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CAPSTONE PROJECT REPORT

UCLA Institute of Transportation Studies

Cool Pavement Evaluation

Sun Valley, Los Angeles

Project Lead: Falak Fatima Zaidi
Faculty Advisor: Dr. V. Kelly Turner
Client: Bureau of Street Services, Los Angeles (StreetsLA)

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16. Abstract

In recent years, the City of Los Angeles has been leading the efforts to combat Urban Heat. In particular, the City outlined a goal of reducing the urban-rural temperature differential by 3°F by 2035 (Sustainable City pLAn, 2015). To achieve this goal, the Bureau of Street Services (StreetsLA), initiated the installation of solar reflective 'Cool Pavements' across fifteen City Council Districts. The report draws upon three empirical research methods to examine the thermal comfort of the novel Cool Pavements Project in the Sun Valley neighborhood in Los Angeles. For this study, Sun Valley site was selected because the area received three different treatments of the Cool Pavements, and has a patch of regular asphalt pavement within the same neighborhood block.

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This work is dedicated to my father.

Disclaimer

This report was prepared in partial fulfillment of the requirements for the Master in Urban and Regional Planning degree in the Department of Urban Planning at the University of California, Los Angeles. It was prepared at the direction of the Department and of Bureau of Street Services, Los Angeles (StreetsLA) as a Planning Client. The views expressed herein are those of the authors and not necessarily those of the Department.

Cool Pavement Evaluation: Sun Valley, Los Angeles

UCLA Institute of Transportation Studies

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Executive Summary

In the absence of effective adaptation measures, exposure to prolonged heat will increase in frequency, duration, and intensity with continued urbanization and climate change (Jones et al., 2015). These multifold aspects of heat exposure are more pronounced in the urban areas, like Greater Los Angeles than surrounding undeveloped areas. Consequently, for cities like Los Angeles, urban heat is becoming an invisible environmental hazard that poses a growing threat to human health and wellbeing (Matthews T et al., 2017). In recent years, the City of Los Angeles has been leading the efforts to combat Urban Heat. In particular, the City outlined a goal of reducing the urban-rural temperature differential by 3°F by 2035 (Sustainable City pLAn, 2015). To achieve this goal, the Bureau of Street Services (StreetsLA), initiated the installation of solar reflective 'Cool Pavements' across fifteen City Council Districts. This report draws upon three empirical research methods to examine the thermal comfort of the novel Cool Pavements Project in the Sun Valley neighborhood in Los Angeles. For this study, Sun Valley site was selected because the area received three different treatments of the Cool Pavements, and has a patch of regular asphalt pavement within the same neighborhood block.

In a physical environment, any object reacts to both convective and radiant thermal energy. The thermal energy exchange between the object and surrounding air by convection and with the surrounding surface by conduction creates Air Temperature (T_{AIR}) and Surface Temperature (T_{SURF}), respectively. Further, if the thermal energy gets radiated in the form of short-wave and long-wave radiations, from the surface, the net heat gain or loss is defined as Mean Radiant Temperature (T_{MRT}). Thermal comfort is an interactive experience between environmental factors and personal conditions- physical, physiological, and socio-psychological. While physiological and socio-physiological conditions are based on the human body's interaction with the social environment. The parameters for the physical conditions depend on the variables like T_{AIR}, T_{SURF}, T_{MRT}, and Air Humidity.

For thermal comfort, Mean Radiant Temperature (T_{MRT}) and Air Temperature (T_{AIR}) are the two meteorological variables that are relevant to a person's weather experience (Höppe P. et al., 1999; Krüger, E.L. et al., 2010). Therefore, to analyze the impact of the Cool Pavements on human thermal comfort, this study examined three variables T_{AIR}, T_{SURF}, and T_{MRT}. To document variations in these variables, this study used field observations using Kestrel measuring device and micro-climate modeling simulation in ENVI-met for 'At-Present' surface coating at the study site. Along with the 'At-Present' scenario, for comparative analysis, a microclimate simulation with regular asphalt pavement for the complete study area was also modeled in ENVI-met. To study the impact of Cool Pavements during a typical summer period, the simulation input data for the mid of August was used. Furthermore, a questionnaire survey was conducted to assess the impact of reflective pavements on the lifestyle of the residents.

The 12-hour field data collected in mid of November 2019, indicates the absence of any substantial significant differences in T_{MRT} of the four pavement types. The T_{MRT} reading of all three shades of Cool Pavements and asphalt surface, more or less, showed a similar pattern. However, the study's potential limitations were the limited timeframe for this project; the field data were collected in one day in the fall season. Besides the restricted time frame, the heat measurement data was collected using the Kestrel device, which is a comparatively, less sensitive measurement device than MaRTy. Similar to the field data, while interpolating T_{AIR} for the entire study area for August 2019, the 24-hour micro-climate simulations showed that the regular asphalt pavement recorded higher T_{AIR} than the Cool Paved streets. In contrast, the simulation output also showed that the Cool Pavements recorded higher T_{MRT} than in the scenario with the regular asphalt pavements. This result may be attributed to the higher reflectance value or albedo of the Cool Pavements, in comparison to the regular pavements. However, due to the lack of material heat storage in ENVI-met, the simulation output leads to an overestimation of the longwave radiation emitted by walls during the daytime (M. Nikolopoulou M. et al. (2001). Lastly, the questionnaire survey results indicate that thirteen out of the twenty participants found the experience while using the open spaces as either cooler or felt freshness and tranquility.

In conclusion, more field investigations are needed to verify the generality and validity of these results for other locations and climatic conditions. As noted previously in the limitations of the field and the micro-climate stimulating study, future experiments should focus on similar inclusive research models, conducted over a more extended study period. Future research models should include the following methods:

1. An annual multi-season field observation should be collected using a more sensitive measurement device- MaRTy.
2. The micro-climate simulation modeling experiments need to investigate the combined impact of variations related to adding shade trees on sidewalks, cool roofs, and the Cool Pavements. The simulation input model should extrapolate the cool or reflective coatings over larger street networks and areas.
3. Along with comparing the Cool Pavements with the regular pavements, the study should also measure the differences within each variation of Cool Pavements over an extended period, which otherwise did not get called out in the responses of the residents.


2

Background

By mid-century, in Los Angeles, the annual number of days with maximum temperature above 95°F would increase from 1.4 days to 10.2 days (Hall et al., 2015). This dramatic jump in heat days, as shown in **Figure 1**, is based on current greenhouse gas emissions projections. The Hall study demonstrated that Urban Heat will become an increasingly salient issue in the region and that the interventions could potentially moderate those heat increases. In fact, by the end of the century, interventions can reduce the average temperatures from the projected 8.2°F to just 3°F.

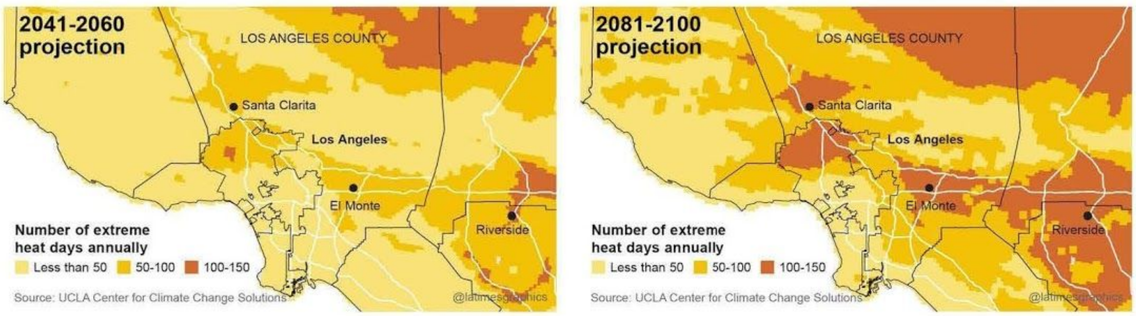

Figure 1- Los Angeles neighborhoods, like Sun Valley, are expected to see an increased number of heat days.

Los Angeles, like cities throughout the world, is experiencing the dual pressures of climate change and the Urban Heat. The Greater Los Angeles area is roughly six degrees warmer than the surrounding areas (Lei Zhao et al., 2014). The difference in temperatures is due to the Urban area Island (UHI) phenomenon. UHI elevates afternoon and evening temperatures compared to surrounding undeveloped regions (Oke, 1982).

The elevated UHI levels have a significant impact on human health and thermal comfort, especially on the pedestrians (Elnabawi, M.H. et al., 2019). Thermal comfort is a subjective integrated response caused by the combined effect of atmospheric conditions and physical, physiological, psychological, and behavioral factors (Johansson et al., 2014). The thermal discomfort and heat stress may lead to more severe health problems, especially among the vulnerable population. However, it is comparatively harder to assess thermal comfort, especially outdoor thermal comfort, as they are less stable than the indoor conditions. The outdoor thermal comfort needs to be investigated in the context of the urban form of the physical infrastructure, surface materials, and landscapes. These urban form elements create local scale and microscale climates that vary widely across space and time (Middel et al., 2014). In a physical environment, any object reacts to both convective and radiant thermal energy. The thermal energy exchange between the object and surrounding air by convection and with the surrounding surface by conduction creates Air Temperature (T_{AIR}) and Surface Temperature (T_{SURF}), respectively. Evaluating human thermal comfort is often associated with variation in the Air Temperatures (T_{AIR}), but multiple studies have found that it is better associated with Mean Radiant Temperature (T_{MRT}) (Höppe P. et al., 1999; Krüger, E.L. et al., 2010). Mean radiant temperature (T_{MRT}) is a critical metric for human thermal comfort, that aggregates the shortwave and longwave radiation flux to which a body is exposed (Thorsson S. et al., 2014). Urban heat mitigation interventions influence both T_{MRT} and T_{AIR}. Therefore, any Urban heat mitigation intervention, which develops materials, methods, and policies to change the urban fabric and landscape, will influence thermal comfort levels (Akbari H et al., 2016).

In California, the City of Los Angeles is leading the efforts to combat Urban Heat and have outlined a goal of reducing the urban-rural temperature differential by 3° F by 2035 (Sustainable City pLAn, 2015). This goal has led to the implementation of multiple City-level policies. Some of the policies include- a) extending Urban Canopy by planting 90,000 trees by 2021, b) enacting an ordinance in 2014, to install solar reflective coatings on the roof of new and renovated buildings, and finally c) installation of solar reflective 'Cool Pavements' across the fifteen city council districts.

Cool Streets or the Cool Pavements are perhaps the most noticeable of all the policies. Streets and the parking lots in the city, collectively amount to about 10 percent of the total land area. With nearly 28,000 lane miles of asphalt roads, it can potentially have a significant impact on altering thermal comfort levels. The Cool Streets or the Cool Pavement Project is a pilot program spearheaded by the Bureau of Streets Services, Los Angeles (StreetsLA). In 2015, the StreetsLA initiated this program and began to change the surface of the asphalt pavements to 'Cool Pavements' using solar reflective coatings. A general premise of this intervention is that the low albedo or solar reflecting black Asphalt Pavements contribute to the UHI by absorbing solar energy and then emitting heat slowly throughout the day, leading to elevated temperatures, especially in the late afternoon and early evening. StreetsLA installed the Cool Pavements across fifteen Los Angeles Council districts. These fifteen sites were selected based on the tool developed by the Trust for Public Land Climate-Smart Cities. The tool identified the areas which demonstrated the most need for cooling while incorporating socio-economic data to ensure equity (Decision Support Tool for a Climate-Smart Los Angeles, TPL, 2017).

This report presents the results of a mixed-method analysis of the impact of Cool Pavements in the Sun Valley neighborhood in Los Angeles, California. The Sun Valley neighborhood was selected for this study because it received three different treatments of the Cool Pavements. T_{MRT} and T_{AIR} are the two meteorological variables relevant to a person's weather experience or thermal comfort; therefore, this study uses field observations and micro-climate modeling simulations to document variations in these variables. The objective of this study is:

1) Differentiate Thermal Impact of Different Solar Reflective Coatings and Asphalt: Field climate data were collected on the hottest day in November 2019, using Kestrels sensors. T_{MRT} and T_{AT} were observed for 12 hours, to assess and compare the thermal comfort associated with three types of solar reflective coatings and untreated asphalt. Additionally, surface temperature (T_{SURF}) readings were also collected concurrently using an infrared thermometer to assess differences across reflective coating colors and asphalt.

2) To Evaluate Neighborhood Scale Microclimate With and Without Cool Pavements: Two micro-climate simulations using ENVI-met were run for the study-area neighborhood to interpolate T_{MRT} and T_{AIR} for the entire study area, including sidewalks and yards.

3) To Understand Residents' Perceptions of Cool Pavements in their Neighborhood: A questionnaire was administered to twenty residents. The objective was to assess the impact of the reflective pavements on the lifestyle of the residents.

The report will also go through a brief analysis of the available literature studies done on the reflective pavements, hence further asserting the need for this study. Furthermore, along with the evaluation, the report's objective is to highlight the scope for future research possibilities.


3
COOL°LA
Cool Pavement Neighborhood
Cooling Los Angeles one block at a time.

Literature Study Review

In this section, I will analyze the existing academic literature, which has, over the last three decades, extensively examined the causes and the impact of the Urban Heat and its mitigation strategies- especially the solar reflective pavements.

Urban heat mitigation strategies generally fall into either of the following categories- a) urban greening, b) climate-sensitive urban form design, or c) change in materials and material properties (Middel A. et al., 2020). The Cool Pavements pilot project is part of the latter category, as it uses a new solar reflective coating- Cool Seal- over asphalt surfaces. It is a water-based, emulsion sealcoat, formulated with light-colored pigments, designed to achieve lower surface temperatures through its lighter color and reflectivity (GuardTop, 2018).

The solar reflectivity also fluctuates with variation in pigmentation of the surface coating. To assess change in reflectivity in different lighter pigmented surfaces, Synnefa A. et al. (2011) examined solar spectral properties and the thermal performance of five (green, red, yellow, beige, and off-white) color thin layer asphalt samples. They studied the solar reflective difference in these five samples compared to the conventional regular asphalt surface. This study's spectrophotometric results showed that higher values of solar reflectance characterize the colored thin layer asphalt samples compared to the asphalt. Further, the statistical analysis of the surface temperatures shows that all the colored thin layers of asphalt samples demonstrate lower surface temperatures than black asphalt. Among all the samples, the off-white sample recorded a maximum temperature differential of 12°C. These lighter colored solar-reflective surfaces reflect more sunlight than darker colors and therefore have a higher albedo. Albedo is the quantitative measure of the total solar reflectivity. The higher level of absorption by darker-colored surfaces results in warming of the surrounding air as well. Confirmed by a study done by M. Pomerantz et al. In 2003, stated that making urban spaces lighter in color, could be one of the practical measures to mitigate UHI. As it increases the amount of sunlight getting reflected, both visible and invisible (mostly infrared).

Fluctuating the albedo numbers have shown an impact on the T_{AIR}. Research by Sen S. et al. (2019) concluded that by increasing ground surfaces' albedo by 0.28–0.40 led to a significant T_{SURF} drop of 9.0 °C. Further, results from multiple studies on Cool Pavements show a substantial effect on urban T_{AIR} (Akbari H et al. (2001). Besides T_{AIR}, Cool Pavements can significantly lower the surface temperatures and thus, convective heat release to the surrounding air (Tsoka S. et al., (2020). To situate the correlation between the T_{SURF} and the T_{AIR} further, Carnielo E. et al. (2013) ran a simulation using ENVI-met modeling, which showed a significant reduction of T_{AIR} closely correlated with the surface solar reflectance. The decline in T_{AIR} due to Cool Pavements saw a decrease of 8% after every 3 m height from the surface level. Likewise, based on the Weather Research and Forecasting model, the research study done by Mohegh A. et al. (2017), found that an albedo increase of 0.4 of the Cool Pavements leads to reductions in the annual average surface temperature (T_{SURF}). The range of reductions varied from 0.18 to 0.86°C and was highest during the late morning and early evening. They also found the temperature reductions to be higher in summers than in winter. However, the authors also noted that these variations might be due to differences in weather conditions or surrounding physical infrastructure (Mohegh A. et al., 2017).

Internationally, researchers across Europe have analyzed the Cool Pavements Project sites as well. M. Santamouris et al. (2011) examined a reflective pavement area of about 4500 square meters in an urban park in the Greater Athens area. They took the measurements of the climatic conditions before and after the installation of the Cool Pavements. The results showed a reduction in the peak ambient temperature during a typical summer day. Hence, concluding that Cool Pavements are an efficient technique and improve thermal comfort conditions considerably. Similarly, a case study by Battista G. et al., (2016), analyzed the relationship between urban T_{AIR} and the design of built and natural environments by using ENVI-met microclimate modeling tools. The result showed that a significant reduction of T_{AIR} closely correlated with the surface solar reflectance. This case study was a guiding tool for me, as I worked through creating similar micro-climate modeling simulation for the study area in the Sun Valley neighborhood in Los Angeles.

There have been concerns and critique of the Cool Pavements as well. They range from measuring its effectiveness in reducing temperatures, glare caused by high reflectivity, light-colored surface getting darker with time, and finally the reduction in the albedo values with wear and tear of the surface.

Tsoka S. et al., (2018), in their research, found that the materials' cooling potential reduces significantly for the aged albedo values. The analysis revealed that the T_{SURF} and T_{AIR} reduce by 50% when the aged albedo values in the Cool Pavements. Reducing T_{AIR} may affect the radiant balance with the environment, too. This phenomenon studied by Evyatar E et al. (2013) shows that the reduction in T_{SURF} leads to a reduction in long-wave emission, which is offset by the increased reflection of solar radiation. Consequently, instead of the expected improvement in thermal comfort, it increases the thermal stress to which pedestrians are exposed. Similarly, in the context of Los Angeles, Taleghani M. et al. (2016) studied the impacts of heat mitigation strategies on pedestrian thermal comfort. The results showed that the Cool Pavements increased reflected sunlight from the ground to pedestrians at a set of unshaded receptor locations. H. Akbari et al. (2001) have addressed the concerns related to glare and light-colored surface coating getting darker with time. His paper suggested that if we change the surface coating by not black asphalt, with an albedo of about 0.05–0.12, but with the application of a product with an albedo of about 0.35, It will be similar to that of cement concrete. It is widely known that cement concrete does not have glare issues. The author suggests that because the pavement is similar to a cement concrete road, therefore, the light color of the solar reflective pavement will persist after extended usage.

The effectiveness of solar reflective coatings is highly context-dependent. The Cool Pavements, when supported by sustainable infrastructure, have shown promising results. For example; For improving the thermal comfort during the afternoon in unshaded locations, adding street trees proved to be the most effective strategy. The combination of the Cool Pavements installed in already shaded sites shows the most significant thermal comfort results (Taleghani M. et al., 2016). Though the reflective surfaces likely perform differently between intervention sites, effectiveness depends on the background climate and built environment (Qin et al., 2015). Adding shade trees, tall buildings, and street orientation also plays a significant role in reducing urban heat (Middel A. et al., (2014). While explaining the purpose of street orientation in increasing thermal comfort, Pearlmutter D. et al. (2006) concluded that a compact street canyon geometry reduces pedestrian heat gain during most summer hours, but is conditional and depends on design aspects such as street axis orientation.

To understand how various surfaces, especially concrete pavement, behave in terms of solar reflection, I observed and documented the T_{SURF} of the concrete sidewalks. The results are in the data analysis section of the report. I referred to the study done by Hui Li (2016) and Pomerantz P. et al. (2001) to have a baseline understanding of the effect of concrete pavements on thermal comfort. Hui Li concluded that as compared to impermeable pavements, permeable pavements like PCC tend to remain cooler for longer, as it captures more water, the dew after the subsequent evaporation of the water will cool the pavement. Although a caveat is that permeable surfaces may produce higher temperatures during the peak daytime hours.

The majority of the Urban Heat studies have supported the need for mitigation strategies to combat Urban Heat Island Effect and either have quantitatively evaluated the Cool Pavements project or have directed policy analysis. But the resident's interaction with solar reflective pavements has not been analyzed yet. The Evaluation of Cool Pavements Project aims to fill this research gap, i.e., by analyzing the relationship between the thermal comfort of the users and the Cool Pavements. This study takes into account residents' interaction and response to the solar reflective pavements.

Moreover, the relationship between albedo and surface temperature is well established, the performance of solar reflective coatings once deployed in real-world interventions is less well understood. This is due to ambiguities tied to design - composition (reflectance value), configuration (spatial arrangement), coverage (scale of application), complexity (presence of multiple cooling features, like vegetation and shade) - and the extent of edge effects at the boundary between cool and conventional pavement.


4

Study Area And Research Question

As mentioned in the Introduction section, out of the fifteen sites, for this project, my study area focuses on the Cool Paved Pavements at Arminta Street and Bakman Avenue intersection in Sun Valley, Los Angeles. The study area for this project is a residential area, as shown in **Figure 2**, which has a little over one hundred single-family homes, located next to Cool-Paved streets.

Figure 2- Study Area showing Locations of Cool Streets and the Asphalt Pavements

Eighty percent of the community in the study area are primarily Spanish speaking and about Ninety-two percent of the community members at the study site are sixty-five years old or younger (CalENviroScreen Data, 2018). This data points to the potential for diverse usage of the streets like walking, dog walking, skating, biking, etc., and for active use of front yards and backyard.

Research Question and Hypothesis:

This project's primary goal is to examine the real-world impact of the Cool Pavements in reducing the T_{MRT} and T_{AIR} and its effect on the lifestyle changes of the neighborhood community. Capitalizing on the LA Cool Streets program as a novel experiment and building on the preliminary literature findings, this study addresses two outstanding questions:

RQ1: How do surface, air, and radiant temperature vary across the treated pavement with different reflectance values?

H1: I hypothesized that as reflectance values increase, surface temperature will decrease, and MRT will increase proportionally.

To answer the first question, I measured surface, air, and globe temperature, along with humidity, wind speed, and other biometeorological variables using the Kestrel sensor, on Cool Pavement treated areas. These study areas (see **Figure 3**) for Cool Pavements are Two shades of light-grey treatment by Street Bond (between Bakman Ave. to Tujunga Ave.), another light grey treatment by Guard Top (between Fair Ave, and Bakman Ave.), and Asphalt surface.

1. Lighter Colored Cool Pavement, Installed by StreetBond
2. Darker Colored Cool Pavement, Installed by StreetBond
3. Cool Pavement, Installed by GuardTop
4. Asphalt Pavement

Figure 3- Location of the Kestrels Devices Placed on the Four Types of Surfaces

The study compares the surface, air, and mean radiant temperatures from early noon to late night, as the radiation from the urban heat island is maximum after evening. Besides examining these streets, I also collected the radiant temperature measures of concrete paved sidewalks (shaded and non-shaded) and surfaces with grass and dirt.

RQ2: What are residents' perceptions of the cooling benefits of pavement in the treatment areas?

H2: I hypothesized that residents' perceptions of the cooling benefits of treated streets will correspond to how they use the treated areas.

To answer the second question, I co-developed a questionnaire- to systematically gage resident perceptions and use of streets. I asked the residents about a variety of hypothesized effects of cool streets including but not limited to surface temperature (e.g., dog walking, kids playing), comfort, glare, night brightness/safety, energy consumption, aesthetics, active transportation, and driving experience. I asked how residents are using their backyard areas, front yards, and patio areas to delve further on their usage within their property lines. Importantly, at what time of the day, they actively use these streets.


5

Research Methods

Part I- Heat Measurement Field Data and Analysis

To calculate Mean Radiant Temperature (T_{MRT}) of the Cool Pavements, in mid of November 2019, I used four Kestrel 4400 Heat Stress Meter, (refer **Figure 4**) to record the parameters which contribute to the T_{MRT}. Kestrels device records the meteorological variables relevant to a person's weather experience like Globe Temperatures (T_G) Heat Index, Wet Bulb Globe Temperature, Air Temperature (T_{AIR}), Humidity, wind speed, and surface temperature (T_{SURF}), at 1.1-m height, which is the center of gravity of the human body for standing subjects. To maintain the regularity in the readings, the variables were recorded at regular intervals of a minute from 11:00 hrs. to 22:00 hrs. The four Kestrel devices were placed on different types of surfaces, as marked in figure no. 3 in the previous section. To calculate the comparative differential of T_{MRT} on various surfaces, four locations were chosen based on the different kinds of surface coatings in the neighborhood (Refer **Figure 5**).

Figure 4 (a,b)- Heat Measurement Devices- Kestrel (left) and Heat Gun (right)

The idea behind calculating T_{MRT} on-site measurements at different surface types is to understand the variation in the thermal impacts of different kinds of Cool Pavements. In hot and dry environments, T_{MRT} is the primary driver of human thermal comfort and the most human-relevant heat metric (Middel et al. 2016). The Cool Pavements Project is in the pilot phase; therefore, the comparative difference in T_{MRT} helps to realize the best possible option in increasing the thermal comfort, which is the primary objective of the Cool Pavements Project.

Figure 5 (a,b)- Kestrel Placed on Cool Paved Surface Installed by GaurdTop (left) and Lighter Colored Cool Surface Paved by StreetBond (right)

Figure 5 (c,d)- Kestrel Placed on Lighter Colored Cool Surface Paved by StreetBond (left) and on the Asphalt Top (right)

In the mid of the month of November 2019, these measurements were taken from 11:00 hrs. to 20:00 hrs. in a span of a day. The maximum temperature recorded was 85 °F or 29.4 °C (The Weather Channel, 16th November 2019). The Kestrel devices noted the variables like Wet Bulb Temperature, Barometric Pressure, Headwind, Station Pressure, Heat Stress Index, Natural Wet Bulb Temp, Relative Humidity, Wet Bulb Globe

Temperature, Altitude, Air Temperature, Wind Speed, Globe Temperature, etc. To calculate the Mean Radiant Temperature. I calculated mean radiant temperature T_{MRT} [°C] from observed globe temperature T_G [°C], air temperature T_{AIR}[°C], and wind speed V_A [ms−1] for all transect locations using the following formula:

MRT= (((globe temp.+ 273.15) ^4 + (1.1*10^8 * windspeed^ (0.6))/ ((0.95*0.0245^ (0.4)) * (globe temp. - air temp.))) ^ (0.25))-273.15

The globe temperature (T_G) is the quantity that is measured directly by a globe thermometer. It is placed on the top of the Kestrel heat measurement device, which is used to measure globe temperature (T_G) and mean radiant temperature (T_{MRT}). The thermometer contains an ordinary thermometer fixed inside the blank copper sphere of diameter 100 mm. This sphere is coated with matt black color and is placed at a height of 1.1 meters.

In addition to evaluating the Mean Radiant Temperature (T_{MRT}) among the pavements mentioned above, I measured the heat reflectance on the surfaces besides Cool Pavements. at regular intervals of half an hour from 11:00 hrs. to 22:00 hrs. using the Heat Gun (refer figure 4). Surfaces, both shaded and unshaded surfaces, like concrete, textured concrete, grass and soil/dirt, as shown in the following **Figure 6**:

Figure 6 (a,b)- Study Site Locations for Concrete (left) ; Dirt and Grass Surface (right)

A- Concrete Slightly Textured Unshaded
B- Concrete Textured Shaded
C- Plain Unshaded
D- Concrete Textured Unshaded

A- Grass Surface Along E-W Direction
B- Grass Surface Along N-S Direction
C- Dirt Surface

Part II- Micro-Climate Modeling and Analysis

This study compares the impact of existing urban form and the pavement type on the typical-summer micro-climate temperatures. The goal is to compare and investigate the performance of T_{MRT} and T_{AIR} in two scenarios in the study area neighborhood. As shown in the 3-D **Figures 7a and 7b** below, two scenarios differ in the street pavement type- one has cool paved streets (i.e. At-Present site condition), and the other assumes that these streets have regular asphalt top.

Figure 7a- Scenario 1: At-Present Pavement Layout Showing Streets with Cool Pavements in the Study Area

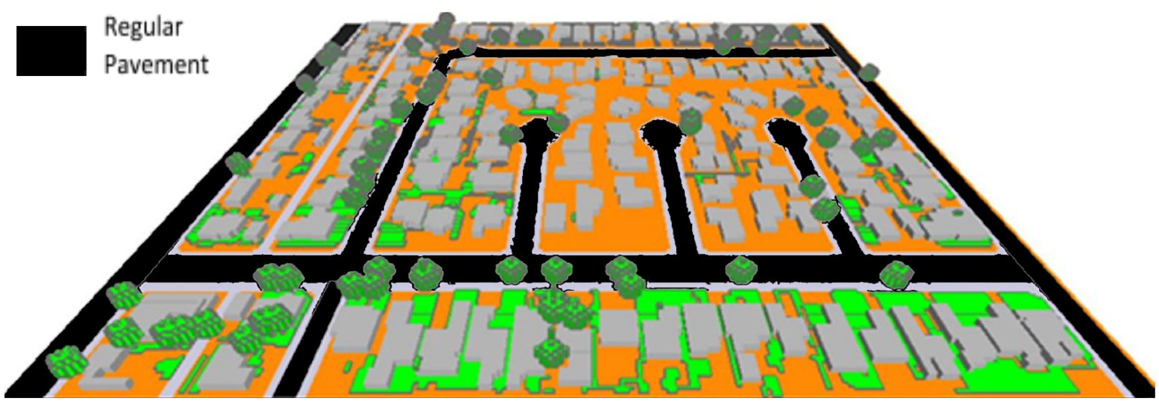

Figure 7b- Scenario 2: Pavement Layout showing Streets with Asphalt Top in the Study Area

To investigate the impact of the pavement type, we simulated micro-scale thermal interactions for T_{MRT} and T_{AIR} for the study area using a three-dimensional microclimate model ENVI-met (Version-4). The ENVI-met software is a three-dimensional Computational Fluid Dynamics model that simulates surface-plant-air interactions in urban environments (Middel A. et al., 2013). To study the impact on a typical summer period, we ran a simulation for a 24-hour long duration for August 11, 2019. The selected day recorded a high temperature of 82° Fahrenheit at 15:00 hrs. and 62° Fahrenheit at 04:00 hrs. (MesoWest, 2020).

To create a 3-D digital representation of the site, as shown above, the area input file (.inx) was set up. The .inx file had the arrangement of the built structures, vegetation data, soil profile information. By taking reference to a Google Earth figure (.bmp) file to create the physical characteristics of the site, I produced 3-D area input files in ENVI-met with a grid resolution of 2 m, resulting in area input files of 245X250X15 grids. We ran ENVI-met for a 24-hour period, starting at 06:00 hrs. with a model output at every 60 minutes.

Part III- Resident Questionnaire and Analysis

The impact of the reflective pavements on the residents' lifestyle, and their 'perceived' thermal comfort while using Cool Paved streets, is an unexplored subject. Therefore, to investigate the impact of the Cool Pavements Project on the daily lives of the residents living in proximity to the Cool Paved streets, qualitative research involving a resident questionnaire was conducted on February 20, 2020. The questionnaire revolved around the process of outdoor space usage, especially in spaces like sidewalks, patios, front yards, and the backyards of the residents. As discussed earlier in the study area section, 90% of the residents are below 65 years old; therefore, it was essential to understand how and when this diverse age group of residents uses these open areas.

Furthermore, I tried to analyze the frequency of usage, as well. The analysis of usage frequency was achieved by asking questions related to the change in the daily activities since the installation of the Cool Pavements. As the study site is a predominantly Spanish-speaking neighborhood, I was assisted by a Spanish-to-English translator, to ensure 'easy and effective' communication. The questionnaire consisted of eight questions. For the full questionnaire, refer to Appendix A.1. The aim was not just to get a Yes/no answer but to understand the process of the outdoor uses. Therefore, each of the eight questions fell into following broad categories:

1. The demographics: How long a resident has been living in the area.
2. The usage of the neighborhood: Type and quantity of outdoor space usage.
3. Change in Frequency: Change in residents open area usage since Cool Pavements installation, and finally
4. Any other outstanding urban-heat related issue.

Participants were recruited by going door-to-door, and the questionnaire was administered to the residents living next to the Cool Paved streets. To record the questionnaire responses, I knocked at 105 residences in the study area from 8 am to 6:30 pm and asked residents and passersby for their responses. I received responses from twenty residents. Residents, in general, did not permit audio recording. Therefore, the participant's responses were noted down from the Spanish translated verbatim in real-time.

All the unique themes that came up in all the twenty interviews were cataloged. I noted these themes as unique if they were only seen in the transcripts of one interviewee, or overlapping if the themes came up across interviews. An interesting aspect of doing the survey questionnaire was to note the frequency of the diverse usage of the outdoor spaces by the residents.


6

Findings

Part I- Analysis of Heat Measurement Field Data of T_{MRT}, T_{AIR}, and T_{SURF}

The comparative analysis of the T_{MRT} suggests that all four types of pavements show a similar pattern throughout the day. The T_{MRT} for all the pavements rises until approximately 14:00 hrs. Then, it experiences a sudden drop at around 16:00 hrs. The maximum temperature (T_{MRT}) reading for all the pavement types was recorded between 13:00 hrs. and 14:00 hrs. The Darker Colored StreetBond pavement recorded highest T_{MRT} of 44.8°C at 13:46 hrs., followed by the GuardTop Pavement- 44.4°C at 13:14 hrs., then by the Lighter Colored StreetBond Pavement- 43.7°C at 13:46 hrs. (as shown in **Figure 8**). The Asphalt pavement recorded the lowest T_{MRT}- 42.7°C at 13:14 hrs. The range of the T_{MRT} variation was 2.1°C. A similar pattern of the T_{MRT} indicates similar thermal comfort levels for all pavement types.

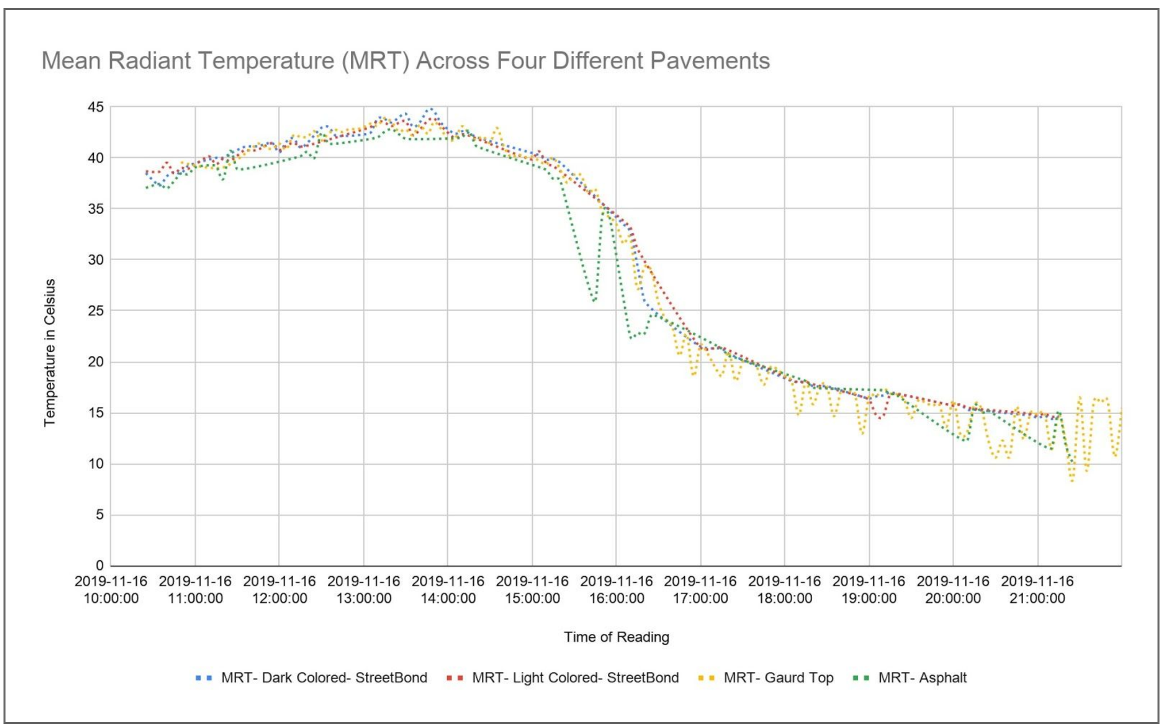

Figure 8: Pattern of T_{MRT} Same Across All the Four Types of Pavements

The T_{AIR} readings recorded using Kestrel devices and the T_{SURF} readings were recorded at a span of every thirty minutes from 11:00 hrs. to 22:00 hrs. using Heat Guns. The graph below (**Figure 9**) shows the comparison between T_{AIR} and T_{SURF} recorded at four different types of pavements. The average pattern in all the four types of pavements shows that the T_{SURF} was higher than T_{AIR}. Drop-in temperature readings were recorded for all the pavements at around 14:00 hrs. The highest average difference between T_{SURF} and T_{AIR} recorded was by Darker Colored StreetBond Pavement at 5°C. The average difference (T_{SURF} - T_{AIR}) recorded by the other three pavements showed a similar range. The Lighter Colored StreetBond, GuardTop, and Asphalt pavement recorded a difference of 3.75°C, 3.14°C, and 3.14°C, respectively.

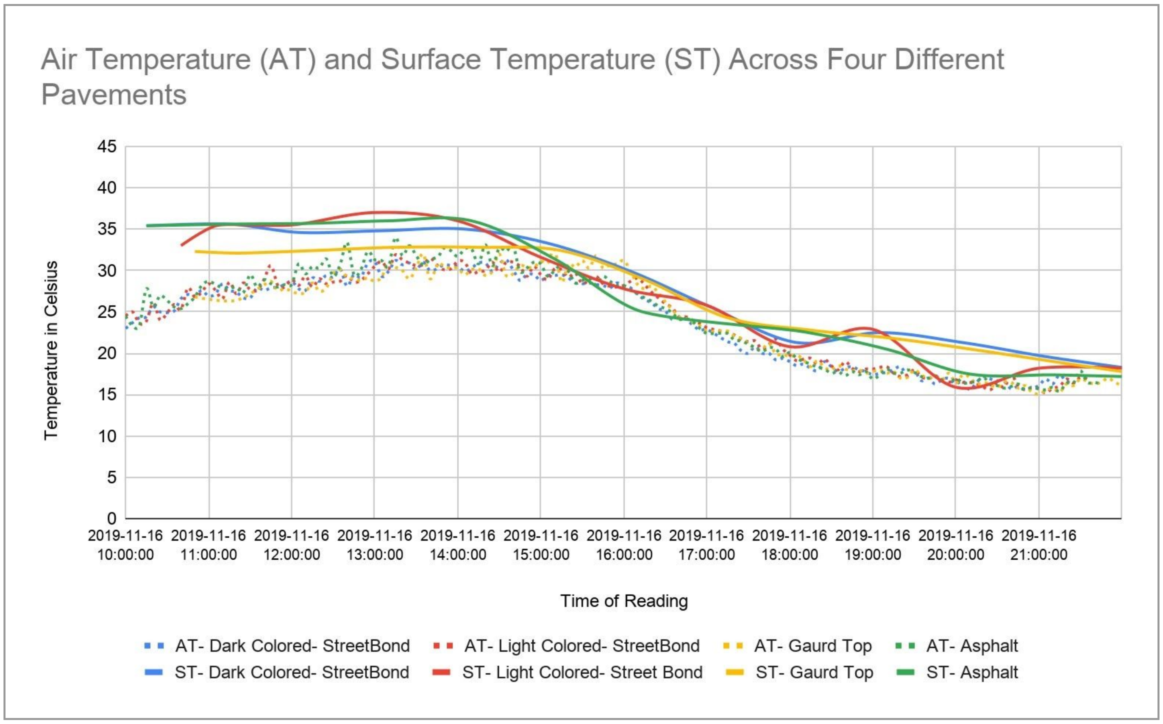

Figure 9: In General, T_{SURF} recorded Higher Temperature Reading than T_{AIR} Across All the Four Types of Pavements

As can be predicted, the Heat Gun readings for concrete pavements T_{SURF} shows that plain textured unshaded recorded higher temperatures than the rest of the concrete pavements (refer **Figure 10**). Lowest T_{SURF} was recorded on the shaded concrete surface.

Further, the initial results for T_{SURF} for ground cover having grass on top and dirt along the sidewalks show that the dirt surface recorded higher T_{SURF} than the grass top. Also, after 13:30 hrs., the T_{SURF} drastically dropped for dirt surface and recorded a lower T_{SURF} than the grass surface (refer **Figure 11**). Interestingly, the grass cover along Bakman Avenue recorded higher T_{SURF} than along Arminta Street.

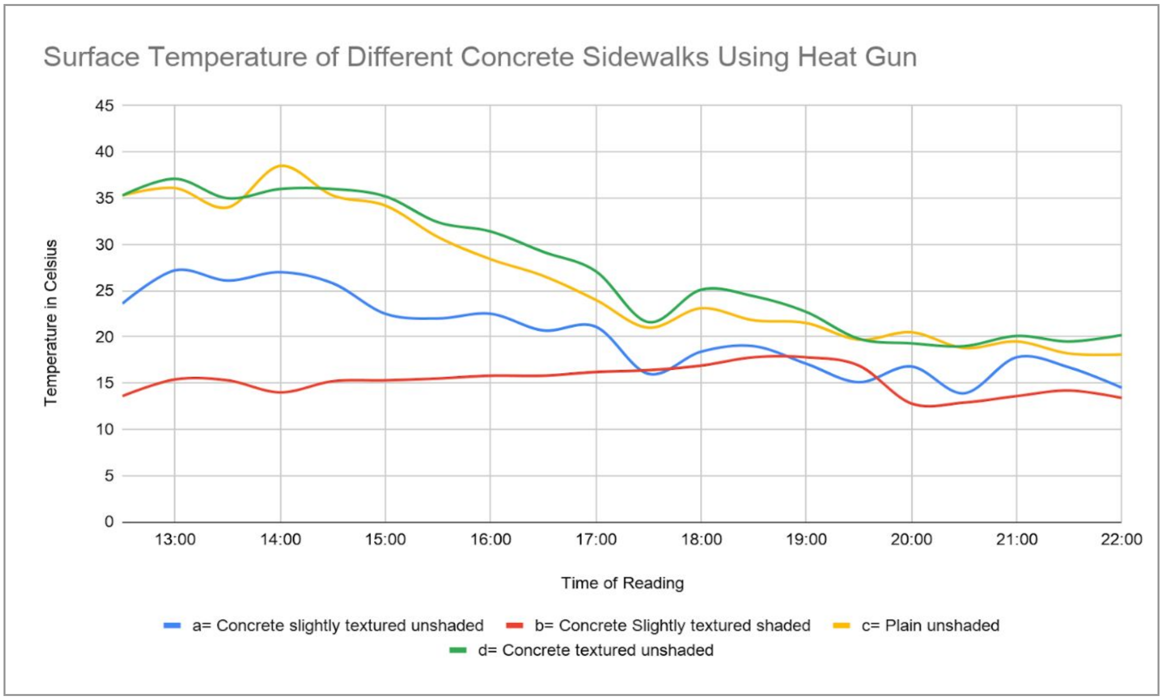

Figure 10: Shaded Concrete Recorded Lowest T_{SURF}, Further Asserting the Case for Planting Shade Trees for Shade Along Sidewalks for Thermal Comfort.

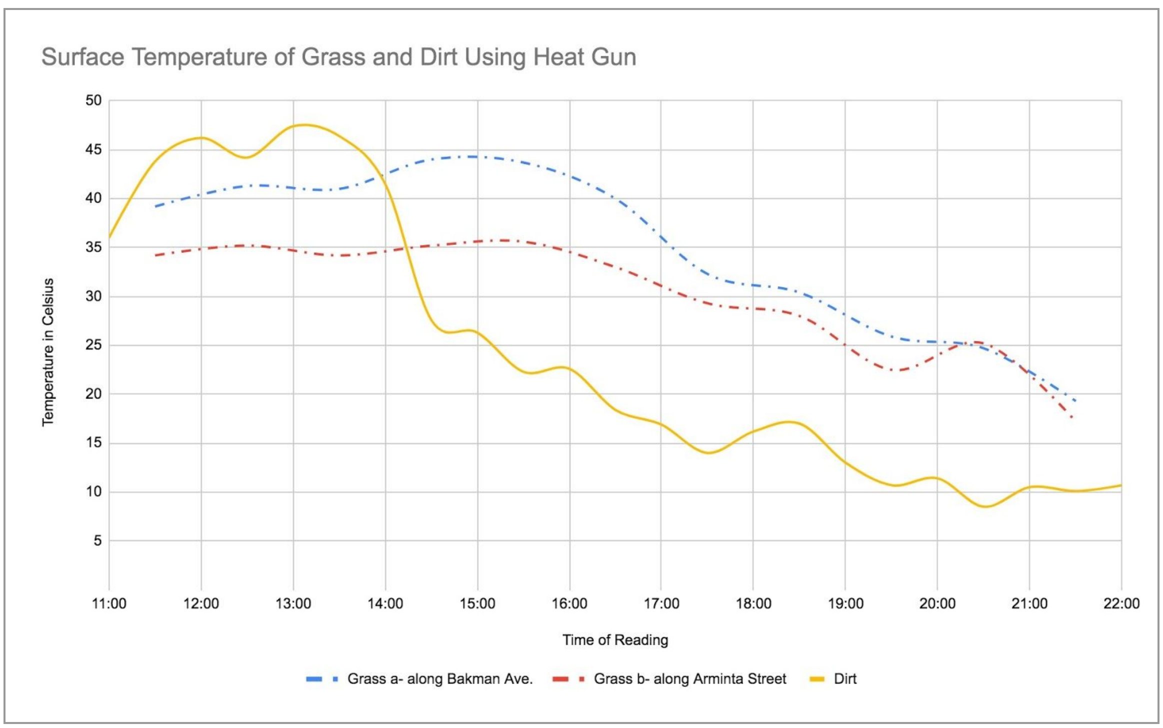

Figure 11: After 13:30 hrs., The Dirt Surface Recorded Lower T_{SURF} than the Surface with Grass Cover

The observation for this analysis revealed that T_{MRT} reading of all four surfaces, more or less, showed a similar pattern. There were not any substantial significant differences as anticipated. Although, it was interesting to see that in general, T_{SURF} was higher than T_{AIR}, which perhaps suggests that the temperature felt at the above-ground level is lower than at the surface. The lower T_{SURF} recorded for different concrete pavements, grass, and dirt surfaces suggest that using a combination of different surfaces may increase the pedestrian's thermal comfort using the sidewalks.

The absence of any significant variations in the readings points towards a few limitations to the field data collected. The data were collected in one day in the fall season because of the limited timeframe for this project using Kestrels. Kestrels are a less sensitive measurement device as compared to MARty. It is a biometeorological instrument platform that measures all meteorological variables relevant to a person’s weather experience to assess the thermal impacts of albedo increase on pedestrians. Therefore, ideally, to achieve a more clear or significant temperature reading of T_{MRT}, T_{AIR}, and T_{SURF}, I suggest collecting multi-season data over a more extended period using MARty.

Part II- Analysis of Micro-Climate Modeling

In the following discussion, I compare air temperature and mean radiant temperature of two scenarios for the Study Area, one with 'At-Present Pavements' and the other with Asphalt Pavements.

Scenario-1:

As can be seen from the simulation figures below (refer **Figure 12**), the overall study area's simulation results show that T_{AIR} values vary between 19.70 °C and 30.20 °C. For a typical August day, the T_{AIR} is highest at 14:00 hrs. Similarly, if we focus on the T_{AIR} on the sidewalks and the pavements, the inner streets, especially at cul-de-sacs, recorded higher temperatures from 14:00 hrs. to 20:00 hrs. than the surrounding areas. At noon, the T_{AIR} on the asphalt pavements was higher than on the Cool Paved Streets.

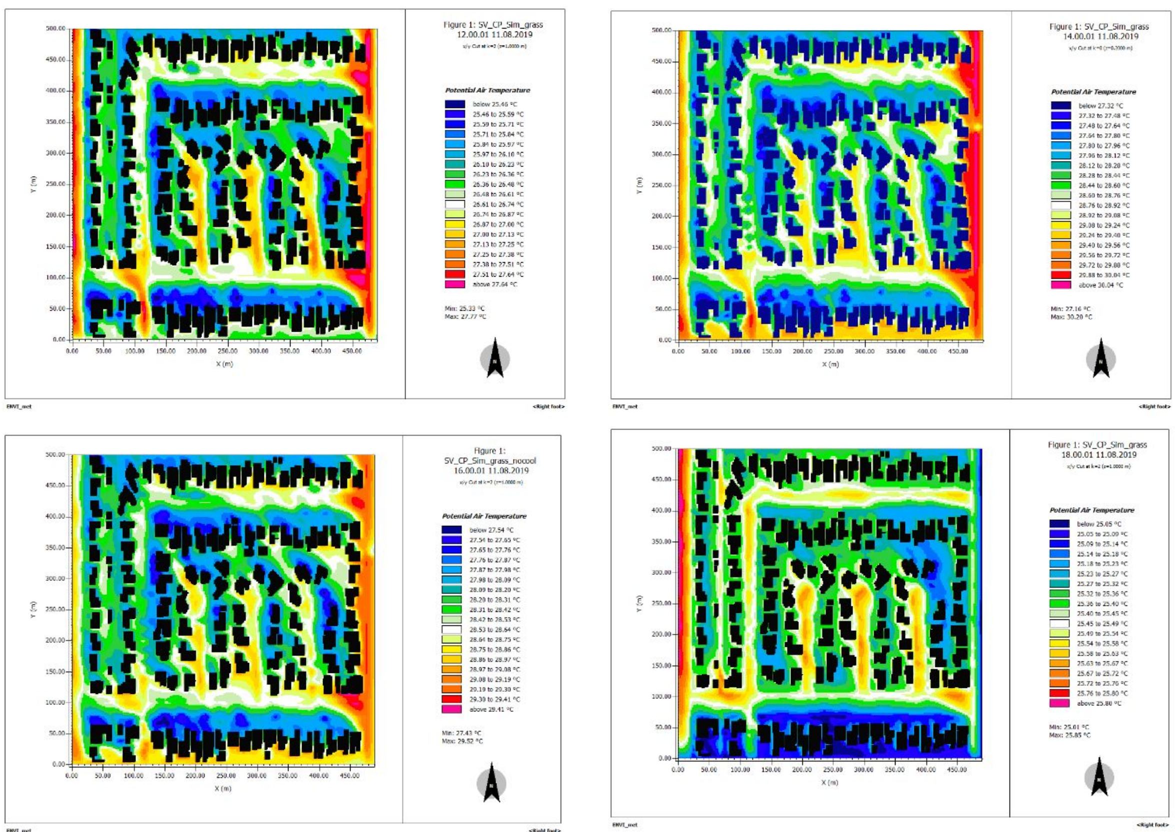

Figure 12- ENVI-met output of T_{AIR} at 12:00 hrs. (top left), 14:00 hrs. (top right), 16:00 hrs. (bottom left), and at 18:00 hrs. (bottom right)

The simulation output shows a gradual increase in T_{AIR} from 08:00 hrs. up till 16:00 hrs. (see appendix B.1-a), and then an approximate 3.5 °C drop from 16:00 hrs.' to 18:00 hrs.

The simulation results for T_{MRT} show that mean radiant temperature increases from 08:00 hrs. to 16:00 hrs (see **Figure 13**). For a typical summer day in August, the study area temperatures vary between 12:30 °C and 71.29 °C. For the pavements and sidewalks, the output results from the simulation point out that the maximum T_{MRT} of 68.95°C is at 14:00 hrs. and a minimum at 22:00 hrs. (see appendix B.1-b).

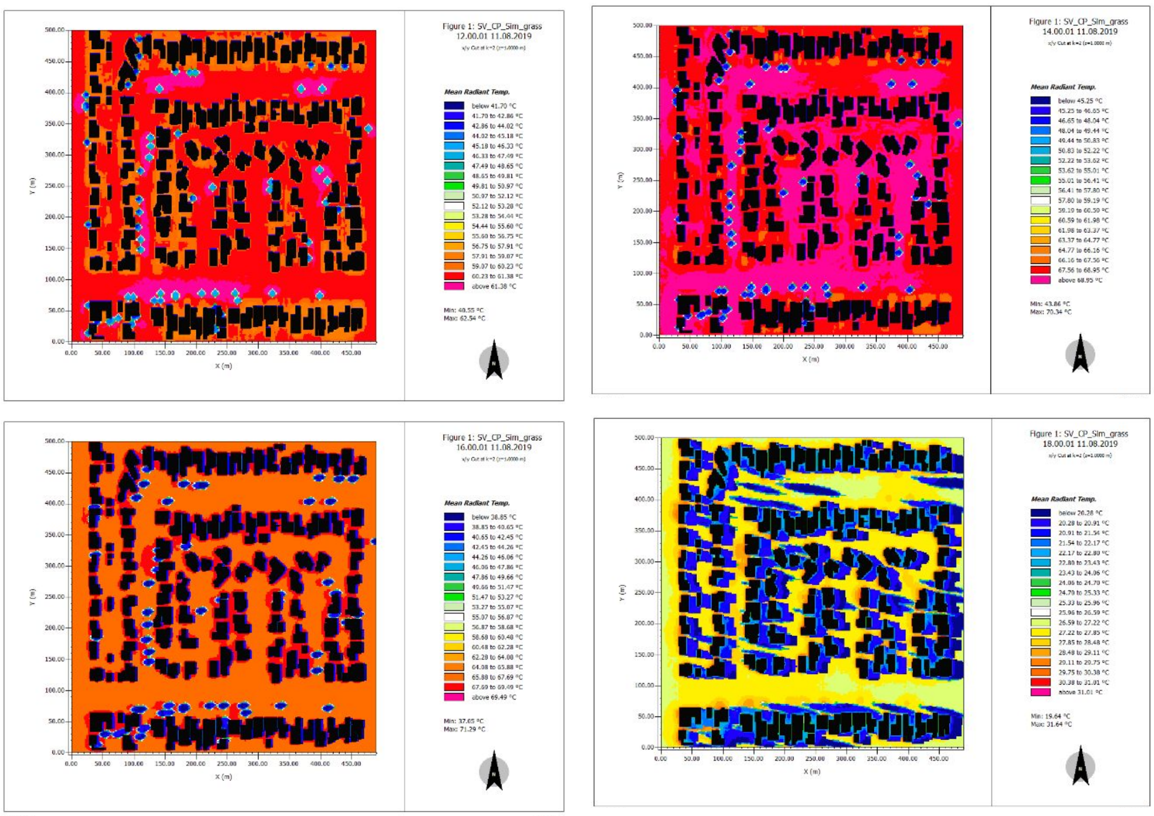

Figure 13- ENVI-met output of T_{MRT} at 12:00 hrs. (top left), 14:00 hrs. (top right), 16:00 hrs. (bottom left), and at 18:00 hrs. (bottom right)

Scenario 2:

The simulation output for the study area with regular or asphalt pavements shows that T_{AIR} gradually increases from 08:00 hrs. up till 14:00 hrs. and then records a drop of 2.62 °C at 16:00 hrs. As shown in **Figure 14** below, the maximum T_{AIR} for the overall site is 30.05°C at 14:00 hrs. Similarly, on the sidewalk and the pavements, the simulation output shows the highest T_{AIR} of 29.46°C at 14:00 hrs.

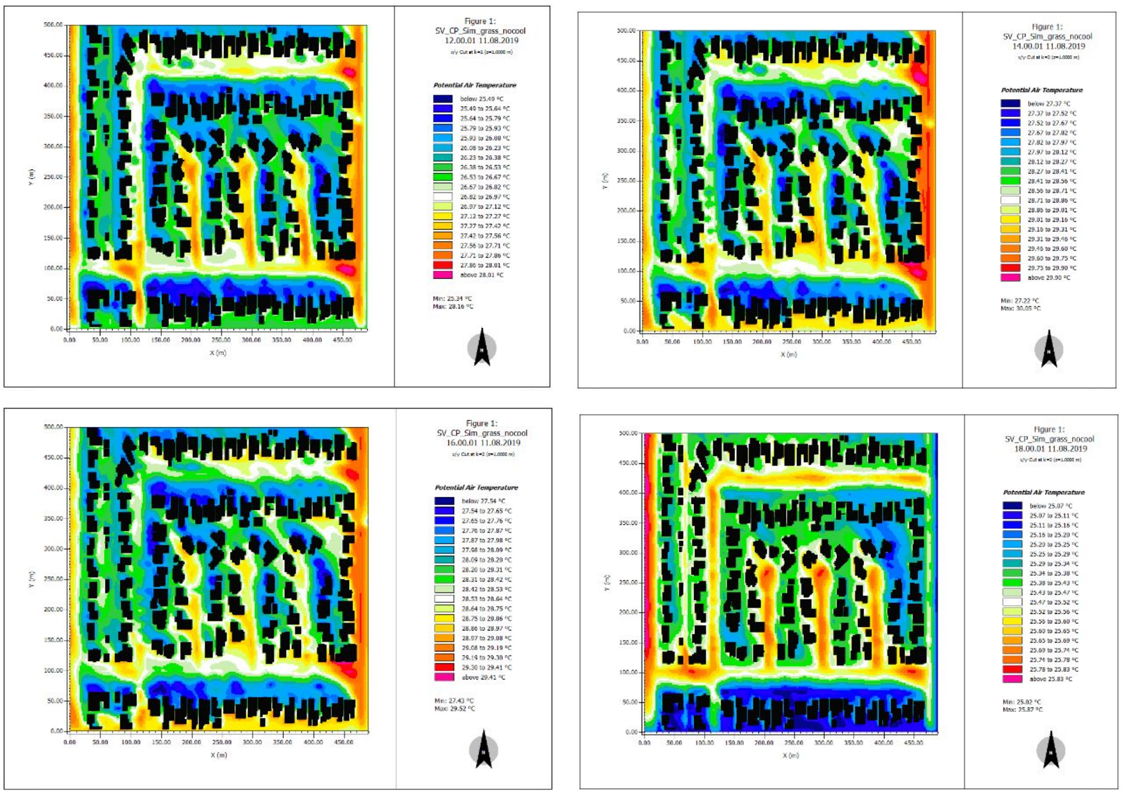

Figure 14- ENVI-met output of T_{AIR} at 12:00 hrs. (top left), 14:00 hrs. (top right), 16:00 hrs. (bottom left), and at 18:00 hrs. (bottom right)

The simulation output for T_{MRT} shows that for a typical August day, the maximum (70.91°C) T_{MRT} is expected at 16:00 hrs. and lowest (12.39°C) at 22:00 hrs. (see appendix B.2-b). The T_{MRT} sees a gradual increase from 08:00 hrs. up till 16:00 hrs., and similar to the field results, the T_{MRT} starts to drop after 16:00 hrs. As shown in **Figure 15** below, on the sidewalks and the pavement, at 14:00 hrs., the TMRT is highest (68.53 °C).

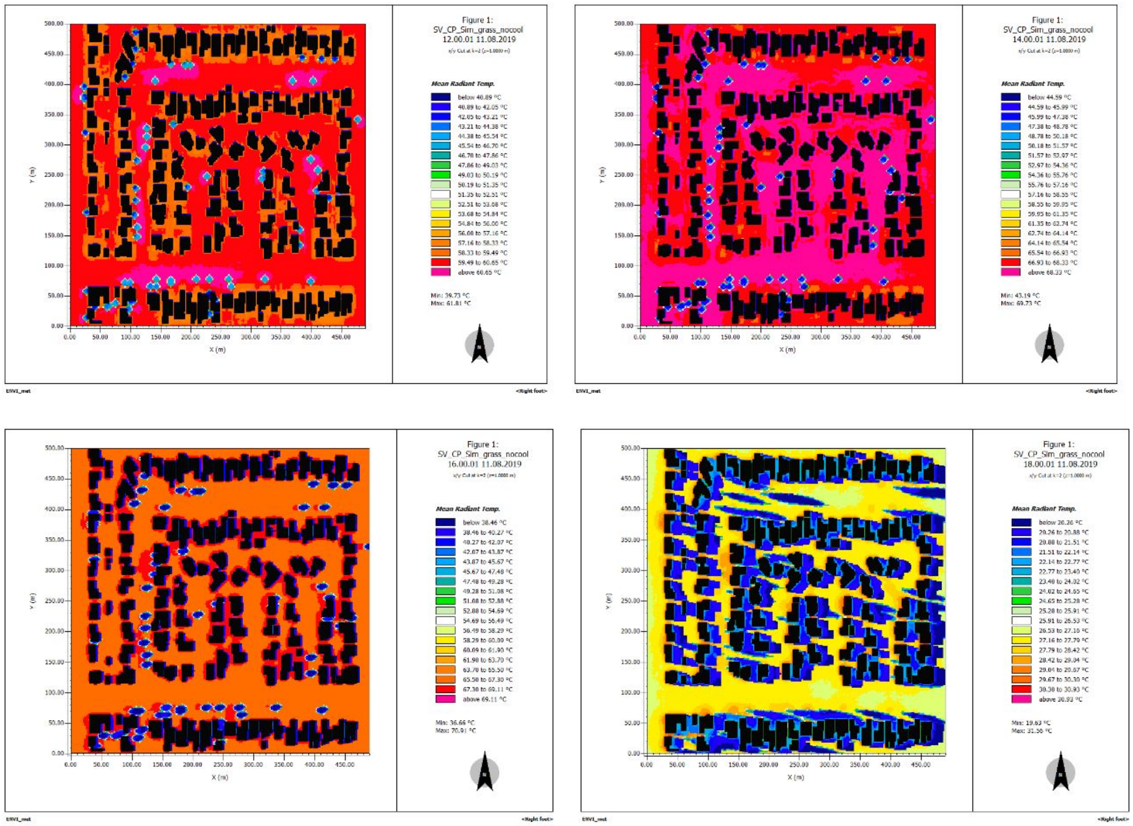

Figure 15- ENVI-met output of T_{MRT} at 12:00 hrs. (top left), 14:00 hrs. (top right), 16:00 hrs. (bottom left), and at 18:00 hrs. (bottom right)

To further compare T_{AIR} and T_{MRT} in the two scenarios in ENVI-met, I created the 'Difference Maps' of the two simulation outputs in Leonardo. The values vary between -0.57 to 0.27. There is approximately no difference in the air temperature of the two scenarios recorded between 20:00 hrs. and 22:00 hrs. (see appendix B.3-a). As shown in the index in the **figure 16** below, the negative values point to higher T_{AIR} for the regular/ asphalt pavements scenario. Therefore, to conclude, the results for T_{AIR} showed that the regular pavement records higher T_{AIR} than one with the Cool Paved streets.

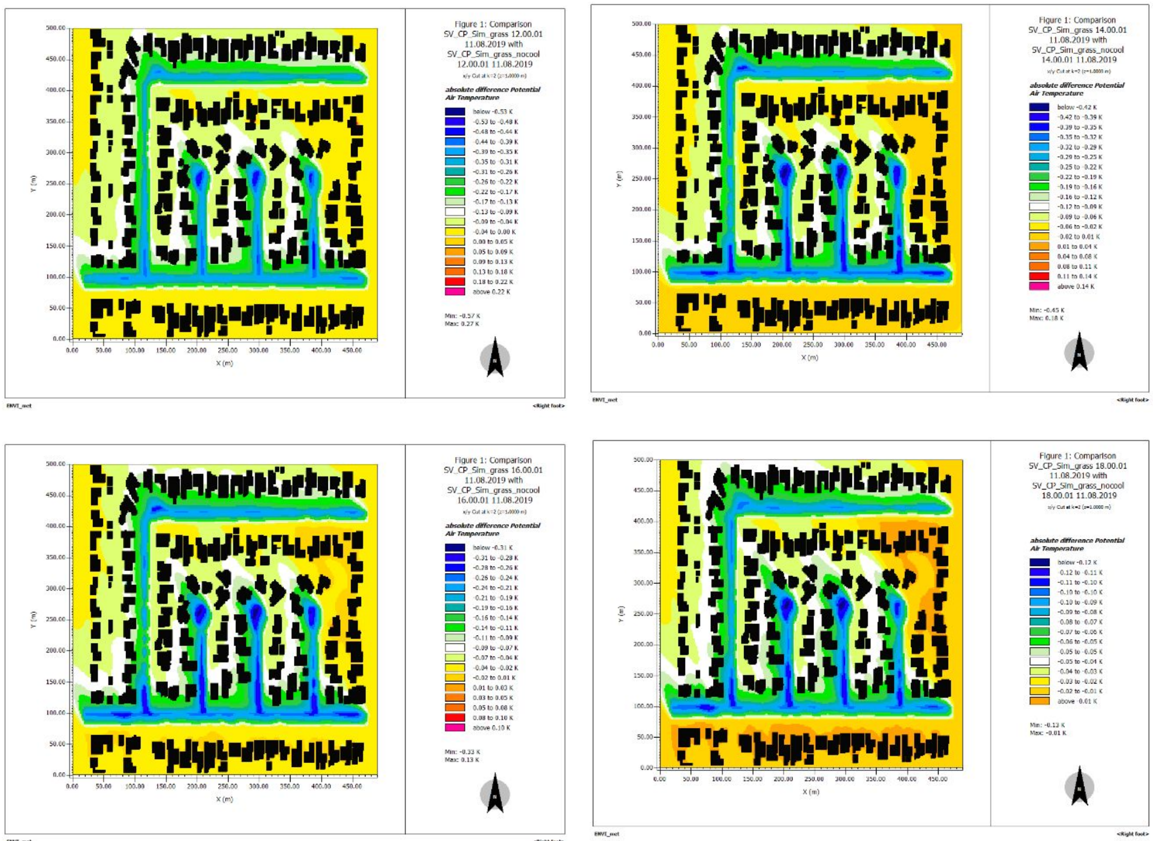

Figure 16- Comparative Maps of T_{AIR} for the Two Scenarios at 12:00 hrs. (top left), 14:00 hrs. (top right), 16:00 hrs. (bottom left), and at 18:00 hrs. (bottom right)

On the contrary, T_{MRT} results from the 'Difference Maps' of the two scenarios showed the opposite pattern than the T_{AIR}. The difference in T_{MRT} between the two scenarios is highest at noon. No difference in the mean radiant temperature is recorded between 18:00 hrs. and 22:00 hrs. for the two scenarios (see appendix B.3-b).

The difference in the T_{MRT} values is positive, as shown in the **Figure 17** below. The values vary between -0.02 to 0.93. In conclusion, the scenario with the Cool Pavements recorded higher T_{MRT} than the scenario with the regular pavements, and hence lower thermal comfort.

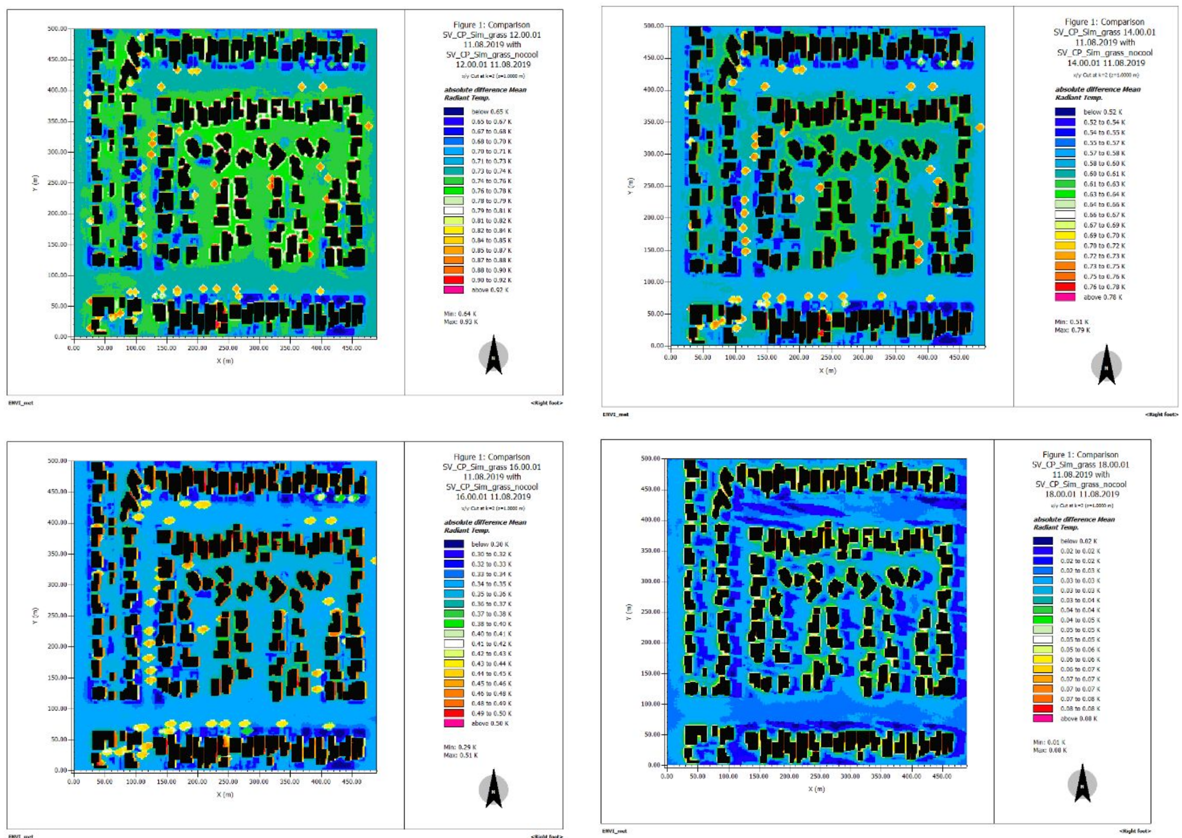

Figure 17- Comparative Maps of T_{MRT} for the Two Scenarios at 12:00 hrs. (top left), 14:00 hrs. (top right), 16:00 hrs. (bottom left), and at 18:00 hrs. (bottom right)

Part III- Analysis of Resident Questionnaire

As per the responses received, the Participants and their families are using the outdoors for walks, dog walking, biking, skating, cleaning patios, or are just spending time in their yards and patios. Most of the participants mentioned taking a walk in the neighborhood as part of their daily routine. Using patio areas and taking care of their gardens in their front and backyards, was the second most mentioned activity. It is also important to note that only 35% of the respondents said that their family uses outdoor spaces as part of their daily routines.

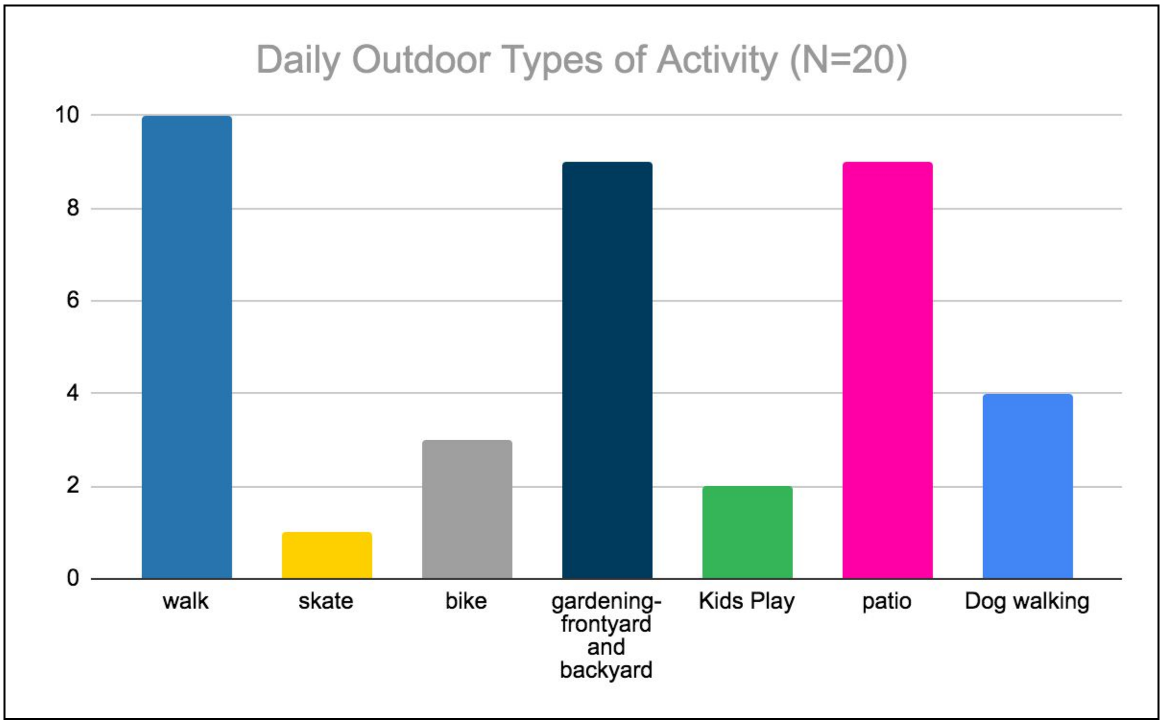

Figure 18- Walking, Gardening, and Using Patio Spaces Are Popular Outdoor Uses.

One of the vital aspects of understanding the daily patterns of outdoor space usage, concerning thermal comfort was the recognition of the preferred outdoor usage times for residents. The results, as depicted in **Figure 18,** showed that twelve out of twenty participants and their families are using the streets in the morning hours. Usage in evening and afternoon hours showed a similar usage pattern. Nine out of twenty participants are using outdoors in the evening, and eight out of twenty are using in the afternoon hours.

Further, to understand the likeliness of the top four activities mentioned by the residents, as per the preferred times of the day, the results showed that:

1. Six out of twenty people are more likely to walk in the neighborhood in the morning and five out of twenty in the evening hours.
2. A person biking in the neighborhood is equally likely to bike in the morning and the afternoon hours.
3. Out of the fifteen participants, who spend their time gardening in their front yards and backyards, seven preferred afternoon and five participants preferred to do so in the afternoon.
4. Out of eleven participants using their patios, five were more likely to use their patio spaces in the afternoon (45.5%), and four people preferred morning (36.4%).
5. Half of the participants walked their dog in the morning hours, then followed by evening.

Seventeen out of twenty participants have been residents of the study area for more than ten years. It is safe to say that most of the participants have an extensive interaction period with the streets, in some form or the other. As previously mentioned in the methodology section, the questionnaire did not have yes-no questions; they were open-ended and focused on the user's process. Seven out of twenty participants said that their families, in general, don't actively use streets or outdoor areas. Regarding the perception of thermal comfort, respondents recorded their responses into mainly four categories, which were as follows:

1. Six out of the twenty participants said that they felt more cooling in the neighborhood, since the application of the Cool Pavements.

"It feels less hot. Now, me and my family come out on weekends, and lay blankets out on the front yard and spend the time outside. I would describe my experience as fairly good..........
......Since the application of the cool pavements, a lot of people from other neighborhoods walk in our neighborhood."

2. Seven out of twenty participants or thirty-five percent of the individuals said they were not sure whether they felt less hot or more heat, but they got a feeling of freshness and tranquility while walking through these streets.

"I started spending more time outside after 2015. It feels fresher on the front yard than on the rear yard."
"Normally, it's always hot here that's why it is named as the sun valley. On an average, it reaches 80 degrees Fahrenheit. After the application of the Cool Pavements, it feels a little bit fresher."
"I feel tranquil and fresh while walking through these streets."

3. Three out of twenty participants or Fifteen percent did not feel any change in thermal comfort.

"I would like to see more shade trees in my neighborhood. I generally like the Cool Pavements here, but I'm not sure about any temperature difference."

4. Though none of the participants mentioned that they felt more heat than before the application of the Cool Pavements, one participant did say that since 2015, every room at the individual's house has air conditioners now.

An overwhelming majority of the responses, about fourteen out of twenty mentioned that their usage of the outdoor spaces has remained unchanged since the application of the Cool Pavements in the neighborhood **(refer figure 19)**.

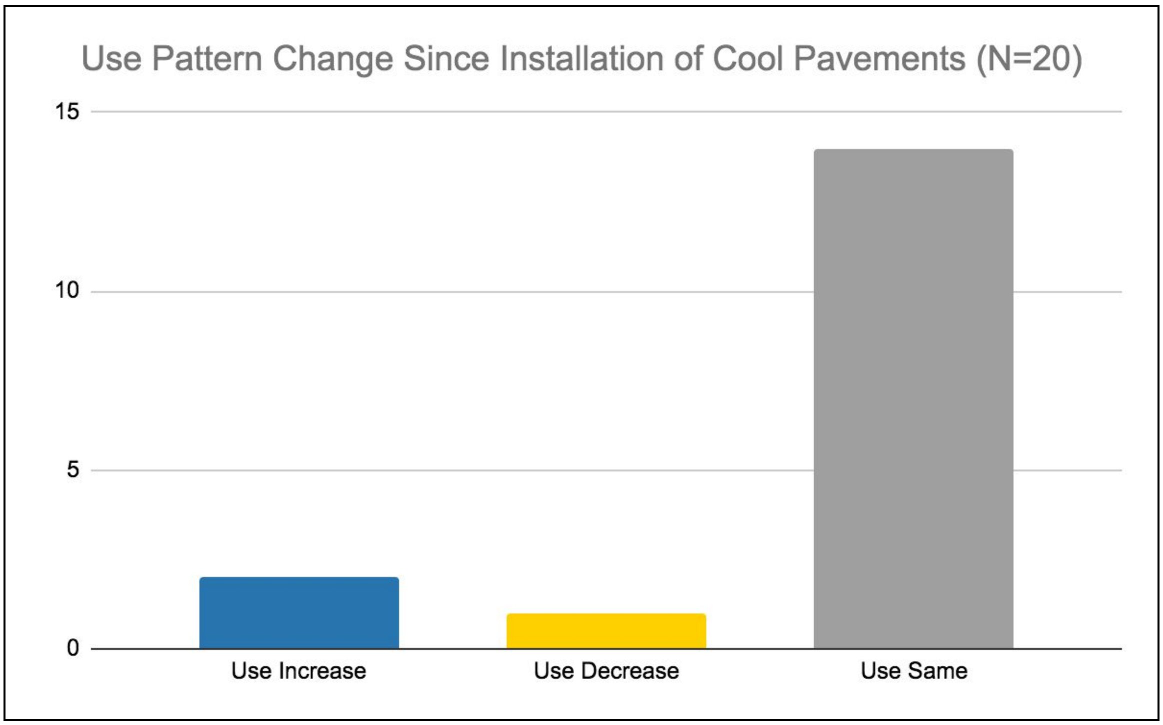

Figure 19- Pattern of the Eighty-Five of the Participants is Unchanged Since the Application of the Cool Pavements.

It was interesting to note that about half of the participants who spent their time in their front yard/ backyards or did go for walks felt less hot since the application of the Cool Pavements. Similarly, the feeling of freshness and tranquility was quoted a maximum number of times by the participants who regularly walked in the neighborhood or did gardening.

Responses on the Appearance of the Cool Paved Surfaces

1. Seven out of twenty participants felt that the Cool Paved streets look “nicer, cleaner and wider” than the asphalt streets.

“Because of the reflection, now it is less of a reason to spend time outside. I would like to see more trees and shade in the neighborhood. I don’t like the Cool Pavements. If it were meant to cool, it has not worked. Now, it’s usually brighter, more reflective, and that reflection goes directly to the house.”

2. Two out of twenty participants did not like the Cool Paved surfaces, specifically because the Cool Paved Streets looked comparatively brighter than the asphalt surfaces, hence causing the blinding effect.

Overall, thirteen people found the Cool Pavements to be less hot than the regular pavement and felt fresh or tranquil while using the Cool Paved streets. Ten out of twenty survey participants noted that they “like and recommend” Cool Pavements, and The same number of individuals mentioned that they would like to see more trees in the neighborhood. In April 2020, the Urban Forestry Division and StreetsLA, to further enhance the Cool Pavements project planted trees along the Cool Streets.

Besides the feedback analyzed in this section, for future study, it would be an interesting exercise to interview residents who have their houses in the same neighborhood but live next to the asphalt coated streets.


7

Conclusion

The present work aimed to investigate the impact of Cool Pavements on the physical mechanisms- T_{AIR}, T_{SURF}, and T_{MRT} that drive thermal comfort. The report examined three empirical research methods to evaluate the thermal comfort of Cool Paved Streets in Sun Valley, Los Angeles: field measurement, microclimate simulation, and questionnaire. The results from the field heat measurement collected using Kestrel sensors on 16th November '19 failed to show significant differences in T_{MRT} of the four pavement types. The T_{MRT} reading of all three shades of Cool Pavements and asphalt surface, more or less, showed a similar pattern. Hence, as per the measured field data, there is no significant difference in the thermal comfort between all the pavement types. However, the study's potential limitations were the limited timeframe for this project; the field data were collected in one day in the fall season. Besides the restricted time frame, the heat measurement data was collected using the Kestrel device, which is a comparatively, less sensitive measurement device than MaRTy.

To study the impact of Cool Pavements during a typical summer period, the study area's micro-climate simulation was not grounded as per the field data conducted in November 2019. Hence, to predict the micro-climate in the study area in hotter months, the simulation input data for the mid of August was used, one of the hottest months in Los Angeles. The simulation model outputs at 1 meter showed that the Cool Pavements recorded higher T_{MRT} from 12:00 hrs to 18:00 hrs than in the scenario with the regular pavements. Therefore, the simulation output predicted that the thermal comfort is higher on regular pavements than on the Cool Pavements in the study area. This result may be attributed to the higher reflectance value or albedo of the Cool Pavements, in comparison to the regular pavements. However, due to the lack of material heat storage in ENVI-met, the simulation output leads to an overestimation of the longwave radiation emitted by walls during the daytime (M. Nikolopoulou M. et al. (2001).

Apart from calculating T_{MRT}, while evaluating the subjective experience of the Cool Pavements on the residents' lifestyle and thermal comfort, it was evident from the questionnaire results that thirteen out of the twenty participants found the experience while using the open spaces as either cooler or felt freshness and tranquility.

Future Research Recommendations

More field investigations are needed to verify the generality and validity of these results for other locations and climatic conditions. As noted previously in the limitations, to further validate the observations made in this report, future experiments should focus on similar inclusive research models as shown in this study but should be conducted over a more extended study period. Future research models should include the following methods:

1. Annual multi-season field observations should be collected using the MaRTy measurement device.

2. Along with comparing the Cool Pavements with the regular pavements, the study should also measure the differences within each variation of Cool Pavements, which otherwise did not get called out in the responses of the residents.

3. The future micro-climate simulation modeling experiments need to investigate the combined impact of variations related to adding shade trees on sidewalks, cool roofs, and the Cool Pavements. For the micro-climate simulation study, the input model should extrapolate the cool or reflective coatings over larger street networks and areas.


8

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All The Photographs Are By The Author, Except on Page Separator On 5, 8, 16, and 49.

Photo Source Links- Page 5 And Page 16
https://www.mnn.com/earth-matters/climate-weather/blogs/how-los-angeles-beating-heat-white-painted-streets

Photo Source Link- Page 8-
https://www.5newsonline.com/article/news/local/outreach/back-to-school/los-angeles-is-painting-some-of-its-streets-white-and-the-reasons-why-are-pretty-cool/527-b46f6079-d980-4faf-a2a5-e8ab9af88582

Photo Source Link- Page 49-
https://www.lamag.com/citythinkblog/l-a-s-most-interesting-and-unusual-streets/


9

Appendix

A.1) Survey Interview Questions: Cool Pavements Project, Sun Valley

Issue: Understanding the demographics

1. How long have you been a resident of this neighborhood?

Issue: Understanding the Usage of the neighborhood

1. On a typical day in your neighborhood, when are you most likely to walk/ bike/ etc.?
2. When are you most likely to spend time in your yard/ driveway/ elsewhere?
3. Can you describe how other members of your family use the neighborhood on a typical day?

Issue: Understanding the interaction with the Cool Pavements

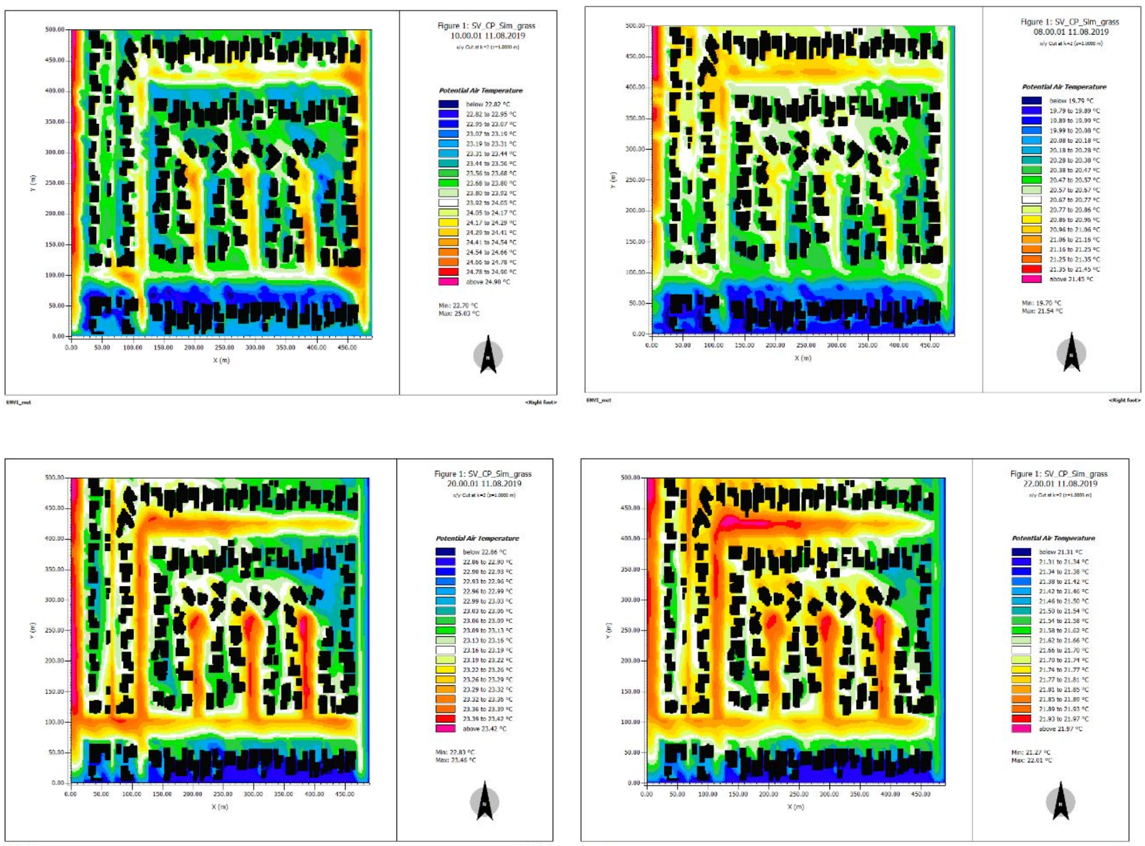
1. How has your interaction with the neighborhood changed, since the application of the Cool Pavements in your Neighborhood?
2. How has your family been using the streets, sidewalks since the application of the Cool Pavements?
3. How would you describe your experience in walking through the cool paved streets in your neighborhood?

Issue: Other outstanding urban-heat related issues

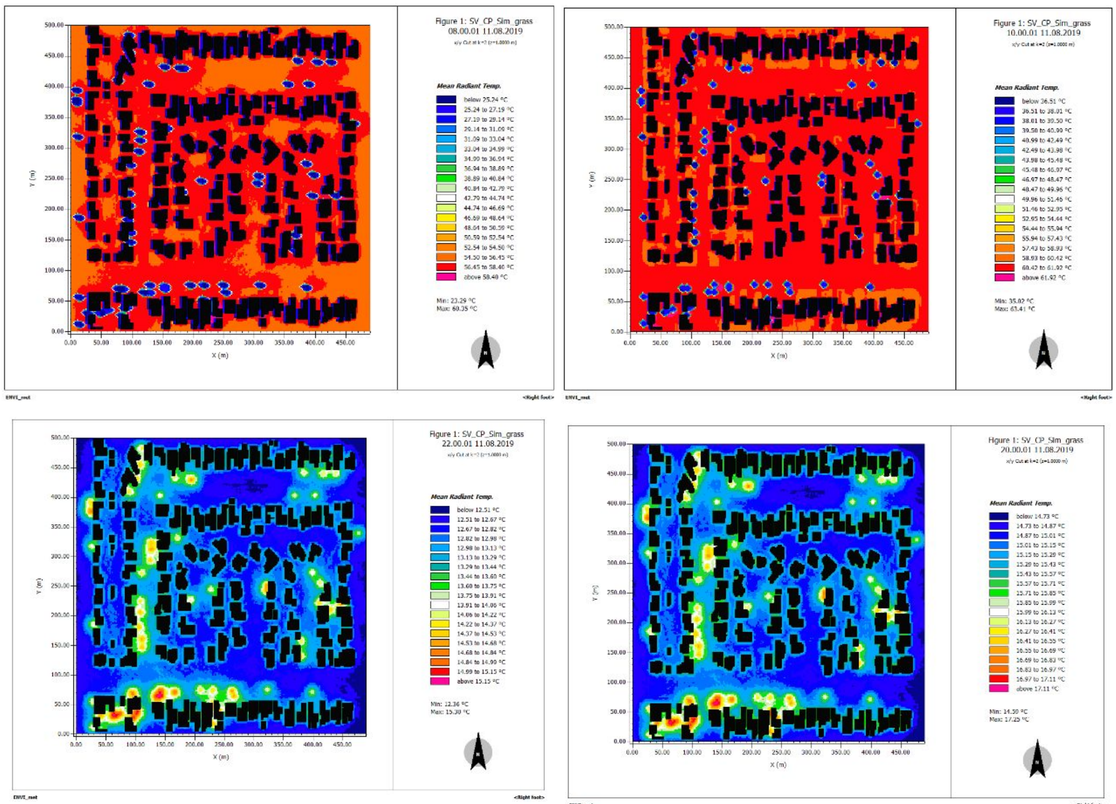
8) Do you have any other comments about the project?

B.1) ENVI-met Simulation Results 'At-Present Scenario'

a- ENVI-met output of T_{AIR} at 08:00 hrs. (top left), 10:00 hrs. (top right), 20:00 hrs. (bottom left), and at 22:00 hrs. (bottom right)



b- ENVI-met output of T_{MRT} at 08:00 hrs. (top left), 10:00 hrs. (top right), 20:00 hrs. (bottom left), and at 22:00 hrs. (bottom right)



B.2) ENVI-met Simulation Results ‘Regular Pavement Scenario’

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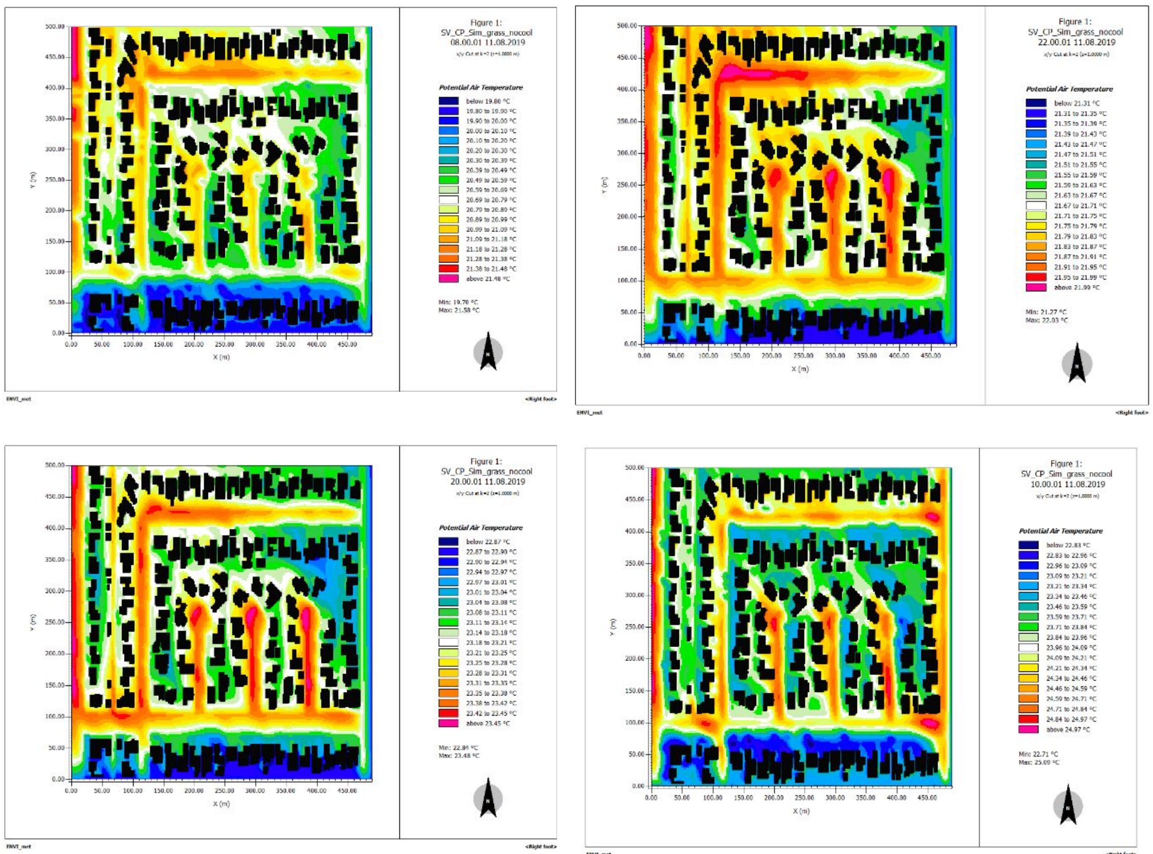

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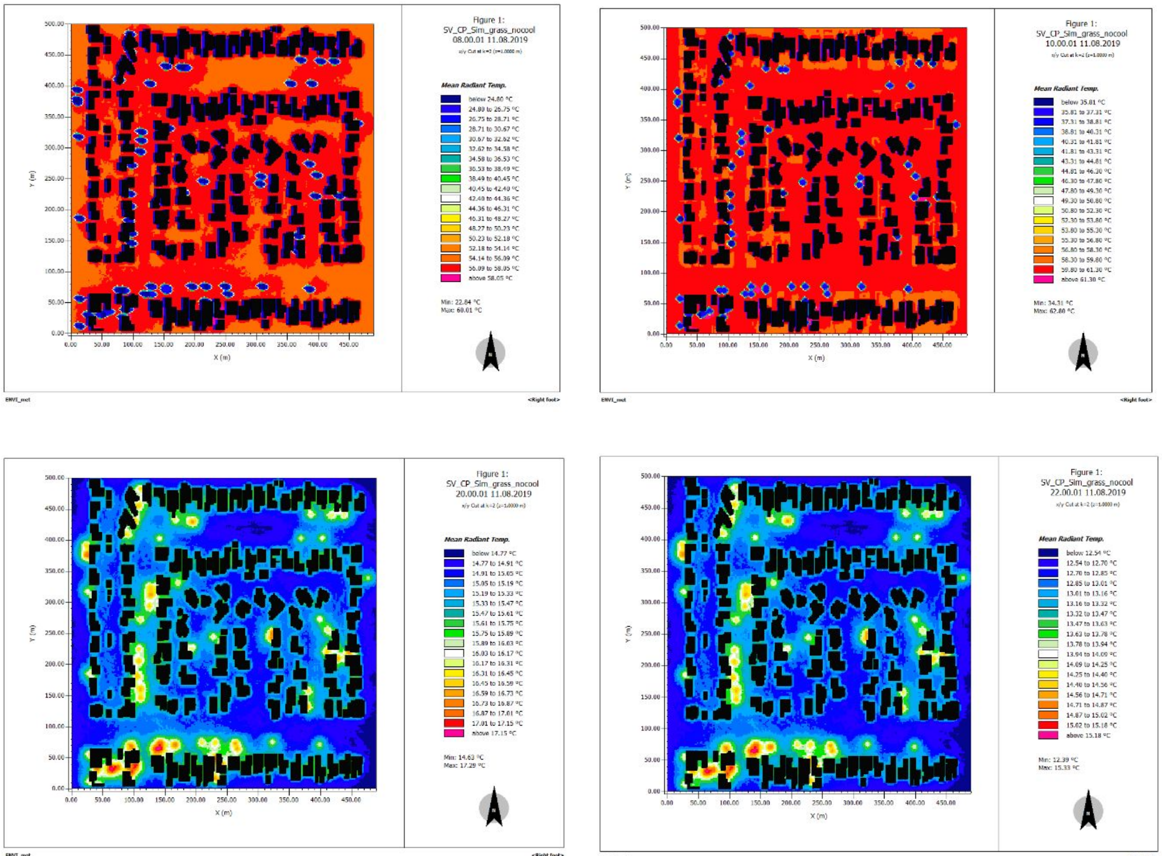

B.3) ENVI-met Simulation Results 'Comparative Scenario'

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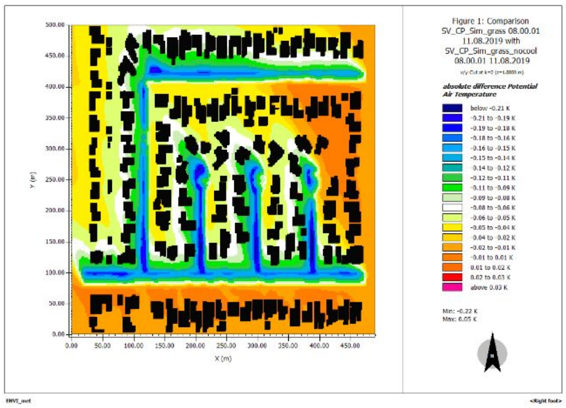

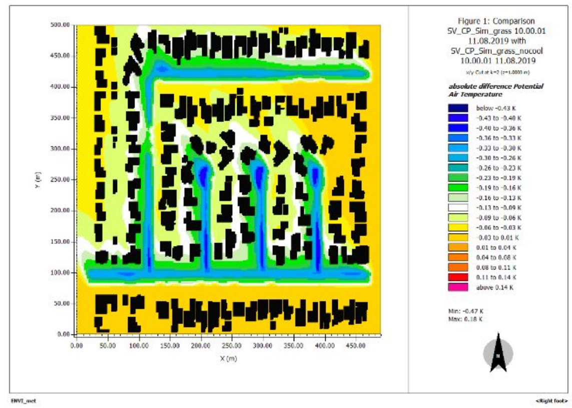

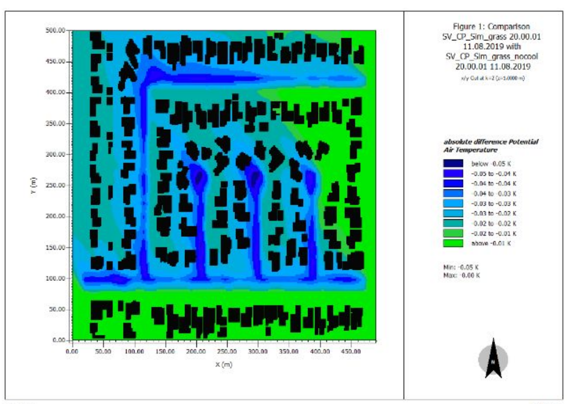

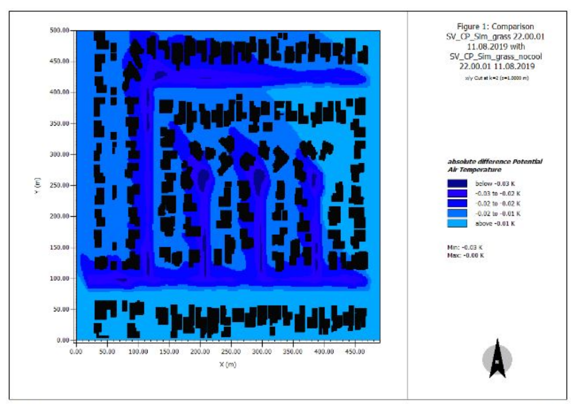

b- ENVI-met output of T_{MRT} at 08:00 hrs. (top left), 10:00 hrs. (top right), 20:00 hrs. (bottom left), and at 22:00 hrs. (bottom right)