CONTINUED EVALUATION OF COOL PAVEMENT AS AN URBAN HEAT MITIGATION MEASURE

Neil Debbage, Wei Zhai, Esteban López Ochoa, Ryun Jung Lee, Haoming Qin, Huang Huanchun, Elliott Coleman, Dana Griggs, Katie Mainez & Matt Kenney

UTSA

Final Report
Submitted to the City of San Antonio Office of Sustainability
May 2025

EXECUTIVE SUMMARY

Extreme heat is one of the most pressing weather 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, began a cool pavement pilot program in collaboration with the University of Texas at San Antonio in 2023. The findings from the 2023 summer fieldwork are available in the first report. To continue monitoring the performance of the cool pavement over time and evaluate an additional cool pavement product, data was collected again in the summer of 2024. This report focuses on the findings from the 2024 field campaign and offers comparisons with the results from 2023.

Drone photograph looking northeast at the SolarPave (SealMaster) cool pavement installation at SW 21st St. (Image Credit: AccuWeather).

The 2024 project evaluated the effectiveness of three different cool pavement treatments at five test sites across San Antonio during the summer. The products included Durashield produced by GAF Streetbond, SolarPave produced by SealMaster, and CoolSeal produced by GuardTop. For each site, meteorological measurements were collected at the cool pavement installation as well as a representative control in the neighborhood. Specifically, the surface temperature, air temperature, wet bulb globe temperature, albedo, and components of the net radiation budget were assessed 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 and were influenced by the characteristics of the control road. The SolarPave (SealMaster) product displayed the most consistent and statistically significant decreases in surface temperature with an average reduction of 9.4°F during the afternoon testing period. This decline in surface temperature was much larger than that observed in 2023 because an asphalt slurry was applied to the control street. When comparing the cool pavement surface to fresh asphalt, the CoolSeal (GuardTop) product also exhibited substantial afternoon surface temperature reductions that exceeded 10°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 and control sites was -0.14°F, indicating that the cool pavement locations experienced only marginally lower air temperatures. When combining the night and morning measurements, the mean air temperature difference was -0.32°F, which suggested that the cool pavement products might have a greater impact on reducing nocturnal air temperatures. The largest reduction in air temperature observed at a cool pavement site was 1.4°F, but this was one of only three cool pavement samples (out of a total of 40) that exhibited an air temperature reduction greater than 1°F.

Similar findings were observed for the wet bulb globe temperature as only small differences were typically documented between the cool pavement and control sites. The average difference in the mean wet bulb globe temperature between the cool pavement and control sites during the daytime was 0.39°F, which indicated that heat stress at the cool pavement installations was marginally higher. However, given the accuracy of the instrument used to collect the data and the small magnitude of the differences, it was challenging to determine conclusively if there were notable overall differences in either the air or wet bulb globe temperature between the cool pavement sites and control sites.

The radiation budget measurements indicated that the SolarPave (SealMaster) product exhibited the highest albedo (0.29). The albedo values observed in 2024 were generally similar to those documented in 2023. Therefore, the reflectivity of the cool pavements did not appear to deteriorate over the course of the year.

Overall, the results from 2024 were in general agreement with the 2023 report as well as studies conducted in Phoenix and Los Angeles, which also documented the clear potential for cool pavement to reduce surface temperature while simultaneously highlighting it's more modest impact on air temperature.

ACKNOWLEDGEMENTS

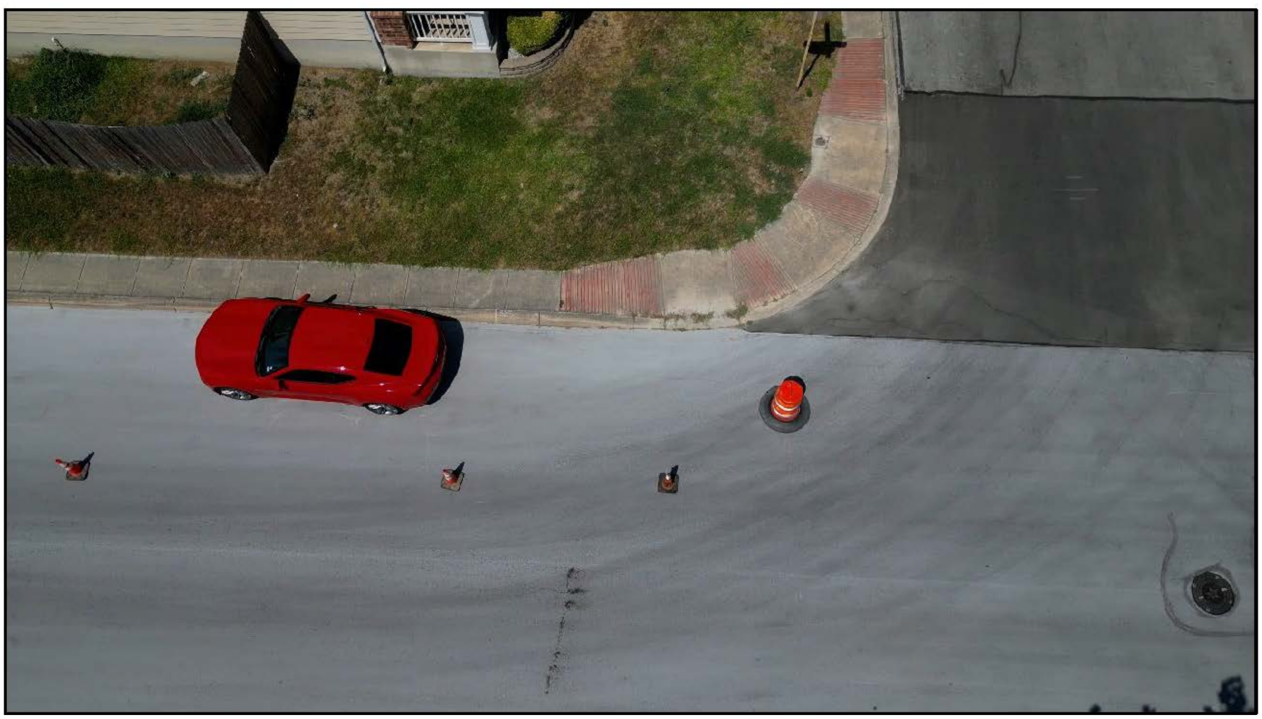
The authors would like to thank several individuals and organizations who provided valuable support throughout the project, which was critical for its successful completion.

City of San Antonio Office of Sustainability
Douglas Melnick - Chief Sustainability Officer
Leslie Antunez - Senior Municipal Sustainability Manager

City of San Antonio Public Works Department
Anthony Chukwudolue - Assistant Director
Daniel Carrión - Project Control Manager

The University of Texas at San Antonio
Martha Luna - Senior Administrative Associate
Rozlyn Pena Wilkins - Business Service Center Specialist III

TRP Infrastructure Services



Drone photograph of the SolarPave (SealMaster) cool pavement installation at Mountain Star (Image Credit: AccuWeather).

THE UNIVERSITY OF TEXAS AT SAN ANTONIO RESEARCH TEAM

Neil Debbage, Ph.D.
Principal Investigator
Associate Professor
Department of Political Science and Geography

Wei Zhai, Ph.D.
Co-Investigator
Assistant Professor
School of Architecture and Planning

Esteban López Ochoa, Ph.D.
Co-Investigator
Assistant Professor
School of Architecture and Planning

Ryun Jung Lee, Ph.D.
Co-Investigator
Assistant Professor
School of Architecture and Planning

Haoming Qin
Graduate Research Assistant
School of Architecture and Planning

Huang Huanchun, Ph.D.
Postdoctoral Researcher
School of Architecture and Planning

Elliott Coleman
Graduate Research Assistant
School of Architecture and Planning

Dana Griggs
Undergraduate Research Assistant
Department of Earth and Planetary Sciences

Katie Mainez
Undergraduate Research Assistant
Department of Political Science and Geography

Matt Kenney
Undergraduate Research Assistant
Department of Political Science and Geography

TABLE OF CONTENTS

1. INTRODUCTION

Urban areas are exposed to 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 higher temperatures associated with urban heat islands impact environmental, social, and economic systems. The benefits of reducing elevated temperatures within urban areas include fewer heat related deaths and illnesses, lower energy consumption during the summer, reduced infrastructure maintenance cost, and increased weather resilience within the context of broader global climatic changes. Additionally, addressing urban heat inequities through the lens of environmental justice can help reduce 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 examined the effectiveness of cool pavement, which is one strategy that cities are exploring to address urban heat extremes. 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 pavement aims 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 several cool pavement installations and control sites during the summer of 2024. This was the second consecutive summer of data collection, which enabled an evaluation of cool pavement performance over time and the inclusion of an additional cool pavement product. This report provides an overview of the COSA cool pavement installations, outlines the methods used by the UTSA research team to collect and analyze field data, and presents the major findings regarding cool pavement performance in 2024. The report also includes comparisons with the initial results from the 2023 report.

2. CITY OF SAN ANTONIO COOL PAVEMENT PROGRAM

San Antonio's extreme summer temperatures make the city an ideal location to test innovative technologies, such as cool pavement, that potentially mitigate excessive urban heat. Summertime high temperatures in San Antonio regularly surpass 90°F and prolonged heatwaves can occur where high temperatures remain above 100°F 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 an expanded pilot program of cool pavement technology. The pilot was supported by COSA's Resiliency, Energy Efficiency and Sustainability Fund and helped 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 for the initial pilot were installed across COSA's ten city council districts beginning in April and ending in July 2023. A second round of cool pavement installations that focused on several of the most heat vulnerable communities in the city occurred in 2024, but these sites were not included in this study since they were installed in September and October 2024 after the summer fieldwork was completed.

2.1 COOL PAVEMENT PRODUCTS

Three types of cool pavement were assessed in this study, including CoolSeal produced by GuardTop, Durashield produced by GAF Streetbond, and SolarPave produced by SealMaster. The SolarPave (SealMaster) and Durashield (GAF Streetbond) products were evaluated in both 2023 and 2024 while the CoolSeal (GuardTop) product was only assessed in 2024 since the final installation did not occur until the middle of July 2023 after fieldwork that summer was well underway. Each cool pavement product has a different appearance and utilizes various physical mechanisms to reduce temperature. The CoolSeal (GuardTop) and SolarPave (SealMaster) products were each tested at two different locations while the Durashield (GAF Streetbond) product was tested at one location for a total of five study sites (**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 in May 2023 at Carol Crest. 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.

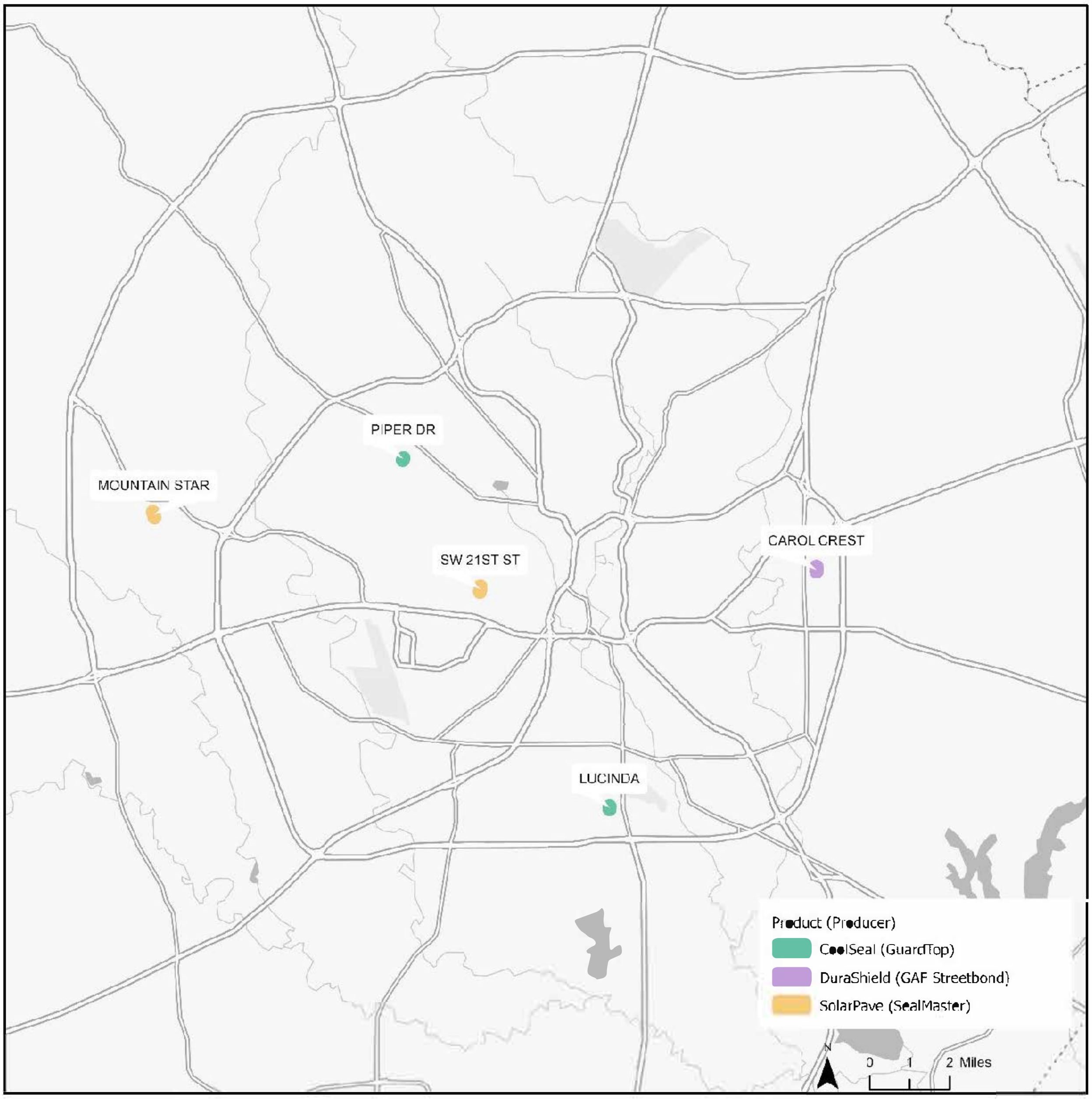


Figure 1. Location of the five cool pavement study sites in San Antonio by product type and producer.

2.1.2 SealMaster: SolarPave

The SolarPave product from SealMaster is a spray-on acrylic polymer emulsion coating that was installed in May 2023 at SW 21st St. and Mountain Star. 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 GuardTop: CoolSeal

The CoolSeal product from GuardTop is a water-based, asphalt emulsion sealcoat that was installed in July 2023 at Piper Dr. and Lucinda. The product is a light gray color and also has a minimum SRI of 33 (**Figure 2c**). The product must be applied to asphalt surfaces and is not compatible with concrete or composite pavements. The product can potentially mitigate urban heat and extend the life of the roadway.

Figure 2. Examples of the cool pavement products evaluated in the study: a) Durashield (GAF Streetbond) at Carol Crest, b) SolarPave (SealMaster) at Mountain Star, and c) CoolSeal (GuardTop) at Piper Dr.

3. METHODS

The design of this study was modelled largely on previous research conducted by Arizona State University, which focused on the Phoenix, AZ cool pavement program.[4] The same approach was used in San Antonio during both 2024 and 2023 to enable meaningful comparisons between the two years. The data collection period in 2024 spanned from June 17th to September 13th. 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 specific study plot locations selected were areas of the cool pavement with minimal amounts of shadowing from adjacent trees and houses so that solar exposure was maximized. The plot locations were also chosen 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 was 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 cool pavement treatment sites.

Location		Cool Pavement Characteristics			Data Collection Dates (2024)	
Road Site	**District**	**Manufacturer**	**Product**	**Installation**	**Phase I**	**Phase II**
Piper Dr.	7	GuardTop	CoolSeal (water based sealcoat)	July 2023	28-June 10-July	12-September 13-September
Lucinda	3	GuardTop	CoolSeal (water based sealcoat)	July 2023	17-June 3-July	- -
Carol Crest	2	GAF Streetbond	Durashield (water/acrylic based)	May 2023	24-June 5-July	5-September 6-September
Mountain Star	4	SealMaster	SolarPave (water/acrylic + polymer based)	May 2023	26-June 17-July	29-August 30-August
SW 21st St.	5	SealMaster	SolarPave (water/acrylic + polymer based)	May 2023	1-July 12-July	- -

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. The road surface at the control site was quite worn when it was evaluated in 2023, but an asphalt slurry was applied by Public Works prior to the data collection in 2024. The slurry application meant that the control surface had a darker appearance in 2024 relative to 2023.

3.1.2 Lucinda

The Lucinda site was located north of IH-410 near Stinson Municipal Airport in District 3. The cool pavement installation on Lucinda ran south from E Ashley Rd. to Sams Dr. The middle portion of the cool pavement was selected for evaluation to avoid the more pronounced tree canopy coverage located closer to E Ashley Rd. and to minimize interference with driveway access. Due to the relatively large block sizes in the neighborhood, there were only two proximate roads to consider for the control: Leah Dr. to the west and Ely Dr. to the east. The urban morphology on Leah Dr. was notably different due to the presence of relatively new sidewalks on either side of the road so Ely Dr. was selected as the control site (**Figure A2**).

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 majority of Mountain Star. The Mountain Star cool pavement 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. The specific cool pavement test plot extended southwest from Wildhorse Run to the alley, which helped avoid blocking additional traffic since on-street parking was common in the neighborhood (**Figure A3**). Because 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 control street underwent maintenance after data was collected in 2023 but before the 2024 field campaign, as an asphalt slurry was applied in May 2024. This resulted in a much darker control road surface in 2024 compared to 2023.

3.1.4 Piper Dr.

The Piper Dr. site was located between Bandera Rd. and Culebra Rd. to the west of St. Mary's University in District 7. The cool pavement installation spanned the length of the block between Loy Dr. and Freeman Dr. The northern half of this block was selected for the cool pavement test plot to minimize tree shading. Due to the lack of other proximate streets with the same orientation, the portion of Piper Dr. north of Loy Dr. was used as the control (**Figure A4**). This control area consisted of fresh asphalt and was an active construction project as curbs and sidewalks were being installed. This resulted in two different portions of Piper Dr. being used as a control for the two phases of fieldwork. During Phase 1, the portion of Piper Dr. from Loy Dr. to the alley was used while the segment of Piper Dr. northeast of Repose Ln. was used for Phase 2. This shift was necessary to avoid a conflict with the construction efforts, which resulted in the initial control area used during Phase I being covered in dust and dirt.

3.1.5 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 A5**). 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

The same instruments used in 2023 were deployed again at each field site in 2024 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 the meteorological data.

Instrument	Meteorological Variable	Units
FLUKE 572-2	Surface Temperature	°F
FLIR E4	Surface Temperature (with picture)	°F
Kestrel 5400 WBGT HST	Air Temperature	°F
	Globe Temperature	°F
	Wet Bulb Globe Temperature	°F
	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 met 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 temperature 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 were 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.

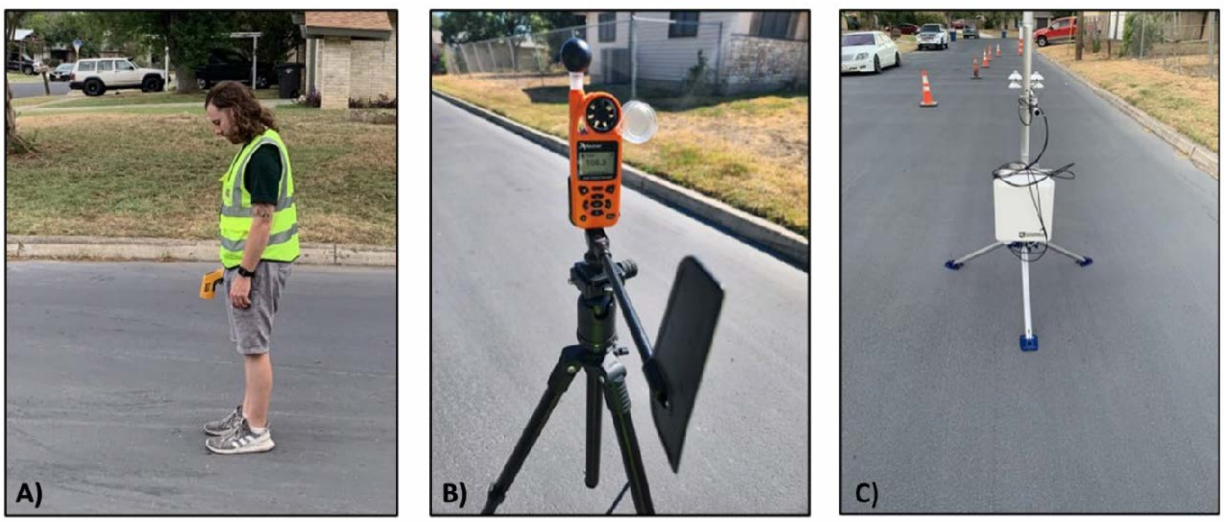


Figure 3. The a) FLUKE 572-2 infrared thermometer, b) Kestrel 5400 Heat Stress Tracker, and c) Hukseflux NR01 4-component net radiometer deployed in the field.

3.3 FIELD CAMPAIGNS

The fieldwork was conducted from June 17^{th} to September 13^{th} in 2024. A total of 16 days of fieldwork were performed, excluding initial site visits for planning and additional trips to the sites to evaluate the level of surface wetness after several rainfall events. For each field day, traffic cones were set out the evening prior to close one lane of the street at both the cool pavement and control testing plots (**Figures A1-A5**). 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 the site-specific observations.

3.3.1 Phase I

Phase I consisted of two fieldwork sessions (Session 1: June 17th - July 1st and Session 2: July 3rd - 17th). During each session, all five sites were visited. Therefore, each site was characterized by two days of data after the completion of Phase I (**Table 1**). For 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 for 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 for 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). FLIR E4 thermal imagery and surface temperature measurements were also collected at each site to complement the FLUKE measurements. Photographs were taken during the noon and afternoon sessions to identify potential maximum differences between the cool pavement surface temperature and adjacent untreated road surfaces.

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 potential 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.

3.3.2 Phase II

Phase II consisted of three fieldwork sessions (Session 1: August 29th & 30th; Session 2: September 5th & 6th, and Session 3: September 12th & 13th). Since one NR01 net radiometer was available, only three sites were included in Phase II. Carol Crest, Piper Dr., 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 near the net radiometer.

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 two sessions were combined into one dataset. This produced a potential maximum sample size of 24 for each one-hour observation period at each site (i.e., 12 observations during each hour window x 2 site visits). Points that were in shade were removed from the dataset to prevent the cooler temperatures from biasing the averages. Additionally, points where shadows had a clear lag effect on temperature were also removed. Once the observations impacted by shadowing were excluded, 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). A 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. The data sources are the same as those utilized in the 2023 report to enable fair comparisons.

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 five 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, Piper Dr., and Lucinda since these installations were imbedded within traditional subdivisions (**Table 4**). SW 21st St. was mixed in terms of land use, as Jeremiah Rhodes Middle School, which bordered the road to the west, increased the portion of commercial land use.

All the areas surrounding the cool pavement were developed but to varying degrees according to the land cover data. Mountain Star and SW 21st St. were both primarily characterized by medium intensity development. Low intensity development was more abundant at Piper Dr., Lucinda, and Carol Crest (**Table 4**).

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 coverage for Carol Crest, SW 21st St., and Lucinda was slightly more expansive with values ranging from 25% to 27%. Piper Dr. exhibited the most robust tree canopy within the 200ft buffer as the coverage exceeded 30%.

Remotely sensed land surface temperatures varied by 5°F between the coolest location (Piper Dr.) and warmest location (Mountain Star). This generally aligned with the differences in tree canopy coverage (**Table 4**). There were also only marginal differences (less than 3°F) between the 200ft and 500ft buffer results, which highlighted that the resolution of the remotely sensed imagery was largely insufficient to detect highly localized temperature variations.

Table 4. Cool pavement site characteristics within the 200ft and 500ft buffer of each installation.

	PIPER DR.		LUCINDA		CAROL CREST		MOUNTAIN STAR		SW 21ST ST.	
	200ft	500ft	200ft	500ft	200ft	500ft	200ft	500ft	200ft	500ft
LAND USE (%)										
Road	24.56	22.28	23.30	13.70	28.87	24.28	20.72	25.41	21.87	16.36
Single-Family	75.44	73.42	65.09	71.78	67.66	58.80	79.28	74.20	46.20	43.81
Multi-Family	-	0.61	-	-	-	-	-	-	-	-
Vacant	-	3.69	11.61	13.36	3.47	15.91	-	0.39	4.96	12.65
Commercial/Office	-	-	-	1.16	-	0.67	-	-	26.97	27.18
Utilities/Industrial	-	-	-	-	-	0.34	-	-	-	-
LAND COVER (%)										
Developed, Open Space	20.0	33.6	11.1	22.1	4.4	16.6	-	1.2	17.0	22.4
Developed, Low Intensity	53.3	48.8	52.8	40.4	77.8	50.9	12.8	17.4	25.5	33.3
Developed, Med Intensity	26.7	17.6	33.3	36.0	17.8	29.4	76.6	72.5	48.9	37.6
Developed, High Intensity	-	-	2.8	1.5	-	3.1	10.6	8.4	8.5	6.7
Shrub/Scrub	-	-	-	-	-	-	-	0.6	-	-
TREE CANOPY (%)	36.9	38.4	25.0	26.0	25.7	26.8	22.6	23.9	26.5	29.4
LAND SURFACE TEMP. (°F)	107.3	107.3	110.9	109.1	110.9	110.9	112.7	110.9	109.1	107.3

Based on the GIS analysis, built and natural environmental factors that often influence urban heat were examined across the sites. **Figure 5** compares both heat-generating factors, including commercial land use, roads, and developed land cover, and heat-reducing factors, such as open space and tree canopy coverage, with land surface temperatures. Sites with higher land surface temperatures typically exhibited a greater proportion of commercial land use, roads, and developed land cover while sites with lower land surface temperatures were characterized by more open space and tree canopy coverage.

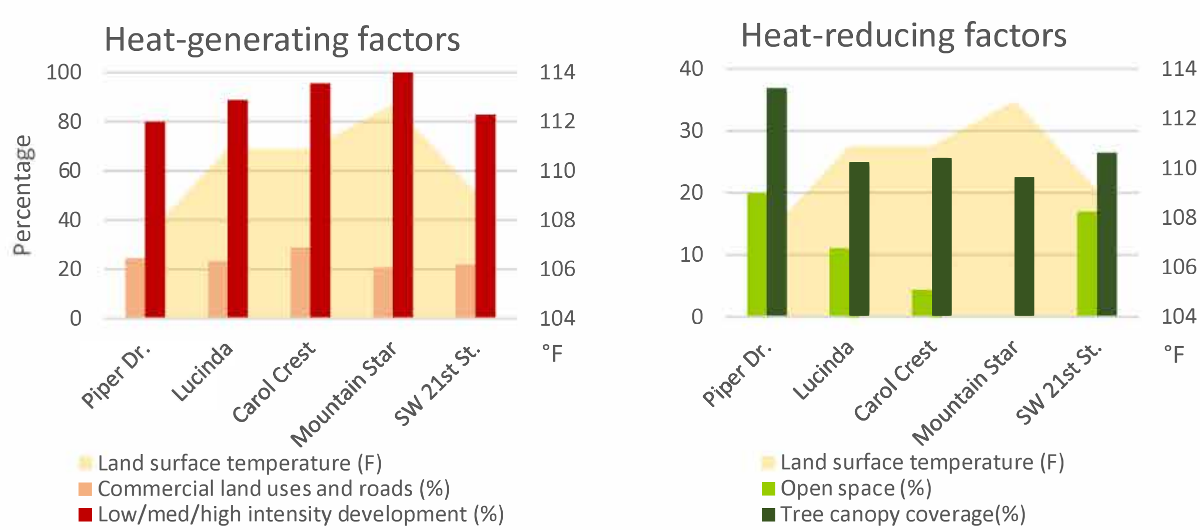


Figure 5. Heat-generating and heat-reducing factors within the 200-foot buffer of the five cool pavement sites compared with surface temperature.

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**). At Piper Dr., both sites were characterized by similarly high proportions of single-family residential land use. Although the cool pavement and control site included a mix of developed open space, low-intensity development and medium-intensity development, the specific percentages differed as the cool pavement site exhibited greater quantities of developed open space and medium-intensity development. The tree canopy coverage percentages were very similar for both sites, and the land surface temperatures were 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.

	PIPER DR.		LUCINDA		CAROL CREST		MOUNTAIN STAR		SW 21ST ST.	
	CP	CON	CP	CON	CP	CON	CP	CON	CP	CON
LAND USE (%)										
Road	27.30	25.34	26.34	23.85	28.37	26.27	23.13	19.80	19.55	19.00
Single-Family	72.70	74.66	65.50	73.58	71.63	71.30	76.87	80.20	32.72	37.10
Multi-Family	-	-	-	-	-	-	-	-	-	-
Vacant	-	-	8.16	2.56	-	0.18	-	-	3.16	0.94
Commercial/Office	-	-	-	-	-	2.24	-	-	44.56	42.95
LAND COVER (%)										
Developed, Open Space	21.1	9.5	16.0	7.7	-	9.1	-	-	27.3	28.0
Developed, Low Intensity	47.4	76.2	52.0	76.9	81.8	40.9	5.0	28.0	27.3	28.0
Developed, Med Intensity	31.6	14.3	28.0	15.4	18.2	50.0	80.0	64.0	36.4	44.0
Developed, High Intensity	-	-	4.0	-	-	-	15.0	8.0	9.1	-
TREE CANOPY (%)	35.0	35.3	28.3	31.0	28.7	16.9	25.1	25.7	14.6	24.1
LAND SURFACE TEMP. (°F)	107.3	107.3	110.9	109.1	110.9	110.9	112.7	112.7	110.9	109.1

At Lucinda, the cool pavement site and control site displayed similarities in terms of land use, as both included a mix of single-family residential, roads, and vacant lots. In terms of land cover, both sites were primarily dominated by low-intensity development, but the cool pavement site displayed more land cover diversity, which resulted in a much lower percentage of low-intensity development. Only small differences were observed for the tree canopy coverage and land surface temperatures.

The cool pavement site and control site at Carol Crest also shared land use similarities but differed regarding land cover and tree canopy percentage. 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.

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

The meteorological conditions experienced in 2024 during the field campaign were vastly different from 2023. Generally, high pressure dominated the San Antonio region with less regularity in 2024, which resulted in lower temperatures and more opportunities for rainfall. In 2024, there were only 27 days where the high temperature exceeded 100°F, which was less than half of the 75 days observed in 2023. Fieldwork was postponed twice to avoid wet cool pavement conditions due to the precipitation produced by Tropical Storm Alberto in June. Additionally, fieldwork was postponed once during Hurricane Beryl in July because of the high probability of overcast and windy conditions. Although data was never collected when precipitation or wet surface conditions were present at the cool pavement and control sites, convective storm activity occurred on several of the fieldwork days in other portions of Bexar County. The more varied weather patterns in 2024 provided insights into cool pavement performance under a wider array of atmospheric conditions.

For the first field session of Phase I, the maximum temperatures ranged from the mid to upper 90s (**Figure 6**). June 24th and 26th were slightly cooler since they followed Tropical Storm Alberto. Each day exhibited a similar diurnal pattern with regards to wind strength, as wind speeds generally increased through the afternoon and evening. June 17th was particularly windy as speeds exceeded 20kt on multiple occasions in the evening. The pronounced winds likely enhanced mixing, which could potentially minimize the impacts of cool pavement on air temperature. The relative humidity patterns were also similar between each day with afternoon values ranging between approximately 40% and 50%.

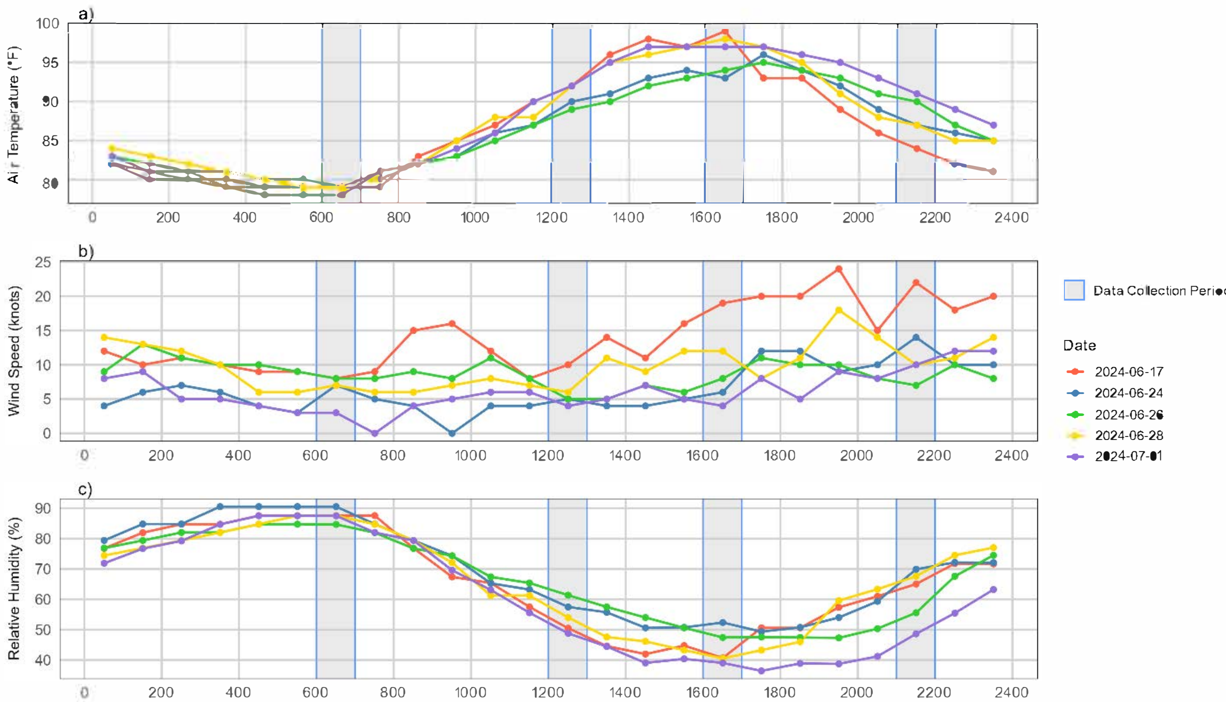


Figure 6. Meteorological characteristics at KSAT ASOS for field session one of Phase I.

The meteorological conditions for the second session of Phase I were more varied (**Figure 7**). July 10th and 12th displayed cooler temperatures due to convective storm activity present in other portions of Bexar County. The relative humidity values were also unsurprisingly higher on those two days. The other three days of the second session were more typical with high temperatures in the upper 90s and relative humidity values falling to 40% in the afternoon. Winds were slightly calmer during the second session when compared to the first session, and they exhibited a less pronounced diurnal pattern. Overall, the differences across the Phase I days helped assess the performance of the cool pavement products under various meteorological conditions. The weather plots also illustrated that the warmest and coolest portions of the day were generally captured by the sampling strategy.

The first session of Phase II, which occurred at Mountain Star, was characterized by similar temperatures at the cool pavement site (August 29th) and the control site (August 30th) (**Figure 8**). Both days displayed high temperatures in the low 90s. The winds gradually increased throughout each day and the diurnal trends in relative humidity were reasonably analogous. For the second session of Phase II at Carol Crest, the temperature differences were more pronounced (**Figure 8**). The day (September 5th) data

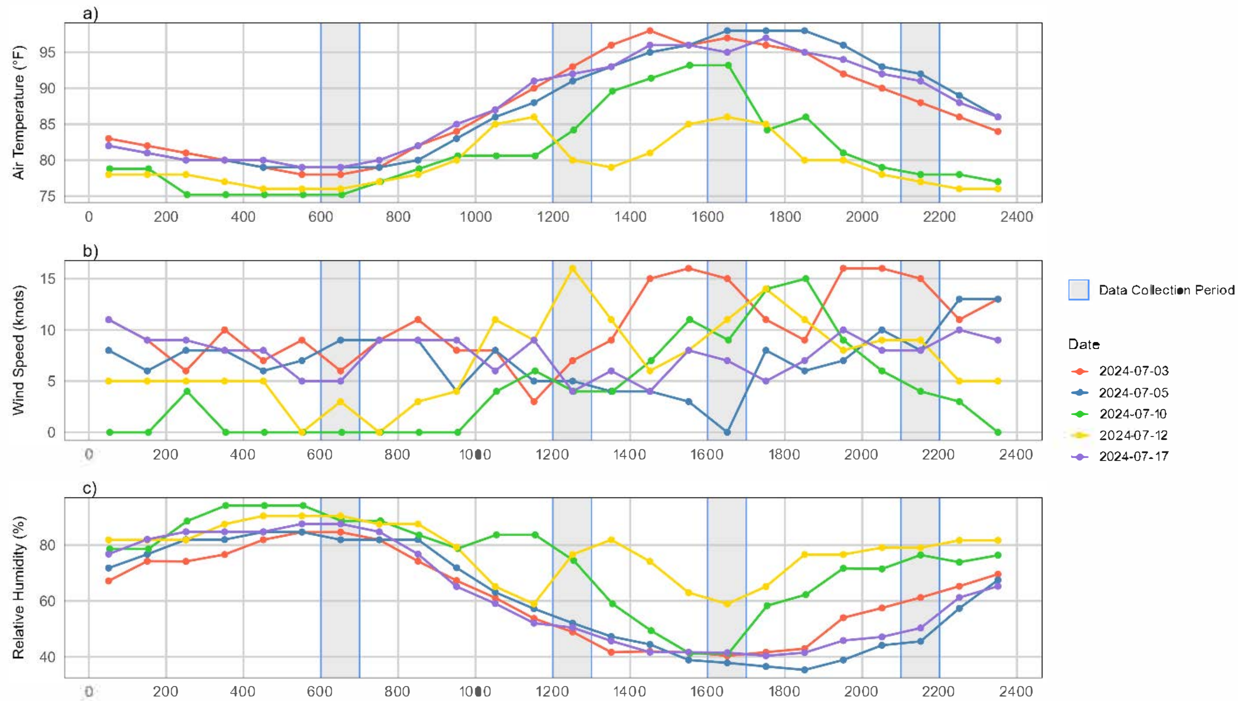


Figure 7. Meteorological characteristics at KSAT ASOS for field session two of Phase I.

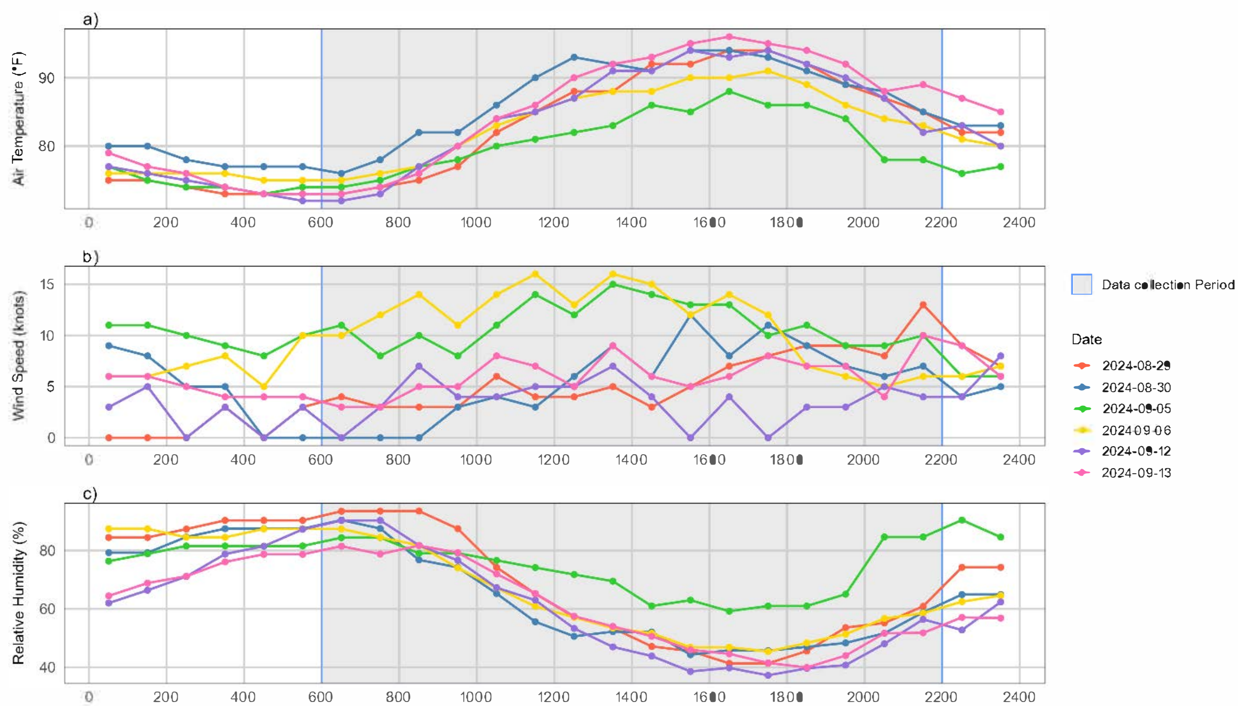


Figure 8. Meteorological characteristics at KSAT ASOS for Phase II.

collection occurred at the cool pavement site was cooler, as hourly temperature observations did not exceed 90°F. The relative humidity was also higher throughout the afternoon and evening. The final session of Phase II occurred at Piper Dr. The air temperature and relative humidity profiles were similar at both the cool pavement (September 12th) and control site (September 13th). There was a slight difference in terms of wind speeds as calmer conditions were present throughout the day at the cool pavement (**Figure 8**). 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.

4.3 SURFACE TEMPERATURE DIFFERENCES

The surface temperature differences between the cool pavement sites and control sites were generally modest in the morning for the Durashield and CoolSeal products, as both exhibited temperature reductions of less than 1°F (**Table 6**). The SolarPave sites displayed more substantial differences in surface temperature with decreases of 1.9°F and 2.7°F prior to sunrise. When considering the statistical significance of the differences, the surface temperatures of the CoolSeal and SolarPave cool pavements were significantly lower than the control surfaces.

By noon, differences in the surface temperatures were more pronounced and all statistically significant with the exception of Lucinda and SW 21st St. The largest negative difference occurred at Mountain Star as the SolarPave product was 12°F cooler than the control site. This was a more substantial reduction than observed at noon in 2023 when the Mountain Star cool pavement surface was only 3.5°F cooler. The difference can be attributed to the asphalt slurry applied to the control site between field campaigns and suggests that SolarPave cool pavement provides moderate surface temperature reductions relative to a worn residential street and notable surface temperature decreases relative to fresher asphalt. A similarly large surface temperature decrease of 10°F was observed for the CoolSeal product at Piper Dr. because the control was fresh asphalt. Contrastingly, the CoolSeal product at Lucinda exhibited marginally warmer surface temperatures, which was at least partly attributable to the worn nature of the control street. The changes to the surface of the Carol Crest control site also influenced the results. In 2023, the Carol Crest Durashield product was 3°F warmer than the worn residential control street, but after the application of an asphalt slurry at the control site the cool pavement surface temperature was 6°F cooler. The SW 21st St. surface characteristics remained unchanged between the 2023 and 2024 field campaigns, so it provided the best barometer for genuine change over time. The surface temperature reduction in 2024 (-3.1°F) was almost 1°F greater than that observed in 2023 (-2.3°F). This might indicate that the SolarPave product performs better under the relatively cooler conditions encountered in 2024 when compared to the extreme heat of 2023.

Table 6. Differences in surface temperature between the 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 influenced by shadows. Statistically significant differences are indicated by p-values in bold.

Product	Site Name	Avg. CP Surface Temp (°F)	CP N	Avg. CON Surface Temp (°F)	CON N	Difference	T-Value	P-Value
Morning (6:00 am - 7:00 am)								
Durashield	Carol Crest	88.98	24	89.79	24	-0.80	-1.36	0.18
CoolSeal	Lucinda	87.05	24	88.03	24	-0.98	-2.51	**0.02**
	Piper Dr.	88.23	24	89.18	24	-0.95	-2.76	**0.01**
SolarPave	Mountain Star	87.16	24	89.84	24	-2.68	-3.83	**0.00**
	SW 21st St.	86.55	24	88.45	24	-1.90	-2.84	**0.01**
Noon (12:00 pm - 1:00 pm)								
Durashield	Carol Crest	128.11	24	133.83	18	-5.72	-4.25	**0.00**
CoolSeal	Lucinda	130.58	19	128.74	24	1.84	1.49	0.14
	Piper Dr.	121.77	24	131.79	24	-10.02	-3.36	**0.00**
SolarPave	Mountain Star	119.48	24	131.73	24	-12.25	-7.62	**0.00**
	SW 21st St.	124.65	24	127.79	24	-3.13	-1.45	0.16
Afternoon (4:00 pm - 5:00 pm)								
Durashield	Carol Crest	138.51	24	145.59	17	-7.08	-3.10	**0.00**
CoolSeal	Lucinda	137.00	24	136.32	22	0.68	0.56	0.58
	Piper Dr.	130.51	24	141.15	24	-10.63	-3.79	**0.00**
SolarPave	Mountain Star	123.98	24	135.78	24	-11.79	-5.81	**0.00**
	SW 21st St.	128.41	24	135.47	24	-7.05	-2.96	**0.00**
Night (9:00 pm - 10:00 pm)								
Durashield	Carol Crest	102.94	24	105.00	24	-2.05	-1.81	**0.08**
CoolSeal	Lucinda	100.10	24	101.00	24	-0.90	-1.11	0.27
	Piper Dr.	98.75	24	100.22	24	-1.46	-1.24	0.22
SolarPave	Mountain Star	99.50	24	103.30	24	-3.80	-6.27	**0.00**
	SW 21st St.	98.66	24	102.32	24	-3.66	-2.15	**0.04**

The surface temperature differences in the afternoon were very similar to those observed at noon. The CoolSeal product at Piper Dr. and the SolarPave Product at Mountain Star both displayed statistically significant surface temperature reductions greater than 10°F relative to the fresh asphalt control surfaces. Significantly lower (~7°F) surface temperatures were also observed at Carol Crest and SW 21st St. Lucinda was again an outlier as the cool pavement surface was marginally warmer (0.7°F) than the worn control street.

The differences in surface temperature at night were less pronounced than the daytime periods but more notable than the morning. The SolarPave sites displayed significant reductions approaching 4°F while the Durashield product exhibited a 2°F decrease. The CoolSeal sites only displayed marginal reductions in surface temperature at night, which failed to exceed 1.5°F and were not statistically significant.

Although comparing the averages across the sampling grid provided a robust approach to quantify the typical surface temperature changes, point samples were also taken via the FLIR E4 to provide visuals that better highlighted the complexities of the surface temperature differences (**Figure 9**). At the Mountain Star SolarPave site, a 10°F reduction was observed between the cool pavement and adjacent fresh asphalt in the afternoon (**Figure 9a-c**), which aligned with the overall average findings from **Table 6** since the control was also fresh asphalt. However, when the cool pavement was compared with the adjacent worn residential street the reduction was only 5°F (**Figure 9d-f**) and more analogous to the afternoon findings from the other SolarPave site at SW 21st St. The differences in surface temperature at Lucinda were also more diverse when considering

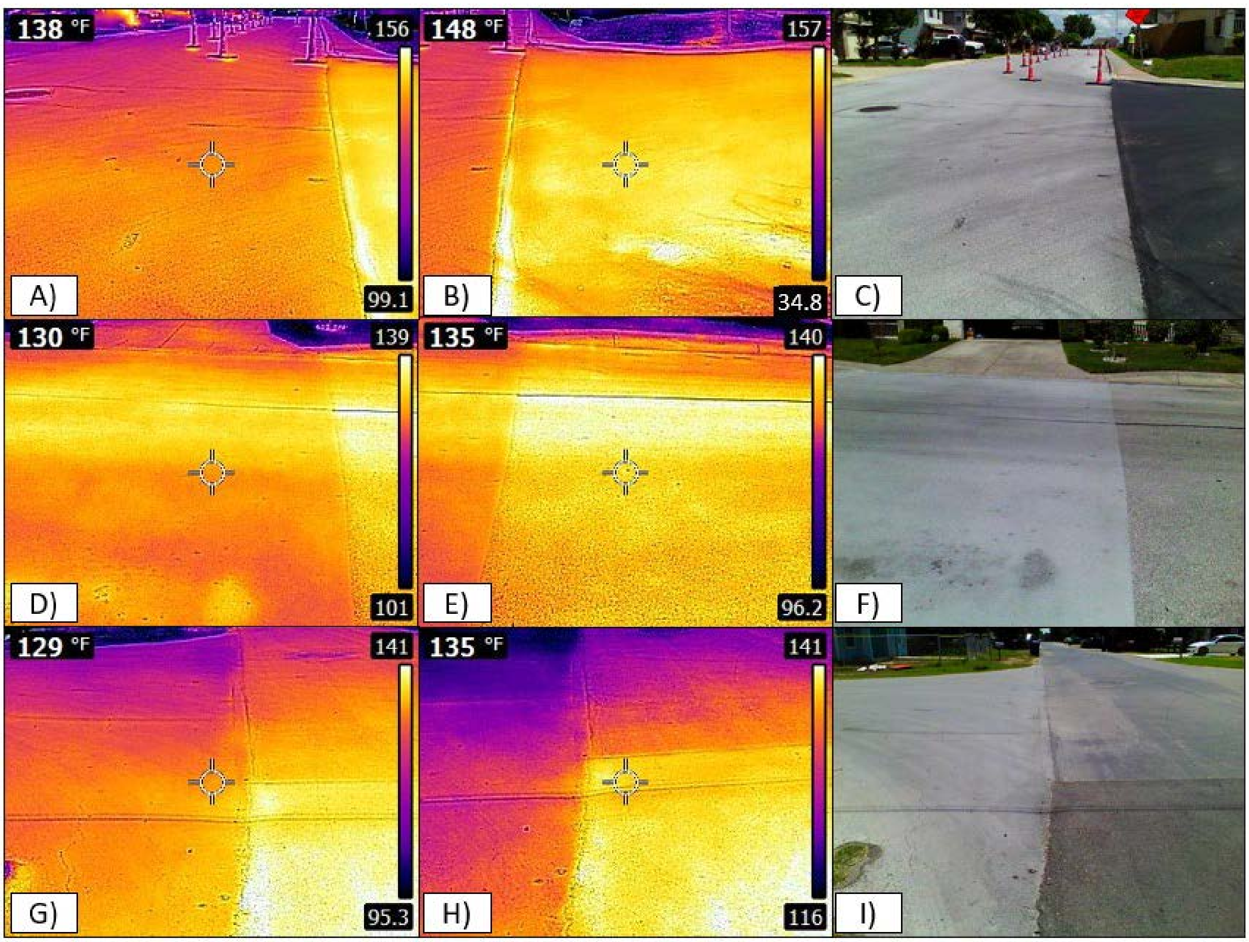


Figure 9. Surface temperature differences observed at Mountain Star during the afternoon session on June 26th (a-f) and at Lucinda during the noon session on July 3rd (g-i).

adjacent seams that exhibited different surface characteristics. For example, when the cool pavement was compared with a small patch of fresh asphalt it was 6°F cooler (**Figure 9g-i**), which contrasts with the warmer surface temperatures documented by the grid sampling method since the control street was worn. Collectively, the thermal imagery results helped emphasize the importance of considering the specific nature of the control site when interpreting the statistics reported in **Table 6**.

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 -0.14°F, indicating that air temperatures at the cool pavement sites were only marginally lower. This suggests that the potential cooling associated with the lower surface temperatures of the cool pavements did not substantially outweigh other environmental factors such as atmospheric mixing. The average difference in the mean air temperature was 0.03°F (i.e., the cool pavement sites were slightly warmer) when only the noon and afternoon sessions were analyzed. When combining the night and morning measurements, the mean air temperature difference was -0.32°F, which indicates that the cool pavement products might have a greater impact on decreasing nocturnal air temperatures. However, given the accuracy of the Kestrel and the small magnitude of the differences, it is challenging to conclusively determine 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 substantial alterations in air temperature occurred for particular products and sites during individual time periods. The results for the Durashield site at Carol Crest were consistent with the overall trends (**Figure 10**). In the morning, the temperatures at the cool pavement were 0.4°F and 0.2°F lower than the control. These differences were statistically significant despite the small magnitude. During the noon and afternoon periods, no statistically significant differences were observed. Contrasts emerged again at night as the Carol Crest cool pavement was significantly cooler during both visits, although the magnitude of this reduction was still modest (i.e., <0.7°F).

The Mountain Star SolarPave site displayed statistically significant reductions in air temperature during the morning and night sessions (**Figure 11**). Similar to the Durashield product, the decreases in the morning temperature at the cool pavement site were marginal and averaged 0.3°F across both visits. The magnitude of the differences increased slightly at night when the cool pavement was on average 0.5°F cooler than the control site. The Mountain Star cool pavement exhibited a varied influence on air temperature during the daytime. At noon on June 26th, the cool pavement was significantly warmer (1.7°F) while on July 27th in the afternoon it was significantly cooler

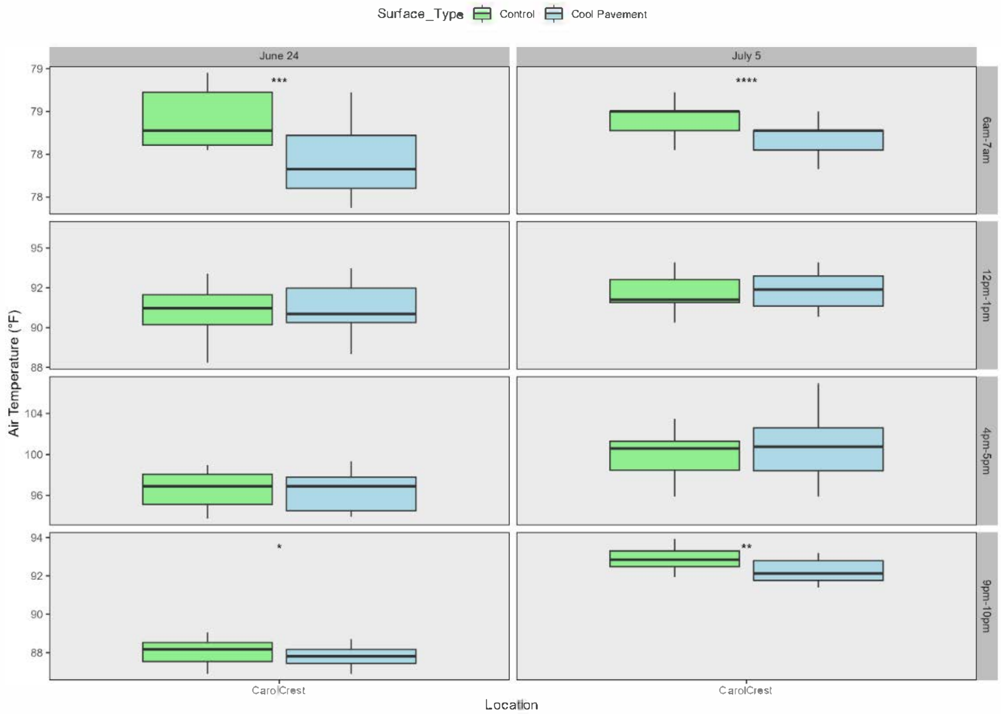


Figure 10. Air temperature differences for the Carol Crest Durashield site by day and time. Level of statistical significance is indicated by the asterisks where: * p-value <= 0.05, ** p-value <= 0.01, *** p-value <= 0.001, and **** p-value <= 0.0001.

Figure 11. Air temperature differences for the Mountain Star SolarPave site 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.

(1.3°F). These air temperature contrasts were the largest positive and negative statistically significant differences observed during the 2024 field campaign. The mixed results seem to suggest that the notable surface temperature reductions observed at Mountain Star when comparing the SolarPave product to fresh asphalt did not necessarily translate into consistent air temperature reductions during the daytime.

The differences in air temperature for the other SolarPave site located at SW 21st St. were very similar to the findings for the Durashield product. Temperatures were statistically significantly lower at the cool pavement installation relative to the control during the 6:00 am - 7:00 am and 9:00 pm - 10:00 pm sessions (**Figure 12**). The magnitude of these differences was again modest as the cool pavement air temperatures were between 0.4°F and 0.7°F lower. SW 21st St. exhibited the largest (1.4°F) and third largest (1.3°F) reductions in air temperature of any site and time period during the afternoon session. However, despite the large magnitudes, these differences were not statistically significant.

The CoolSeal product demonstrated the smallest number of significant differences between the cool pavement and control sites (**Figures 13 & 14**). When considering the Piper Dr. location, two statistically significant but modest (<0.3°F) reductions in air temperature were observed on June 28th during the morning and night but no statistically

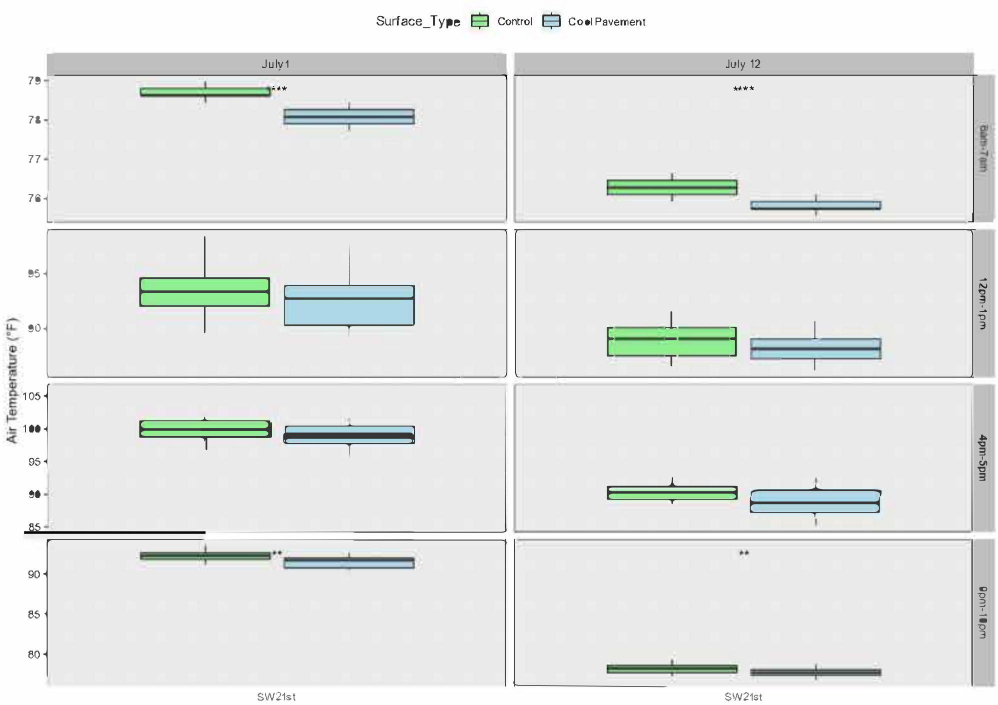


Figure 12. Air temperature differences for the SW 21st St. SolarPave site by day and time. Level of statistical significance is indicated by the asterisks where: * p-value <= 0.05, ** p-value <= 0.01, *** p-value <= 0.001, and **** p-value <= 0.0001.

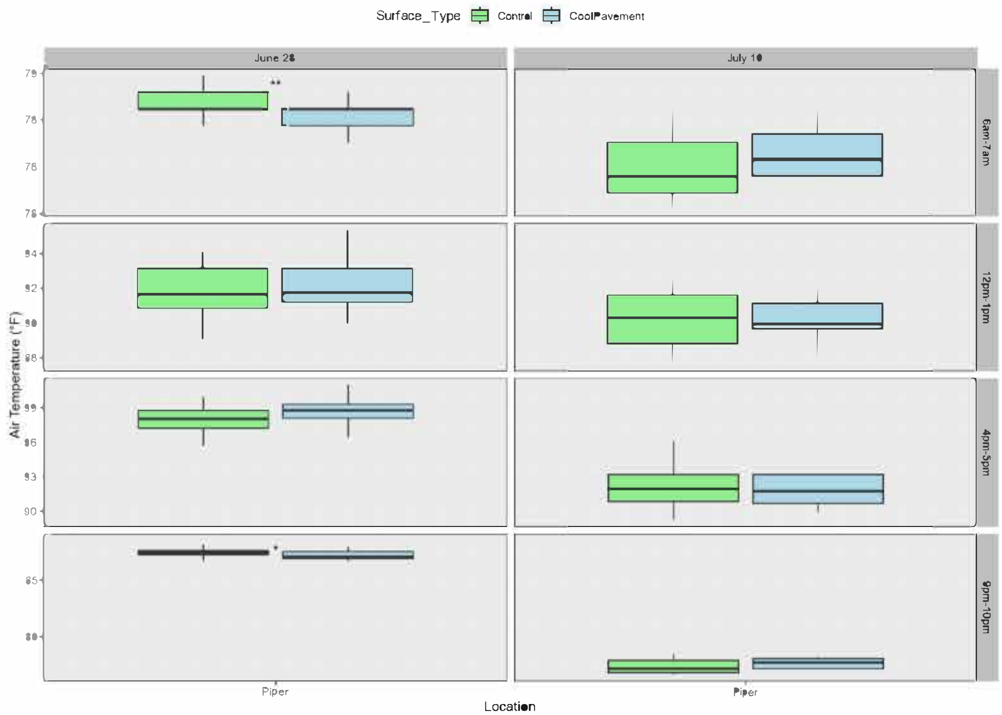


Figure 13. Air temperature differences for the Piper Dr. CoolSeal site by day and time. Level of statistical significance is indicated by the asterisks where: * p-value <= 0.05, ** p-value <= 0.01, *** p-value <= 0.001, and **** p-value <= 0.0001.

Figure 14. Air temperature differences for the Lucinda CoolSeal 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.

meaningful differences were documented during any session on July 10th (**Figure 13**). The diminished contrasts between the cool pavement and control on July 10th might be attributable to the convective activity present throughout Bexar County that day. The Lucinda CoolSeal site also exhibited only two statistically significant differences between the cool pavement and control (**Figure 14**). On July 3rd, the morning air temperature average observed at the cool pavement was significantly lower, but the reduction was a modest 0.2°F. The cool pavement installation was significantly warmer on June 17th in the afternoon. The 1.2°F increase in air temperature relative to the control was the second largest positive contrast observed, but this may have been due to the strong winds, which approached 20 knots, supporting a high degree of atmospheric mixing that afternoon.

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 0.39°F, which suggests that heat stress at the cool pavement installations was marginally higher. This aligns with other studies[4] that have documented increases in heat stress at cool pavement sites due to the increased quantities of reflected sunlight. However, given the accuracy constraints of the Kestrel globe temperature, this small difference should still be considered somewhat inconclusive.

The Durashield site at Carol Crest displayed increases in the WBGT during three of the four daytime site visits (**Figure 15**). The WBGTs were between 0.7°F and 0.9°F higher at the cool pavement site relative to the control, but only the increase during the afternoon on July 5th was statistically significant. There was one sampling period on June 24th at noon when a lower WBGT was observed at the cool pavement site.

Both SolarPave cool pavement installations exhibited no statistically significant differences in the WBGT during the noon or afternoon periods (**Figures 16 & 17**). At Mountain Star, the mean WBGTs were always higher for the cool pavement relative to the control. The most notable increase occurred on June 26th at noon as the mean cool pavement WBGT was 1.8°F greater than that observed at the control. This contrast, which reached marginal statistical significance (p-value = 0.06), was the largest elevation of heat stress observed at any cool pavement site. A different pattern emerged for SW 21st St., as the WBGTs were marginally lower at the cool pavement site for three of the four daytime periods. These decreases were modest and ranged between 0.07°F and 0.9°F.

There were also no statistically significant differences in the WBGT observed at the Piper Dr. CoolSeal site (**Figure 18**). The mean WBGTs were elevated for the Piper Dr. cool pavement relative to the control site for all four daytime sessions but these increases never

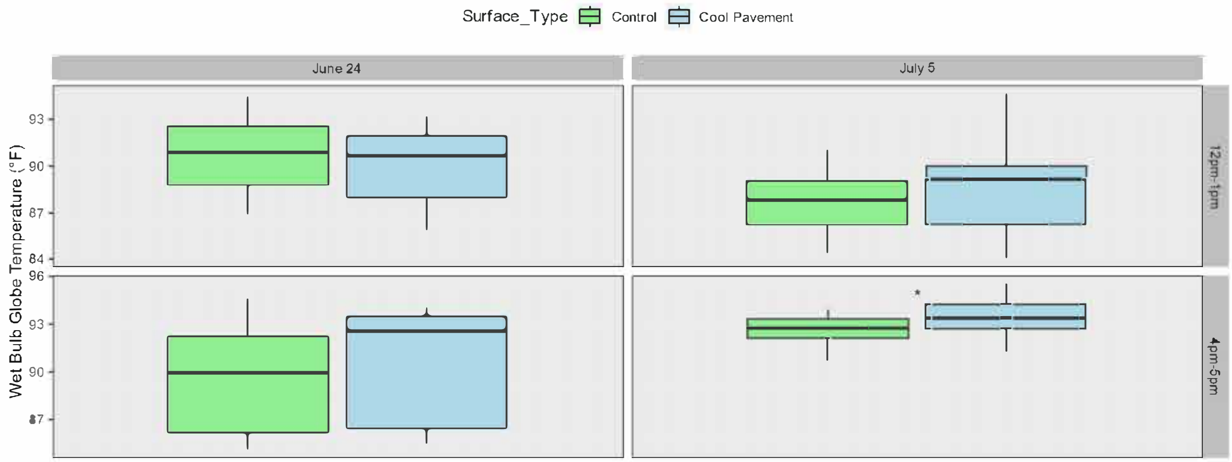


Figure 15. WBGT differences for the Durashield site at Carol Crest by day and time. The asterisks indicate statistical significance where: * p-value <= 0.05, ** p-value <= 0.01, and *** p-value <= 0.001.

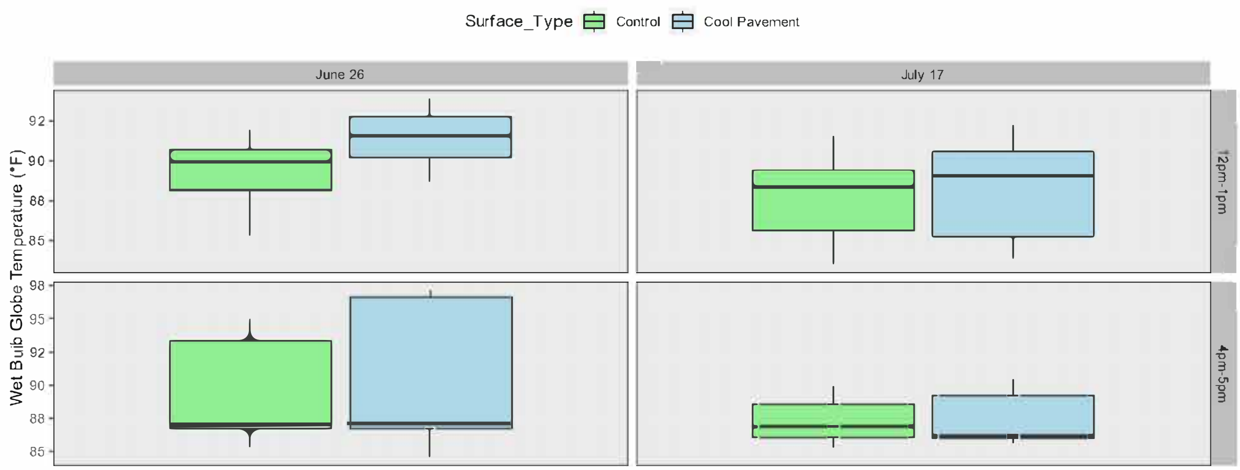


Figure 16. WBGT differences for the SolarPave site at Mountain Star by day and time. The asterisks indicate statistical significance where: * p-value <= 0.05, ** p-value <= 0.01, and *** p-value <= 0.001.

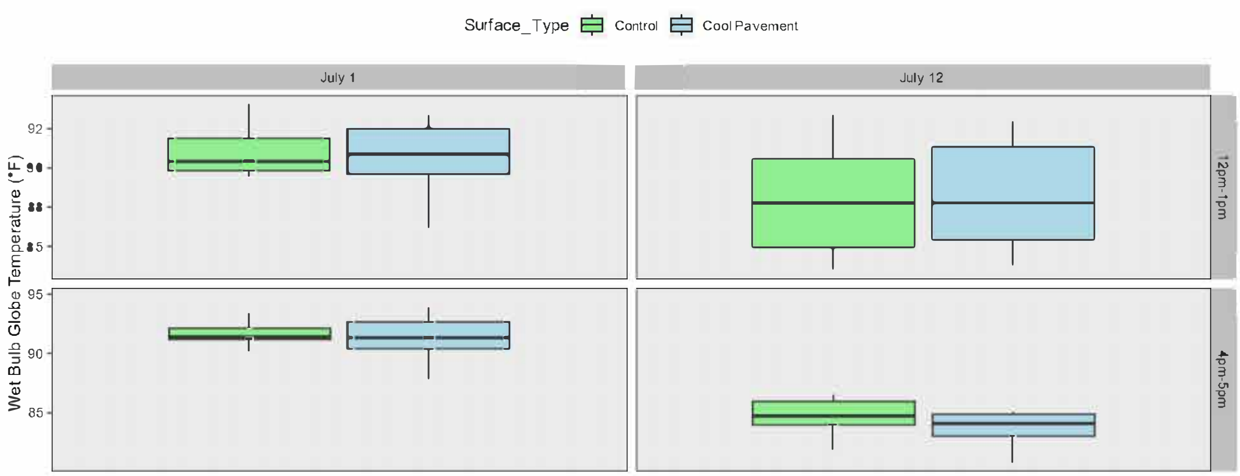


Figure 17. WBGT differences for the SolarPave site at SW 21st St. by day and time. The asterisks indicate statistical significance where: * p-value <= 0.05, ** p-value <= 0.01, and *** p-value <= 0.001.

exceeded 1°F. The WBGT differences at the Lucinda CoolSeal site were more complex (**Figure 19**). A statistically significant increase in the WBGT occurred on June 17th between 4:00 pm and 5:00 pm. Specifically, the mean WBGT observed at the cool pavement site was 1.7°F higher than the control, which was the second largest WBGT increase documented in the study. Interestingly, the WBGTs were marginally (0.1°F - 0.5°F) lower at the Lucinda cool pavement for the remaining three daytime analysis periods, although these reductions were not statistically significant.

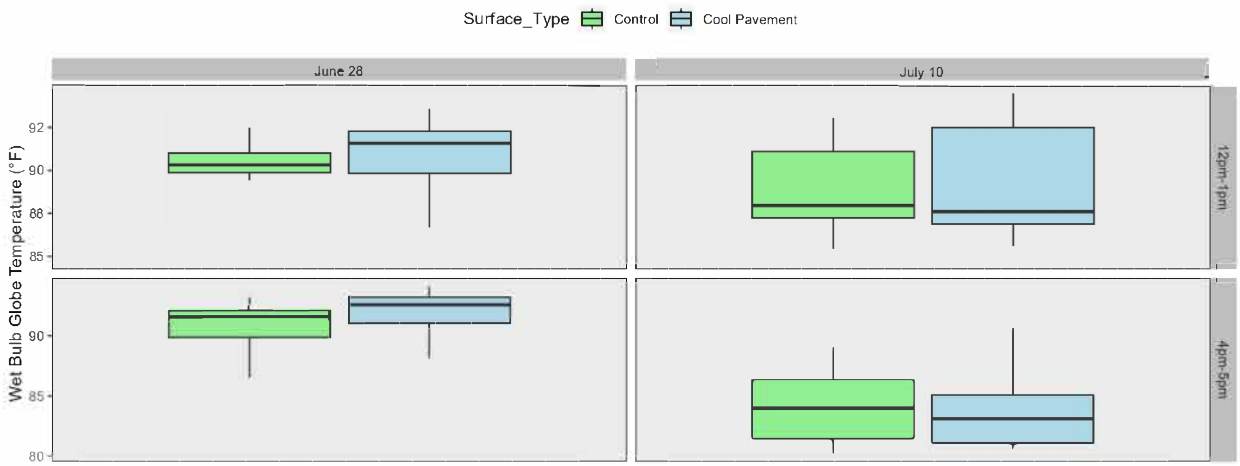


Figure 18. WBGT differences for the CoolSeal site at Piper Dr. by day and time. The asterisks indicate statistical significance where: * p-value <= 0.05, ** p-value <= 0.01, and *** p-value <= 0.001.

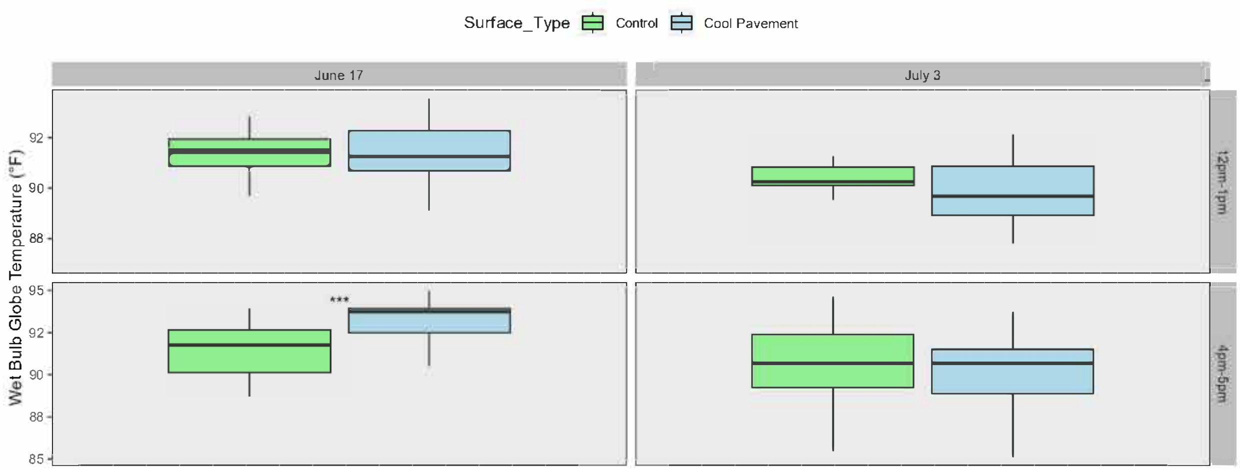


Figure 19. WBGT differences for the CoolSeal site at Lucinda by day and time. The asterisks indicate statistical significance where: * p-value <= 0.05, ** p-value <= 0.01, and *** p-value <= 0.001.

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 highest albedo of the cool pavement products. Specifically, the cool pavement at Mountain Star reflected 29% of the shortwave radiation, which was almost five times greater than the albedo of the control site. The albedo of the Mountain Star cool pavement increased by 0.01 relative to the 2023 baseline value. This suggests that at least within a year there is minimal deterioration in the reflective properties of SolarPave. The marginal increase may have been attributable to rain cleaning the cool pavement surface prior to visiting the site in 2024. The control albedo decreased notably to 0.06 in 2024 due to the application of the asphalt slurry, which certainly contributed to the larger average surface temperature reductions documented at Mountain Star in 2024 relative to 2023.

The second highest cool pavement albedo was observed for the Piper Dr. CoolSeal site. The CoolSeal product reflected 20% of the incoming shortwave radiation. This was double the albedo value of the control surface, which was relatively fresh asphalt. Since Piper Dr. was not included in the 2023 study, no temporal comparisons were available. The lowest cool pavement albedo occurred at Carol Crest. The Durashield product exhibited an albedo of 0.15, which was 0.03 lower than when the product was evaluated in 2023. This highlights a marginal reduction in the reflective characteristics of the Durashield product over time. The Carol Crest control site albedo was much lower in 2024, which again highlighted the impact of the asphalt slurry applications on road reflectivity.

The control sites generally exhibited lower albedo values in 2024 and were within the typical range for fresh asphalt.[5] This suggests that cool pavement may have a greater impact on solar reflectivity and surface temperatures if it is applied to fresh asphalt surfaces rather than worn streets that often have albedo values that are generally similar to cool pavement surfaces.

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. When available, values from 2023 are reported in parentheses.

	Mountain Star (SolarPave)	Piper Dr. (CoolSeal)	Carol Crest (Durashield)
Cool Pavement	0.29 (0.28)	0.20	0.15 (0.18)
Control	0.06 (0.22)	0.10	0.08 (0.16)

4.7 RADIATION BUDGET DIFFERENCES

The results for the individual components of the net radiation budget generally aligned with the surface temperature and albedo measurements. At Mountain Star, the incoming shortwave radiation peaked at approximately 900 W/m^2 on both August 29th when the cool pavement was evaluated and August 30th when data was collected at the control site (**Figure 20**). The noise observable in the diurnal pattern for both days is likely attributable to cloud coverage obstructing a portion of the incoming sunlight. The outgoing shortwave radiation was much greater at the cool pavement site (269 W/m^2 vs 51 W/m^2) during the afternoon due to the high albedo of the surface. Additionally, the outgoing longwave radiation observed for the cool pavement was 75 W/m^2 lower than the control, which reflects the lower surface temperatures of the SolarPave product relative to the fresh asphalt slurry. A lower net radiation flux was also exhibited by the cool pavement surface.

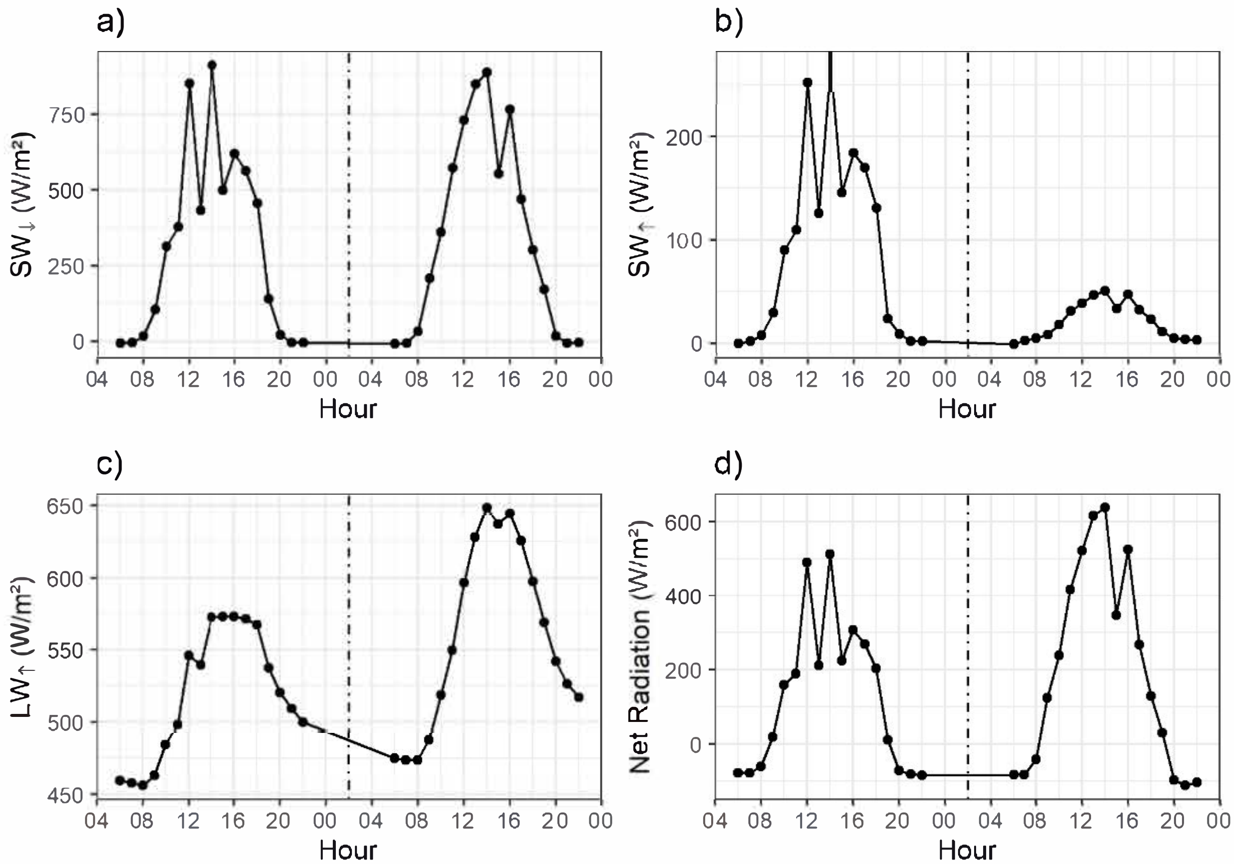


Figure 20. The a) shortwave incoming, b) shortwave outgoing, c) longwave outgoing, and d) net radiation budget at Mountain Star for August 29th and August 30th from the SolarPave cool pavement site (left of dotted line) and control site (right of dotted line).

The incoming shortwave radiation at Piper Dr. was very similar each day and not heavily influenced by cloud coverage (**Figure 21**). This suggests that the days were comparable, which was also supported by the data from the KSAT ASOS (**Figure 8**). Similar to Mountain Star, a higher flux of outgoing shortwave radiation was observed for the CoolSeal cool pavement relative to the fresh asphalt control. The reflected shortwave peaked at 172 W/m^2 for the cool pavement site in the afternoon but only reached 85 W/m^2 at the control, which was expected given the notable albedo differences between the surfaces. The outgoing longwave radiation and net radiation balance were also lower for the Piper Dr. cool pavement relative to the control.

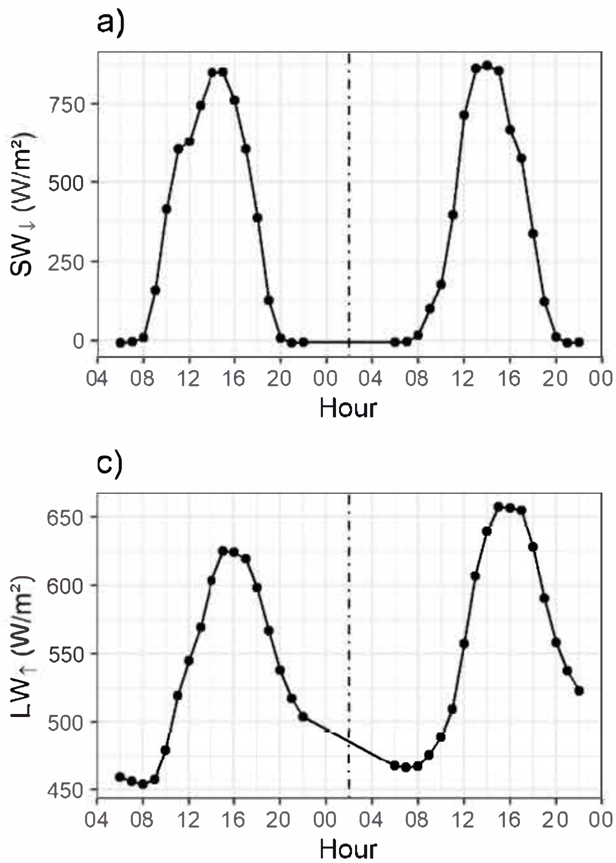


Figure 21. The a) shortwave incoming, b) shortwave outgoing, c) longwave outgoing, and d) net radiation budget at Piper Dr. for September 12th and September 13th from the CoolSeal cool pavement site (left of dotted line) and control site (right of dotted line).

The Carol Crest study days displayed more substantial differences between the cool pavement site visit on September 5th and the control site visit on September 6th (**Figure 22**). September 5th was the coolest day included in Phase II, which was partly explained by the low incoming shortwave radiation flux that never exceeded 700 W/m^2. When data collection occurred at the control site the following day, temperatures were warmer and the incoming solar radiation reached 843 W/m^2 in the afternoon. Despite the higher incoming solar radiation flux at the control site, the outgoing shortwave radiation flux was 31 W/m^2 greater for the Durashield cool pavement due to the higher albedo of the surface relative to the asphalt slurry. A similar pattern was observed for the outgoing longwave radiation as the cool pavement flux maximum was only 563 W/m^2 while the control flux peaked at 615 W/m^2 due to the warmer surface temperatures. Finally, the net radiation was also lower for the Carol Crest cool pavement site relative to the control.

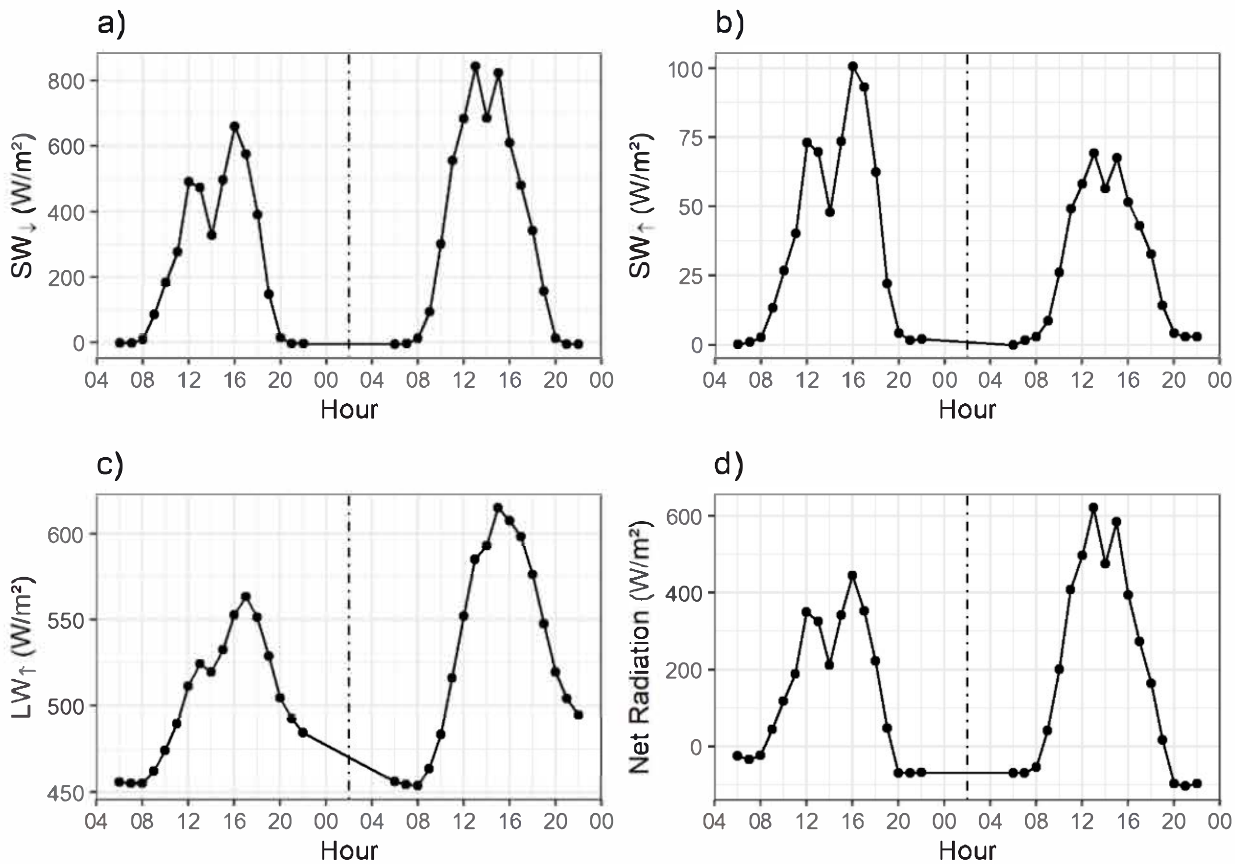


Figure 22. The a) shortwave incoming, b) shortwave outgoing, c) longwave outgoing, and d) net radiation budget at Carol Crest for September 5th and September 6th from the Durashield cool pavement site (left of dotted line) and control site (right of dotted line).

5. DISCUSSION AND CONCLUSIONS

Overall, the findings highlighted a clear potential for cool pavement to reduce surface temperatures. This was particularly true when comparing the SolarPave and CoolSeal products at Mountain Star and Piper Dr. to the fresh asphalt surfaces. At these sites, daytime surface temperatures were over 10°F lower for the cool pavement, which was a much more notable surface temperature reduction relative to the findings from 2023. 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. There was some evidence that air temperatures were lower at the majority of the cool pavement sites in the morning and at night, but the magnitude of this reduction was less than 0.5°F. Very few significant differences were observed for the WBGT.

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 visibility, which warrant consideration when deciding if/where to install cool pavement.

Three of the questions posed at the end of the 2023 report were clarified through the continued monitoring of the cool pavement in 2024.

1. **What is the most appropriate control surface against which cool pavement performance should be evaluated?** Since several of the control sites were resurfaced with an asphalt slurry between the 2023 and 2024 field campaigns, the impact of the control site surface characteristics on the results has been more explicitly quantified. For surface temperatures, the decreases were roughly twice as large when comparing against fresh asphalt control surfaces in 2024 relative to the worn control streets in 2023. Interestingly, the larger surface temperature reductions yielded only a small change in the morning and night air temperature reductions, which increased to -0.3°F in 2024 from -0.1°F in 2023. The differences in the control site surface characteristics also did not produce more notable contrasts in the WBGT.

2. **What is the long-term durability of cool pavement?** The monitoring of several cool pavement locations in 2023 and 2024 provided initial insights into the durability of the cool pavement performance over time. Although there are certainly concerns that the light-colored cool pavement surfaces could become dirty and worn, which would reduce the albedo values, this was not observed in the data. The albedos calculated in 2024 were generally similar to those documented in 2023. Although a formal durability assessment was beyond the scope of this study, issues with cracking and peeling of the SolarPave product were observed particularly at SW 21st St. This might be attributable to the higher traffic volume and greater speed of travel on SW 21st St. relative to Mountain Star.

3. **How does the CoolSeal (GuardTop) product perform in San Antonio?** Due to installation challenges encountered in 2023, 2024 was the first year that the CoolSeal product by GuardTop was evaluated. The CoolSeal product exhibited a higher albedo than the Durashield and PlusTi materials. Robust surface temperature reductions were observed when comparing the CoolSeal with fresh asphalt at Piper Dr. However, this was not the case at Lucinda where the control

street was worn and displayed lower surface temperatures during the daytime relative to the cool pavement.

Despite these additional insights, there are still several questions that remain and likely warrant additional investigation.

1. **Is the modest impact of cool pavement on air temperature a matter of scale?** The cool pavement installations evaluated in the 2024 study ranged from one to three 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. For example, the cool pavement installations in September and October 2024, which were not included in this study, might have a greater impact on air temperature since they often incorporated several neighboring streets.

2. **Would a more controlled testing design be informative?** A difference of differences approach would perhaps more comprehensively control for the vast array of confounding factors that complicated comparisons between the sites and the different cool pavement products. In this experimental design, the cool pavement site and control site are visited prior to the cool pavement installation to quantify the baseline differences in the micro-meteorological conditions. After the cool pavement is installed, the cool pavement and control site differences are again quantified. The difference between the differences before and after the cool pavement installation would provide a more direct and explicit causal connection between the presence of cool pavement and temperature changes. Obviously, this approach would require high levels of coordination between COSA and UTSA.

3. **What is the most beneficial order of operations?** Since the cool pavement installation process has been connected to the broader road maintenance schedule, a pattern has emerged where adjacent and nearby roads are undergoing construction, maintenance, or rehabilitation after the cool pavement has been installed. This may reduce the longevity of the cool pavement since heavy equipment is often staged on the cool pavement surface. Additionally, asphalt deposits and black tire markings from the fresh paving have been observed on several of the cool pavement surfaces. A more optimal order of operations for preserving the cool pavement surface might be to install the cool pavement last after any other scheduled road work is performed in the neighborhood.

Ultimately, a multifaceted approach that combines innovative technologies with nature-based solutions will likely be necessary to mitigate the negative impacts of urban heat extremes because of the scale and dynamic nature of heat hazards. 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 program 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.

REFERENCES

1. Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108(455), 1–24.

2. U.S. Environmental Protection Agency (2012). "Cool Pavements." In: Reducing Urban Heat Islands: Compendium of Strategies. Available Online: https://www.epa.gov/heat-islands/heat-island-compendium.

3. City of San Antonio (Accessed 2023). Cool Pavement Program. Available Online: https://www.sanantonio.gov/PublicWorks/Projects/Cool-Pavement-Program#:~:text=The%20water%2Dbased%20asphalt%20treatment,is%20compatible%20with%20traditional%20asphalt.

4. Schneider, F. A., Ortiz, J. C., Vanos, J. K., Sailor, D. J., & Middel, A. (2023). Evidence-based guidance on reflective pavement for urban heat mitigation in Arizona. *Nature Communications*, 14(1), 1467.

5. Middel, A., Turner, V.K., Schneider, F.A., Zhang, Y., & Stiller, M. (2020). Solar reflective pavements—A policy panacea to heat mitigation? *Environmental Research Letters*, 15, 064016.

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 Lucinda 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 Piper Dr. cool pavement installation as well as the cool pavement testing site and control testing sites.

Figure A5. 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).

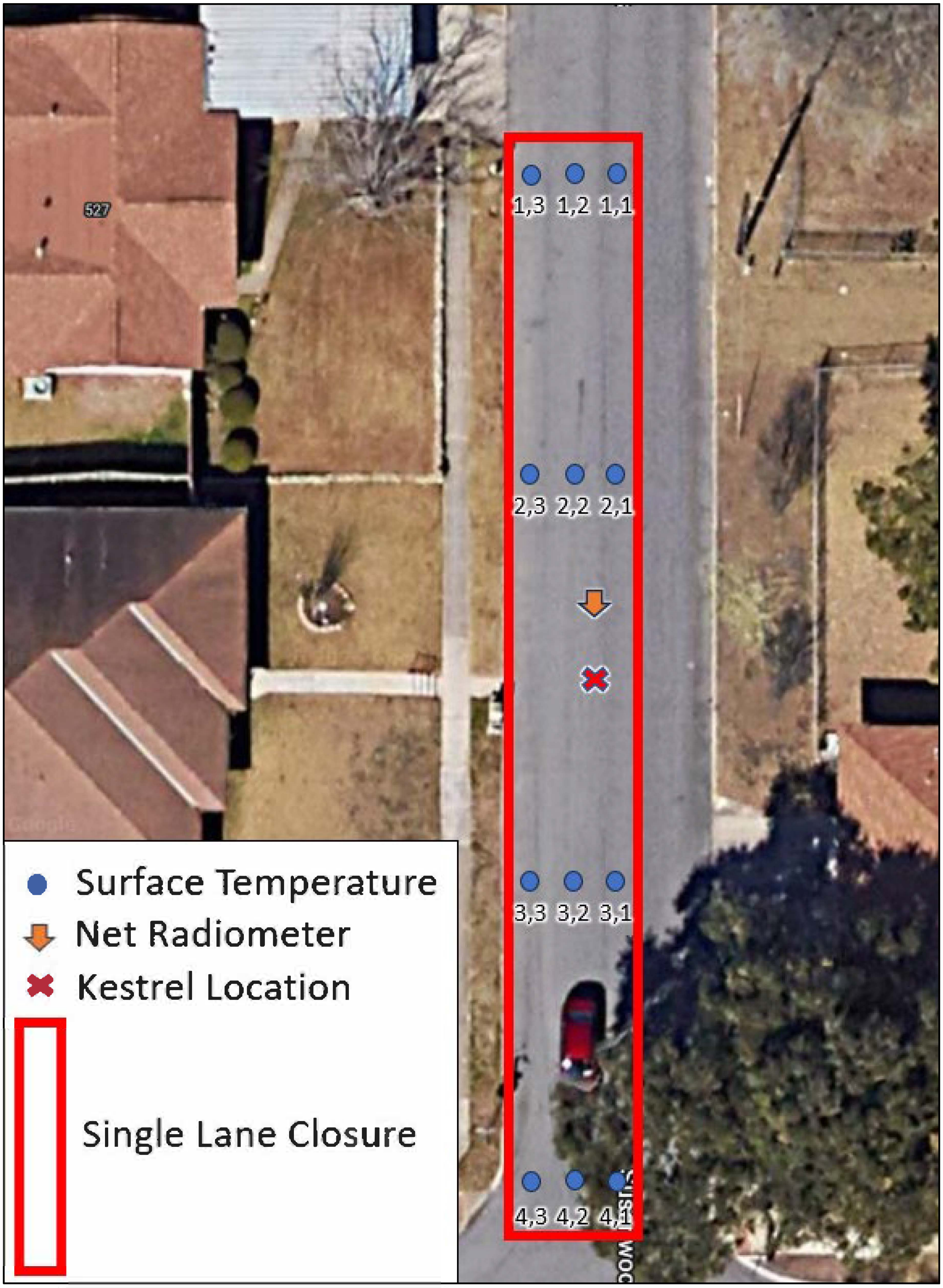


Figure B2. Fieldwork data collection schematic for the Carol Crest control site showing the surface temperature grid and Kestrel location during Phase I and the net radiometer location during Phase II (Imagery Source: Google Maps).

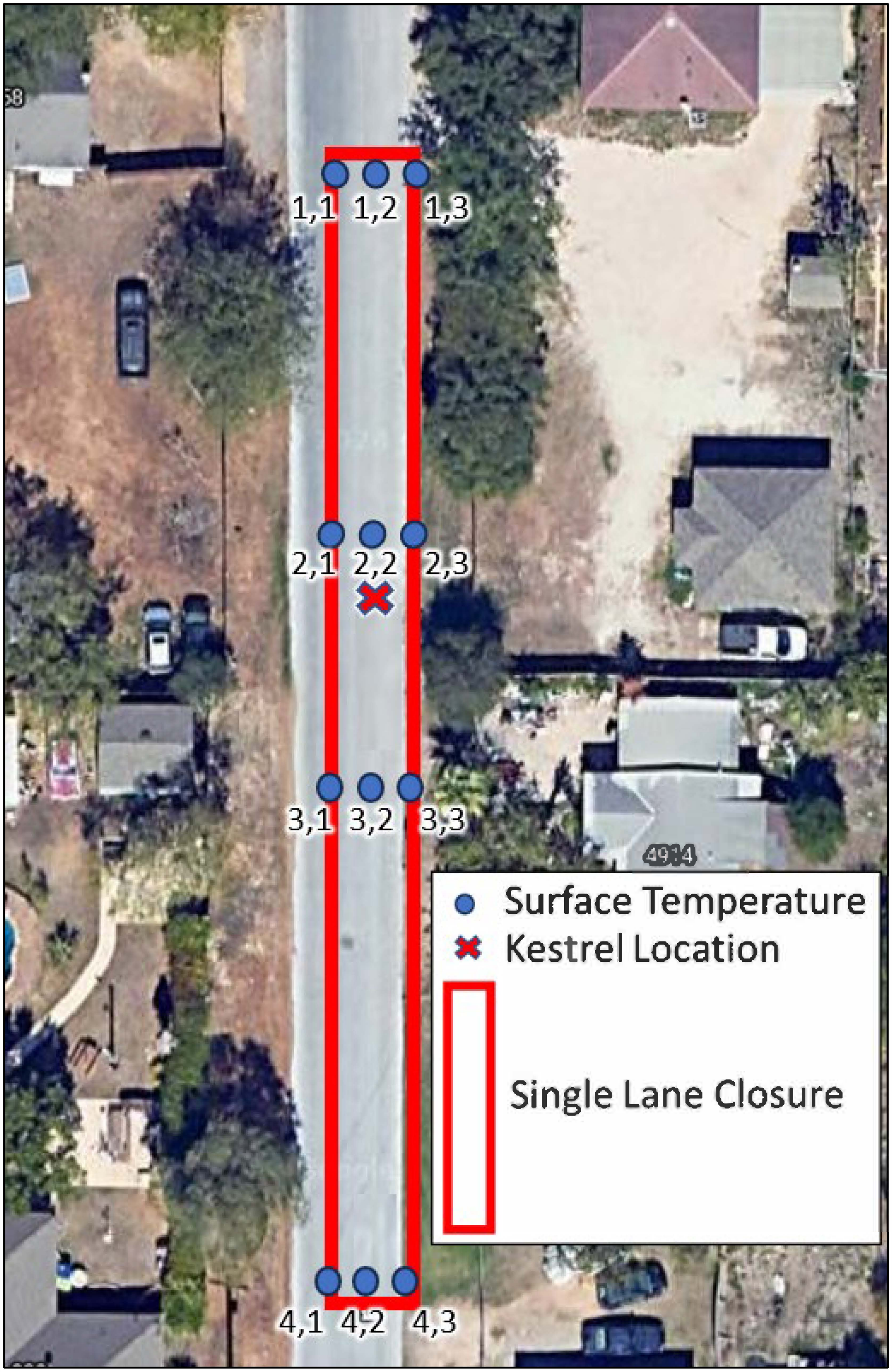


Figure B3. Fieldwork data collection schematic for the Lucinda cool pavement site showing the surface temperature grid and Kestrel location during Phase I (Imagery Source: Google Maps).

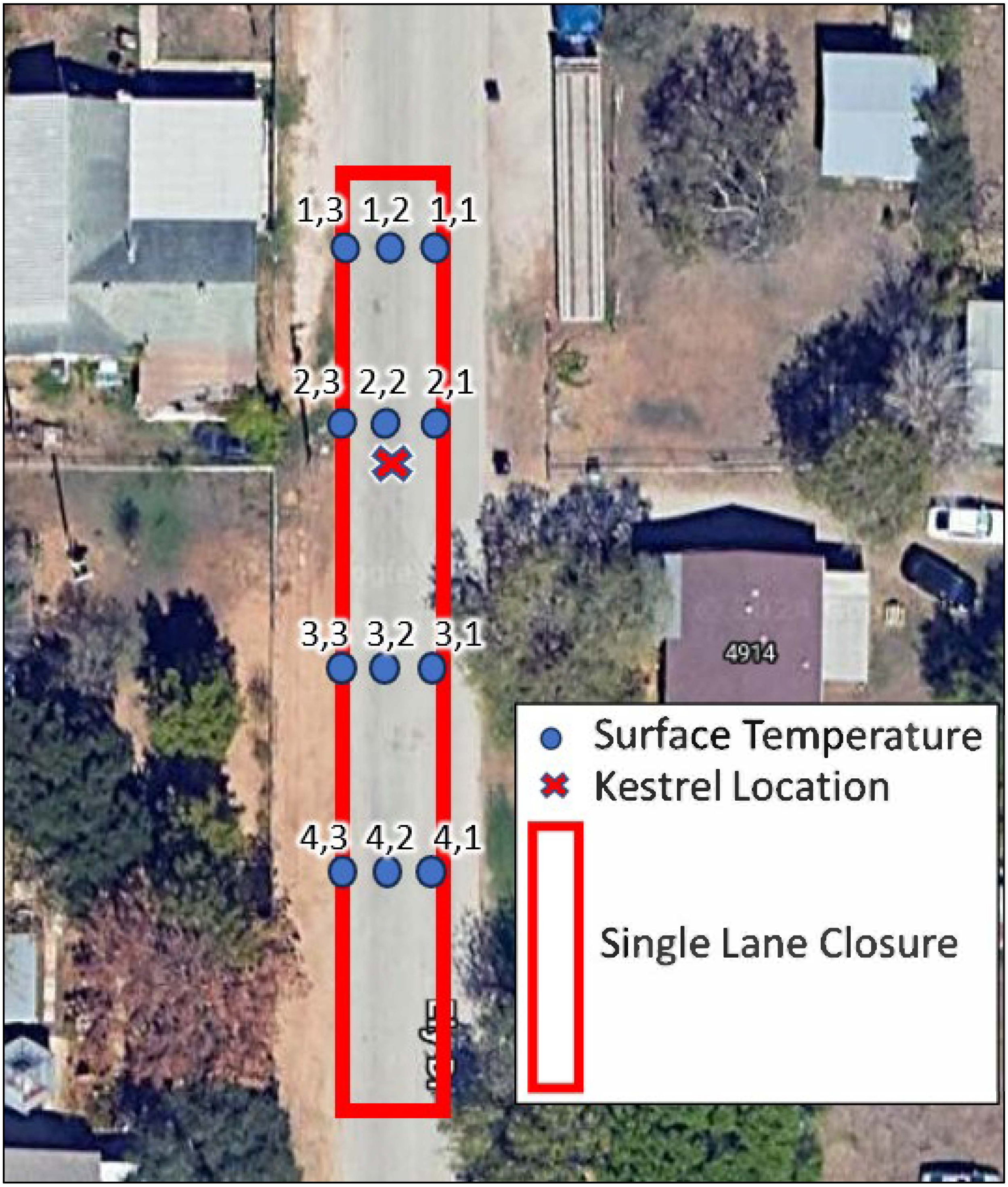


Figure B4. Fieldwork data collection schematic for the Lucinda control site showing the surface temperature grid and Kestrel location during Phase I (Imagery Source: Google Maps).

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).

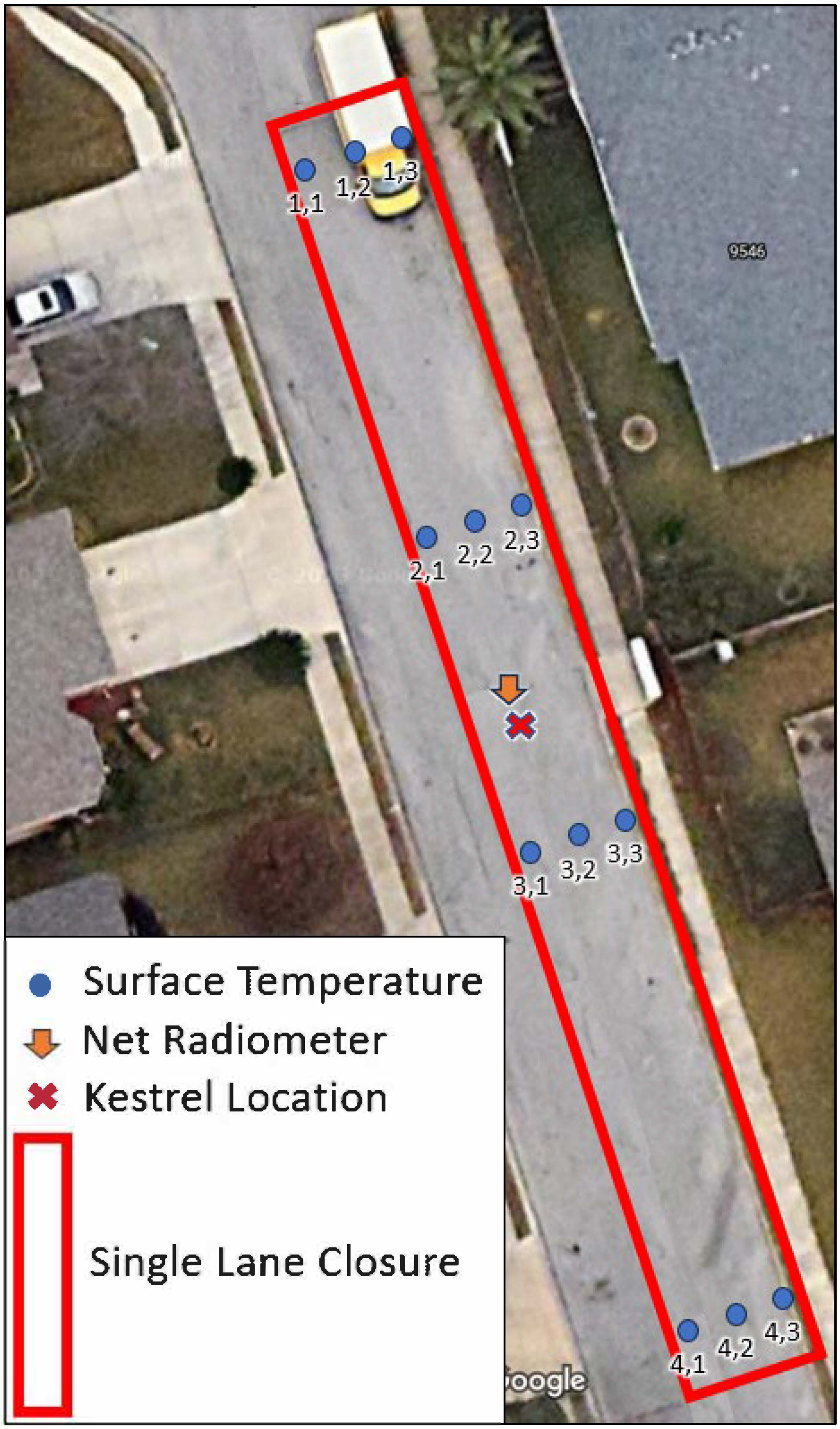


Figure B6. Fieldwork data collection schematic for the Mountain Star control site showing the surface temperature grid and Kestrel location during Phase I and the net radiometer location during Phase II (Imagery Source: Google Maps).

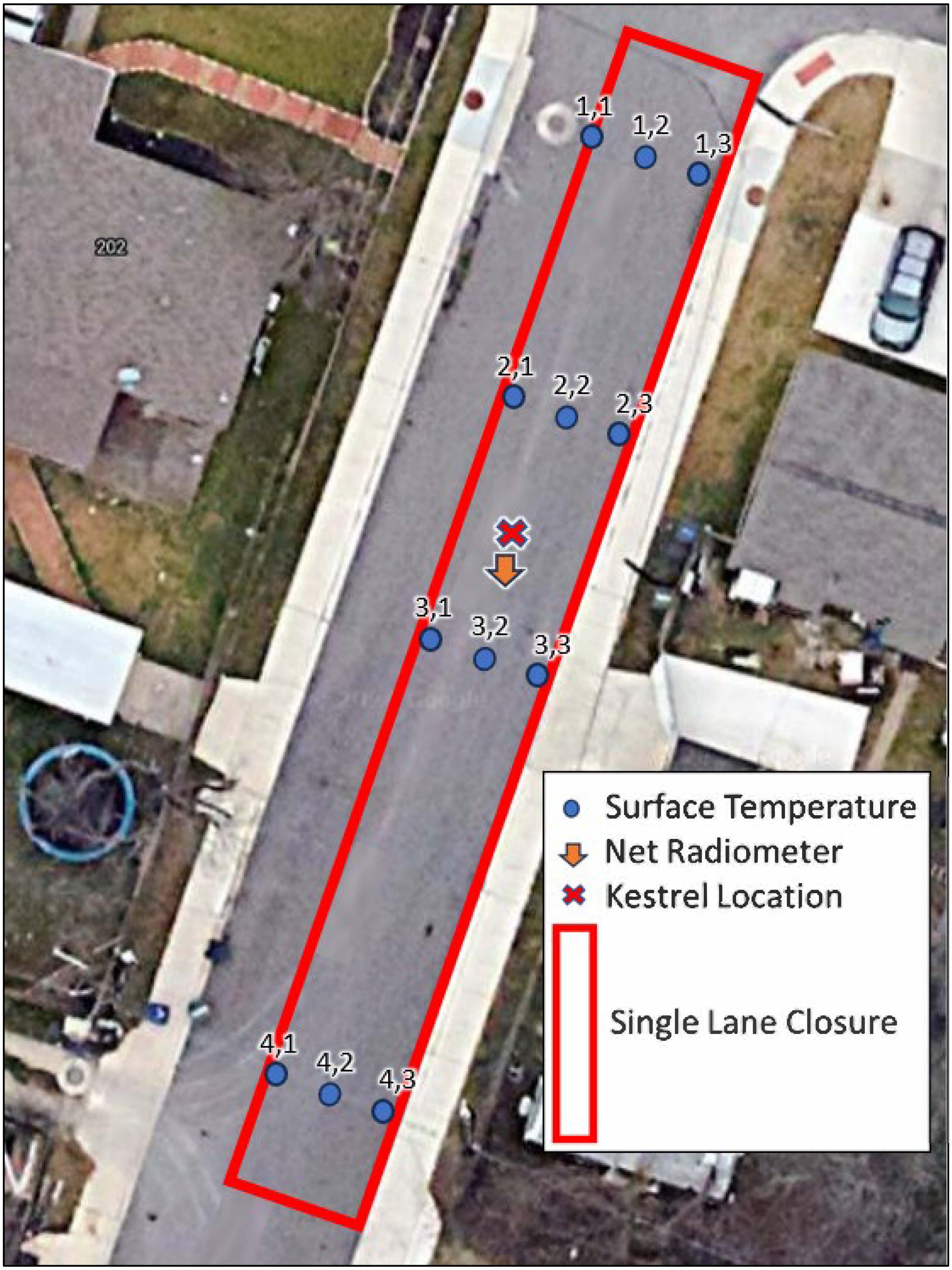


Figure B7. Fieldwork data collection schematic for the Piper Dr. cool pavement site site showing the surface temperature grid and Kestrel location during Phase I and the net radiometer location during Phase II (Imagery Source: Google Maps).

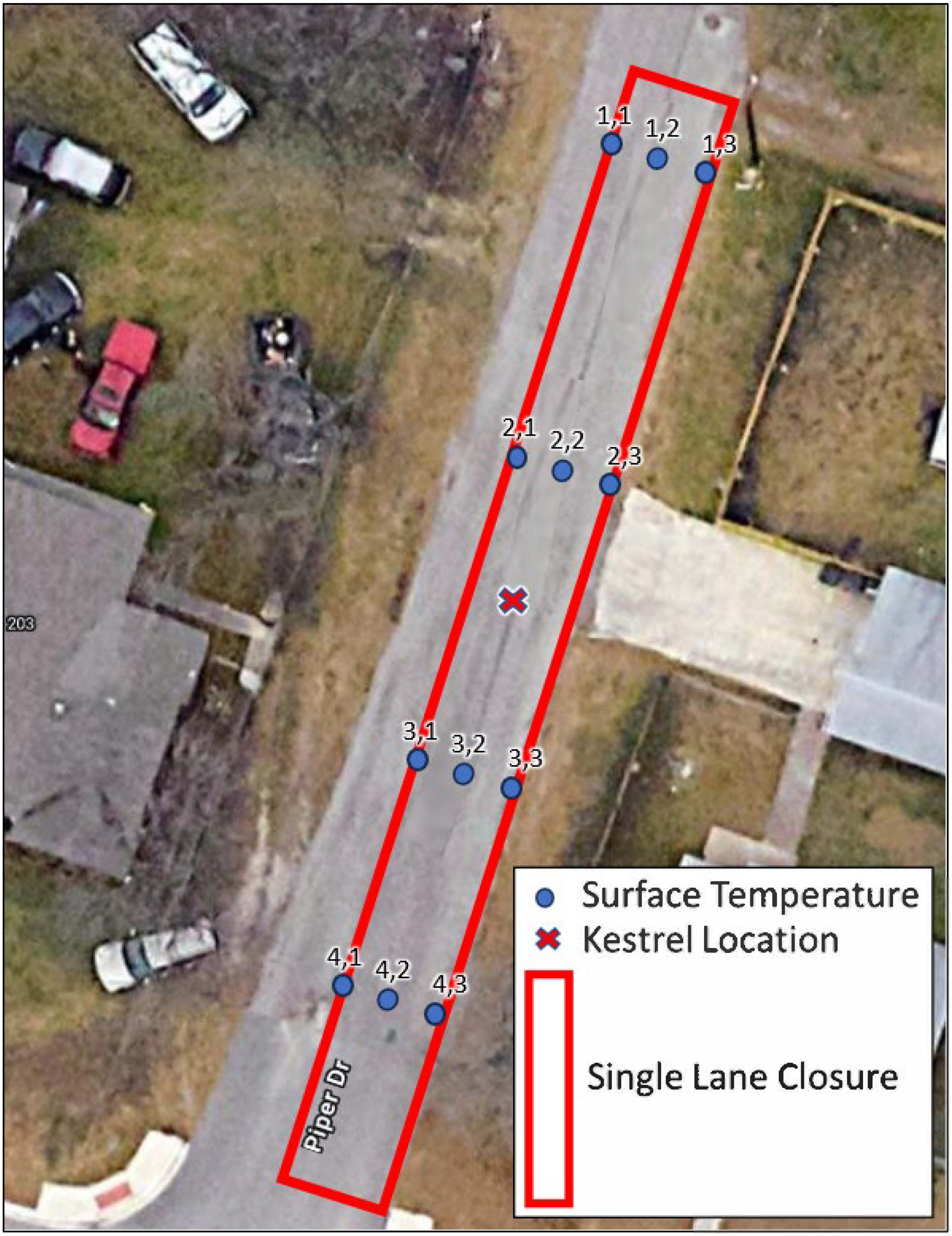


Figure B8. Fieldwork data collection schematic for the Piper Dr. control site site showing the surface temperature grid and Kestrel location during Phase I (Imagery Source: Google Maps).

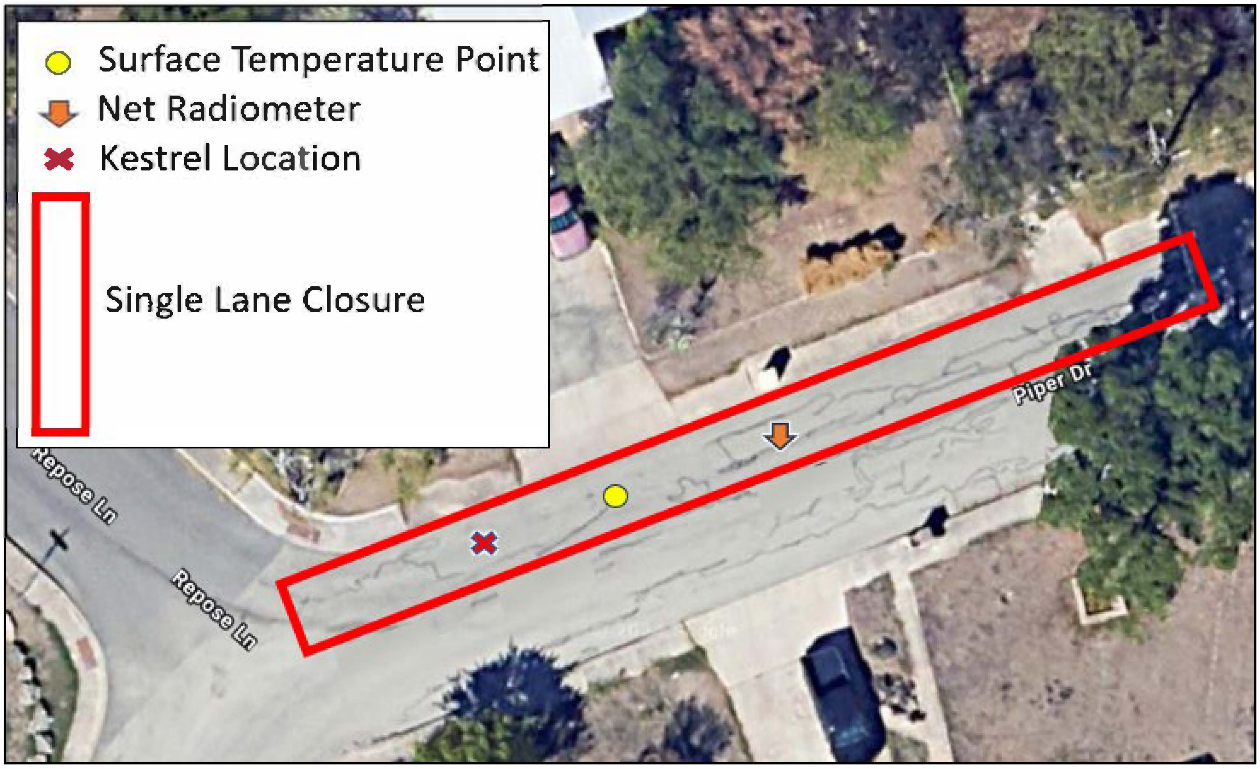


Figure B9. Fieldwork data collection schematic for the Piper Dr. control site showing the net radiometer, surface temperature point, and Kestrel location during Phase II (Imagery Source: Google Maps).

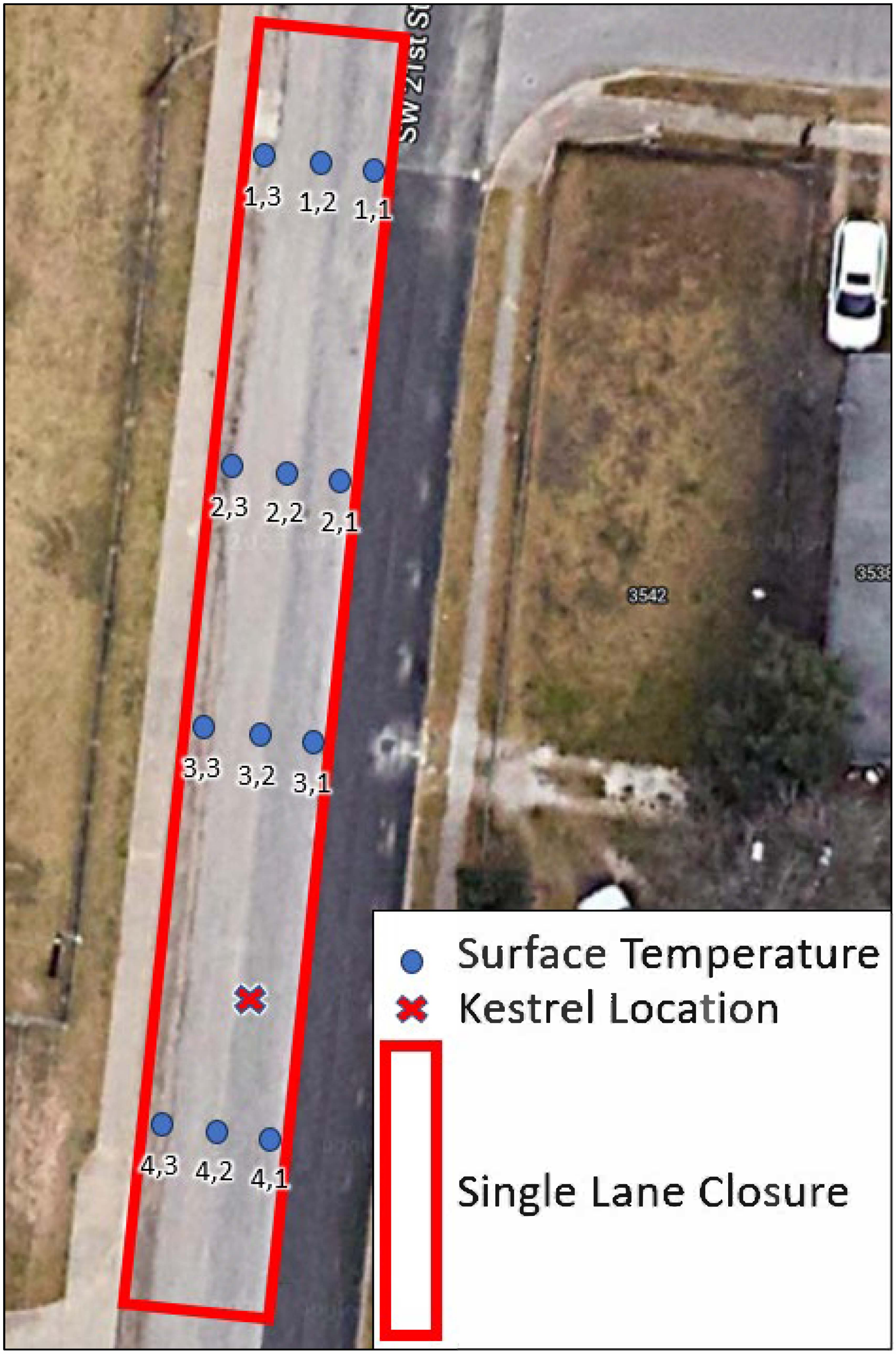


Figure B10. Fieldwork data collection schematic for the SW 21st St. cool pavement site showing the surface temperature grid and Kestrel location during Phase I (Imagery Source: Google Maps).

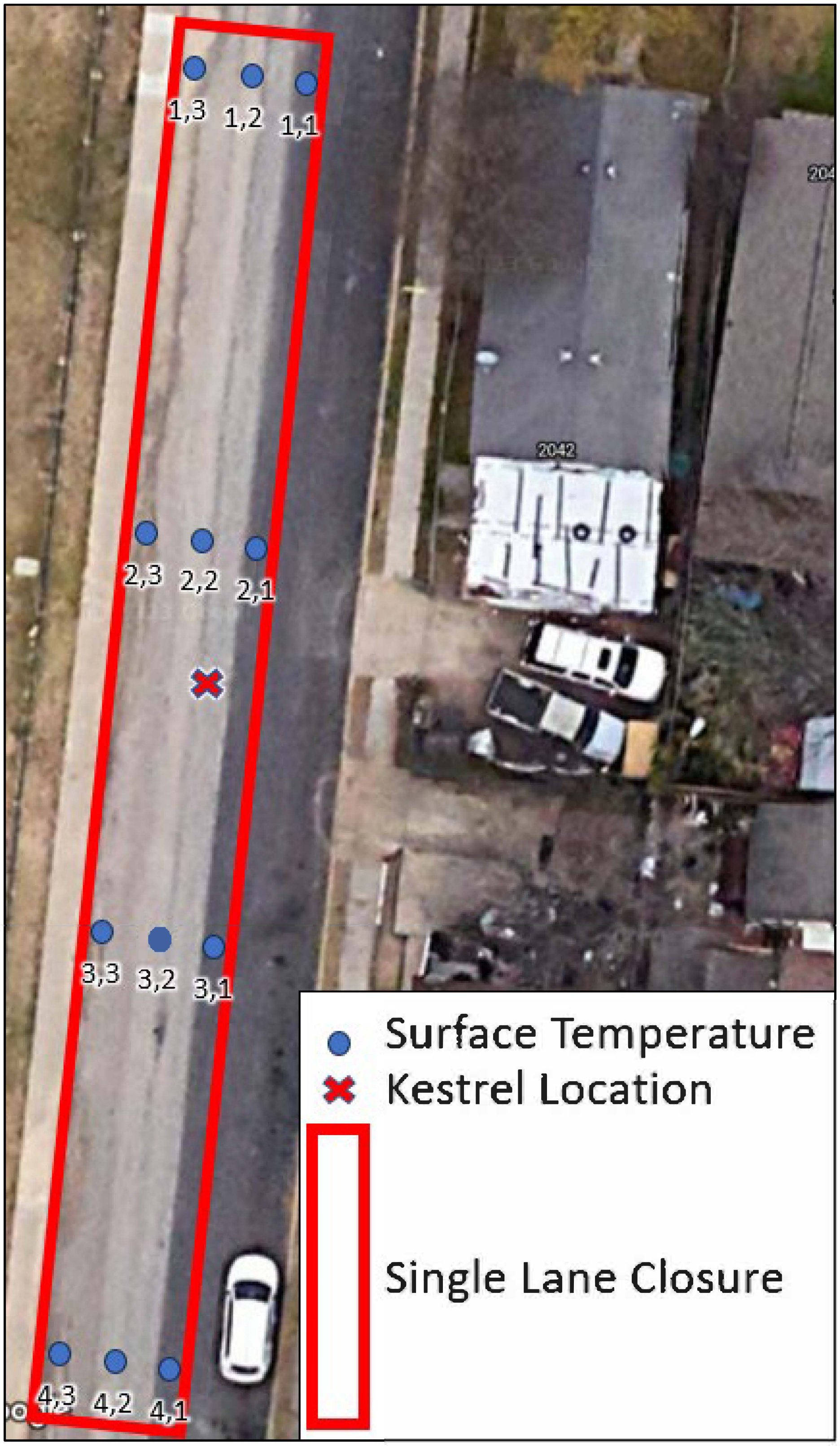


Figure B11. Fieldwork data collection schematic for the SW 21st St. control site showing the surface temperature grid and Kestrel location during Phase I (Imagery Source: Google Maps).

APPENDIX C: CHARACTERISTICS OF COOL PAVEMENT SURROUNDINGS

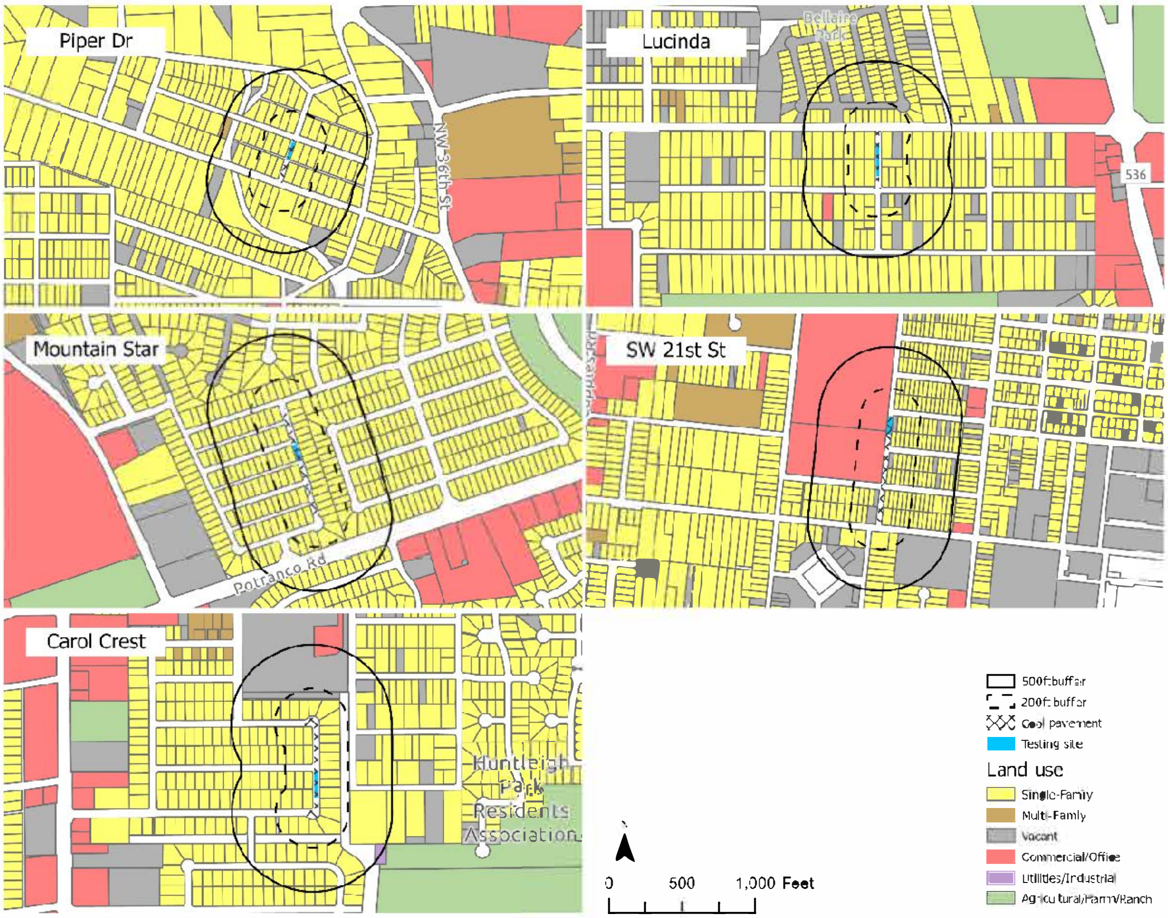


Figure C1. Land use surrounding each cool pavement installation.

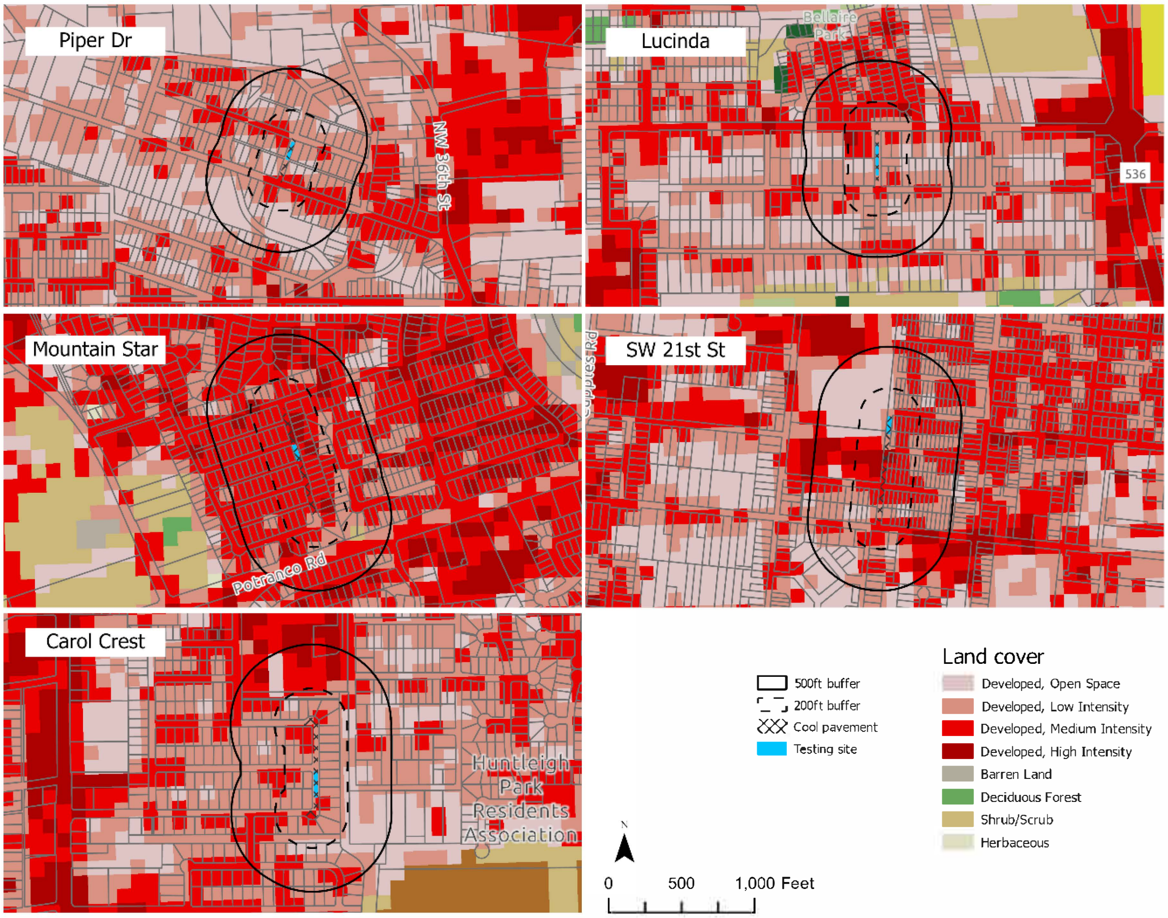


Figure C2. Land cover surrounding each cool pavement installation.

Figure C3. Tree canopy surrounding each cool pavement installation.

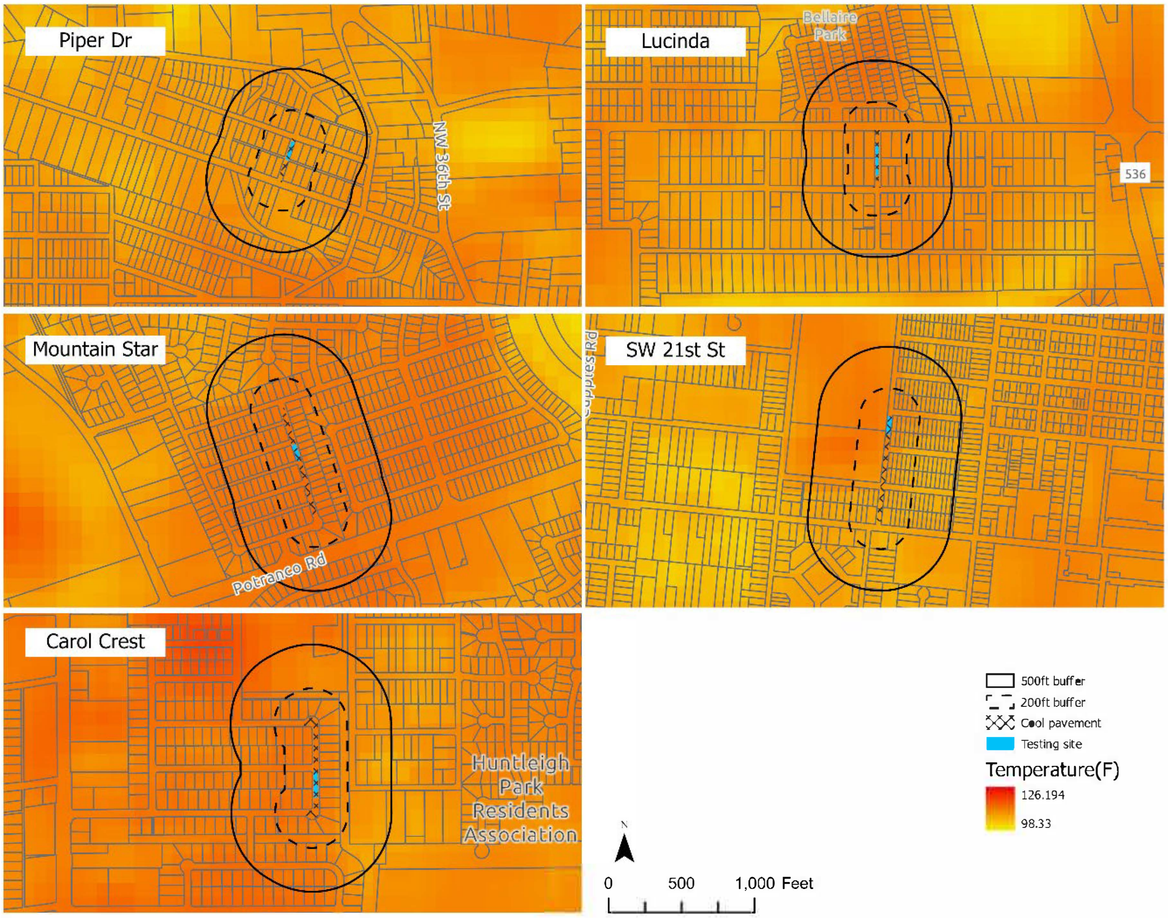


Figure C4. Surface temperature surrounding each cool pavement installation.