **** p-value <= 0.0001.

4.5 WET BULB GLOBE TEMPERATURE DIFFERENCES

Since the WBGT is a measure of heat stress in direct sunlight, the daytime site visits at noon and 4:00 pm were the focus of this portion of the analysis. The average difference in the mean WBGT between the cool pavement and control sites during the daytime was -0.13°F (i.e., heat stress at the cool pavement sites was marginally lower). However, given the accuracy constraints of the Kestrel globe temperature, this small difference should be considered largely inconclusive.

The Durashield sites displayed mixed results for the WBGT during the daytime (**Figure 15**). For the noon sampling periods, statistically significant differences were observed in late July with higher WBGTs at the Carol Crest cool pavement and lower WBGTs at Spiral Creek. In the afternoon, the Spiral Creek cool pavement exhibited statistically significantly higher WGBTs for two of the three site visits.

For the PlusTi sites, no statistically significant differences were observed for the noon to 1:00 pm period (**Figure 16**). The Grant Ave. cool pavement displayed consistent reductions in WBGTs in the afternoon, with two of the three site visits producing statistically significant differences. This might be attributable to the PlusTi product focusing primarily

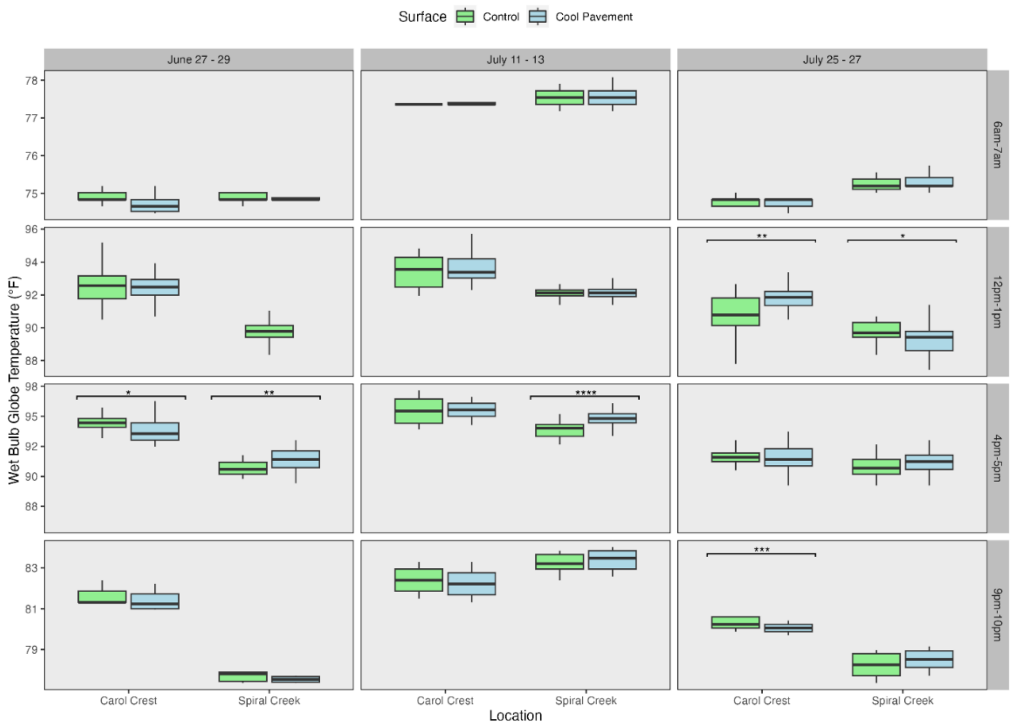

Figure 15. WBGT differences for the Durashield sites by day and time. Level of statistical significance is indicated by the asterisks where: * p-value <= 0.05, ** p-value <= 0.01, *** p-value <= 0.001, and **** p-value <= 0.0001. The Kestrel malfunctioned at the Spiral Creek cool pavement in June, so it is omitted.

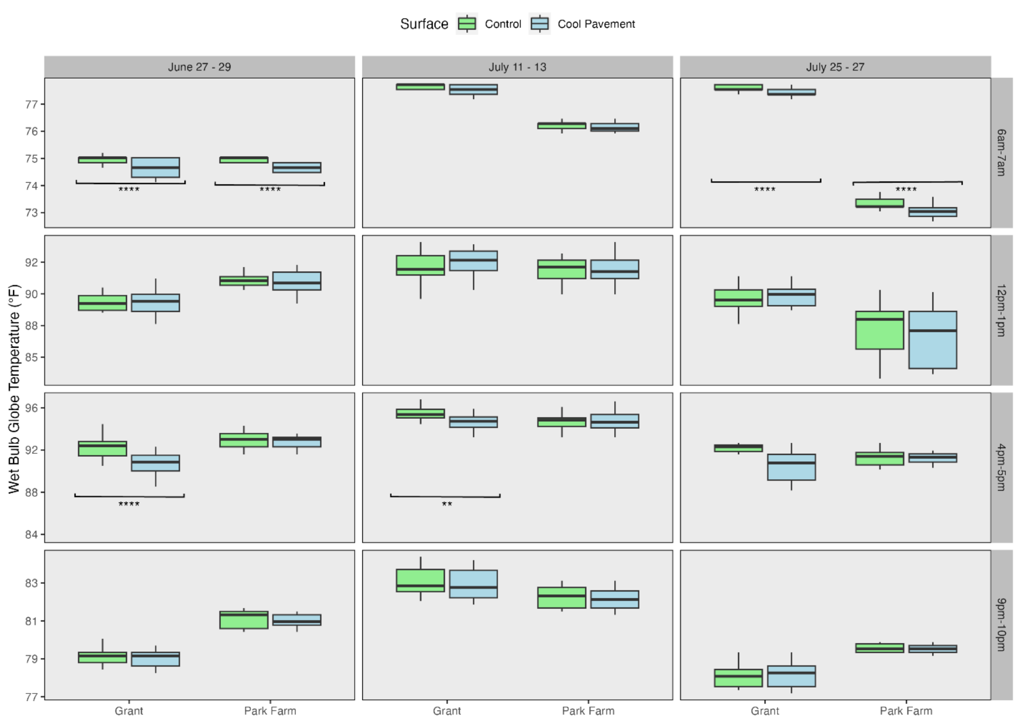

Figure 16. WBGT differences for the PlusTi sites by day and time. Level of statistical significance is indicated by the asterisks where: * p-value <= 0.05, ** p-value <= 0.01, *** p-value <= 0.001, and **** p-value <= 0.0001.

on emissivity alterations rather than albedo, but it may have also been influenced by the relatively newer and darker nature of the cool pavement road surface relative to the control. The average reduction in the mean WBGT at the Grant Ave. cool pavement in the afternoon was 1.2°F.

Only two statistically significant differences in the WBGT were observed for the SolarPave sites (**Figure 17**). Both occurred in June during the afternoon sampling period, as the WBGTs at Mountain Star and SW 21st St. were significantly lower for the cool pavement. Specifically, the 3.3°F reduction in the WBGT at SW 21st St. was the largest WBGT decrease observed for any cool pavement site. This seems to suggest that any increase in heat stress due to additional incident solar radiation because of the higher albedo of the cool pavement surface was more than offset by the decrease in the air temperature that day.

Figure 17. WBGT differences for the SolarPave sites by day and time. Level of statistical significance is indicated by the asterisks where: * p-value <= 0.05, ** p-value <= 0.01, *** p-value <= 0.001, and **** p-value <= 0.0001.

4.6 ALBEDO DIFFERENCES

The albedo measurements, which evaluated the reflectivity of the surfaces, revealed several differences between the various products (**Table 7**). The SolarPave material displayed the largest increase (0.06) in albedo relative to the control. The cool pavement at Mountain Star reflected 28% of the shortwave radiation whereas the control street reflected only 22%. The Durashield product increased the albedo by 0.02. Contrastingly, the PlusTi product was associated with a lower albedo than the control site. The cool pavement at Grant Ave. reflected 14% of the shortwave radiation while the control street reflected 21%. This is potentially due to the PlusTi product focusing primarily on altering the emissivity of the surface rather than the albedo. Additionally, since the material is a penetrate rather than a coating, the difference might also be partly attributable to the differing road surfaces.

The control sites generally exhibited high albedo values. For example, the albedo for fresh asphalt typically ranges between 0.06 and 0.08.[5] This suggests that due to wear and tear as well as exposure to the natural elements typical streets in San Antonio may often have albedo values that are more analogous to cool pavement surfaces than fresh asphalt.

Table 7. Average albedo for each site calculated using the hourly averages of the incoming and outgoing shortwave radiation fluxes between noon and 4:00 pm.

	Carol Crest (Durashield)	Grant Ave. (PlusTi)	Mountain Star (SolarPave)
Cool Pavement	0.18	0.14	0.28
Control	0.16	0.21	0.22

4.7 RADIATION BUDGET DIFFERENCES

The results for the individual components of the net radiation budget aligned with the surface temperature and albedo measurements. At Carol Crest, the incoming shortwave radiation was very similar on August 17th when the cool pavement was evaluated and August 18th when data was collected at the control (**Figure 18**). This suggests that the days were comparable, which was also supported by the data from the KSAT ASOS. The outgoing shortwave radiation was greater (173.0 W/m^2 vs. 162.5 W/m^2) at the cool pavement site during the afternoon due to its higher albedo. The outgoing longwave flux was marginally higher for the cool pavement site (692.4 W/m^2) relative to the control (689.7 W/m^2). Modest differences were also observed for the overall net radiation budget, which suggests that the Durashield product had a minimal impact on the radiation fluxes.

The incoming shortwave radiation at Grant Ave. differed slightly between the two study days (**Figure 19**). Additional clouds likely reduced the incoming shortwave radiation in the afternoon when the control site was evaluated. Despite the higher incoming shortwave flux, outgoing shortwave radiation at the cool pavement was much lower in the afternoon (132.0 W/m^2 vs. 187.5 W/m^2). This was expected given the low albedo of Grant Ave., which was related to the PlusTi product focusing primarily on emissivity alterations. The outgoing longwave radiation was greater for the cool pavement. It is challenging to untangle if this increase was primarily due to emissivity alterations by the product or the surface being hotter since direct measurements of emissivity were not collected.

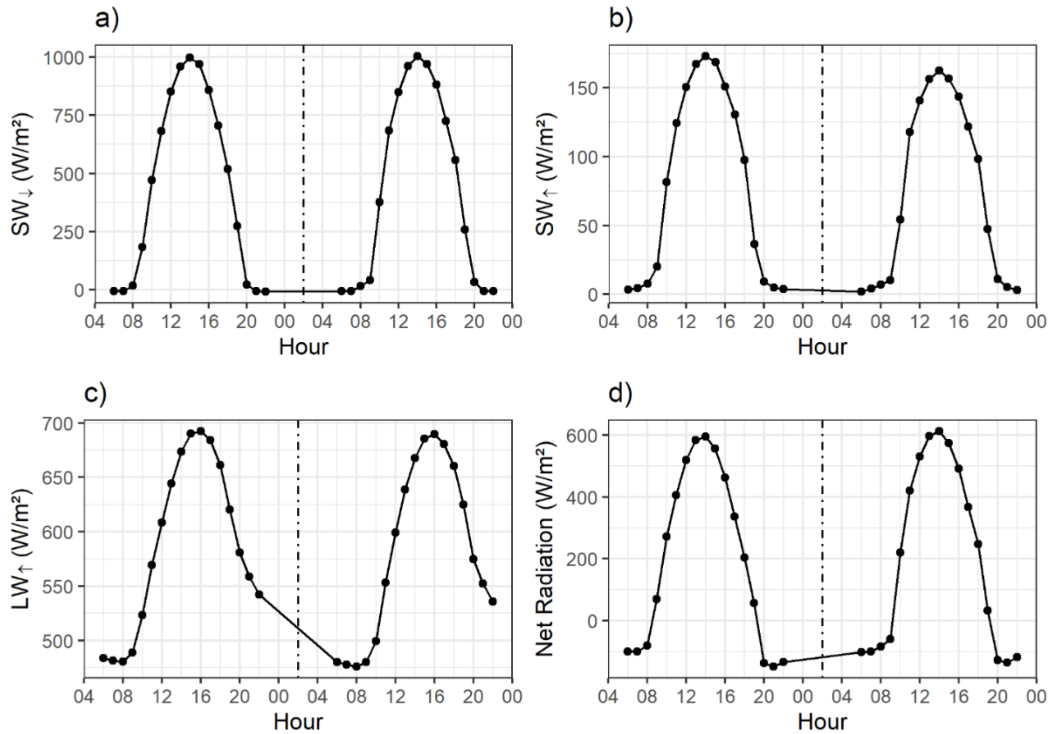

Figure 18. The a) shortwave incoming, b) shortwave outgoing, c) longwave outgoing, and d) net radiation budget at Carol Crest for August 17th and August 18th from the cool pavement site (left of dotted line) and control site (right of dotted line).

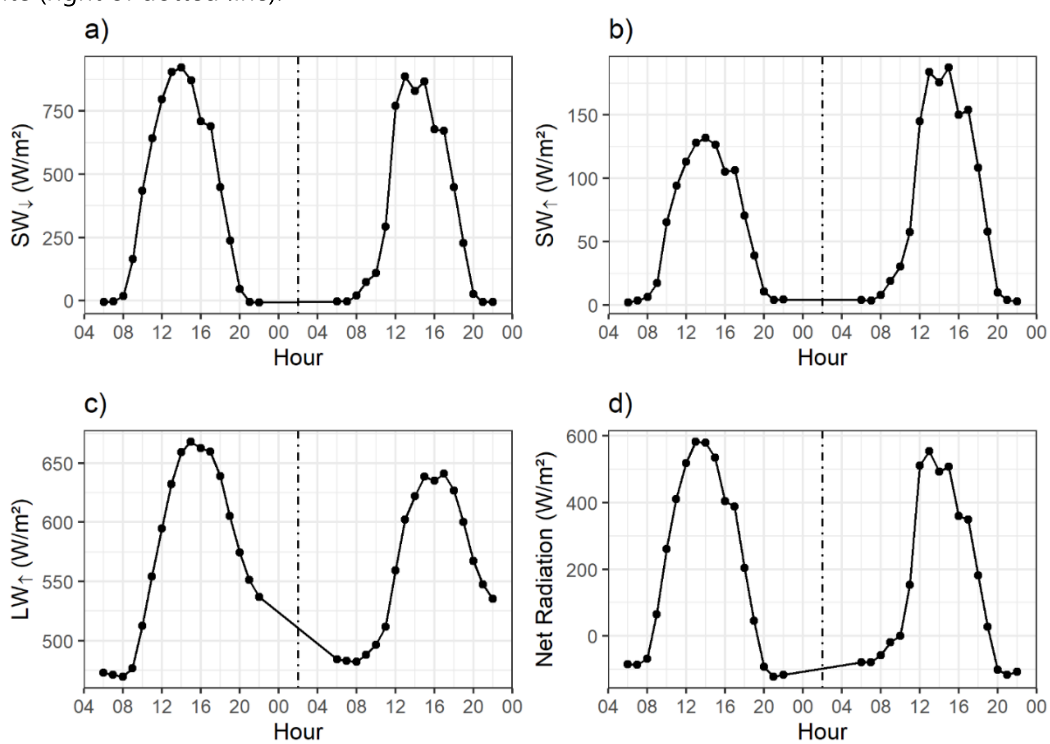

Figure 19. The a) shortwave incoming, b) shortwave outgoing, c) longwave outgoing, and d) net radiation budget at Grant Ave. for August 24th and August 25th from the cool pavement site (left of dotted line) and control site (right of dotted line).

The incoming shortwave radiation at Mountain Star displayed differences between the two study days that were similar to Grant Ave. Scattered clouds on September 1st resulted in a slight reduction in the incoming shortwave radiation at the control site (**Figure 20**). The outgoing shortwave radiation was more pronounced at the cool pavement site (260.9 W/m^2 vs. 207.3 W/m^2) due to its high reflectivity. Additionally, the outgoing longwave radiation at the cool pavement was marginally lower (627.3 W/m^2 vs. 629.8 W/m^2), which was likely attributable to the cooler surface temperatures observed at Mountain Star.

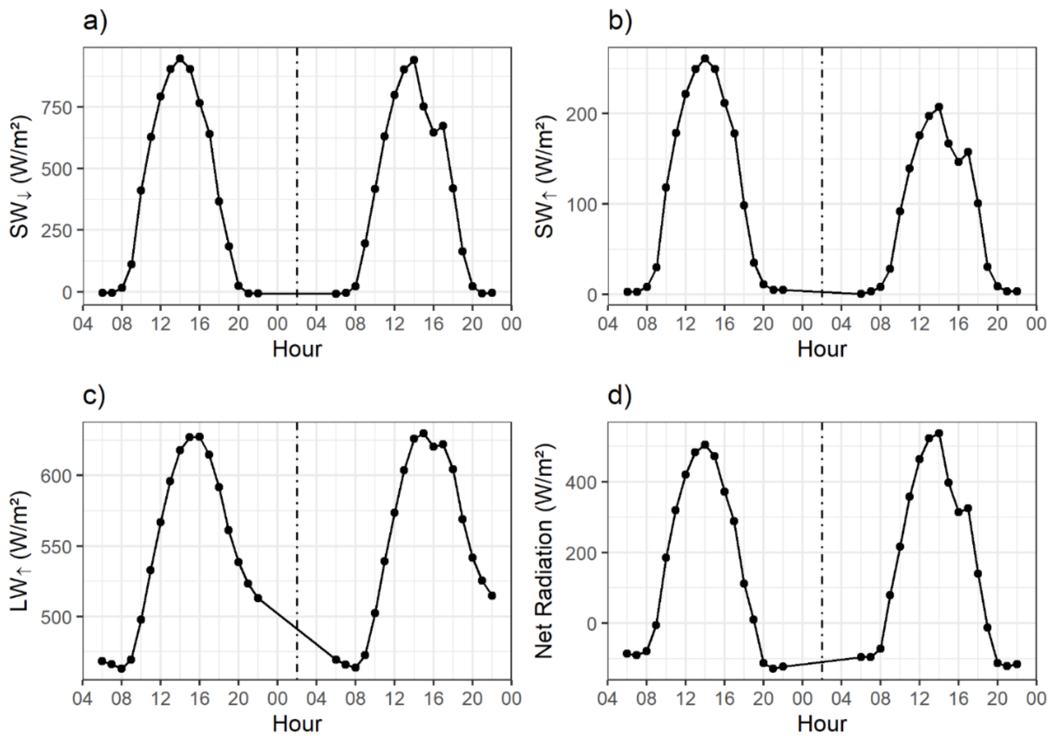

Figure 20. The a) shortwave incoming, b) shortwave outgoing, c) longwave outgoing, and d) net radiation budget at Mountain Star for August 31st and September 1st from the cool pavement site (left of dotted line) and control site (right of dotted line).

5. DISCUSSION AND CONCLUSIONS

Overall, the findings highlighted a clear potential for cool pavement to reduce surface temperatures. This was particularly true for the SolarPave product, which displayed consistent reductions in surface temperatures during the daytime at both sites. The results for the other temperature metrics (i.e., air temperature and WBGT) were more inconclusive in nature due to the small magnitude of the differences between the cool pavement and control sites as well as the accuracy of the instruments used during the fieldwork. Studies focused on cool pavement installations in Phoenix[4] and Los Angeles[5] have reached similar conclusions. It appears that cool pavement may not be a "silver bullet" solution for mitigating urban heat, but it can perhaps be used effectively in certain locations (e.g., places where shade-based approaches are not feasible), particularly if reducing surface temperatures is the main goal. There are also other potential benefits associated with cool pavement that were not within the scope of this study, such as increased road durability and improved air quality, which should be considered when deciding if/where to install cool pavement.

The findings from the summer pilot also raised additional questions that likely warrant additional investigation, such as:

1. **Is the modest impact of cool pavement on air temperature a matter of scale?** The cool pavement installations included in the pilot ranged from one to four residential blocks on individual roads. Given the potential for atmospheric mixing due to winds and other confounding environmental factors, the installations were perhaps too small and isolated to produce a meaningful reduction in air temperature. Evaluating larger installations (e.g., entire subdivisions, entire parking lots, multiple adjacent subdivisions, etc.) could potentially provide insights regarding if cool pavement is more effective when deployed over larger areas. It should be noted that the Phoenix pilot did incorporate larger cool pavement installations than those analyzed in this study but still found a negligible impact on air temperature.

2. **What is the most appropriate control surface against which cool pavement performance should be evaluated?** The surface temperature results highlighted the importance of considering the specific character of the control surface. Reductions in surface temperature were identified when comparing the cool pavement against a representative street in the neighborhood, but these surface temperature reductions were more notable when fresh asphalt was used as the baseline. Due to wear and weathering, the control streets exhibited a relatively high albedo. Therefore, replacing a typical worn street surface with a cool pavement surface may

only produce a modest cooling influence and have a negligible impact in terms of reducing the broader urban heat island effect. One approach that could better evaluate the effective cooling impact of cool pavement would be to install the cool pavement material during a period of stable atmospheric conditions and collect measurements immediately before and after the installation.

3. **Would a more controlled testing environment be informative?** Although it is important to evaluate cool pavement performance in different portions of the city, this increased the amount of confounding factors and complicated comparisons between the sites and the different products. Exploring side-by-side installations of different products would help more accurately evaluate differences between various cool pavement materials.

4. **What is the long-term durability of cool pavement?** Although this study included 15 days of fieldwork, it was based on one individual summer immediately following the installations. Continued monitoring over time will be important to provide a more comprehensive evaluation of cool pavement performance. For example, the light-colored cool pavement surfaces could become dirty overtime, which would likely result in gradual reductions in the albedo. Monitoring this deterioration and devising a comprehensive upkeep plan would help maximize cool pavement performance. A formal durability assessment was beyond the scope of this study, but issues with cracking and peeling of the SolarPave product were observed throughout the summer fieldwork.

5. **What is the emissivity of cool pavement materials?** Since the PlusTi product is designed to primarily alter emissivity, rather than albedo, directly measuring emissivity values in the field would help evaluate its performance. Observing the emissivity would also enable the SRI to be calculated for each cool pavement material and compared with the factory specifications.

6. **Does street orientation matter for cool pavement installations?** The majority of the streets included in the pilot had a predominantly north-south orientation. The orientation of the road has implications for the level of shadowing over the road surface. Evaluating cool pavement performance on east-west roads would help determine if road orientation influences the degree of cooling. Additionally, formally evaluating cool pavement performance in shade will be important to understanding if cool pavement should be combined with other heat mitigation measures such as street trees.

7. **How does the GuardTop product compare to the materials evaluated in this study?** Unfortunately, the GuardTop product was not incorporated in the study due to initial installation issues. It would be informative to evaluate its performance relative to the SolarPave, PlusTi, and Durashield products. The various cool pavement materials evaluated in this study were quite diverse and performed differently. It is important to recognize the internal diversity of cool pavement products and test new materials accordingly.

8. **Would constructing a mesonet help San Antonio monitor its climate adaptation progress?** In meteorology, a mesonet is a dense network of meteorological sensors designed to monitor mesoscale (down to ~1.5 miles) atmospheric phenomena. Building a fine scaled mesonet would enable detailed monitoring of the atmospheric conditions throughout the city, including the urban heat island effect. The mesonet could help monitor the broader cooling impacts of heat mitigation measures that are implemented as part of San Antonio's Climate Action and Adaptation Plan. This could be particularly useful as projects expand beyond initial pilots and become broader in spatial scope. The mesonet would also enable the real-time monitoring of temperature extremes (e.g., which specific portions of the city are hottest during heat waves).

Ultimately, a multifaceted approach that combines innovative technologies with nature-based solutions will likely be necessary to mitigate the negative impacts of the urban heat island effect because of its scale and dynamic nature. Cool pavement could be one part of this solution, but it should not be the only approach pursued given the growing body of work highlighting its modest impacts on air temperature. The San Antonio cool pavement pilot is one important step towards establishing a holistic urban heat mitigation approach, which will be necessary to ensure the future livability and economic vitality of San Antonio.

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APPENDIX A: SITE MAPS OF COOL PAVEMENT AND CONTROL PLOTS

Figure A1. Location of the Carol Crest cool pavement installation as well as the cool pavement testing site and control testing site.

Figure A2. Location of the Grant Ave. cool pavement installation as well as the cool pavement testing site and control testing site.

Figure A3. Location of the Mountain Star cool pavement installation as well as the cool pavement testing site and control testing site.

Figure A4. Location of the Park Farm cool pavement installation as well as the cool pavement testing site and control testing site.

Figure A5. Location of the Spiral Creek cool pavement installation as well as the cool pavement testing site and control testing site.

Figure A6. Location of the SW 21st St. cool pavement installation as well as the cool pavement testing site and control testing site.

APPENDIX B: FIELDWORK SCHEMATICS

Figure B1. Fieldwork data collection schematic for the Carol Crest cool pavement site showing the surface temperature grid and Kestrel location during Phase I and the net radiometer location during Phase II (Imagery Source: Google Maps).

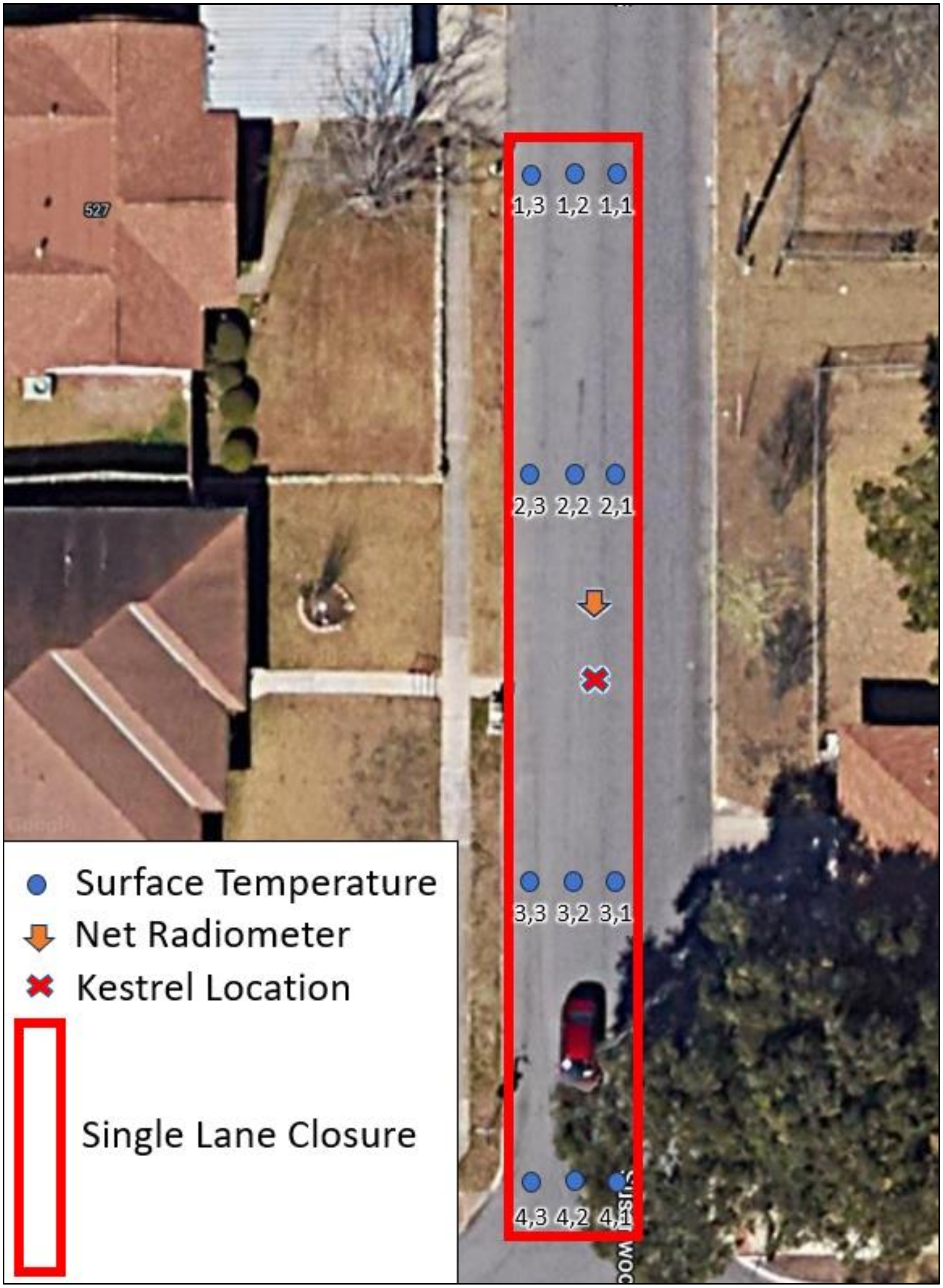

Figure B2. Fieldwork data collection schematic for the Carol Crest control site showing the surface temperature grid and Kestrel location during Phase I and the net radiometer location during Phase II (Imagery Source: Google Maps).

Figure B3. Fieldwork data collection schematic for the Grant Ave. cool pavement site showing the surface temperature grid and Kestrel location during Phase I and the net radiometer location during Phase II (Imagery Source: Google Maps).

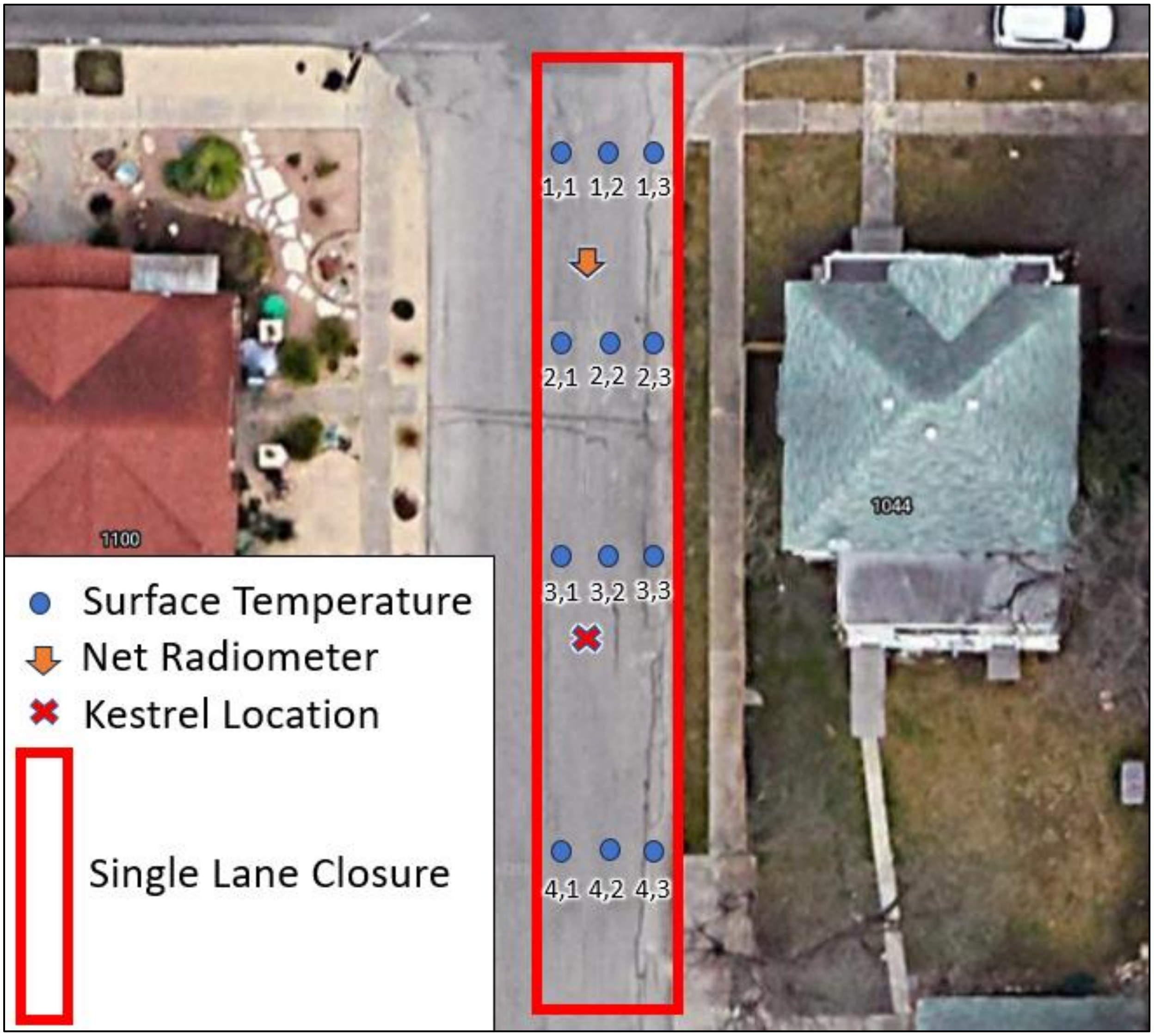

Figure B4. Fieldwork data collection schematic for the Grant Ave. control site showing the surface temperature grid and Kestrel location during Phase I and the net radiometer location during Phase II (Imagery Source: Google Maps).

Figure B5. Fieldwork data collection schematic for the Mountain Star cool pavement site showing the surface temperature grid and Kestrel location during Phase I and the net radiometer location during Phase II (Imagery Source: Google Maps).

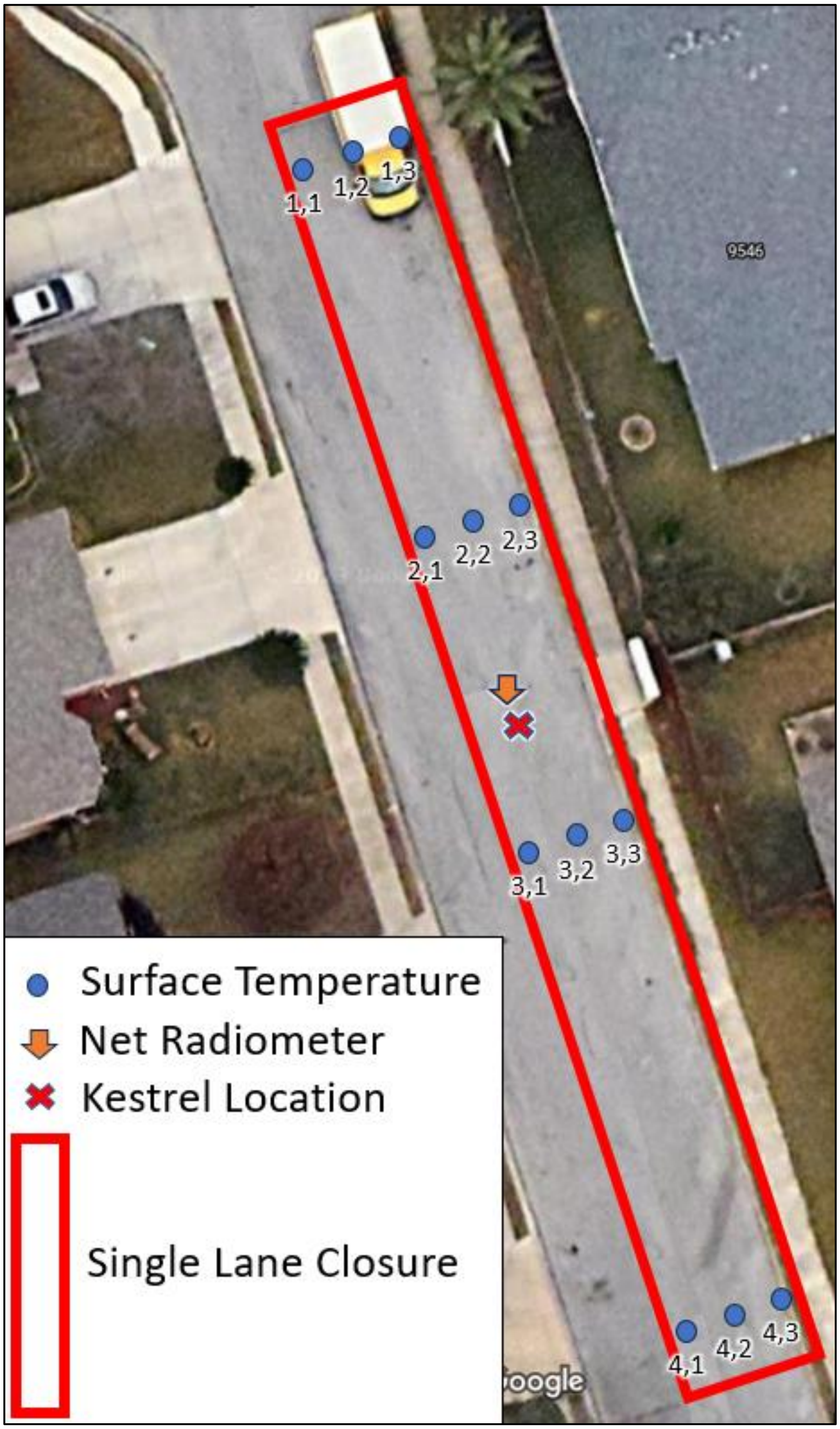

Figure B6. Fieldwork data collection schematic for the Mountain Star control site showing the surface temperature grid and Kestrel location during Phase I and the net radiometer location during Phase II (Imagery Source: Google Maps).

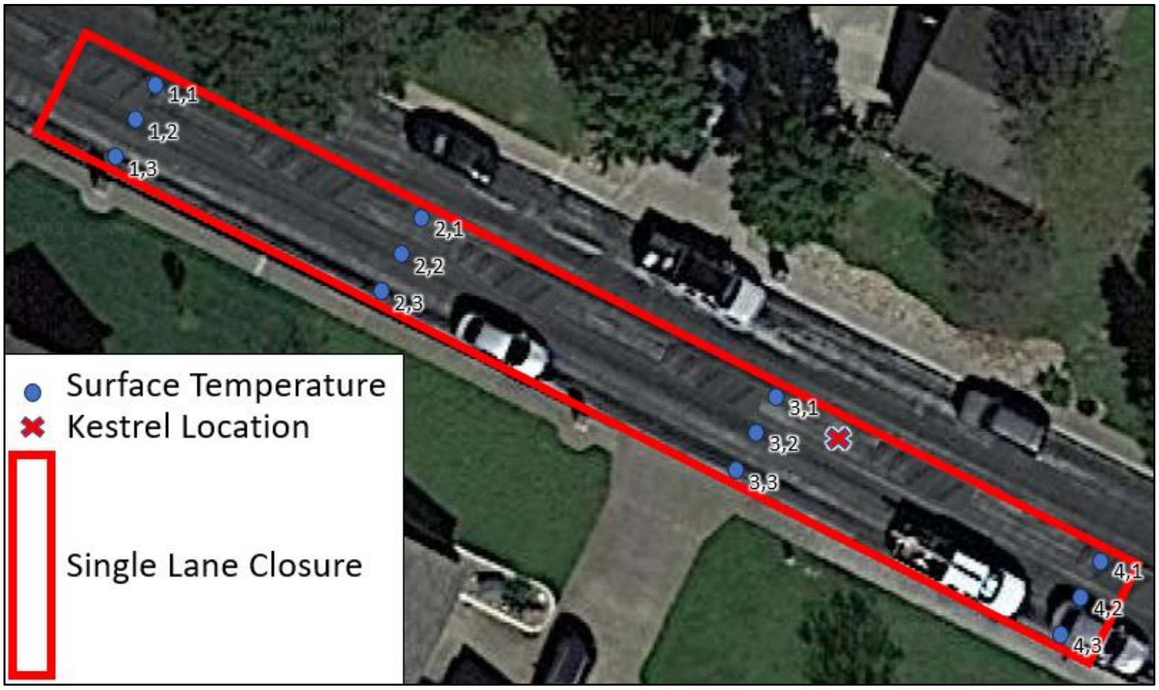

Figure B7. Fieldwork data collection schematic for the Park Farm cool pavement site showing the surface temperature grid and Kestrel location during Phase I (Imagery Source: Google Maps).

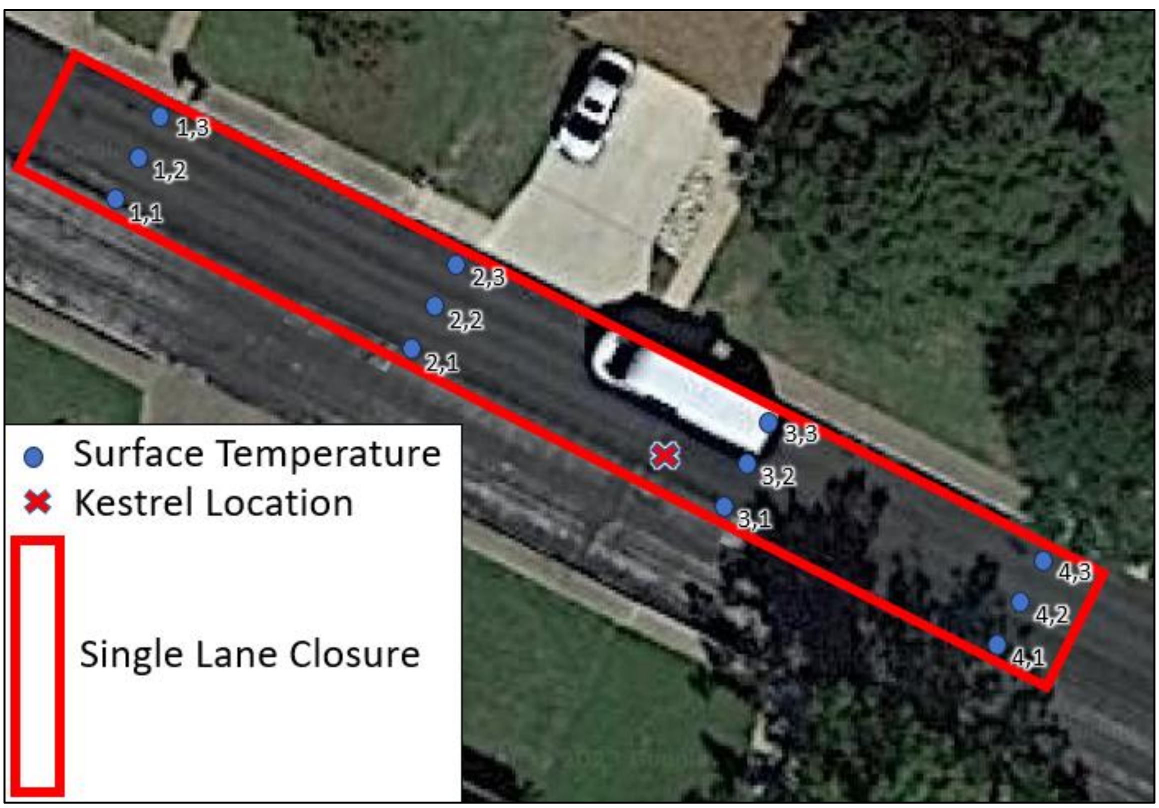

Figure B8. Fieldwork data collection schematic for the Park Farm control site showing the surface temperature grid and Kestrel location during Phase I (Imagery Source: Google Maps).

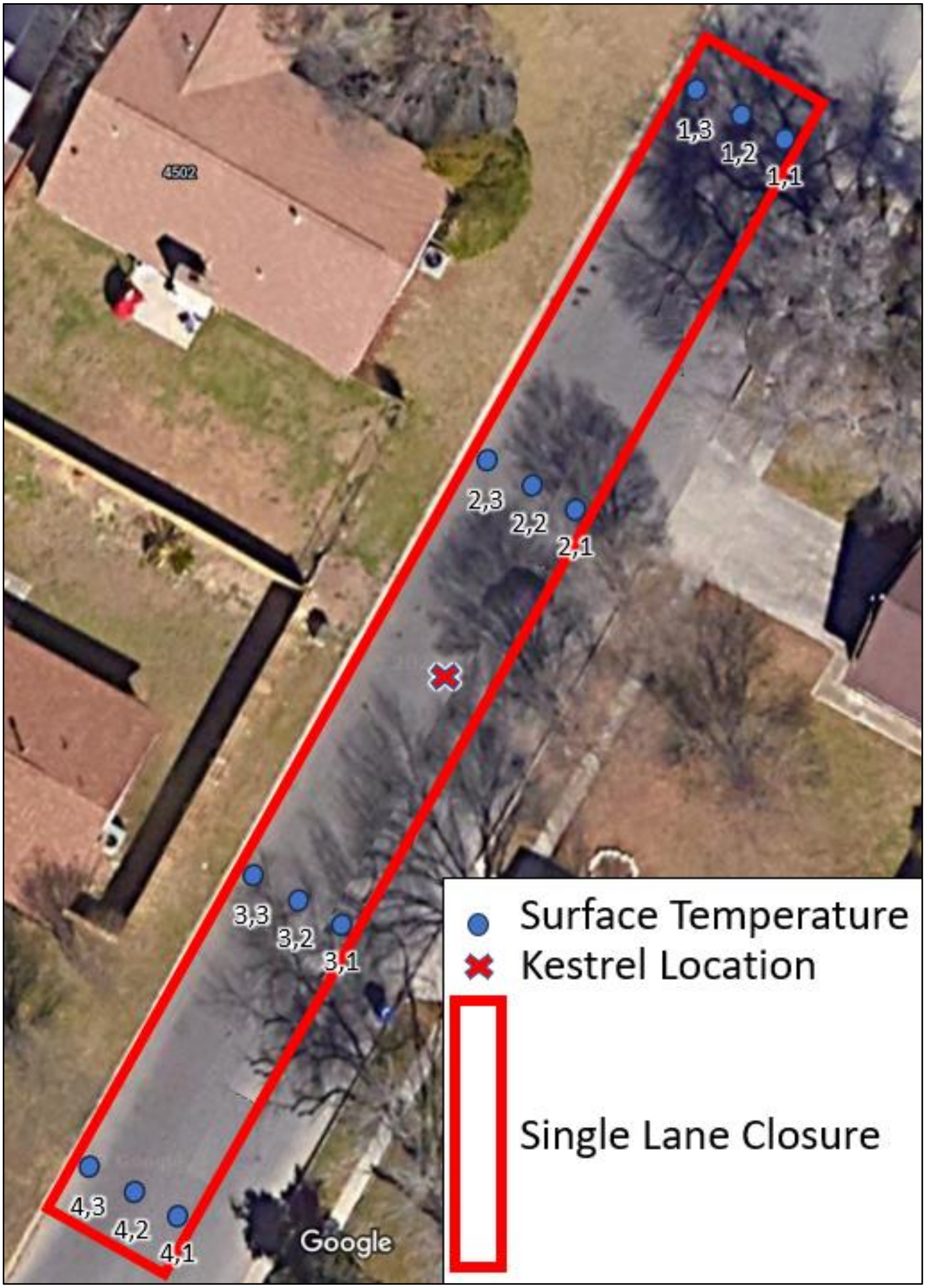

Figure B9. Fieldwork data collection schematic for the Spiral Creek cool pavement site showing the surface temperature grid and Kestrel location during Phase I (Imagery Source: Google Maps).

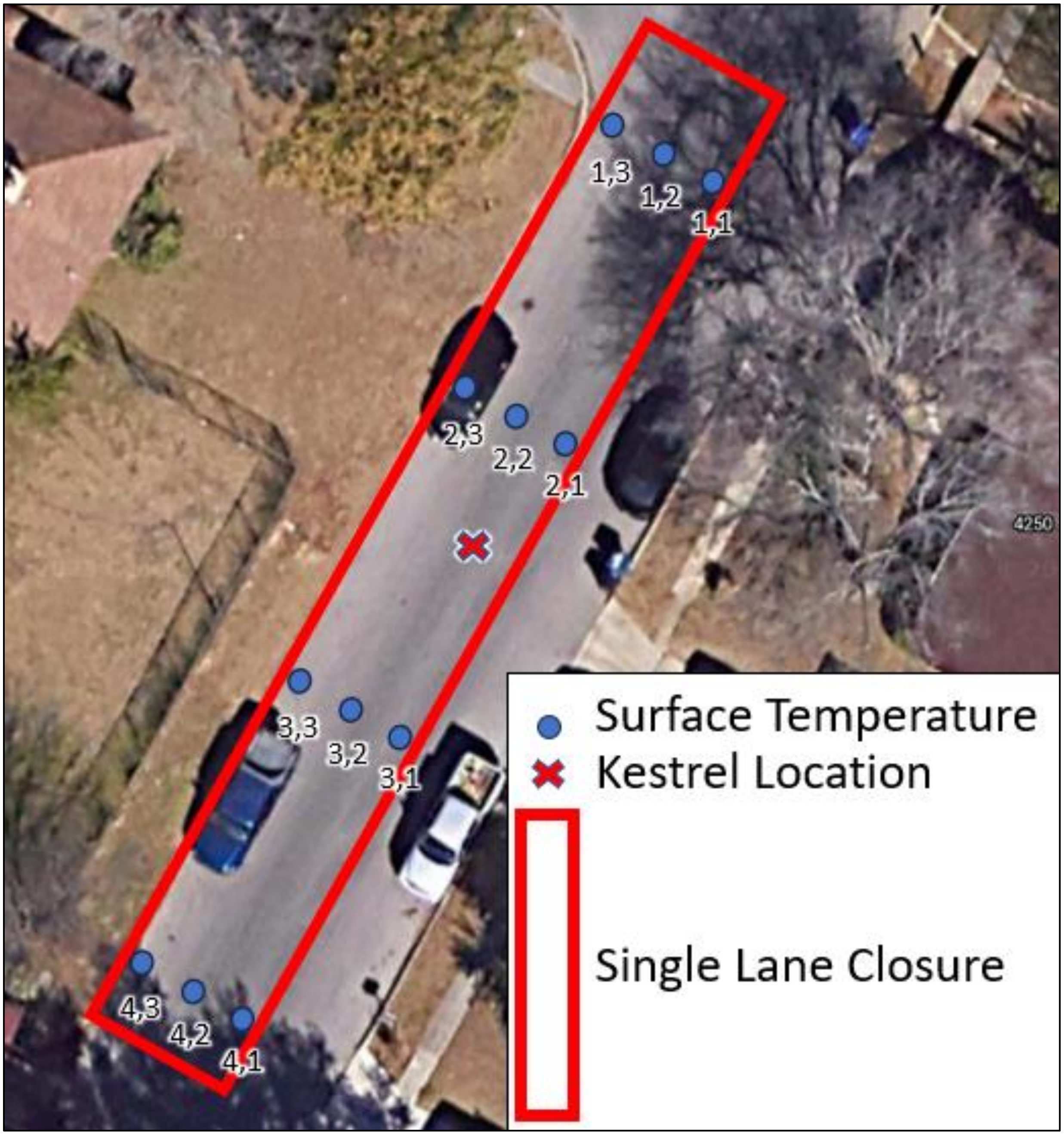

Figure B10. Fieldwork data collection schematic for the Spiral Creek control site showing the surface temperature grid and Kestrel location during Phase I.

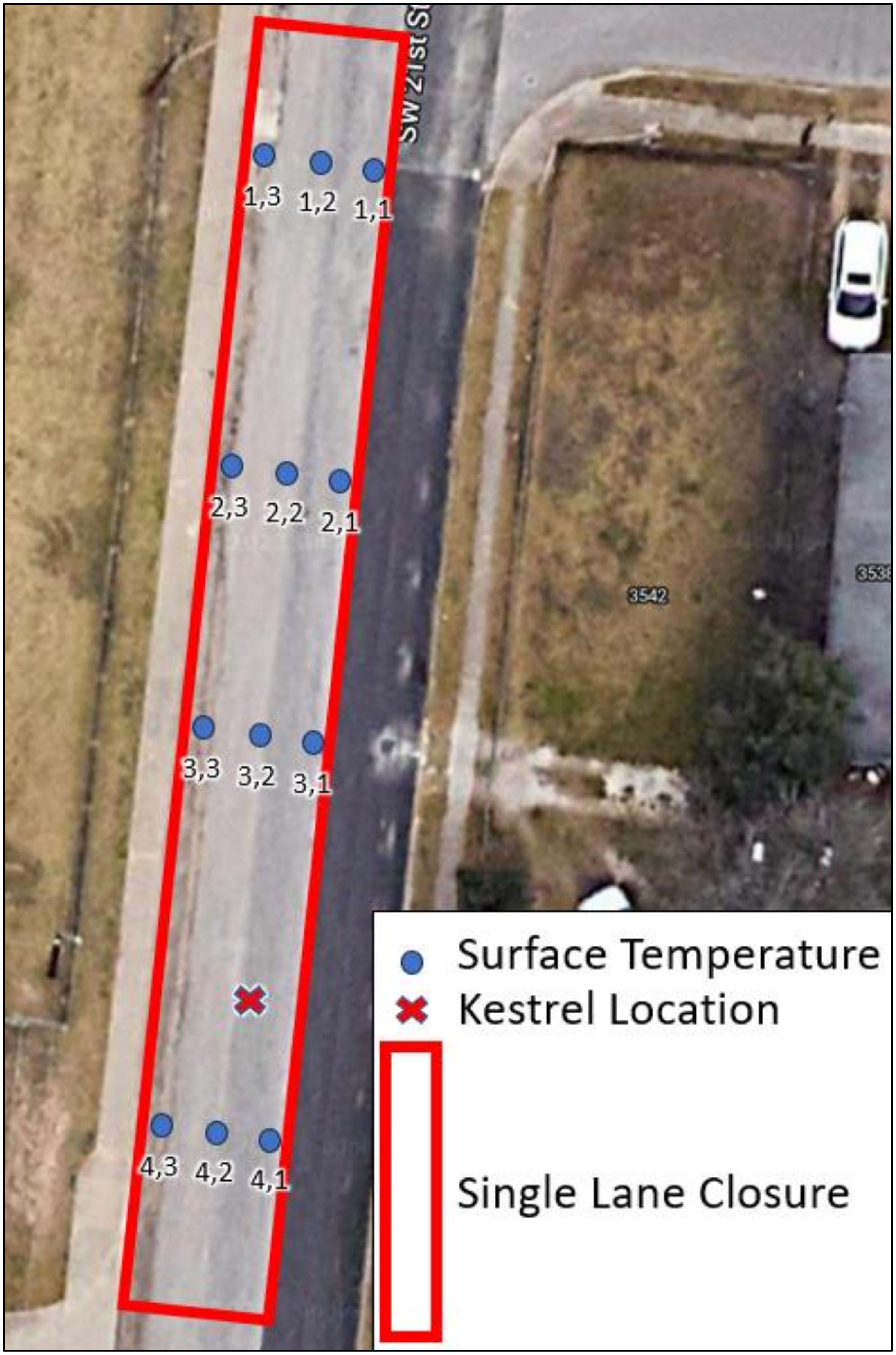

Figure B11. Fieldwork data collection schematic for the SW 21st St. cool pavement site showing the surface temperature grid and Kestrel location during Phase I (Imagery Source: Google Maps).

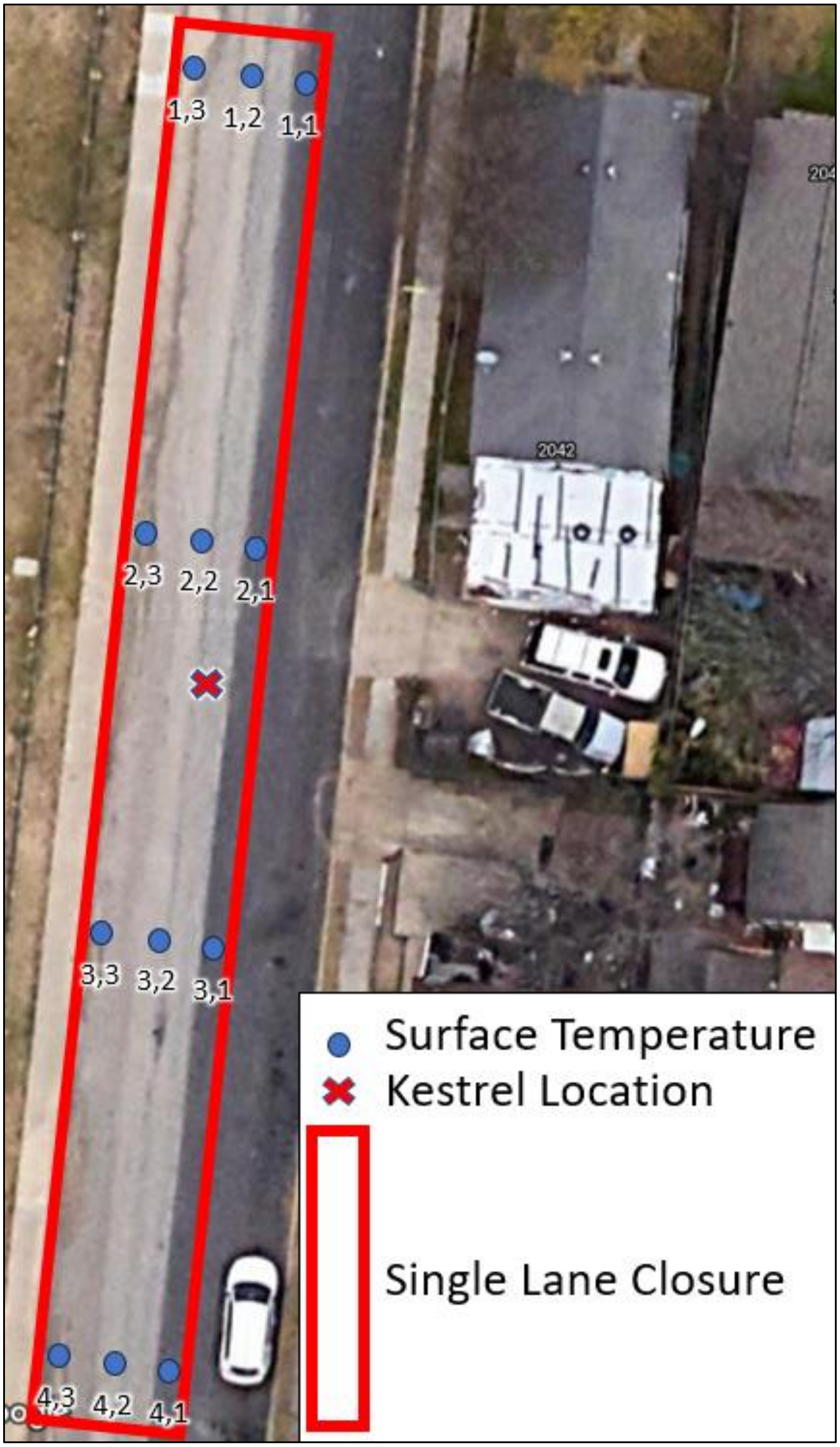

Figure B12. Fieldwork data collection schematic for the SW 21st St. control site showing the surface temperature grid and Kestrel location during Phase I (Imagery Source: Google Maps).

APPENDIX C: CHARACTERISTICS OF COOL PAVEMENT SURROUNDINGS

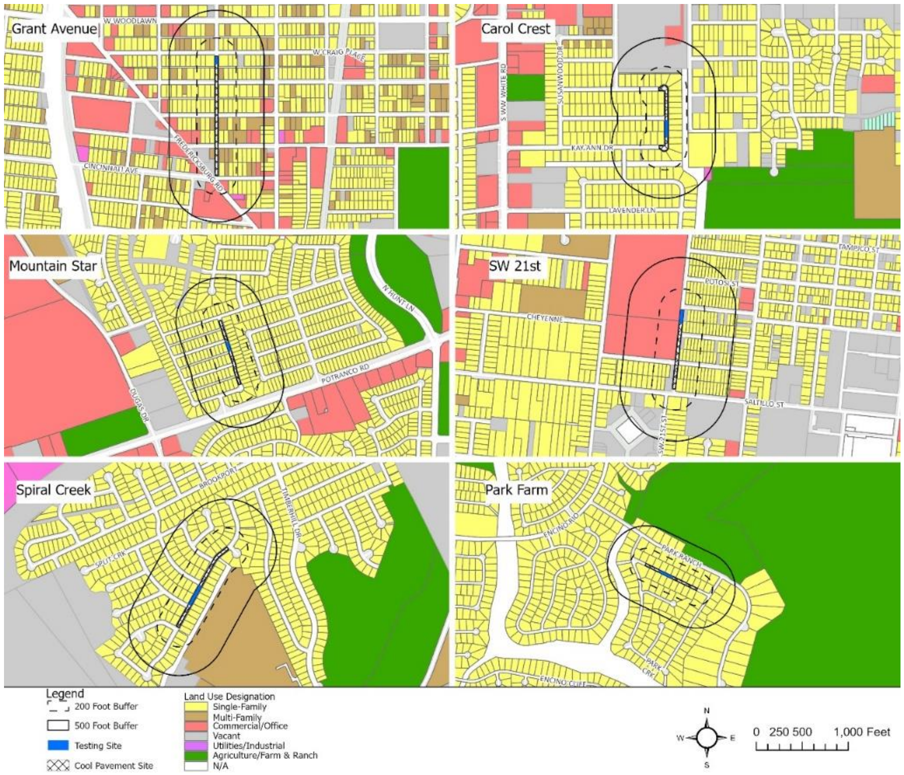

Figure C1. Land use surrounding each cool pavement installation.

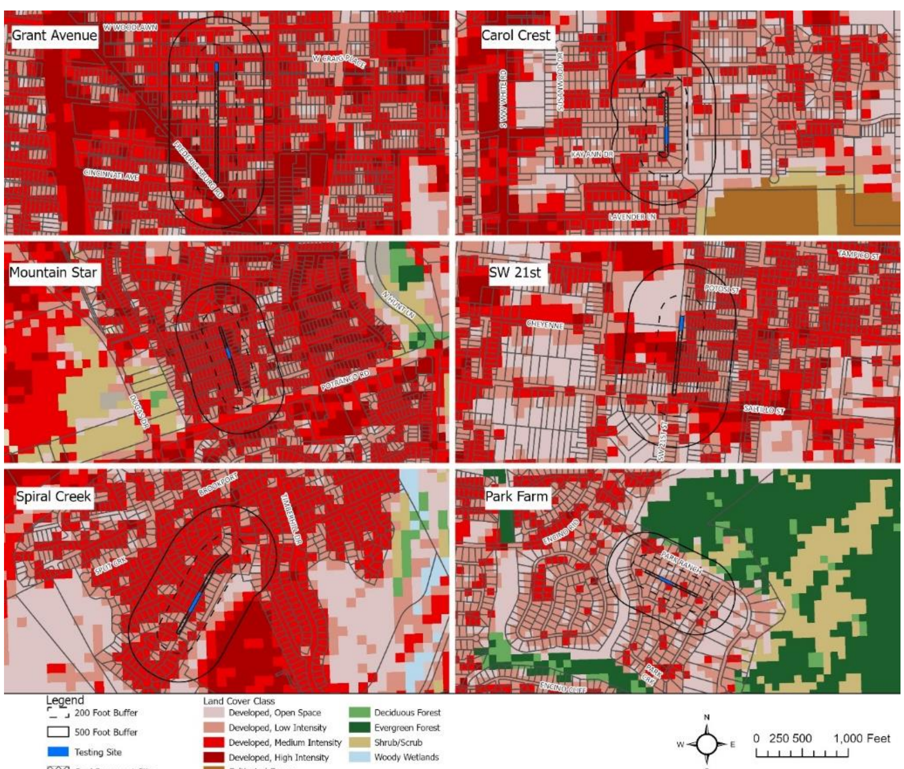

Figure C2. Land cover surrounding each cool pavement installation.

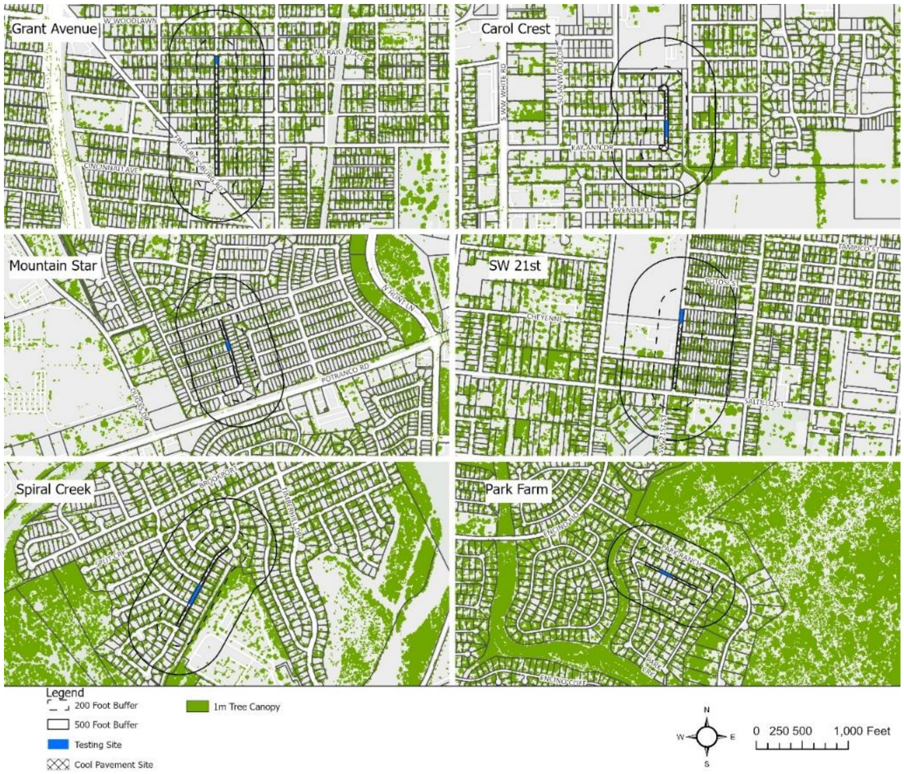

Figure C3. Tree canopy surrounding each cool pavement installation.

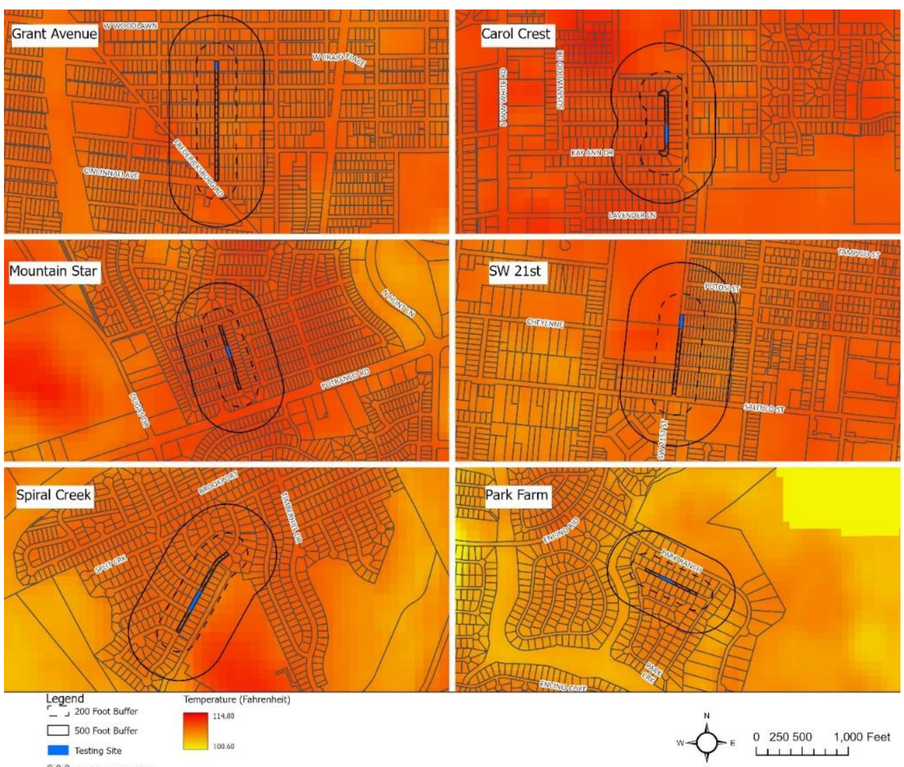

Figure C4. Surface temperature surrounding each cool pavement installation.