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Sidewalk landscape structure to enhance pedestrian thermal comfort in Kathmandu Metropolitan City

by

Arpana Shakya

A THESIS

SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER IN

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DEPARTMENT OF ARCHITECTURE

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DECLARATION

I hereby declare that the thesis entitled "**Sidewalk landscape structure to enhance pedestrian thermal comfort in Kathmandu Metropolitan City**" submitted to the Department of Architecture in partial fulfillment of the requirement for the degree of Master Science in Energy Efficient Building, is a record of an original work done under the guidance of Asso. Prof. Dr. Sanjaya Uprety and Ar. Barsha Shrestha, Institute of Engineering, Pulchowk Campus. This thesis contains only work completed by me except for the consulted material which has been duly referenced & acknowledged.

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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled "Sidewalk Landscape Structure to enhance pedestrian thermal comfort in Kathmandu Metropolitan City " submitted by Arpana Shakya in partial fulfillment of the requirements for the degree of Master in Energy Efficient buildings.

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Abstract

The thermal comfort of pedestrians in the outdoor spaces of urban areas has deteriorated due to the urban densification. Street being major outdoor space that can promote physical activity, and especially with the emerging concept of walkable cities, thermal comfort in streets should be given utmost importance. Thermal comfort for pedestrians is the absence of any sense of discomfort when interacting with the outdoor thermal environment. This study aims to evaluate the effectiveness of various landscape measures to enhance pedestrian thermal comfort. The study adopted the quantitative approach and used the simulation and questionaire survey as methodological tools to mmet its objectives. The study was conducted on both sidewalks of Durbarmarg, one of the dense and busy streets of Kathmandu. The microclimatic modeling software ENVI-met 5.03 was used to create different interventions in landscape (trees and pavement) to see its effect on the thermal environment of sidewalks. The results of the simulation showed that increasing the leaf area density, tree canopy size and height can reduce the air temperature by 0.2 ℃ and Mean radiant temperature by 4.86 ℃. Among the various pavement materials in various scenarios for the simulation, the light concrete pavement showed the highest decrease in terms of the air temperature (0.579 ℃) however the mean radiant temperature was highest (7.22℃) for the same material. Hence, for the high reflective surfaces, the surface /air temperature is reduced but it increases the mean radiant temperature and hence might not be appropriate for the thermal comfort of the pedestrians. The study concludes that proper selection of pavement materials and high leaf area density of trees can enhance the thermal comfort for the pedestrians in sidewalks.

Keywords: Pedestrian thermal comfort, Sidewalks, ENVI-met

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1 CHAPTER ONE INTRODUCTION

1.1 Background

Urban areas has expanded its boundaries due to the rapid population growth which is changing the urban morphology: density of buildings, built geometry, vegetation percentage and nature of ground cover (Faragallah & Ragheb, 2021) . This has also led to the phenomenon called urban heat island effect. The heat island effect elevates city temperatures, increases cooling energy demand, and degrades urban comfort conditions. In cities, the outdoor environment is extremely important because it includes a variety of activities for pedestrians. The comfort level of pedestrians in outdoor spaces directly affects the presence of people outside. The pleasant feeling people have when interacting with their surroundings is a rough definition of pedestrian comfort. The concept of pedestrian thermal comfort falls under the umbrella concept of pedestrian comfort. ASHRAE defines human thermal comfort as condition of the mind that expresses satisfaction with the thermal environment which is determined by environmental and individual variables. Outdoor thermal comfort is mainly related to thermo-physiology, i.e. physiology and heat balance of the human body (Hoppe, 2002) that is directly affected by meteorological conditions.

The thermal comfort of streets is particularly important because they have a high potential to promote physical activity. This is evidenced by the fact that they are frequently used for walking and other outdoor activities. Sidewalks are pedestrian paths that run along a street. The primary purpose of a sidewalk is to provide pedestrian mobility and access to buildings, parks, and other attractions. There are three zones on sidewalks: the clear zone, the service zone, and the transition zone. The transition zone is the space between the free zone and the building entrance, while the service zone contains street furniture such as benches, streetlights, and trash cans.

Traditionally, streets are constructed with an impermeable pavement layer. The amount of solar radiation absorbed by street surfaces, as well as their orientation and geometry, create their own microclimate. The microclimate of streets affects the comfort of pedestrians walking. Walking is the most natural way of getting around and therefore the most common way of getting around in cities like Kathmandu. Walking for short distances in communities could be one of the promising strategies to reduce Vehicle

Miles Traveled (VMT), transport-related energy consumption, and associated environmental impacts. Walkability, or the ease with which pedestrians can move around a city, is cited by many urban planners as the factor that makes a city livable. Improving outdoor thermal comfort enhances walkability. Microclimatic design of streets requires a conceptual understanding of how landscape factors can strongly influence microclimatic components such as wind and solar radiation (Brown & Gillespie, 1995).

Green spaces or properly designed landscapes are one of the most important bioclimatic design elements for thermal comfort. There are two types of landscape design elements: soft landscape design elements and hard landscape design elements. Soft landscaping elements on sidewalks generally include trees and grass, while hard landscaping elements include pavers and street furniture. Natural environments in neighborhoods, such as trees and grassy areas along sidewalks, can help create comfortable thermal conditions that encourage pedestrians to engage in healthy outdoor activities. Trees provide direct shade by intercepting sunlight through their canopy, providing welcome relief to pedestrians (Sun et al., 2021). In addition, the shade provided by street trees minimizes maintenance requirements for sidewalks by reducing fatigue cracking, rutting, shoving, and other surface damage (Kim, et al., 2018). Paving materials also have a strong effect on the street microclimate and represent one of the main contributors to the increase of urban heat island (Faragallah & Ragheb, 2021). As per EPA (Environment Protection Agency), Conventional pavers can reach peak temperatures of 120-150°F (48-67°C) in summer and release the excess heat into the air above them. Many studies have suggested the use of cool pavements that reflect solar radiation instead of storing it.

Improving microclimatic conditions helps in development of cities as the energy use of the surrounding buildings is affected (Panagopoulos, n.d.). Green spaces like trees, bushes, grass can help to cool cities and save energy. Trees provides shade to individual houses during summer and evapotranspiration from trees can reduce urban temperatures. Akbari et al. (1997) found that by adding 3 trees per house in one storey buildings in US cities can reduce the cooling load between 17% and 57%. He also noted that the direct effects of shading account for 10-35 percent of total cooling energy savings. This contributes to higher energy efficiency in cities.

The Kathmandu Valley, with an estimated population of 2.54 million, is growing at an annual rate of 6.5%, making it one of the fastest growing metropolitan areas in South

Asia (Timsina, et al., 2020). Mishra, et al, (2019) study of the urban heat island in Kathmandu found an average temperature difference of 5°C between forested and urban areas in the Kathmandu Valley. Moreover, an annual increase of 0-2°C was found over the last 18 years. This means that Kathmandu is getting hotter day by day. The current urbanization and motorization in Kathmandu does not provide a safe and pleasant environment for walking. Most streets do not even have sidewalks, and those that do exist are either poorly maintained or occupied by parked vehicles and street vendors. Electricity and telecommunication poles were placed indiscriminately throughout the city, often in the middle of sidewalks (The Kathmandu Post, 2022). On some of the sidewalks, there is not a single tree or vegetation to be seen, and the paving of the sidewalks is mostly concrete blocks, which does not make for a pleasant microclimate. In such an environment, thermal comfort for pedestrians on the sidewalks is a distant prospect. Therefore, the study aims to study the existing structure of the sidewalk landscape considering the microclimate of the selected street section in Kathmandu and propose the necessary interventions in the landscape that will improve the thermal environment and increase the thermal comfort of the pedestrians.

1.2 Need of Research

For many years, outdoor thermal comfort research has been one of the most important topics in urban planning, seeking solutions for a more satisfactory thermal environment. Because outdoor environments are more complex than indoor environments, less studies has been done on thermal comfort in open spaces (Nasrollahi, et al., 2020). Since the sidewalk makes up most of the street and outdoor space, it is of utmost importance to provide thermal comfort there. Comfortable sidewalks promote the walkability of the streets. More empirical research is needed to reduce the risks of heat exposure to pedestrians while walking (Kim, et al., 2017).

Many studies have been conducted to show how landscape elements in urban design and planning can improve outdoor microclimate and thermal comfort. Height-to-width ratio and street orientation relative to the sun are well-known parameters for street microclimate. In addition, shading appears to be an effective strategy to reduce heat stress in summer. Previous research has found that street greening, such as shade trees and green spaces, can help reduce uncomfortable thermal conditions for pedestrians. However, quantitative data on the effects of altering various landscape components on sidewalks is still lacking.

No significant studies have been done to improve the thermal environment of the sidewalks of Kathmandu. Many street-improvement projects carried out under the Municipal Infrastructure Improvement Project (MIIP), Kathmandu Sustainable Urban Transport Project (KSUTP) have focused on vehicular movement and drivers' convenience rather than pedestrian comfort, convenience and safety (Shrestha, 2011). In order to promote a walking culture, several streets have been converted into pedestrian walkways (Asia, 2013). Sidewalks were widened and built considering the durability of paving materials, but without considering the thermal impact on the microclimate of the street. Most of the trees along the streets are planted indiscriminately and only for beautification, without considering their impact on the microclimate of the street. Therefore, it is necessary to study the necessary landscaping measures to create a pleasant environment for pedestrians on sidewalks, which affects the comfort of walking outdoors.

1.3 Importance of research

The urban landscape is dominated by concrete and asphalt. Landscaping can have a significant impact on outdoor temperature regulation and pedestrian thermal comfort. This study examines the effects of changing various landscape elements on the thermal environment of sidewalks in a selected street section in Kathmandu. The results of this study will help urban planners, landscape architects, energy experts, and policy makers in developing measures/strategies to improve pedestrian comfort in the streetscape. The results of the study will also help researchers and academicians to conduct further research.

1.4 Problem Statement

Roads are a significant component in urban outdoor space. The transportation these days is vehicle oriented since the widespread use of personal vehicles .Cities have dense road networks, traffic efficiency might have been improved. However, the thermal environment of urban outdoor space has been deteriorated. As a result, air pollution, noise, and temperature stress limit social interactions and economic activity on sidewalks (Lin, et al., 2021). Since a large part of the streets are covered with impermeable black pavements such as asphalt and concrete, which are commonly used as pavements, high surface temperatures are generated (Faragallah & Ragheb, 2021).

They are heat accumulators on the surface and not reflective. For this reason, urban temperatures have been rising steadily for at least the last two decades. Higher summer temperatures in cities can increase the energy required to cool buildings. The higher-than-average temperatures in cities cause people to feel excessively hot in the summer. The streets of Kathmandu are narrow, crowded and confusing. Many national newspapers, including the Kathmandu Post, have noted that walking in Kathmandu is a nightmare and that the city is not designed for pedestrians. Kathmandu ranks last in terms of walkability in the city. According to a 2010 Pedestrian Friendliness Study (an assessment of pedestrian infrastructure and services), 94 percent of street segments in Kathmandu were rated "not walkable." Most streets do not have sidewalks, and those that do exist are in poor condition. The city's sidewalks are mostly paved with concrete blocks. According to the Road Department, there is no space to plant trees in the Kathmandu Valley due to the crowded roads and sidewalks. The lack of open, green spaces has a daily impact on the lives of residents who have little space for walking or other social activities. The expansion of sidewalks has been prioritized over trees planting and vegetation in streets. This leads to the outdoor discomfort which reduces the power of thinking and concentration of pedestrians (Nasrollahi, et al., 2020). It also negatively affects people's health and discourages them from walking. Less walkable streets also mean more use of transportation systems, which increases the energy consumption of the transportation sector. Therefore, improper design of sidewalks in the streets without regard to pedestrian comfort is one of the biggest problems in Kathmandu.

1.5 Objectives of the Study

The main objective of the study is to demonstrate the effectiveness of different landscaping measures to improve thermal comfort on sidewalks considering microclimate of selected area in Kathmandu metropolis.

The sub-objectives include:

- To identify the outdoor comfort parameters and indices and assess the thermal environment of selected area without any alteration.
- To evaluate and compare the impact of modifying various landscape elements on improving thermal comfort for pedestrians.

1.6 Limitations

Kathmandu being a temperate climate, the thermal comfort of the pedestrians should be evaluated during the summer and winter as well. However, the research has studied and evaluated the thermal comfort of pedestrians only during summer. Also, the number of respondents of the survey is only limited to 36 since a major number of people did not want to take part in survey due to various reasons. The software used for the simulation for the research ENVI-met have certain limitations like: The albedo and thermal resistance of the building surfaces are constant and cannot be varied. The building blocks have no thermal mass and only a single constant internal temperature. In addition to that, the albedo values and thermal transmittance of the various pavement materials used in the simulation has been taken from the various sources/sites apart from those which are already in the in-built setting of ENVI-met.

2 CHAPTER TWO LITERATURE REVIEW

2.1 Sidewalk Landscape, Pedestrian thermal comfort and Energy efficiency

Outdoor space is extremely important in cities as it provides a variety of activities for pedestrians. Maximizing the use of outdoor space in summer helps to save energy by reducing the need for indoor cooling. Pedestrian comfort in outdoor spaces has a direct impact on the presence of people outdoors. Pedestrian comfort is the pleasant feeling people experience when interacting with the environment. The generic term of pedestrian comfort is thermal pedestrian comfort. The thermal comfort of outdoor streets is particularly important as they have a high potential to encourage physical activities such as walking.

Many studies have shown how landscape elements in urban design and planning can improve outdoor thermal comfort (Li, et al., 2021). Sidewalk treatments and features of landscape affect the pedestrian thermal comfort can make a significant difference in the perceived walkability of a street. Encouraging walking for short distances could be one of the promising strategies to reduce: Vehicle Miles Travelled (VMT), transport-related energy consumption and associated environmental impacts.

Landscaping is considered as one of the best long-term investment for reducing heating and cooling costs. Clearly vegetative landscaping can be an extremely effective energy-conservation technique. According to Akbari (2002) planting trees in cities can reduce energy consumption for cooling and heating in urban areas by 25%. To achieve maximum efficiency, the trees must be placed scientifically, because the shape, size and foliage of the trees directly influence their shade and the penetration of the sun's rays. The extent of the savings indicates that trees and shrubs reduce the need for cooling not only by providing shade, but also by reducing the penetration of warm air and creating a cool microclimate in the immediate vicinity of the building (Parker, 1978). The materials used for urban pavements and pavements also have a significant impact on pedestrian comfort. During the day, dark materials absorb solar radiation and radiate it again at night. Cool materials, on the other hand, are often suggested to mitigate UHI problems due to their high albedo. This helps to maintain a comfortable microclimate in the streets.

Generally, urban microclimate and comfort are given little importance in the urban design and planning processes. Future attempts to improve energy efficiency in cities should not focus on the building alone, but should include landscaping as an integral component.

2.1.1 Walkability

Walkability is an important feature of pedestrian sidewalks. It is a concept that emphasizes the importance of creating paths that encourage people to walk. This type of non-motorized travel is crucial for sustainable communities (Zayed, 2018). Walkability, or the ease with which pedestrians can move around a city, is cited by many urban planners as the factor that makes a city livable. The walkability of an area is a measure of how suitable it is for walking. Improving walkability helps people's health, the economy and the environment. Basically, walkability refers to the extent to which the built environment facilitates pedestrian mobility. Green infrastructure in cities and towns is an important component and tool for creating pedestrian-friendly streets and environments. Urban greenery affects all aspects of the walkability of cities, including the attractiveness, safety, environmental quality and walking comfort of a street.

Cities that are green are walkable cities. The walkability of a place seems to be a complex interaction of the micro-level characteristics of an individual street and the macro-level characteristics of the neighborhood around that street (Tiemann, et al., 2012). Different sidewalk treatments and different features of sidewalk landscape can make a significant difference in the perceived walkability of a street.

Figure 2-1 Attractive landscape inspire people to walk
Source: Pinterest

2.2 Chronology of Study of Outdoor thermal comfort

Several studies have been conducted to improve the thermal comfort of pedestrians. The research dates back to the last decades of the twentieth century. The first studies on the effects of microclimate on outdoor activities were conducted in 1971 (Chen & Edward, 2012). The number of people sitting on shaded or unshaded benches showed that sunny or shaded conditions affected their willingness to stay or leave. This led to the conclusion that the physical conditions of a place affect people's thermal comfort.

One of the first studies in the field of outdoor thermal comfort based on human behavior was conducted in 2001. In this study, Nikolopoulou et al. (2001) investigated thermal comfort in open spaces in Cambridge, United Kingdom. Thorsson et al. (2004) investigated the impact of biological conditions on people's behavioural patterns via questionnaire survey in a park in Sweden. Lin et al. (2010) studied the effect of shadowing on thermal comfort in outdoor environments. They evaluated thermal conditions on campus using RayMan software to calculate the index PET. It was found that shading from trees and buildings provides a thermally comfortable microclimate in Taiwan's very hot summers and mild winters. In 2012, Wu and Kriksic described the methodologies for microclimate assessment and provided strategies to create pedestrian comfort conditions that are responsive to the local climate. Buccolieri, et al., (2015) studied the effectiveness in reducing thermal stress in urban spaces by incorporating green infrastructure (trees) in urban spaces. Sanusi, et al., (2016) studied three similar north-south orientated streets with three different tree species possessing different canopy and leaf characterisitics in summer. Huang et al. (2016) investigated temperature differences within a university in northwestern China considering different scenarios with increased green spaces, water elements, and highly reflective surfaces using ENVI-met. It was concluded that increasing green spaces led to a maximal reduction of temperature. Salata et al. (2017) measured air temperature within the campus of Sapienza University of Rome, Italy. They found that concrete pavements had higher albedo and lower thermal capacity than those of asphalt, and this could improve thermal conditions. Jamei & Rajagopalan (2018) investigated the effect of street design towards the development of a comfortable microclimate at street level for pedestrians through numerical simulation using City North, Melbourne as a case study. Taleghani (2017) concluded that, among different climatic factors, mean radiant temperature has the greatest impact on thermal comfort in outdoor environments. He also found that using vegetation in urban environments is better than using highly reflective surfaces. Kasim et al. (2018) investigated and measured the physical properties of the landscape setting and its surrounding environment for pedestrians. According to the study's findings, different types of landscape settings have the potential to improve campus environments and lifestyles. Kim et al. (2018) looked into the effect of sidewalk trees and grass on air temperatures. This study found that street trees and vegetated ground help reduce air temperatures, resulting in more thermally comfortable environments for both child and adult pedestrians in hot climates. Fadhlurrahman and Nasrullah set out in 2020 to investigate the effects of shade from various canopy forms at various distances from the trees.

Lin et al. (2021) studied the thermal environment of sidewalks within varied urban road structures. Gachkar, et al.(2021) evaluated outdoor thermal comfort conditions in the microclimate of the urban historic garden of Urmia, Iran for both summer and winter. In 2022, Speak and Salbitano quantified the different microclimates and thermal comfort conditions in six classes of urban morphology, discriminating land types with or without trees.

Studies in recent decades have mainly focused on the effects of green infrastructure (different tree species, canopy size, and leaf characteristics), pavement, and street orientation on pedestrian thermal comfort. These studies investigated the causes and effects that influence human thermal comfort outdoors. However few studies have been done which combines the effect of pavements and vegetation on outdoor thermal comfort. The studies were based on measurements, questionnaire surveys, and simulations. In recent decades, outdoor simulation tools have revolutionized the development of these studies. In many studies conducted in recent years, the evaluation of outdoor thermal comfort was based on the PET (Physiological Equivalent Temperature) index. In these studies, there is a table that defines the relationship between the thermal perception and the PET index or the acceptable temperature in the climate.

2.3 Outdoor thermal comfort

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) defines human thermal comfort as condition of the mind that expresses satisfaction with the thermal environment which is determined by environmental and individual variables.

The six factors affecting thermal comfort are both environmental and personal.

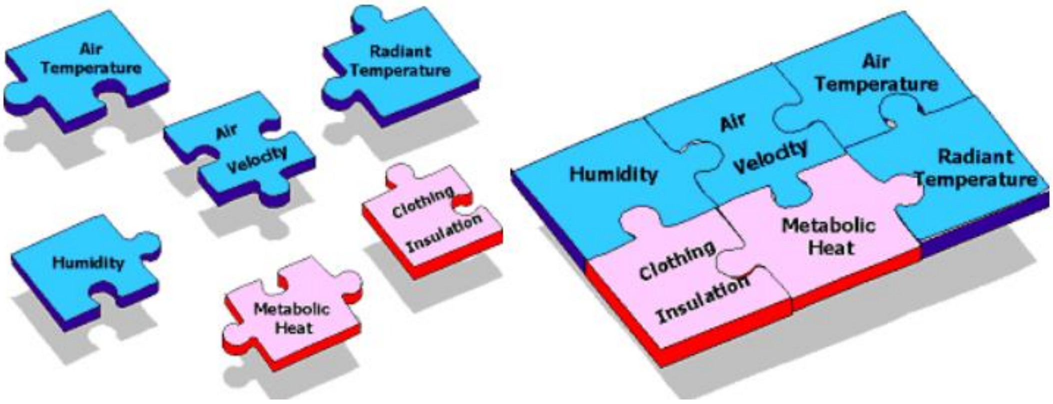


Figure 2-2 Factors of Thermal Comfort
Source: (hse.gov.uk)

Table 2-1 Factors of Thermal Comfort

Environmental	**Personal**
Air temperature	Clothing Insulation
Radiant temperature	Metabolic heat
Air Velocity	
Humidity	

Air temperature

This is the temperature of the air surrounding the body. It is usually given in degrees Celsius (°C).

Radiant temperature

Thermal radiation is heat that radiates from a warm object. Radiant heat can be present when there are heat sources in an environment. The radiant temperature has a greater influence on the heat loss or gain in the environment than the air temperature.

Examples of radiant heat sources are: the sun, fires, electric fires, cookers, oven walls, ranges, dryers, hot surfaces and machines, molten metals, etc.

Air velocity

It is described as the speed of the air moving through the environment and can help cool people if the air is cooler than the environment. Air velocity is an important factor in thermal comfort.

Humidity

The amount of water in the air that results when water is heated and evaporates into the surrounding environment provides humidity. Relative humidity is defined as the ratio of the actual amount of water vapour in the air to the maximum amount of water vapour that the air can hold at that temperature. Relative humidity levels between 40% and 70% have no effect on thermal comfort.

Clothing insulation

Thermal comfort depends largely on the insulating effect of clothing on the wearer. Wearing too much clothing can be one of the main causes of heat stress, even if the environment is not perceived as warm or hot: Clothing is both a potential cause of thermal discomfort and a means of controlling it as we adapt to the surrounding climate.

Work rate/metabolic heat

The more physical work we do, the more heat we produce. The more heat we produce, the more heat must be dissipated so that we don't overheat. The influence of metabolism on thermal well-being is crucial. A person's physical characteristics should always be taken into account when considering their thermal comfort, as factors such as height and weight, age, fitness level and gender can have an impact on their comfort, even if other factors such as air temperature, humidity and air speed are constant.

Outdoor thermal comfort is mainly related to thermo-physiology, i.e. physiology and heat balance of the human body (Hoppe, 2002) that is directly affected by meteorological conditions. There are various parameters for outdoor thermal comfort. They can be categorized into subjective and objective.

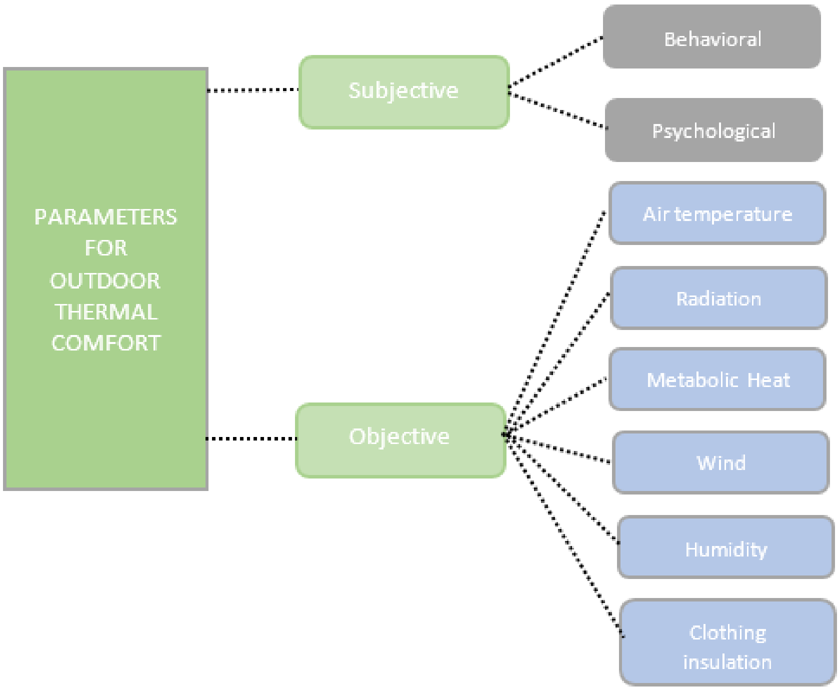


Figure 2-3 Parameters for outdoor thermal comfort

Source: **(Mukherjee & Mahanta, 2014)**

There are three approaches to defining thermal comfort. To begin, the psychological aspect refers to the mental expression of satisfaction with the outdoor thermal condition. Second, the thermo-physiological aspect influences biological reactions and thermal receptors on the skin in response to the external environment. Third, the energetic aspect is concerned with the flow of heat from and to the human body.

Thermal comfort is one of the most important factors influencing pedestrian health, and increasing thermal comfort improves walkability (Nasrollahi, et al., 2020).Thermal comfort plays an important role in encouraging people to use outdoor spaces. The outdoor spaces is of high importance in cities because it include various pedestrian activities.

2.3.1 Thermal comfort Indices

Several Indices are available to evaluate thermal comfort. While thermal comfort indoor is well documented, assessing outdoor thermal comfort is less understood. Assessment methods for outdoor thermal comfort has been originally conceived from those of indoor thermal comfort. A large number of thermal indices are available and most of them have common features, they can be classified as: empirical or rational.

Empirical Indices are based on measurements with subjects or on simplified relationships (ASHRAE, 2001a). These are often limited to estimating the combined effect of air temperature, humidity, and air speed on people engaged in sedentary activity. These empirical indices disregard the importance of human physiology, activity, clothing, and other personal data (height, weight, age, sex). Rational indices are more recent, owing to recent advances in computing techniques, and are based on the human energy balance. In this case, heat transfer theory is used as a rational starting point to describe the various sensible and latent radiation flux exchanges, along with some empirical expressions that describe the effects of known physiological regulatory controls (ASHRAE, 2001a).

Among these, the important outdoor thermal comfort indices are:

Physiological Equivalent Temperature (PET): According to Mayer and Hoppe (1987), "PET is defined as the equivalent air temperature at which the human body's heat balance exists in a typical indoor condition" (work metabolism 80 W of light activity, and clothing of 0.9 clo). PET has advantage in terms of applicability because it can be calculated in degree celsius. PET is also applicable to evaluate outdoor thermal comfort. The figure shows the PET in different climates.

Table 2-2 Neutral physiologically equivalent temperature (PET; acceptable temperatures) in different climates. *Source:* **(Nasrollahi, et al., 2020)**

Geographical Region	Climate	Temperature Range (°C)
Malaysia	Temperate	18–23
Malaysia	Subtropical	26–30
Isfahan, Iran	Hot and dry	23.06–29.73
Central and western Europe	Temperate	18–23
Taiwan	Tropical	26–30
Crete, Greece	Mediterranean	20–25
Athens, Greece	Mediterranean	18–23
Hong Kong	Hot and humid	28
Nis, Serbia	Temperate	18–23
Sao Paulo, Brasilia	Hot and humid	27.2
Hong Kong	Tropical	25–29
Sydney, Australia	Subtropical	26.2
Belo Horizonte, Brasilia	Tropical	19–27
Belo Horizonte, Brasilia	Tropical	16–30
Freiburg, Germany	Continental	18–28
Ibadan, Nigeria	Tropical	23–27
Dhaka, Bangladesh	Tropical	28.5–32.8
Singapore	Tropical	26–31.7
Guangzhou, China	Subtropical	28.54–31

Predicted Mean Vote (PMV): Initially PMV has been developed by Fanger (1972) for indoor spaces . Later on Jendritzky and Nubler (1981) developed a model called Klima-Michel Model (KMM) for applying the PMV index to outdoor environment.

Outdoor Standard Effective Temperature (OUTSET): Gagge *et al.* (1986) proposed the new standard effective Temperature (SET) by improving ET. SET is defined by ANSI/ASHRAE Standard 55-2010 as the air temperature at which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is equal to that from a person in the actual environment, with actual clothing and activity level.

Universal Thermal Climate Index (UTCI): UTCI gives an evaluation of the outdoor thermal environment in the bio meterological applications. It is developed by Hoppe in 2002. UTCI is in degree Celsius scale and it gives imformation about how the weather feels with factors such as wind,solar radiation and relative humidity to the public.It can also be calculated online.

Table 2-3 Based on Fazia Ali TOudert.; (2005),Givoni ,B., Noguchi,M., Saaroni,H.,Pochter,O.,Yaacov,Y.,Feller ,N.,& Becker,S. (2003)

INDICES / FACTORS	PMV	PET	OUTSET
Introduced	Fanger in 1972	Mayer and Hoppe in 1987,1999	Pickup and De Dear in 1999
Parameters Considered	Clothing and Activity levels as variables.	Earlier, it did not consider Clothing and Activity levels as variables. But in the Rayman Model, these variables are added.	Clothing and Activity levels as variables
Range	Limitations in the range of its upper and lower limits. (Temperature only from 10^0 C to 30^0C) Not suitable for tropical climate (extreme temperature).	Assumes RH=50% in the reference indoor situation which actually changes with T_a in outdoor situations. Hence less accurate.	Assumes Vapour Pressure of 12hPa which is constant water content in the air independent from T_a. Hence more accurate.
Applicability	It does not take into account the thermo-regulations of a human body. Hence not very accurate for extreme conditions (typically outdoors).Thus mainly used for indoor areas.	It takes into account the thermo-regulations of a human body. Hence more accurate for extreme conditions (typically outdoors). Hence better than PMV.	It takes into account the thermo-regulations of a human body. Hence more accurate for extreme conditions (typically outdoors). Hence better than PMV.

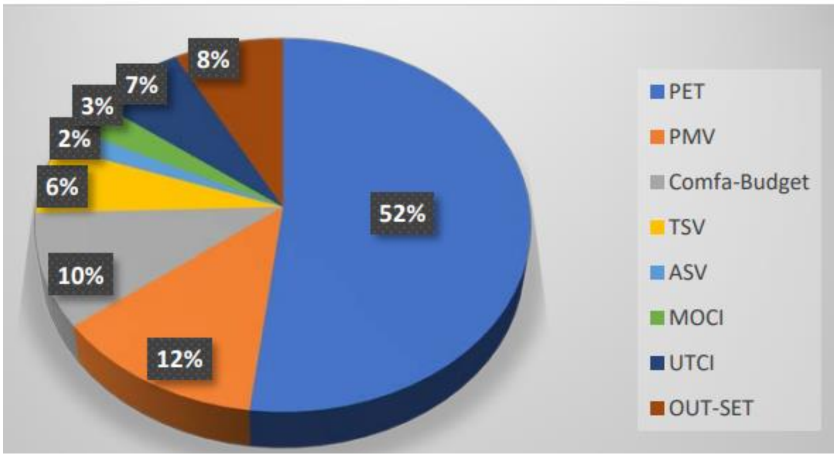


Figure 2-4 Usage percentage of various indices to assess outdoor thermal comfort conditions
Source: **(Nasrollahi, et al., 2020)**

Among the various indices, PET is mostly used to assess the outdoor thermal comfort conditions.

2.3.2 Human energy balance

The energy exchange take place between human and the surrounding environment and the process is expressed by the following equation known as heat energy balance equation:

$$\mathbf{M + W + Q + Qh + Ql + Qsw + Qre = S}$$

where,

M: Metabolic rate (i.e internal energy production by oxidation of food)

W: Physical work output

Q: Net radiation budget of the body

Qh: Convective heat flow (sensible)

Ql: latent heat flow for diffusion of water vapour

Qsw: Latent heat flow due to evaporation of sweat

Qre: Respiratory heat flux (sum of heat flow for heating and humidifying the inspired air)

S: Storage heat flow for heating (positive value) or cooling the body (negative value)

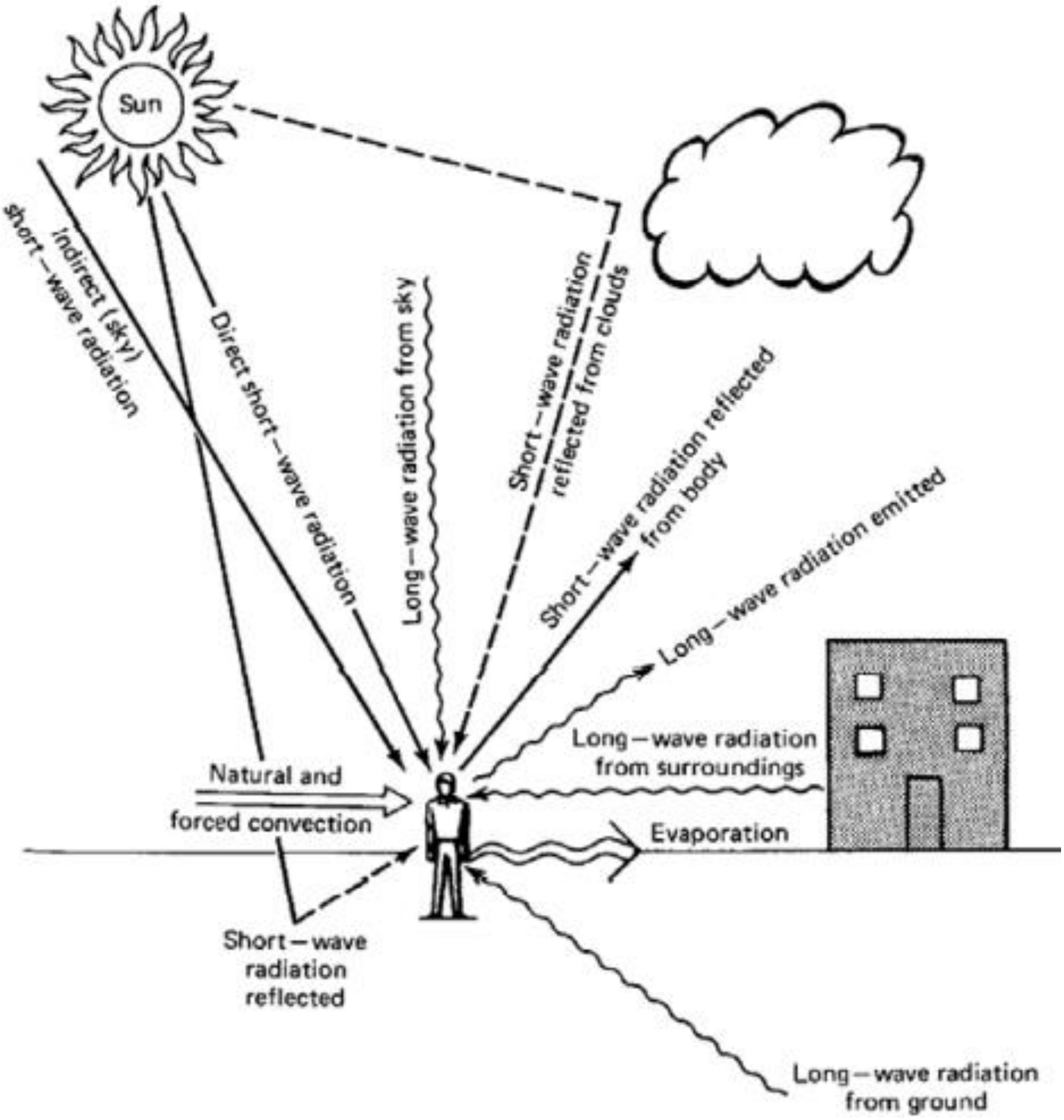


Figure 2-5 Components of Human heat balance

Source: (Houghton ,1985)

2.3.3 Mean Radiant Temperature

Mean radiant temperature is important parameter in assessing the human comfort outdoors. It sums up all the short wave and long wave radiation fluxes absorbed by a human body. Regardless of the comfort index used, Tmrt is the key variable in evaluation thermal sensation outdoors (Toudert, 2005). Tmrt is regarded as the primary driver of human thermal comfort and the most human-relevant heat metric (Middel et al. 2016).

ASHRAE defines mean radiant temperature as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant hear as in the actual non-uniform enclosure. Theoretically, Tmrt applicable outdoors is given by the formula (Fanger,1970):

$$T_{mrt} = \left[1/\sigma_B \left(\sum_{i=1}^{n} E_i F_i + \frac{\alpha_k}{\varepsilon_p} \sum_{i=1}^{n} D_i F_i + \frac{\alpha_k}{\varepsilon_p} f_p I \right) \right]^{0.25}$$

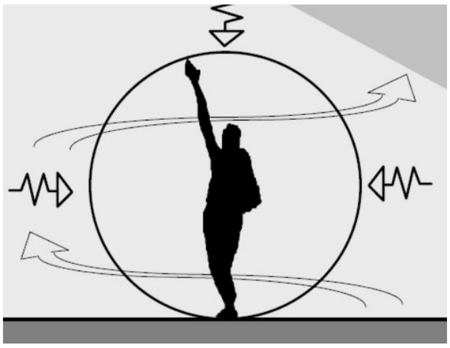


Figure 2-6 Mean Radiant Temperature

Source: designingbuildings.co.uk

Where, n: no of isothermal surfaces in the surrounding

Ei:: long-wave radiation component

Di: Diffuse and diffusely reflected short wave radiation component

Fi: angle weighting factor

I: direct solar radiation impinging normal to the surface

Ak: absorption coefficient of the irradiated boy surface for short-wave radiation

Ep: emissivity of the human body

σ : Stefan boltzman constant

Fp: surface projection factor

2.4 Landscape design

The built environment has impact on the outdoor thermal conditions. Landscaping plays significant role in modifying the outdoor temperature. Landscaping can have major influence on various outdoor microclimate parameters like solar radiation, temperature, relative humidity, wind speed, wind direction and glare. Vegetation influences urban climate by primarily providing shade, evapotranspiration, and directing wind, either as a windbreak or as a wind funnel (McPherson et al. 1994). Shading by volume, shape and leaf density is the important characteristics of tree.

The major concept in landscape in influencing the outdoor thermal comfort is: Sun being the major source of heat gained by various elements in a landscape, the amount of heat gained by them can be controlled by selecting and placing the landscape elements accordingly.

Control of Solar radiation: The sun emits solar radiation that warms the elements of a landscape. When the rays of sun falls perpendicular to the surface of any object, it receives the highest amount of solar radiation. The object with the darker surface absorb more radiation and the hotter it gets, it will reflect the less solar radiation toward the other surfaces. On the other hand, it will absorb less heat and reflect more solar radiation if the object is lighter in cooler. Hence for reducing the air and surface temperature and for controlling radiant temperature, shading provided by vegetation, trees, shrubs can be the important technique for controlling the microclimate in street. Also the light colored pavements can be used.

Control of Air temperature: Air temperature in parks is comparatively lower than that of the other areas in urban areas which is dominated by concrete and asphalt. Shading by trees is a significant measure in regulating the air temperature because of evapo-transpiration process. It is the process in which plants collect the water from ground and evaporates the water through the leaves. It causes the cooling effect.

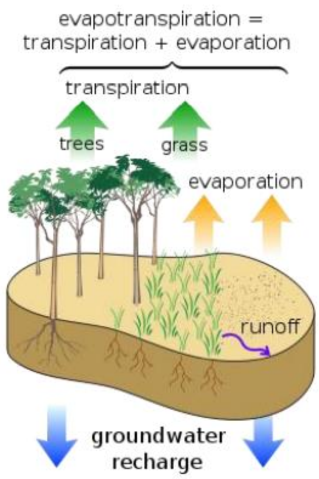


Figure 2-7 Evapotranspiration

Source: Wikipedia

Control of humidity: Trees and vegetation increase the humidity of any site. During hot and dry seasons, they can balance the humidity and thus helps to maintain thermal comfort in a place. The relative humidity increases where plants and trees are nearby but it reduces the air temperature.

Control of Speed and of wind: Wind is the most efficient method of cooling objects. Wind speed varies with the season, but it can be reduced by strategically placing landscape elements. In general, windbreak vegetation with a porosity of around 50% can be successful in the landscape. Vegetation has been shown to be an effective means of controlling wind velocity. A pattern of rows of trees can be an effective way to filter dust and reduce wind speed. Trees and shrubs also help to direct the wind's direction towards or away from the site.

Control of Reflectance (Albedo) and Surface Absorptivity: Landscaping elements can be used to control the rate in which surfaces absorb and reflect solar radiation. To control the amount of solar radiation absorbed or reflected, vegetative ground cover, proper selection of pavement materials can be beneficial.

2.5 Street microclimate

A Street is defined as a "thoroughfare, particularly in a city, town, or village that is wider than an alley or lane and usually includes sidewalks." According to research, the aspect ratio of streets, the proportion of greenery, and the ground surface materials all have a significant impact on the physical environment of a streetscape in terms of the urban street microclimate (Shashua-Bar, et al., 2004, Pearlmutter, et al., 2006, Emmanuel, et al., 2007). Various landscaping elements can be used to control the microclimate in the street. Outdoor climate variables that can be controlled by landscaping include ambient temperature, relative humidity, solar radiation, wind speed, wind direction, and glare. The microclimate of streets influences pedestrian walking comfort.

2.6 Sidewalks

Sidewalks are pedestrian paths that run parallel to a street. Sidewalks and walkways are "pedestrian ways" that allow people to move within the public right-of-way while remaining separated from vehicles on the street. Sidewalks should be provided on both sides of all streets in all urban areas. They improve connectivity and encourage walking by serving as conduits for pedestrian movement and access. Concrete, crushed stone, asphalt, and other materials are commonly used to construct sidewalks. Greening of sidewalks can be done independently or in conjunction with other streetscape elements such as street trees, biological detention basins (rain gardens), or permeable paving. Attractive sidewalk design can encourage people to walk. Sidewalk width, shrub width, tree height, and tree width are design elements for sidewalks.

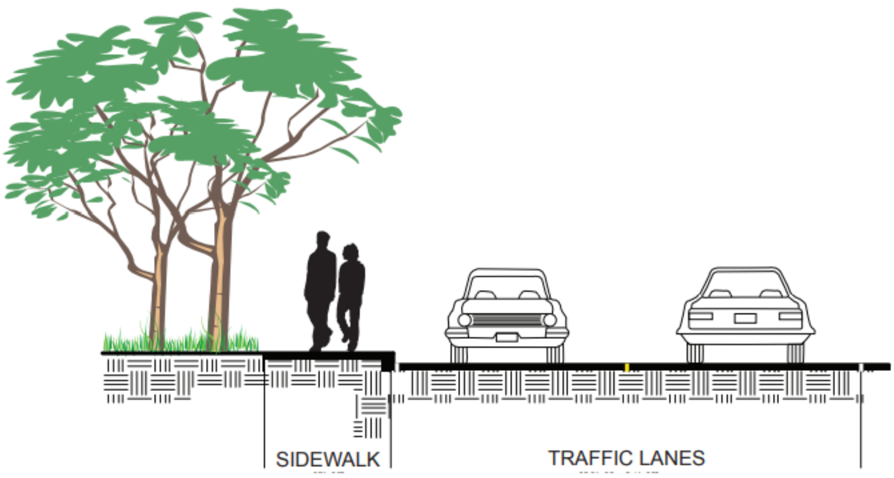


Figure 2-8 Sidewalks
Source: nacto.org

2.6.1 Sidewalk zones

Generally the sidewalks consists of the following zones.

Frontage Zone: The frontage zone is a section of the sidewalk that serves as an extension of the building and includes both the structure and façade of the building that faces the street, as well as the space immediately adjacent to the building.

Pedestrian through zone: It is the main accessible pathway parallel to the street. The zone ensures that pedestrians have a safe and adequate space to walk in residential settings and 8-12 ft wide in commercial settings.

Street Furniture/Curb Zone: It is the section of the sidewalk between the curb and the pedestrian through zone that includes street furniture and amenities such as lighting, benches, and bicycle parking.

Enhancement/Buffer zone: It is the area immediately adjacent to the sidewalk that contains a variety of elements such as curb extensions, parklets, and storm water management features.

In case of urban areas of Nepal, Sidewalks comprise three zones; free zone, service zone and transition zone. The free zone is main pathway for pedestrians, and the service zone is where street furniture like benches, street lamps and trash bins are located, and the transition zone is the space between the free zone and building entrance.

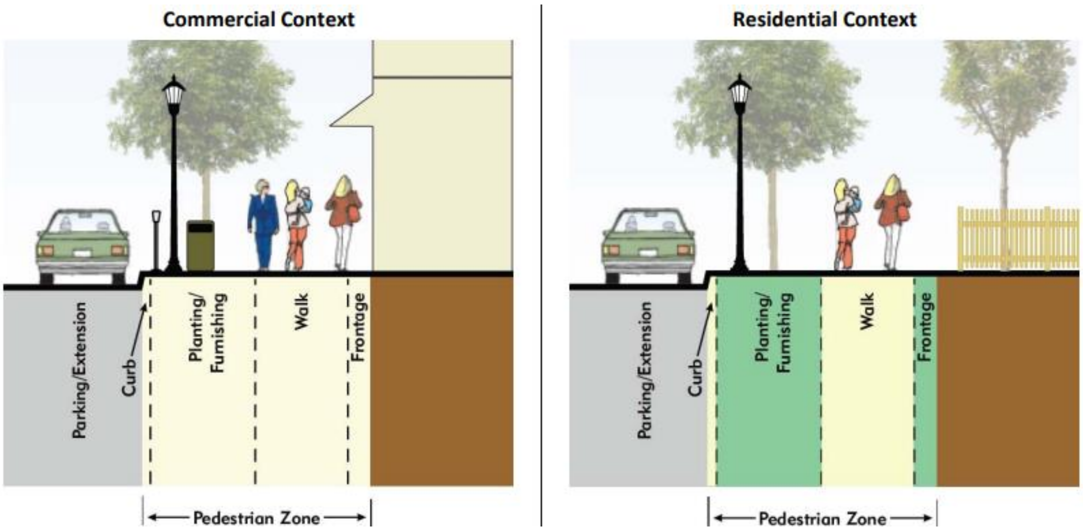


Figure 2-9 Sidewalk zones in Commercial and Residential context

Source: Access Minneapolis; Design guidelines for Streets and Sidewalks

As per Urban Road Standard 2076, for comfortable movement of people with disabilities, the minimum clear width of a footpath should be 2.0 m, but 2.4 m is desirable, at least along arterial and secondary roads.

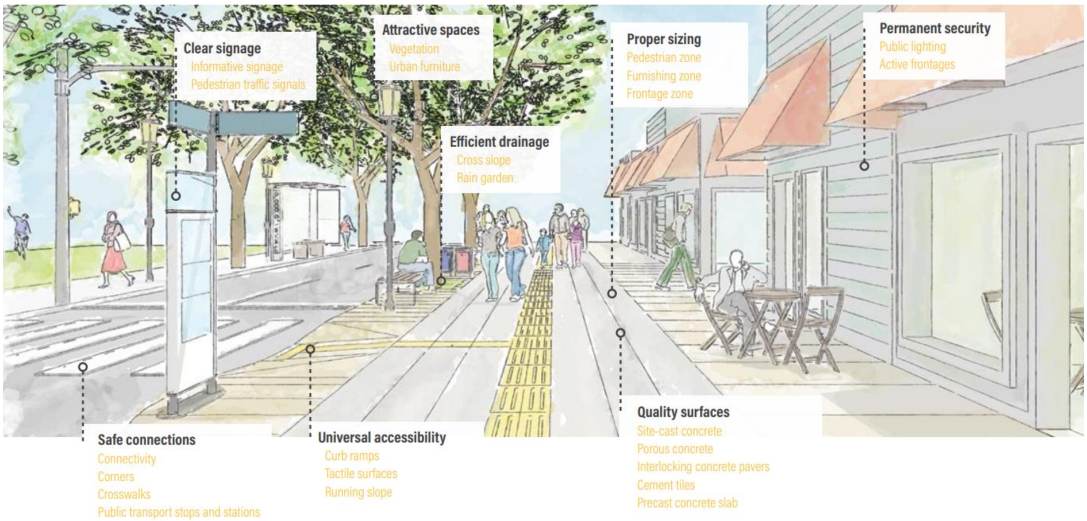


Figure 2-10 The eight principles of the sidewalk and its elements

Source: **(Santos, et al., 2019)**

Table 2-4 Contribution of the eight principles to improving the quality of sidewalks

Source: **(Santos, et al., 2019)**

PRINCIPLES OF THE SIDEWALK	WHAT DOES IT MEAN?	HOW DOES IT CONTRIBUTE TO THE QUALITY OF SIDEWALKS
Proper sizing	Sidewalk width compatible with the use of the area	Provides pedestrians with comfort and safety
Universal accessibility	Use of elements to facilitate access for everyone	Contributes by making urban space more inclusive
Safe connections	Elements that interlink sidewalks and help to build a network	Facilitate and prioritize walking
Clear signage	Series of signs that guide pedestrians within urban spaces	Provides information about the city at the scale of pedestrians
Attractive spaces	Elements that contribute to making spaces more pleasant	Motivate people to walk and occupy urban public spaces
Permanent security	Aspects that provide improved public security in urban spaces	Increases the sensation of security while walking
Quality surfaces	Techniques to ensure a firm and regular sidewalk surface	Provide pedestrians with comfort and safety
Efficient drainage	Techniques to ensure the flow of rain water	Contributes to maintaining sidewalk functionality

2.6.2 Street as a walkable environment

Buildings, open spaces, streets and paths are important urban design elements in a neighbourhood. The legibility and interconnectedness of these elements supports ease of movement and pedestrian accessibility. Sidewalks and streets not only facilitate easy movement for pedestrians, but are also considered the most important public spaces in a city.

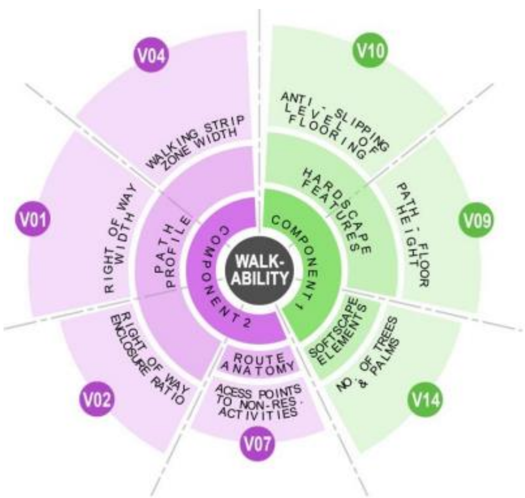


Figure 2-11 Variables of walkability

(Source: **(Zayed, 2018)**

Streets not only facilitate vehicular traffic, but also provide pedestrians with an inviting, safe, aesthetically pleasing and accessible environment with sufficient facilities for pedestrians. The elements of a street along with the overall image of the streetscape contribute to the quality of the walking environment (Kdher, et al., 2016).

Pavements and walkways are considered key elements of pedestrian-friendly streets and should provide pedestrians with safety, accessibility, comfort and efficient mobility when walking on them. Pavements are intended for use by pedestrians. However, pedestrians have to share this space with a long list of obstacles and street furniture, many of which are necessary for traffic regulation. Different pavement designs and different features of the pavement landscape can make a significant difference in the perceived walkability of a street. Considering landscape architecture for sidewalks helps to improve the area, potentially encouraging more people to walk it.

2.6.3 Landscaping elements in sidewalks

There are two types of landscape design elements: soft landscape design elements and hard landscape design elements. Soft landscaping elements on sidewalks generally include trees and grass, while hard landscaping elements include pavers and street furniture. The microclimates of pedestrian walkways are closely related to the environment of the walkway's landscape, such as the types and species of trees. Trees are used as shading devices in pedestrian walkways to protect pedestrians from solar radiation.

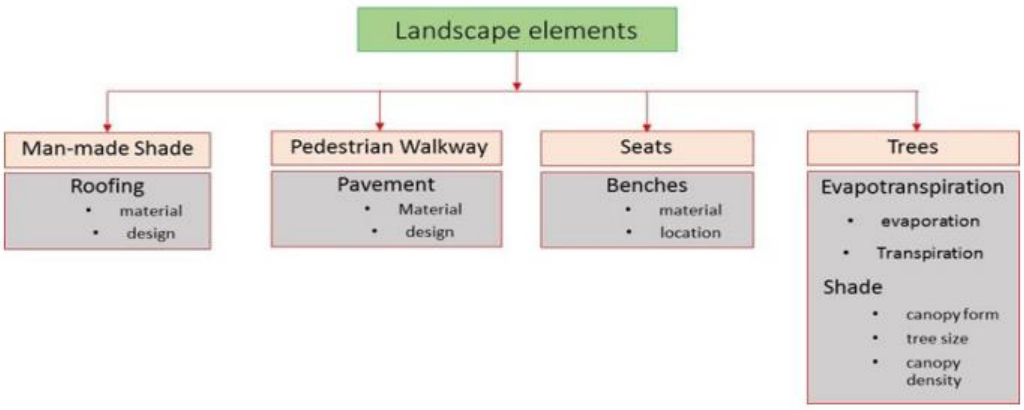


Figure 2-12 Various landscaping elements on sidewalks

Source: **(Kasim, et al., 2018)**

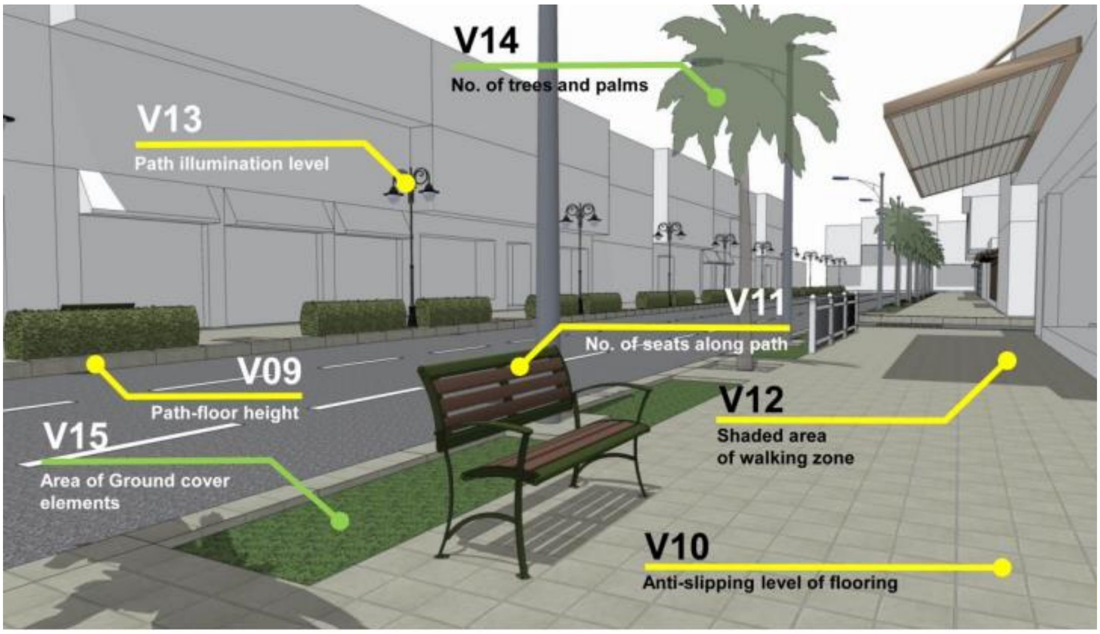


Figure 2-13 Landscape related variables of walkability on sidewalks

Source: **(Zayed, 2018)**

2.6.3.1 Sidewalk paving materials

Pavement is essential component of sidewalks. The materials used on city sidewalks and pavements have a significant impact on pedestrian comfort. Dark materials absorb solar radiation during the day and re-radiate it at night. Because of their high albedo, cool materials are frequently proposed for mitigating UHI issues. The temperature of the ground cover has a significant impact on pavement durability. (Faragallah & Ragheb, 2021).

When compared to vegetated areas, ground covers for roads, pavements around buildings, and so on make up a large percentage (30%- 40%) of a city's land cover in many urban areas. Paving materials have a large impact on urban climate and are a major contributor to the rise of urban heat islands. The amount of solar radiation, released infrared radiation, convection heat transmitted to the ambient air, heat trapped in the material's mass, and heat conducted to the ground determine their thermal equilibrium. Paving materials should be chosen for reflectivity, green manufacturing, and permeability to achieve a comfortable streetscape (Anon., 2004).

2.6.3.2 Modification of thermal properties of pavement materials

Thermal behavior of pavements depends on the thermal properties of pavement materials like thermal conductivity, specific heat capacity, density, solar reflectivity (albedo) and thermal emissivity. Modification of thermal properties could help keep pavements and near surface air cooler.

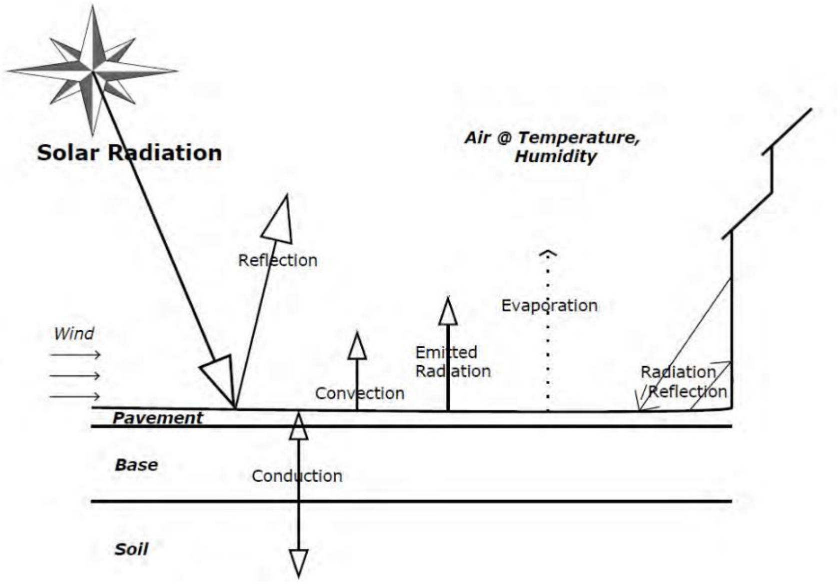


Figure 2-14 Energy balance on pavement surface

Source : ascellibrary.org

There are some of the ways to modify the thermal properties of the pavement materials. They are:

Reduce pavement thermal conductivity

Pavements with low thermal conductivity may heat up at the surface but will not transfer that heat as quickly as pavements with higher thermal conductivity.

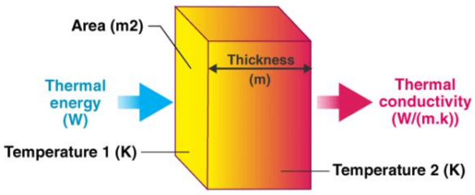
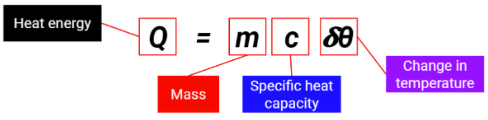


Figure 2-15 Thermal Conductivity

Source: byjus.com

Increase pavement heat capacity

Thick Pavements with increased specific heat capacity as well as density and could increase the effective heat capacity and help reduce the daytime high temperature and increase the nighttime low temperature.



Increase pavement surface reflectance

The percentage of solar energy reflected by a surface, known as albedo. Since less heat is available at the surface to be transferred into the pavement layers below the surface, pavements with high albedo may also help to reduce pavement subsurface temperatures.

Figure 2-16 Surface reflectance of Dark and Cool pavement
Source:Sustainapedia.com

Increase pavement thermal emissivity

A material's thermal emissivity determines how much heat it will radiate per unit area at a given temperature, that is, how readily a surface emits heat. According to research, albedo and emissivity have the greatest influence on how a conventional pavement cools or heats up, with albedo affecting maximum surface temperatures and emissivity affecting minimum temperatures.

2.6.3.3 Cool Pavements

The United States Environmental Protection Agency (USEPA) recently defined cooling pavement as "pavements that offer a range of existing and emerging technologies that communities are investigating as part of their heat island mitigation efforts." The term refers to "Pavement surfaces that are more reflective of solar radiation, improve water evaporation, or have modified thermal properties that allow them to be cooler than traditional pavements" as of recently. They may be able to improve urban microclimates by using advanced cool pavements that are reflective (high albedo) and permeable. These cool materials have changed their properties to lower their surface temperature.

Cool pavements can be achieved using both traditional paving techniques (such as asphalt and concrete) and newer approaches such as coatings or grass paving. Cool pavement technologies are not as advanced as other strategies for reducing heat islands. They do, however, have different properties than regular ones in order to lower their surface temperature.

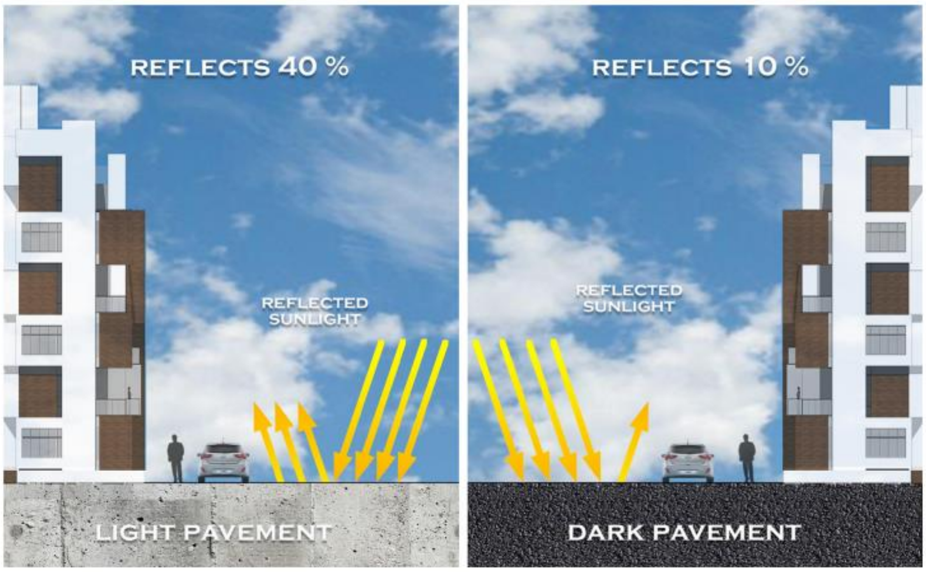


Figure 2-17 The effect of cool pavements on solar radiation.

Source: **(Faragallah & Ragheb, 2021)**

2.6.3.4 Types of Cool pavements

Permeable pavements

Permeable pavements also known as cool pavements, are made of either a porous material that allows storm water to flow through it or nonporous blocks that are spaced apart to allow water to flow between them. Permeable pavement surfaces include pervious concrete, porous asphalt, paving stones, and interlocking pavers. When these pavements are wet, they can aid in temperature reduction through evaporative cooling. Water flows through the voids and into the soil or through the supporting materials beneath.

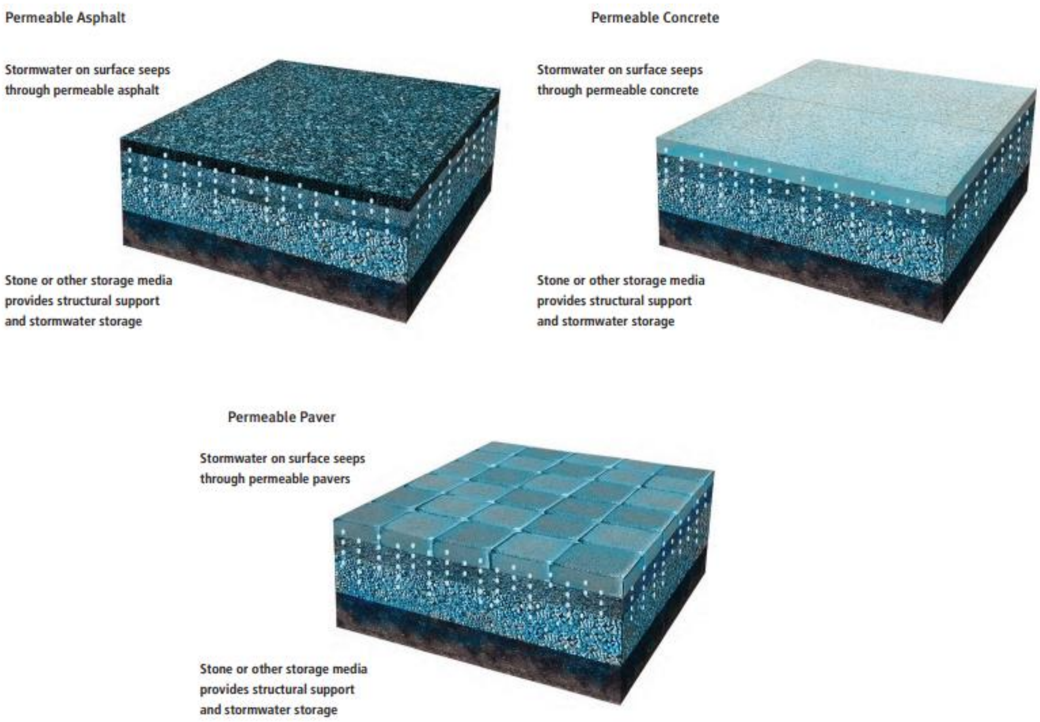


Figure 2-18 Permeable Pavements

Source: **(Anon., 2014)**

Reflective Concrete Pavements

Reflective pavements reduce surface temperature during the day. They are intended for to cool the pavement in hot regions subjected to high levels of solar radiation. Concrete pavements can be most reflective when mixed with whitish cementitious materials. Several experiments have been conducted to investigate the solar reflectance of a variety of regular reflective pavements, such as light-color coating. As per the report, the solar reflectance of newly installed asphalt paving is around 0.05. Depending on the type of aggregate used in the asphalt mix, aged asphalt pavements have a solar reflectance of 0.10–0.18. A light-colored concrete with an initial solar reflectance of 0.35–0.40 that will age to about 0.25–0.30. Hashem and Damon (2012) advised to use cool pavement materials having albedo value of 0.15.

Colored pavements

Color pigments and seals are additives that can be blended with asphalt. They can alter the color of an asphalt binder to make the surface look lighter and more reflective. There is a wide range of pigments that provide several colors. They are commonly used for driveways, walkways and bike paths (Bek, et al., 2018).

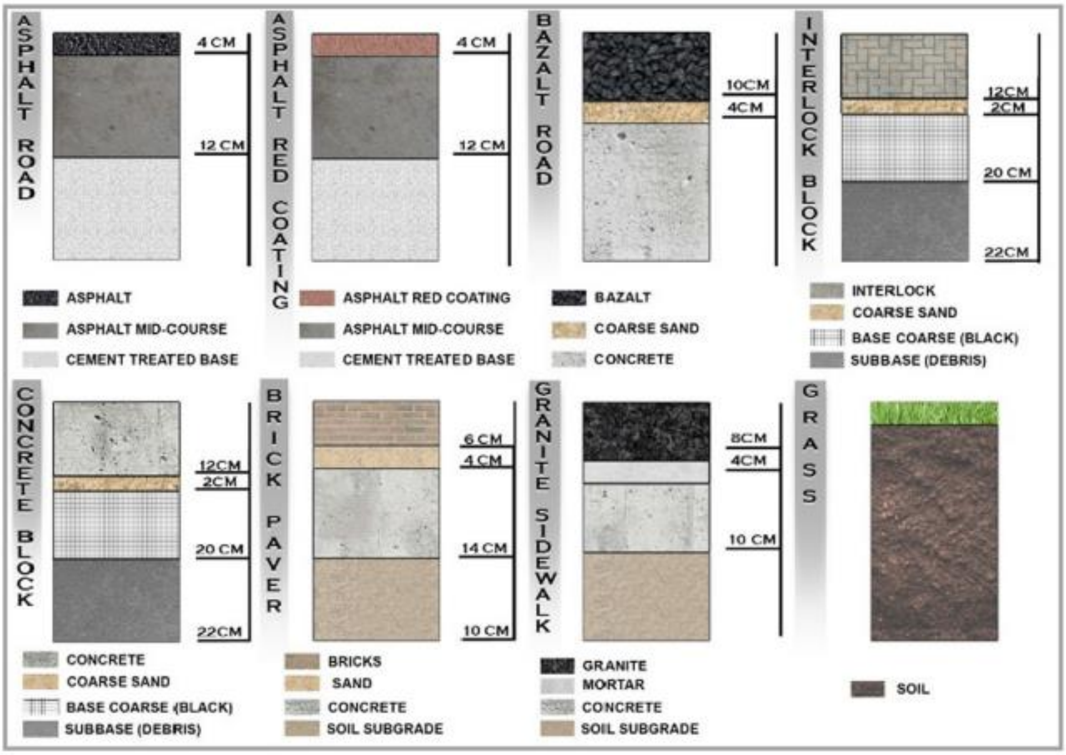


Figure 2-19 Sections through different cool paving materials.

Source: **(Faragallah & Ragheb, 2021)**

2.6.4 Soft landscaping elements in sidewalks

It includes the plant components of landscaping (herbaceous plants, trees, shrubs, grasses, etc.) that are natural in a landscape. Trees can play various roles in urban areas including: aesthetic quality, visual screening and shelter, solar access, screening and wind breaks. The soft landscape can contribute to healthy environment by cooling air, increase in relative humidity providing fresh air supply and noise absorption .

2.6.4.1 Vegetation and thermal comfort

Urban vegetation as a heat-mitigation strategy is considered better than using high albedo materials on the ground for improving pedestrians' thermal comfort (Taleghani, 2018). Vegetation affects outdoor thermal comfort through evapotranspiration, solar reflection, solar shading (shading), and alteration of wind flow. In particular, vegetation provides cooling through transpiration as absorbed solar energy leads to an increase in latent heat (water from vegetation evaporates into the atmosphere), cooling leaf surfaces and surrounding air. Plants absorb solar radiation for photosynthesis and for evaporative heat loses. Energy balance on a leaf specified in the is in the order of 20-40% evaporation, 5-20% reflection, 10-15% heat, 5-30% light transmission and 5-20% photosynthesis (Ramesh, 2016)**.** When the sun's radiant energy hits objects, it converts to heat. Plants reflect back some of these solar rays before they are converted into heat. They retain some of these rays on the surfaces of leaves and branches. As a result, they provide shade and the lower parts of the plants become cooler. The effects of plants on the microclimate through their leaves are shown in Figure. In addition, vegetation increases the total shortwave reflectivity of the city. Therefore, vegetation absorbs and retains less heat than building materials. In addition, tree shading prevents air and surface temperatures from rising because trees intercept solar radiation (Gunawardena, et al., 2017).

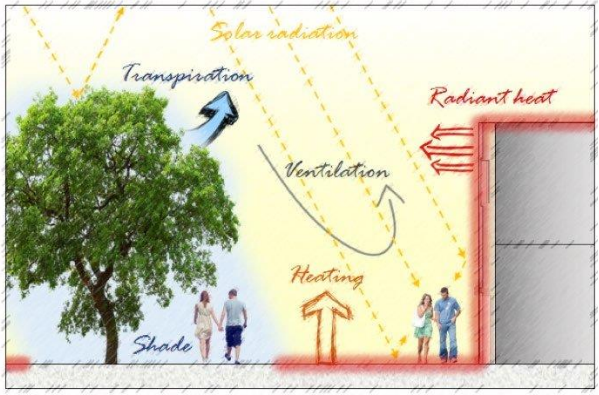


Figure 2-20 Shade provided by tree on outdoor environment *Source: https://whitearkitekter.com*

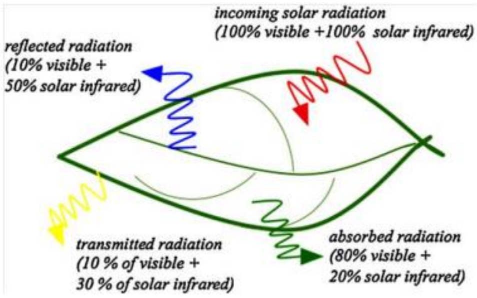


Figure 2-21 Sun rays absorbed (green), reflected (blue) and transmitted (Yellow) by plant leaves

Source: (Kong et al, 2017)

Main characteristics of vegetation affecting outdoor thermal comfort:

Foliage shape and dimensions

The thermal conditions of the environment in terms of cooling and air filtration depend on the amount of foliage. Tree leaves/foliage obstruct the passage of solar rays and consume radiant energy through the process of photosynthesis, thus achieving the desired cooling effect on the thermal environment (Vogel, 1989). The literature indicates that around 80% of the incident solar radiation is controlled within the foliage and only 5% penetrates and reaches the ground (J. Spangenberg, et al., 2007). Foliage affects plants evapotranspiration, which results in reduced air temperatures and increased air humidity. Row/group of trees can create a barrier or increase air flow.

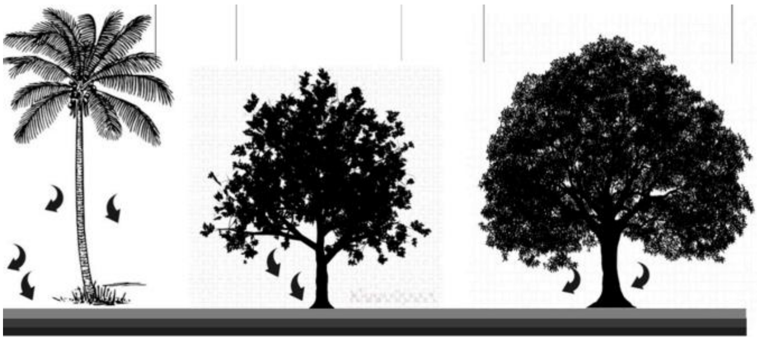


Figure 2-22 Shape and tree canopy

Source: **(Sayad, et al., 2021)**

Height of trunk

In terms of mean radiant temperature, the height of the trunk, depending on the site latitude, determines shadow area. The trunk's height should be reduced to protect it from the winter wind. Trees with a narrower spread and a height of 20'-30' are useful for directing breezes in a specific direction (Ramesh, 2016).

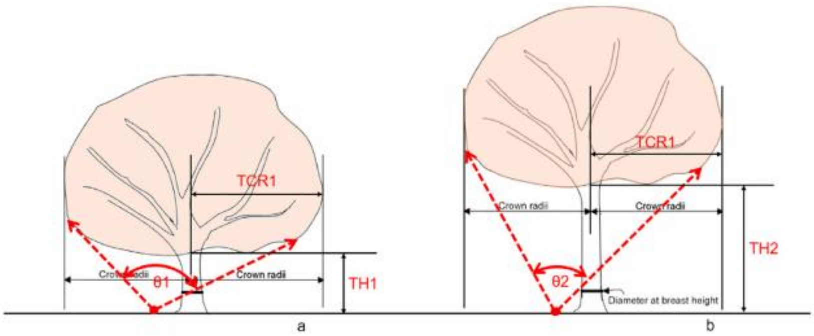


Figure 2-23 Illustration of tree crown radius (Larsen,2020) and canopying degree variation due to different trunk height (TH1<TH2);TH1 causes higher canopying intensity than TH2, for T2 <T1

Leaf area density (LAD)

A leaf area index (LAI) expresses the leaf area per unit ground or trunk surface area of a plant. LAI is a complicated variable that influences not only the size of the canopy, but also its density and the angle at which the leaves are oriented towards each other and towards the light sources. High values of

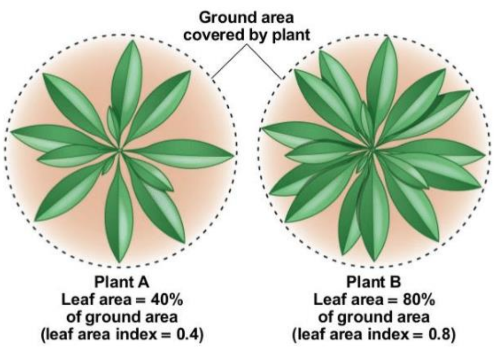


Figure 2-24 Leaf Area Index estimation

LAI reduce the solar radiation transmitted during summer.

Source : www.slideshare.net/hayabranko

LAD determines the air flow through the foliage (low or high). LAD affects plants evapotranspiration, which results in reduced air temperatures and increased air humidity.

Seasonal Cycle

Evergreen trees have the following advantages: places required shade throughout the year, strong visual screening, and part of windbreak or shelter planting. Using evergreen plants in pedestrian areas serves as a windbreak and creates a favorable environment for pedestrians by preventing adverse climatic conditions (Tandogan & Şişman, 2018). Using coniferous trees which break the wind or reduce heat loss in open spaces and increase thermal comfort in urban areas has importance. The deciduous trees are quite suitable for composite climate which allows solar radiation in building during winter and avoid direct radiation during summers.

Table 2-5 Categorization of trees suitable for different climatic zones

Source: (Simmons, 1996)

Sl. no	Common name	Height [m]	Climate zone
Deciduous trees			
1	Florida Elm	15	CC
2	GumboLimbo	15	HD,MO
3	Mulberry	18-24	HD,MO
4	Laurel Oak	18-24	CC
5	Red Mulberry	15	CO,MO
6	Sweet Gum	24	WH
7	Sycamore	30	WH
Evergreen trees			
1	American Holly	12	CC,CS
2	Cherry Laurel	9	CO,MO
3	Dahoon Holly	12	CC,MO
4	Loblolly bay	15	CC,MO
5	Pitch apple	9	WH
6	Red mangrove	22	WH, CO
7	Magnolia	24	CC,MO
8	Red cedar	9	WH, CC
9	spruce pine	30	CC,MO

Note: CC: Cold and Cloudy; CO: Composite; CS: Cold and Sunny; HD: Hot and Dry; WH: Warm and Humid; MO: Moderate

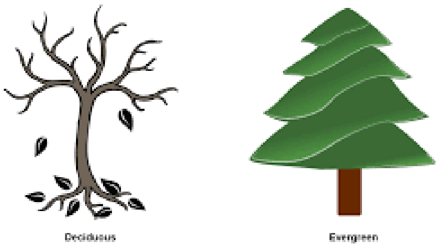


Figure 2-25 Deciduous and Evergreen tree

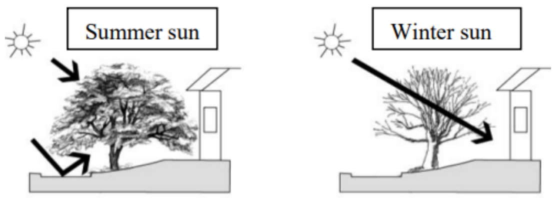


Figure 2-26 Deciduous trees covering the southern side façade,

Source: (Ramesh, 2016).

Daily transpiration

High levels of daily transpiration keep the air flowing through the trees cool. Transpiration entails the absorption of thermal energy, which can reduce summer overheating and increase air humidity. Vegetation, through evaporative cooling, helps to lower the air temperature of the surrounding environment.

2.7 Simulation software for outdoor thermal comfort

The nature of radiation fluxes received by the human body from its surroundings in an urban environment is very complex and hence modelling outdoor human thermal comfort is a difficult task. As seen from the chart, ENVI-met and Rayman are mostly used softwares as the simulation tools regarding outdoor thermal comfort.

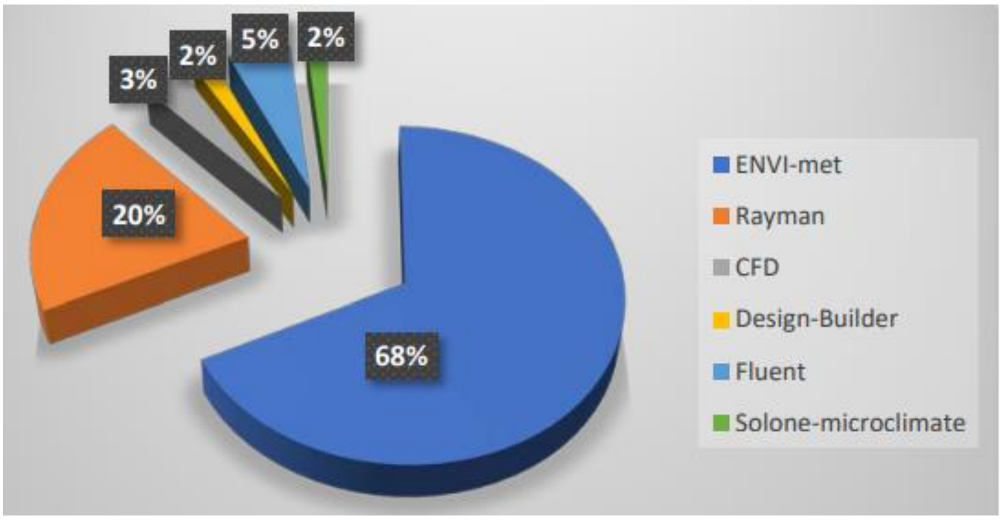


Figure 2-27 Usage percentage of various simulation tools regarding outdoor thermal comfort
Source: **(Nasrollahi, et al., 2020)**

2.7.1 RayMan

RayMan stands for Radiation on the human body. It is developed by Matazarakis in 2007.RayMan estimates radiation fluxes as well as the effects of clouds and solid obstacles on short-wave radiation fluxes. The model, which takes complex structures into account, is appropriate for local and regional utilization and planning. The calculated mean radiant temperature, which is required in the energy balance model for humans, is the model's final output. The three thermal indices PET, SET and PMV can be calculated in RayMan model.

2.7.2 ENVI-met

ENVI-met is a 3D software that analyses micro-scale thermal connections in urban settings. The model incorporates both thermodynamic procedures that occur at the ground surface, walls, roofs, and plants, as well as fluid dynamics features. The software takes into account all types of solar radiation, including direct, reflected, and diffused radiation. The average radiant temperature is estimated by ENVI-met. The calculation of radiation fluxes takes into account plant shading, shielding, and radiation absorption, as well as re-radiation from other plant layers. It also has the advantage of incorporating different types of vegetation to estimate the temperature, vapor and heat exchange in the air canopy (Albdour, et al., 2019).

Advantages of ENVI-met

Because it has several advantages over other simulation software, this simulation software will be used in this study. This model simulates the dynamics of the microclimate over a 24-hour period. All exchange processes, such as wind flows, turbulence, radiation fluxes, temperature, and humidity, are predicted by the model. The model allows for the creation of various vegetation types. ENVI-met considers vegetation as a physiological process that includes evapotranspiration and photosynthesis rather than a porous barrier to wind and solar radiation. The soil in ENVI-met is a volume made up of several layers. A detailed representation of microclimatic changes is possible due to the high spatial (up to 0.5 m horizontally) and temporal resolution (up to 10 s). To run the model with a large number of outputs, a small number of inputs are required. Tmrt, the most important parameter for calculating thermal comfort, can be calculated by ENVI-met.

Limitations of ENVI-met

ENVI-met has certain limitations, however. The tools to create the urban environment are limited to buildings, floors/coverings and trees/vegetation. There are no tools to create other objects such as shadow structures independently of the building blocks. Another major limitation is that the building blocks have no thermal mass and only a single constant internal temperature. In addition, the albedo and thermal resistance of the building surfaces are constant and cannot be varied (Emmanuel & Fernando 2007).

2.8 Review of similar Articles

Table 2-6 List of influential studies conducted on the outdoor thermal comfort relating to the trees, pavements and landscape design

S.N	Title, Authors and year	Study Area	Methodology	Main findings
1	Study of the thermal environment of sidewalks within varied urban road structures (Lin, et al., 2021)	Taipei City, Taiwan	a) This study considered road orientation, number of planting strips, and LAI of trees to develop alternative road structures. b) The road orientations were either North-South (NS) or East-West (EW),	a) Different road structures had similar Ta but varied Tmrt and PET thermal environments. b) A significantly synergistic cooling effect of road orientation, number of planting strips, and LAI of trees on the sidewalks' Tmrt and PET was identified.
2	Sidewalk Landscape Structure and Thermal Conditions for Child and Adult Pedestrians (Kim, et al., 2018)	City of College Station, TX, USA,	a) Ten sidewalk segments were selected based on having the same street orientation (N–S) and similar/adjacent locations, but different vegetation conditions. b) A series of paired t-tests were performed to analyze the mean differences in air temperatures between the two sidewalk settings in each pair.	a) After controlling for all other key physical environmental conditions, sidewalks with more trees or wider grass buffer areas had lower air temperatures than those with less vegetation. Children were exposed to higher temperatures due to their greater exposure to or proximity to the pavement surface, which emits more radiant heat.

3	Microclimate benefits that different street tree species provide to sidewalk pedestrians relate to differences in Plant Area Index. (Sanusi, et al., 2016)	Melbourne, Victoria, Australia	a) Three North-South oriented residential streets in three sub-urbs. b) Microclimatic measurement at streets with tree species of different leaf and canopy characteristics. c) Human thermal comfort from Physiological Equivalent Temperature (PET) estimates.	a) The benefit of microclimate increased with increasing PAI for all three tree species, but there was no significant difference in under-canopy microclimate among tree species when PAI was similar. b) Differences in PAI are paramount in determining the microclimatic and PET benefits. c) Certain tree species have a maximum PAI that should be considered when choosing or comparing tree species for shading and cooling benefits.
4	Thermal comfort interventions of landscape elements in a humid and subtropical residential area in China (Li, et al., 2021)	Guangzhou, China	a) Three enclosed-layout residential communities (“A”, “B” and “C”) and one regular-layout residential community were selected. b) Field surveys were conducted at eight sites in four residential communities in Guangzhou. c) The physical parameters Ta, RH, global radiation (G), wind speed (v) and global	a) The high-reflection ground reduced the thermal acceptable condition of the outdoor space in the summer while improving it in the winter. b) In the case of vegetation, trees provided a cooling effect when solar radiation was high; as solar radiation decreased, wind speed attenuation became more noticeable, and the heating effect of trees appeared.

			temperature (Tg) next to the interviewee were measured. d) Development of intervention scenario and environment simulation using ENVI-met	
5	Use of landscape environmental setting for pedestrian to enhance campus walkability and healthy lifestyle (Kasim, et al., 2018)	Malaysia	a) Theories and gathering knowledge of landscape environment setting attributes. b) Field study to investigate characteristics available in various existing tropical campus environment. c) The landscape environment setting attributes are calculated based on the number of landscape elements in the pedestrian environment. The final stage involved comparing shading to assess thermal comfort on pedestrians.	a) A sustainable campus environment must include shaded walkways, either man-made or shaded by trees, to encourage walking and cycling among campus citizens.
6	Study of Thermal Comfort under The Shade of Varied Tree	Indonesia	a) Observation was carried out to determine the availability of trees that are possible to be observed by selecting tree	a) The findings revealed a relationship between tree canopy density, as measured

	Canopy Form and Distance from The Stem (Fadhulurrahman & Nasrullah, 2020)		species with the appropriate shape of the canopy. b) Air temperature and humidity were measured using a Thermo hygrometer. Wind speed measurements were carried out using an anemometer. c) Correlation analysis is used to determine the strength and direction of the relationship between the Leaf Area Index (LAI) and the distance from the tree to the temperature (˚C) and humidity (%). d) Linear Regression Between Variables	by the Leaf Area Index (LAI), and distance from the tree, as well as temperature and humidity. b) Trees with dense canopy has lower temperature and higher humidity by equation y = -2.0337x + 37.19 for temperature and y = 8.1354x + 48.247 for humidity. Meanwhile, the further the distance from the tree, the higher the temperature and the lower the humidity.
7	The effect of pavement characteristics on pedestrians' thermal comfort in Toronto (Taleghani & Berardi, 2017)	Yonge-Dundas square ,Toronto	a) The microclimate characteristics during the hottest day of the year is assessed in Yonge-Dundas square, Toronto b) Three scenarios are simulated to assess the possible improvements of the microclimate of the square.	a) According to this study, while increasing pavement reflectivity lowers air temperature, it decreases thermal comfort at the pedestrian level.

			c) The simulations results are later used in RayMan) to generate and discuss the Physiological Equivalent Temperature (PET).	
8.	Evaluation of thermal comfort and urban heat island through cool paving materials using ENVI-Met (Faragallah & Ragheb, 2021)	El Mosheir Street Alexandria, Egypt	a) Selection of the case study b) Modelling analyzing the current situation of street c) Simulating and analyzing the current thermal performance d) Proposing different materials e) Simulating and evaluating the results(Choosing best case)	a) The asphalt had a major impact on the temperature increase of the urban form but the basalt had a considerably reduced effect.
9	Effects of Landscape Design on Urban Microclimate and Thermal Comfort in Tropical Climate (Yang, et al., 2018)	Singapore	Two residential quarters at Bedok in southeast Singapore Selected. Parametric Study and Urban Thermal Comfort Assessment: parametric study consists of a base case and seven design scenarios. Other scenarios investigated are designed based on changing different	a) The high-albedo pavement materials and water bodies are ineffective in reducing heat stress in hot and humid climate conditions. b) The most effective landscape strategy for cooling the microclimate is the combination of shade trees and grass.

			landscape elements such as pavement materials (brick, concrete, wood, and light-color granite) and amount of trees, grass, and water bodies.	
10.	Improving Outdoor Thermal Comfort in a Steppe Climate: Effect of Water and Trees in an Urban Park (Teshnehdel, et al., 2022)	El-Golu Park ,Tabriz,Iran	Four different scenarios created: • case 1: current scenario (vegetation + water body); • case 2: no vegetation scenario (water body without vegetation, replaced by bare soil); • case 3: no water body scenario (vegetation without water body, replaced by granite pavement); • • case 4: soil and granite scenario (without vegetation and water body)	a) The results show that while water body evaporation without trees reduces air temperature, it also increases humidity, reducing the positive impact on thermal comfort. b) The combination of water bodies and trees performs better in terms of regulating urban microclimate and thermal comfort.
11	Towards green design guidelines for thermally comfortable streets	Rivierenwijk Neighbourhood, located in the city of	a) Structured Interview b) Cargo-bicycle equipped with micrometeorological measurement sensors;	a) In streets with large tree crowns on both sides, the mean radiant temperature (Tmrt) was 2.5 K lower than in streets without greenery.

	(Klemm, et al., 2013)	Utrecht, The Netherlands	Micrometeorlogical data analysis c) Air temperature (Tair), humidity (h), wind speed (u) and solar radiation measurements to calculate mean radiant temperature (Tmrt) and PET (physiological equivalent temperature) using the human thermal energy model RayMan	b) Tmrt values were observed to be greater on streets with fewer trees and smaller front gardens. People perceived thermal conditions in streets with greenery to be more comfortable than in streets without greenery.
12	Outdoor Thermal Comfort Optimization through Vegetation Parameterization: Species and Tree Layout (Sayad, et al., 2021)	Guelma city, Algeria	a) Two main parameters were investigated, species and tree layout, b) First,microclimate was data collected of a sunny summer day. c) Second, real microclimate data in different was used simulations using the ENVI-met atmospheric model.	a) Ficus Nitida is the most significant species to block solar radiation and provide shade with a maximum reduction of Ta = 0.3 ◦C and UTCI = 2.6 ◦C at 13:00 p.m. b) Tree layout is a determining parameter in the creation of shaded paths, based on the quality of the shadows cast by the trees, namely, their size.
13.	Numerical Study on Microclimate and Outdoor Thermal	Busan, South Korea	a) Based on field measurement results, seven factors were selected, and 32 scenarios were generated using the Taguchi method.	a) The results indicated that the orientation of the main street should be consistent with the prevailing wind direction of Busan.

	Comfort of Street Canyon Typology in Extremely Hot Weather—A Case Study of Busan, South Korea (Wu, et al., 2022)		b) Using ENVI-met to simulate the microclimate and thermal comfort of 32 scenarios in extremely hot weather, the importance and variation characteristics of different factors of pedestrian height on the microclimate and thermal comfort were analyzed.	b) Tree height had a greater impact on the street environment than other tree configuration factors, particularly when the tree height increased from 9 m to 12 m. c) According to the study, thermal comfort in streets with shallow street canyons can be improved by dynamically adjusting the relationship between planting distance and tree height.

2.8.1 Methodological review

The methodology adopted for the study of the outdoor thermal comfort includes the use of simulation software, fieldwork and measurement and combination of simulation software and fieldwork as showin in the figure 2-28.3 articles were selected for the methodological review. The parameters considered in these articles,site selection,days of measurement and other details are tabulated below.

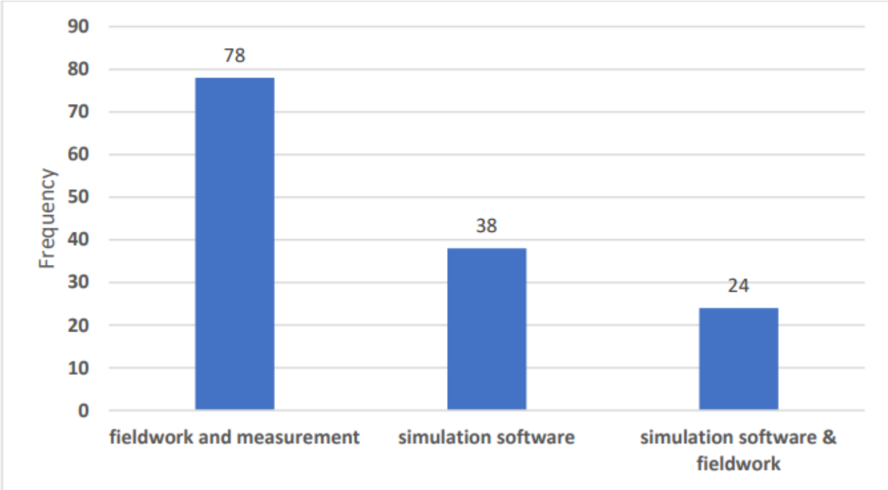


Figure 2-28 Research Methodology regarding outdoor thermal comfort
Source: **(Nasrollahi, et al., 2020)**

Methodological parameters	**Study of the thermal environment of sidewalks within varied urban road structures**	**Evaluation of thermal comfort and urban heat island through cool paving materials using ENVI-Met**	**Thermal comfort interventions of landscape elements in a humid and subtropical residential area in China**
Parameters considered	Road orientation, number of planting strips, and LAI of trees	Pavement materials	Tree, shrubs, reflective surface and pervious ground

Site selection	Aerial photographs and in-situ surveys were used to categorize the road structure of 40-m-wide roads into ten types. The road structure type with the highest percentage (20.8%) of the ten types was chosen.	A large number of population with high density buildings. Vehicle use Vibrant and a central street	(1) All new high rise residential communities that have been primarily built in the last decade; ; 2) High population density, with more than 5000 residents in every residential community; 3) Greening rate greater than 30%, with some spots for outdoor activities.
Microclimatic measurement	Ta, relative humidity, and wind speed , globe temperature	Air temperature was taken on the 8th of August 2020 (a day in the hot dry season).	Air temperature, solar radiation, and wind speed, Globe temperature, Global radiation
a) Device used	A Watchdog Model 2550 Weather Station, A TR-31B	N/A	HOBO Pro V2 U23-001, HD32.3, LP 471 PYRA 02.5
a) Time period of microclimatic measurement	08:00 to 18:00 on July 14, 2017 (a typical hot summer day in Taipei city).	8th of August 2020 (a day in the hot dry season) at 2:00 p.m. (one of the peak temperature hours).	At 1- min intervals during 8:00–19:00 in winter and 7:00–20:00 in summer
Questionnaire survey	N/A	N/A	First part:

Conduction duration: Time frames:			Demographic age and gender Primary activities throughout the day in outdoor spaces Reasons for visiting a particular place Clothing worn, Activity level. Second part: Thermal sensation Thermal comfort Thermal acceptability January to September 2015 18 days 8 to 12 , 14-18 in winter 7-12 and 3-7 in summer when outdoor spaces more frequently used.
Simulation a) Duration b) Domain	Envi V4 24 hours 100 m Χ 100 m Χ 40 m with 100 Χ 100 Χ 30 grids	Envi V4 twelve hours extending from 6:00 a.m. until 6:00 p.m	Envi V4 5:00–20:00

c) Grid sizes d) Biomet setting	1 m at X and Y direction and vertical grids, the lowest 10 grids were 1 m, and the remainder grids were set as increasing with a telescoping factor of 10 %. 35 years old male, 75 kg and 1.75 m tall, having a clothing insulation value of 0.5 clo and a 164.7 W metabolic rate.		

2.9 National Guidelines

2.9.1 Nepal Urban road standard

This is in line with the Nepal Urban Road Standard 2076, which aims to achieve uniformity, especially in the design and construction of urban roads.

2.9.1.1 Types of Urban Road

For the purpose of geometric design urban roads are classified into four categories considering function of the road and traffic level.

Arterial roads (Path)

These roads are often designed for heavy traffic on a continuous route. Together with the motorways (if any), they form the main network for traffic flow through the city. This facility serves inner-city traffic, e.g. between the city centre and remote residential areas or between large suburbs. Parking, loading and unloading is restricted and regulated in most cases.

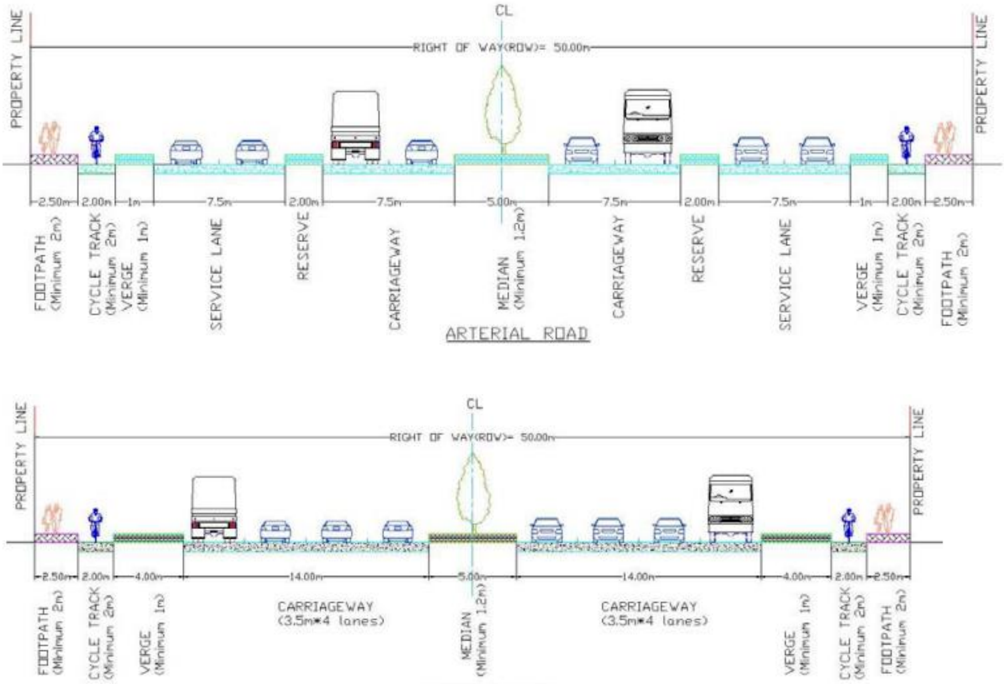


Figure 2-29 Typical Arterial Road Sections option 1 and option 2

Sub-arterials roads (Sadak)

These are roads with a lesser level of travel mobility than arterial roads. These roads place a greater emphasis on access to the surrounding area than arterial roads. Loading and unloading are frequently restricted and regulated in parking lots. The spacing varies from 0.5 km in the CBD to 3.5 km to 5 km on the outskirts of town. Only at junctions or marked crossings are pedestrians permitted to cross.

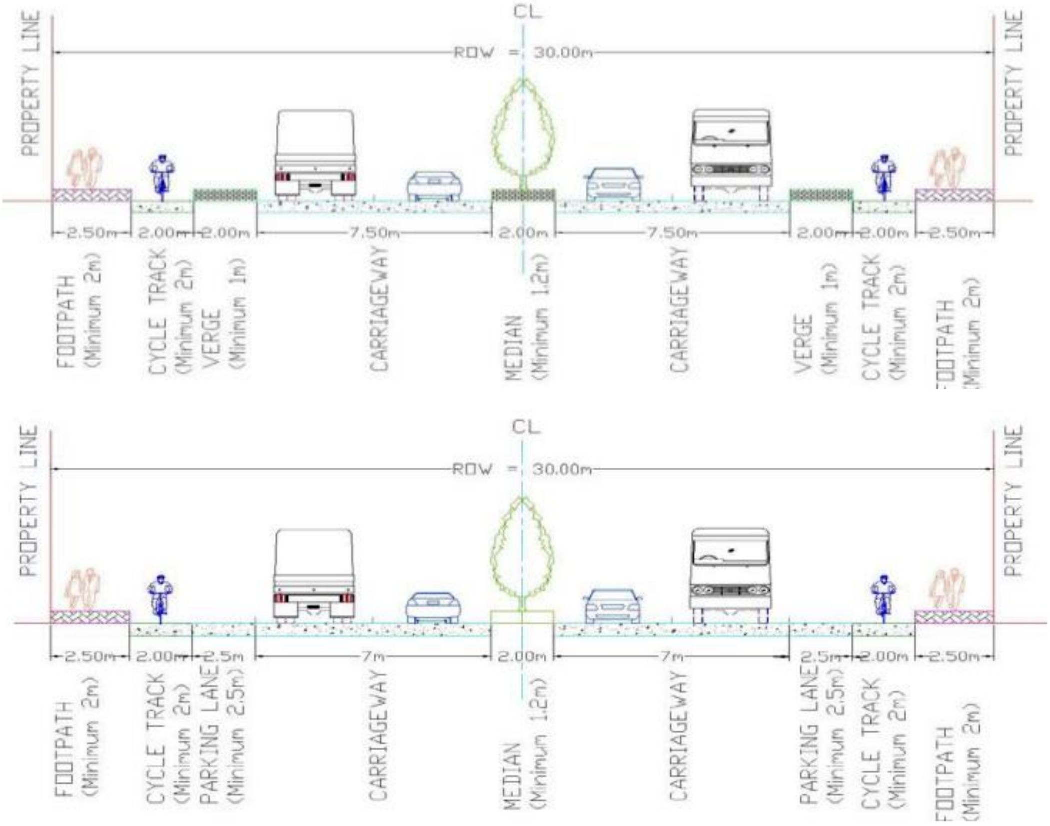


Figure 2-30 Typical Sub-Arterial Road Sections option 1 and option 2

Collector roads (Marg)

A collector road collects and distributes traffic from and to local roads, as well as providing access to arterial and sub-arterial roads. They can be found in residential areas, commercial regions, and industrial locations. Normally, adjoining properties have full access to these roadways

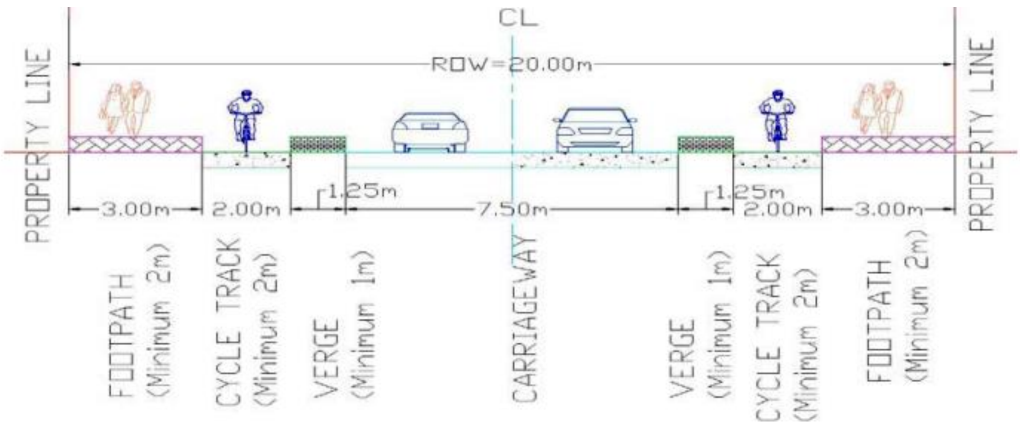


Figure 2-31 Typical Collector Road Section

Local roads (Upa-Marg)

A local road is one that is primarily used to access a home, business, or other nearby property. Normally, such a road does not see a lot of traffic. Along its length, the traffic carried either starts or terminates. Depending on the prominent use of the nearby area, a local road may be residential, commercial, or industrial.

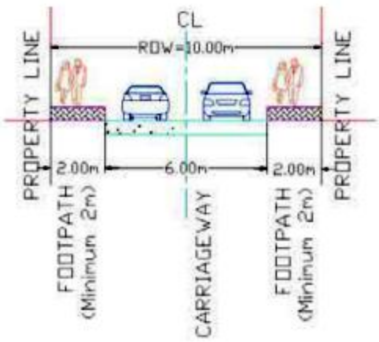


Figure 2-32 Local road section

2.9.1.2 Elements of Urban road

While planning or designing urban road, focus shall be made not only to develop carriage way but to provide essential elements. Therefore, elements that shall be considered at least in built up area if there is availability of land: Carriage way, foot path/Walk way, Cycle track, Street light Utility space (under-ground or above the ground depending on space) Signage, and Other essential road furniture

2.9.1.3 Pedestrian facilities

Footpaths

A good footpath should have the certain characteristics. No breaks or obstructions at property entrances and side streets. Continuous shade provided through tree cover.

To accommodate dead width, the width in commercial and shopping areas should be increased by one metre. Footpaths adjacent to shop fronts should be at least 3.5 metres long, and at least 4.5 metres for longer shop fronts. When determining the width of the footway and grass verge, consideration should be given to the width required to accommodate underground services clear of the carriageway. On slopes or ramps, the capacity should be reduced accordingly.

2.9.1.4 Aesthetics and Landscape design

Regarding the aesthetics and landscape design in sidewalks, certain guidelines are mentioned such as: Depending on the individual trees, canopy size and shape, adequate spacing between trees is required to ensure continuous shade. In dry climates, where plants do not grow as quickly, closer spacing is required. Medium height vegetation should be trimmed directly adjacent to formal crossing to improve the visibility of pedestrian and cyclists. Trees with high branching structure are preferable. To accommodate roots at full development, tree pits should be at least 1m by 1m in size. On narrow sidewalks, 0.5m by 2m tree trenches can provide the same surface area.

2.10 International Guidelines

2.10.1 Street Design Guidelines for Delhi

These are the guidelines conceived by Delhi Urban Art Commission to make streets "Complete Streets". It is an attempt to shift the focus from considerations of vehicular movement to 'Streets for all'. A complete street shall consist of identifiable zones, which have distinguished uses depending on factors including street surroundings/context, street use and width of the street. Primarily, a street may be divided into the following zones:

Pedestrian zone :

- Frontage Zone
- Walkway
- Multi- utility zone (MUZ)
- Edge Zone
- Refuge Islands

Vehicular zone:

- Carriageway
- Non-Motorized Vehicle
- Road Shoulders
- Medians

Key principles

Design: Street should be designed such that the space encourages people to walk & engage in social activities.

Figure 2-33 Complete Street Design
Source: Street Design Guidelines

Ecology: Along with the basic necessity of a good design & unhindered movement of pedestrians, it is very important to consider the ecological aspect. The design should focus on maximizing natural drainage systems using pervious paving materials, reducing heat island effect, and providing for planting for shade and beauty.

Safety / comfort: Pedestrian safety & comfort should be kept on a fore front. The design should address differently-abled by providing accessibility ramps and tactile paving and also focus on areas for trees & high- albedo materials in order to ensure optimal climatic comfort.

Figure 2-34 Pedestrian zone and Vehicular zone in street
Source: Street Design Guidelines

2.10.2 Street Trees

Spacing of Avenue Trees

Some recommendations for tree spacing are provided. Some medium-sized trees require a spacing of 5 to 6 meters, but in most designs, a minimum spacing interval of 10 to 15 meters is required. Where adequate off-set land is available on the side of the road, the nearest row of trees should be at least 4.5 to 5 meters from the edge of the carriageway to be built in the long run. When it is possible to plant two consecutive rows of avenue trees with adequate land width, the row closest to the carriageway can be of ornamental flowering trees, while the one away from it can be of shaded trees.

Planting Design (General Considerations)

Fast-growing trees should be prioritized in urban areas because they have a better chance of survival and growth in populated areas. Nurturing a tree to full maturity takes time, and frequent replacement is not an option. Trees with long life cycles are thus preferred. Species for urban plantation should be smog resistant and tough enough to withstand harsh environments, particularly vehicular pollution.

Trees that shed a lot of leaves should be avoided because it is difficult to keep the roads clean in cities. Trees with umbrella or sub-umbrella crowns (such as neem, mohua, imli, and mango) are better suited for plantation in open areas than trees with linear elongated crowns. Trees that are evergreen all year or almost all year, or that shed their leaves at times other than summer, usually get preference in selection in hot summer regions. As a result, ornamental foliage trees are ideal for use as shade trees along highways.

Figure 2-35 Plantation along footpath; Source: https://www.semcooutdoor.com/columbus/product/brussels-block

Figure 2-36 Green Strip along footpath Source : http://www.raisethehammer.orgarticle/1684/turning_cannon_into_a_complete_street

Trees with dense but deciduous foliage should be preferred for pedestrian roads. These will allow sun rays to penetrate while providing deep shade during the summer.

Otherwise, the area may become dark and desolate during the winter, and pedestrians may avoid it.

2.10.3 Permeable Pavements

Figure 2-37 Honeycomb Pavers allow water permeation
Source: 2017 State of New Jersey Complete Streets Design Guide

Permeable pavement reduces rainwater runoff. It is known as green pavement it allows water to run off instead of damming it up. It captures and stores rainwater by filtering it through voids in the pavement surface into a stone reservoir below and returning it to the drainage system or infiltrating into the ground. The underlying stone or gravel acts as a natural filter, removing impurities from the water and improving its quality. It is often used in car parks, walkways, low-traffic areas and driveways. This eco-friendly pavement is suitable for hot climates like Delhi, high traffic areas and less trafficked areas.

3 CHAPTER THREE RESEARCH METHODOLOGY

3.1 Conceptual Framework

Every research project is governed by a paradigm. A research paradigm is a model or method of research that has long stood the test of time and is considered standard by a large number of researchers in the field. Positivist paradigm highlights that scientific inquiry should rely on observable and measurable facts rather than on subjective experiences**.** Post-positivism is a philosophy that rejects positivism and presents new assumptions in order to unravel the truth. Hence the paradigm shift takes place from positivism to post-positivism. The research falls under the post-positivist paradigm.

Ontological claims of this research is certain landscape interventions in the sidewalks helps to enhance the thermal comfort of the pedestrians which promotes walkability thereby helps to decrease the energy consumption of the cities.

Epistemological position of this research is: The results can be obtained from the quantitative data obtained from the simulation.

3.2 Methods and tools

The methodology for this project will be quantitative approach. There are various outdoor climatic simulation software available, among them ENVI-met will be used.

The study will be comprised of following methods:

Articles/Documents review: The initial phase of any research involves an extensive literature review, mainly focused on the area of study. Various aspects of outdoor thermal comfort, as well as soft and hard elements of landscape design, are examined. Many research articles on the topic of outdoor thermal comfort in streetscape and its findings are examined. This helped to get an overview of the study domain.

Field Study: This consisted of studying the microclimate of the selected street section. This included measuring the width of the sidewalks, trees height and canopy size. The temperature and relative humidity of the site was also measured using the Hobo data logger (Model number:) for 12 days on both sides of the sidewalks. On-site photographs were also taken.

Questionnaire Survey: The thermal comfort survey was done to gain the perception about the thermal environment of the selected street section. A random sample of 36 pedestrians was taken for the survey. The questionaire was divided into 6 parts where first part was to be filled by the surveyor by observation. The rest of the 5 parts consisted of demogrpahic details, purpose of visit, past thermal experience, thermal sensation, thermal comfort and thermal adaptability and preference for microclimate. The full questionaire survey can be found on the Appendix A.

Thermal sensation

1) How do you feel right now?
☐ Very hot +3 ☐ Hot +2 ☐ Warm +1 ☐ Neutral a0 ☐ Cool -1 ☐ Cold -2 ☐ Very cold -3

2) How is your Skin in terms of wetness?
☐ Sweaty ☐ moist ☐ Just right ☐ Dry ☐ Very dry

Preference for microclimate

a) How do you wish for the air temperature to be?
☐ Cooler (-1) ☐ No change (0) ☐ Warmer (+1)

b) How do you wish for the Sun to be?
☐ Weaker sun (-1) ☐ No change (0) ☐ Stronger Sun (+1)

c) How do you wish for the Wind to be?
☐ Weaker wind (-1) ☐ No change (0) ☐ Stronger Wind (+1)

Figure 3-1 Part of Questionnaire for the Survey

Simulation with ENVI-met software: For the outdoor comfort simulation of the sidewalks, ENVI-met 5.03 will be used. The main reasons for selecting ENVI-met as the preferred modelling system are explained as below:

- This model simulates the microclimate dynamics within a daily cycle.
- Different vegetation forms can be generated in the model. ENVI-met considers the physiological processes of evapotranspiration and photosynthesis rather than vegetation as a porous barrier to wind and solar radiation.
- A limited number of inputs are required to run the model with a large number of outputs.
- ENVI-met can calculate Tmrt (Mean radiant temperature), the most important parameter in thermal comfort calculations.

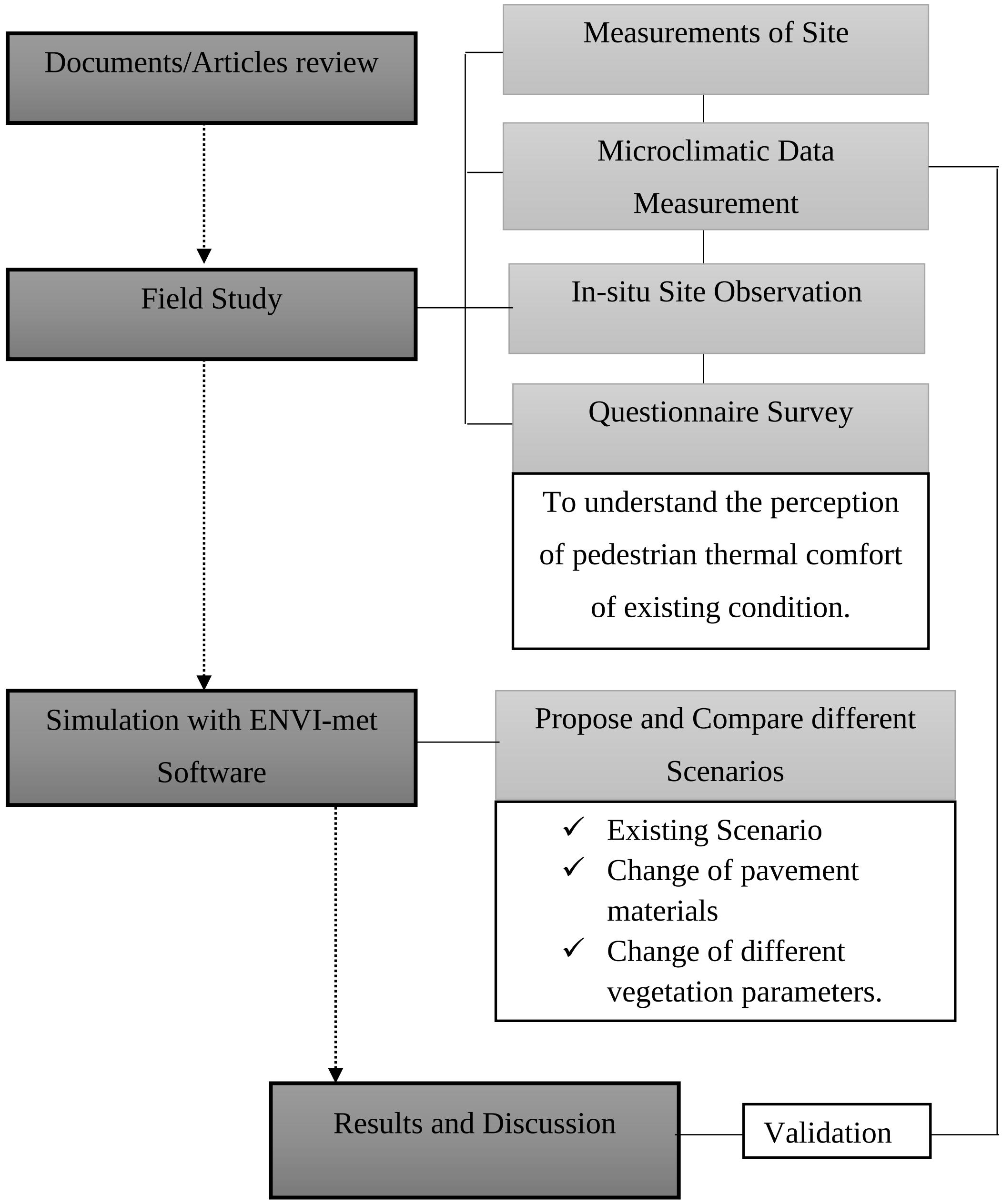


Figure 3-2 Flow diagram of Summary of research method

The figure 3-2 sums up the flow of the research carried out in this research. The research method is broadly categorized as documents/articles review, field study and simulation with ENVI-met Software. The validation of the results of ENVI-met software will be done through the comparison of the data obtained from the microclimatic measurement and from the base case scenario results obtained from the ENVI-met software 5.03.

4 CHAPTER FOUR RESEARCH AREA: KATHMANDU METROPOLITAN CITY

4.1 Background

The Kathmandu Valley, with an estimated population of 2.54 million, is growing at 6.5% annually, making it one of the fastest growing metropolitan areas in South Asia (Timsina, 2020). The rapid increase in population and the number of cars, as well as the densification of limited urban areas, including the haphazard conversion of buildings, have led to conflicts between vehicular and pedestrian traffic, more congestion and traffic accidents, and increased air and noise pollution. Kathmandu has made great efforts in the last decade to make the city car-friendly by widening roads and building multi-lane highways. People, especially pedestrians and cyclists, increasingly find the city unfriendly. Everything else is being displaced by automobiles and motorbikes (Khanal, 2020).

According to a study conducted by Clean Air Network Nepal and Clean Energy Nepal (CEN), pedestrian facilities in Kathmandu are in disrepair. The field survey was conducted in commercial, public transportation, educational, and residential areas and covered 48 road sections totaling 59 kilometers in length. According to the survey results, Kathmandu City has a walkability index of 559. (Safe streets challenge, 2012). Bangkok's index is 121 when compared to other cities. A city with a single number index is considered more pedestrian-friendly. Residential areas from Baneshwor Height to Lazimpat have the highest walkability scores in the following variables: availability of walking paths with maintenance and cleanliness, availability of crossings per stretch, safety at level crossings, motorist compliance with traffic rules, and safety from crime. The Ason Street commercial area has the lowest walkability scores in almost every variable: availability of walking paths, availability of intersections per route, safety at railway crossings, motorist compliance with traffic rules, amenities, disabled infrastructure, and crime safety.

4.2 Street Typology in Kathmandu Valley

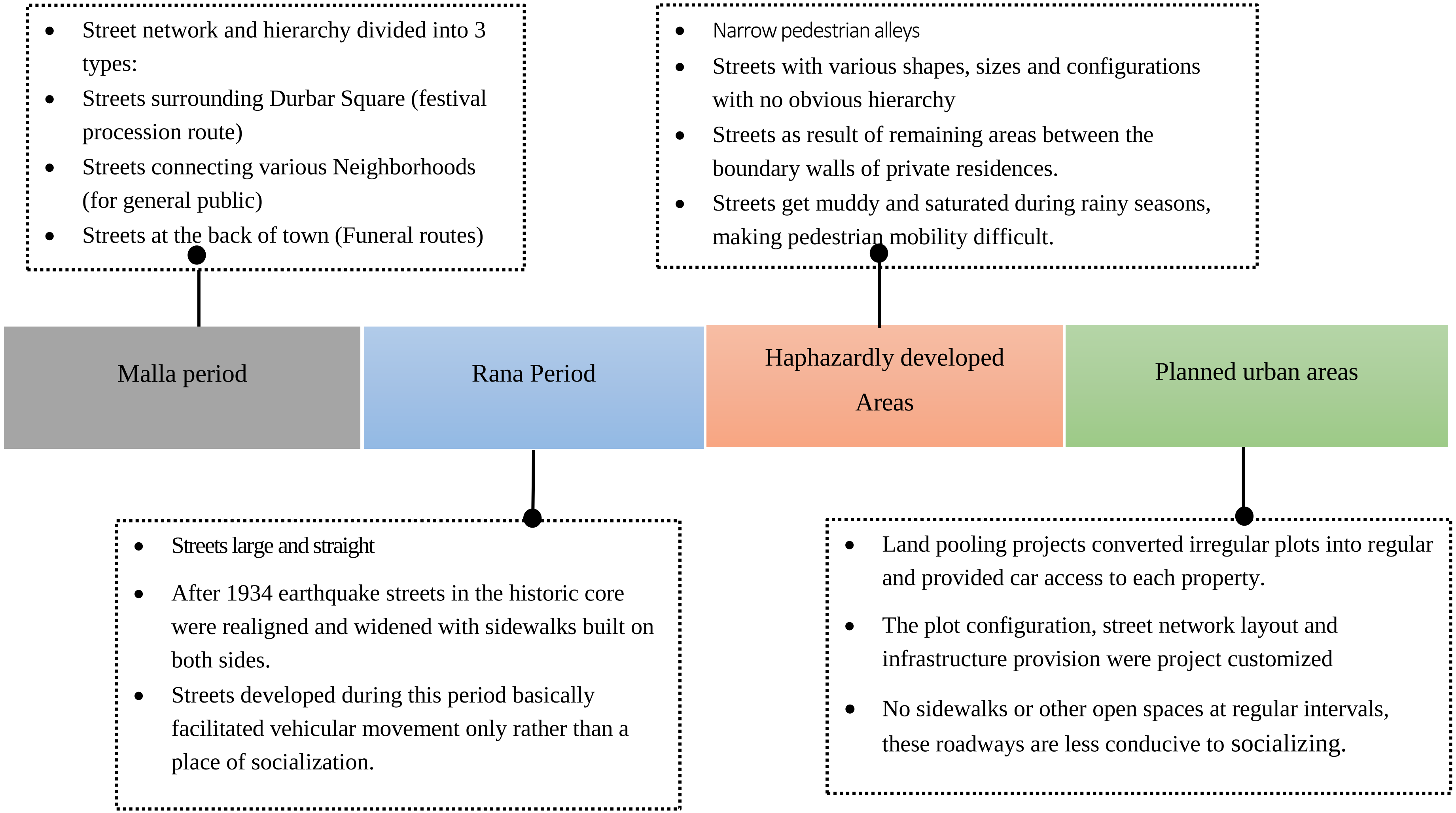


Figure 4-1 Based on (Shrestha, 2011)

4.3 Condition of pedestrian pathways in Kathmandu

The streets of Kathmandu are narrow, crowded and confusing. It has been mentioned in many national dailies that walking in Kathmandu can be a nightmare. When it comes to walkability, Kathmandu is at the bottom of the list. A walkability study (assessment of pedestrian infrastructure and services) conducted in 2010 found that 94% of the road sections surveyed in Kathmandu were classified as 'not walkable'. Less walkable roads also mean more use of transport systems, which increases the energy consumption of the transport sector.

Pedestrians struggle to walk on the footpath at Chabahil-Chuchhepati road in Kathmandu. Both people and vehicles have been forced to suffer due to the delay in the construction of the road stretch. **Elite Joshi /TKP**

A woman covers her nose with a shawl as she walks beside a pile of garbage at Boudha, Kathmandu. Trashes are littered haphazardly in Kathmandu due to lack of proper garbage management system. **Aashruti Tripathy /TKP**

Figure 4-2 Condition of Pedestrian walkways in Kathmandu

(Source: The Kathmandu Post)

There are no sidewalks on most streets, and those that exist are either poorly maintained or crowded with parked cars and street vendors. But that's not all. Electricity and telecommunication poles have been placed indiscriminately all over the city, often in the middle of the pavement. Dangerous cables dangle from these poles and are scattered across the streets, forming a tangle. As if that weren't bad enough, pedestrians in Kathmandu suffer most during the rainy season, when the streets become a puddle trap and occasionally a stream of sewage.

Buddhist monks walk beside the concrete pipes kept for building drainage system at Boudha, Kathmandu. **Biju Maharajan /TKP**

People walk beside a partially slanted telephone wire pole at Narayan Gopal Chok, Kathmandu. **Kabin Adhikari /TKP**

Figure 4-3 Condition of Pedestrian walkways in Kathmandu
(Source: The Kathmandu Post)

Sidewalks are widened and built with the durability of the paving material in mind, but without considering its thermal properties. Most of the trees along the streets are planted indiscriminately and only for beautification, without considering their impact on the microclimate of the street.

The KMC components include activities of (i) side walk improvement and (ii) pedestalization/walkability including walkability in heritage site in different part of Kathmandu city.

4.4 Climate of Kathmandu

Kathmandu lies in the temperate zone and has a mild climate most of the year. The warm season lasts for around 6 months from April 5 to October 10, with an average daily temperature above 80 F (26.6 C) The cool season lasts for around 2.1 months from December 9 to February 11. There are main five seasons in Nepal summer, monsoon, spring, autmn and winter respectively.

Temperature

The monthly average maximum temperature is around 31°C in June, and the monthly average minimum temperature is around 5°C in January as shown in the chart below.

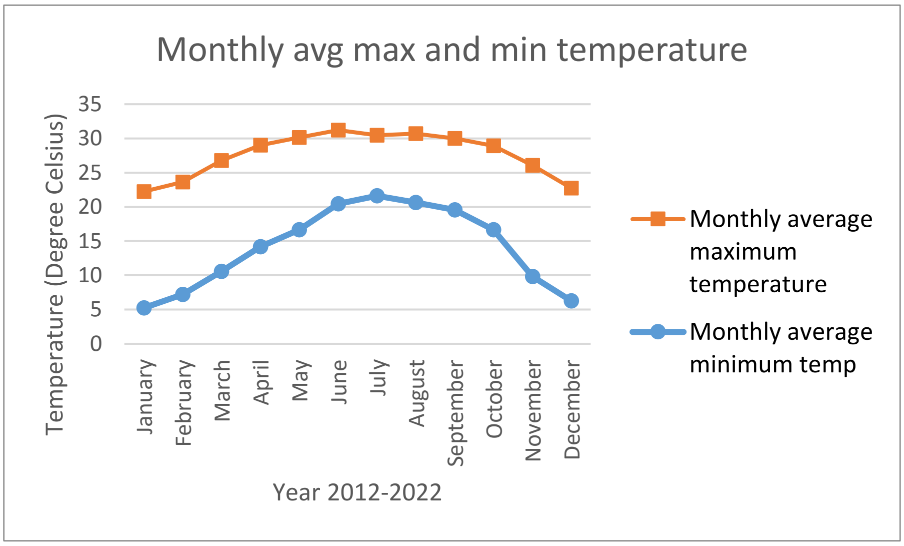


Chart 4-1 Monthly average maximum and minimum temperature from year 2012 to 2022
Source: Department of Hydrology and Meteorology

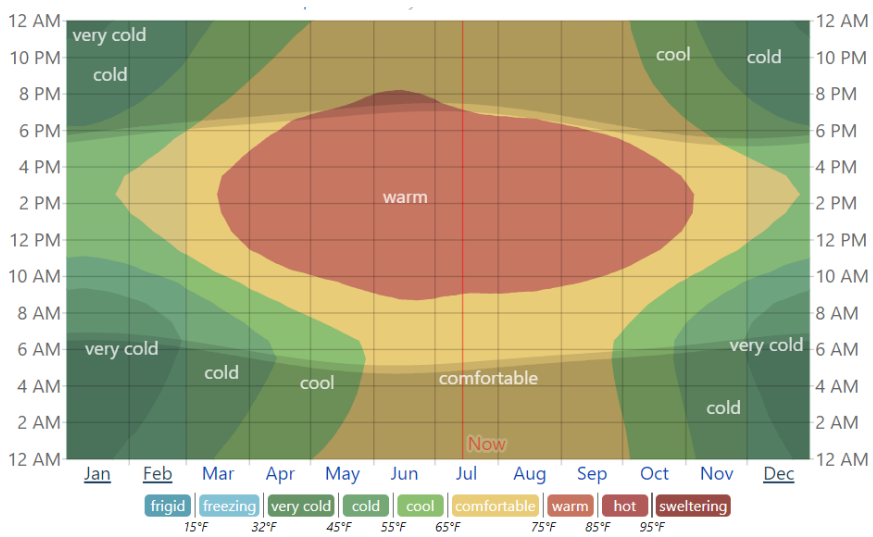


Chart 4-2 Average hourly temperature in Kathmandu Source: (weathersparks.com)

The figure above shows the compact characterization of the entire year of hourly average temperatures. The horizontal axis is day of the year and the vertical axis is the hour of the day, the color is the average temperature for that hour and day.

Relative Humidity

The graph below shows the relative humidity throughout the year. On average, November is with 85.0% the most humid. On average, April is with 53.0% the least humid month. The average annual percentage of humidity is: 74%

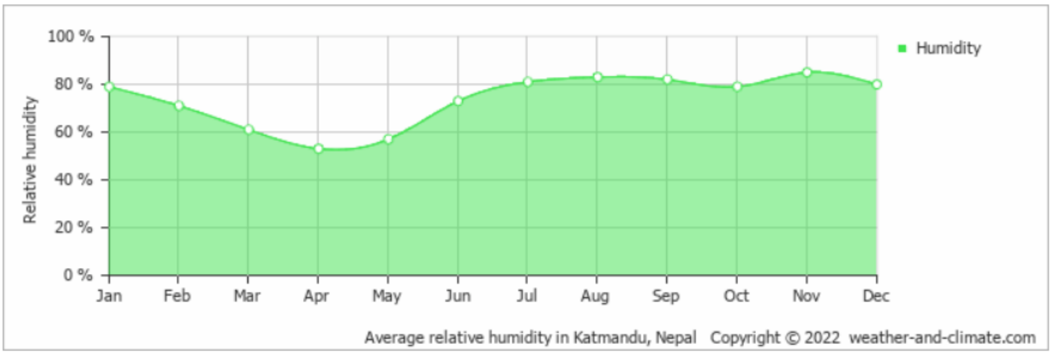


Figure 4-4 Relative Humidity in Kathmandu
Source: weather-and-climate.com

The dew point determines whether perspiration evaporates from the skin, cooling the body, and thus the humidity comfort level. Higher dew points make you feel more humid, while lower dew points make you feel drier. Unlike temperature, which changes rapidly between night and day, dew point changes more slowly, so while the temperature may drop at night, a warm and humid day is usually followed by a muggy night.

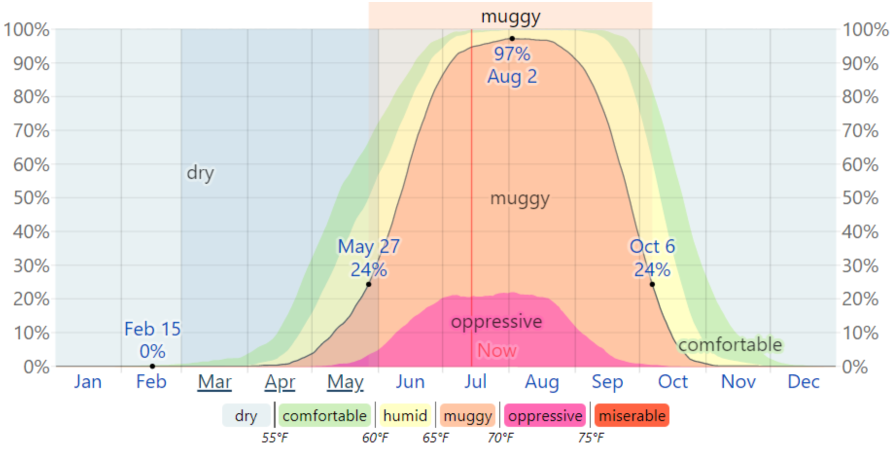


Chart 4-3 Humidity comfort levels in Kathmandu
Source: weathersparks.com

Wind speed and wind direction

The wind at any given location is determined by the local topography and a variety of other factors. The hourly averages are less variable than the instantaneous wind speed and direction. The windier season in Kathmandu lasts approximately 5.1 months, from February 15 to July 19, with a value of 5.0 miles per hour. The windiest month of the year is April, with a value of 6.2 miles per hour. The wind is mostly blowing from the southwest and west.

N ▼ Northern	NE ▲ Northeastern	E ◄ Eeastern	SE ► Southeastern	S ▲ Southern	SW ▼ Southwestern	W ► Western	NW ▲ Northwestern
3.9%	**1.8%**	**7.3%**	**3%**	**25.2%**	**11%**	**44%**	**3.8%**

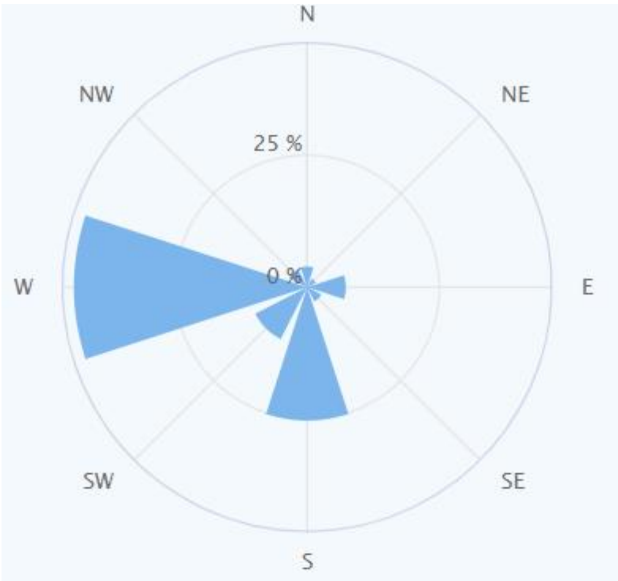


Figure 4-5 Wind rose for Kathmandu
Source: worldweather.info

Wind speed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(mph)	4.3	5.0	5.8	6.2	5.8	5.4	5.0	4.5	4.1	3.9	3.9	3.8
(m/s)	1.92	2.23	2.59	2.77	2.59	2.41	2.23	2.01	1.83	1.74	1.74	1.69

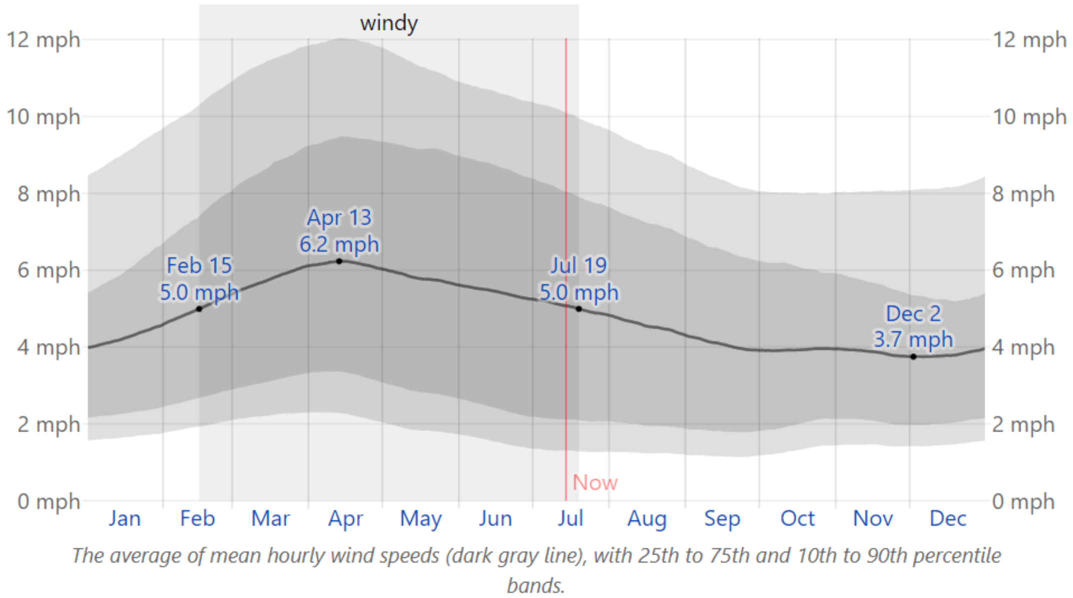


Chart 4-4 Average wind speeds throughout the year in Kathmandu
Source: weathersparks.com

(All the climatic information comes from weatherspark.com, worldweather.info and Department of Hydrology and Meterology).

4.5 Site Area

4.5.1 Selected Street Section

The selected street stretch is located in Durbarmarg. The selected stretch is about 300 metres and oriented N-S.

Durbar marg informally known as King's way is a broad, long avenue in Kathmandu. It leads to the Royal palace of Narayanhiti. Built in 1961 by then crown prince Birendra Bir Bikram Shah Dev, Durbar marg was well known for travel business center having airlines offices, travel agencies, restaurants and tourist shopping destination. Slowly it has flourished as the commercial area being the shopping and entertainment destination for the people. Durbar Marg is regarded as one of the well-kept and clean areas in Kathmandu, and a green belt has been established on the side street.

Figure 4-6 Site map *Source: Google maps*

Figure 4-7 Point 2
Picture Credit: Author

Figure 4-8 Point 1 View of Durbar Marg
Source : thenepalipost.com

Figure 4-9 Bird's eye view
Source: Saurav Agrawal (Kathmandu Kingsway- A Drone film 4k)

Figure 4-10 Different views of Durbarmarg Picture Credit: Author

4.5.2 Pedestrian movement

There is immense amount of flow of pedestrians in the site. Below is the table of the no of pedestrians passing by at certain point in 15 minutes. The flow of pedestrians is more in east facing sidewalk than west facing sidewalk since the east facing sidewalk seems more vibrant from west facing sidewalk. The flow increases in the evening. The table below shows the pedestrian movement in different times and different days.

Table 4-1 Pedestrian movement as observed in site by author

Date and Time	Time span	East facing Sidewalk	West facing Sidewalk
June 23, 6 pm	15 min	224	
June 26, 3 pm	15 min		134
June 27,4.30 pm	15 min	250 36 ppl in 1 min	132
July 1, 10.30 am	15 min	110 ppl	
July 3,9.00 am	15 min		76 pl

4.5.3 Selected Stretch Plan

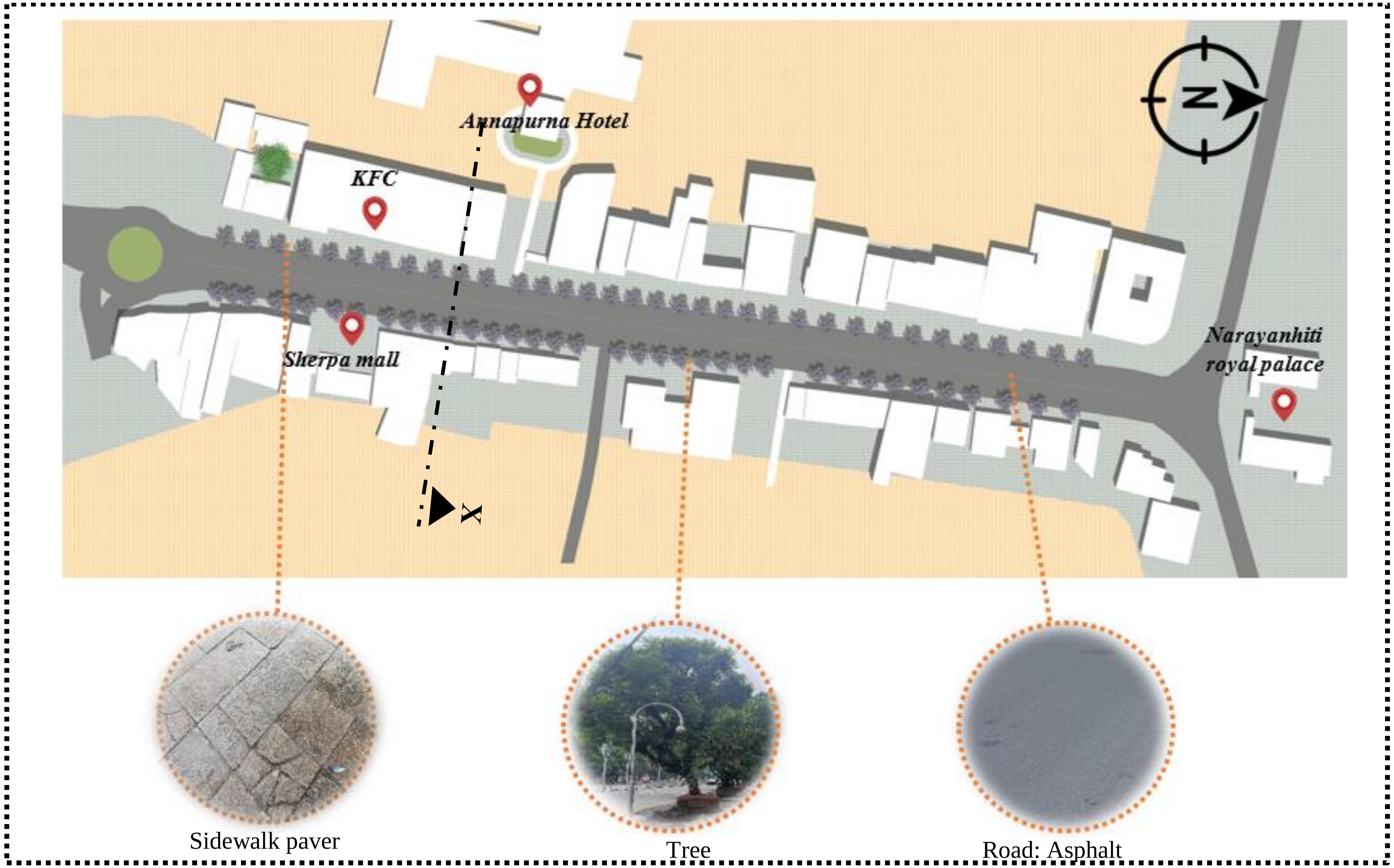
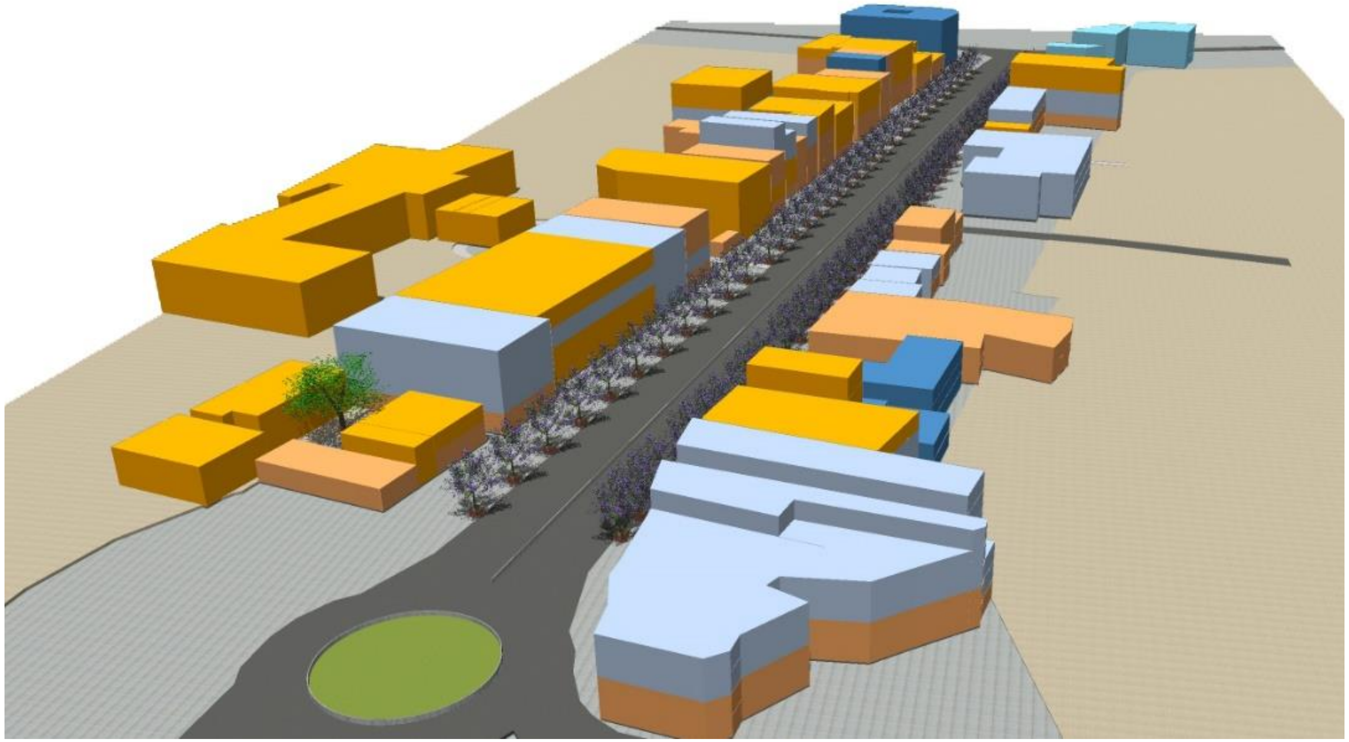


Figure 4-11 Site plan of Durbar Marg

4.6 Volumetric 3d of Selected Stretch



Legend	Types of Buildings
	Café, Restros, Bar and hotels
	Shops
	Offices and banks
	Malls
	Traffic Building

Figure 4-12 Durbarmarg building uses map

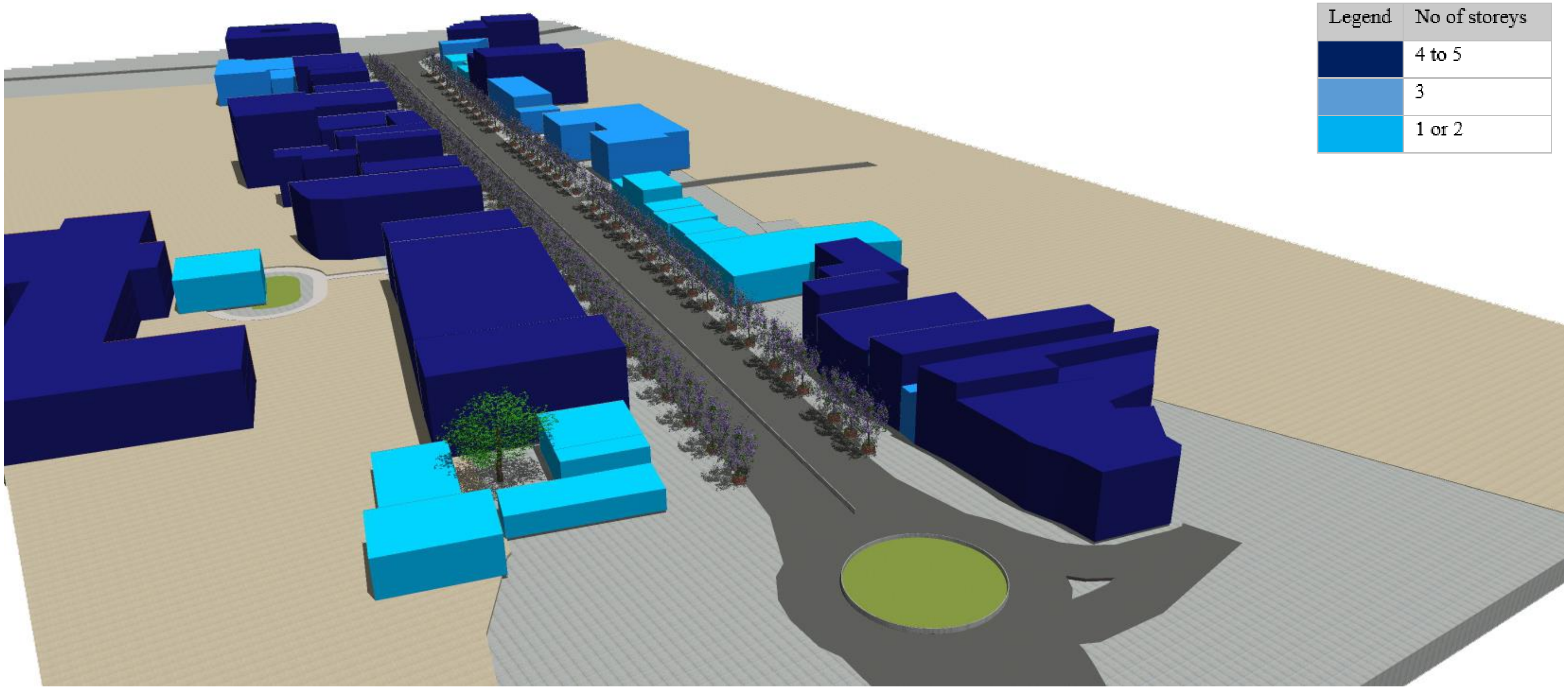


Figure 4-13 Durbarmarg building heights map

4.6.1 Section of Selected Stretch

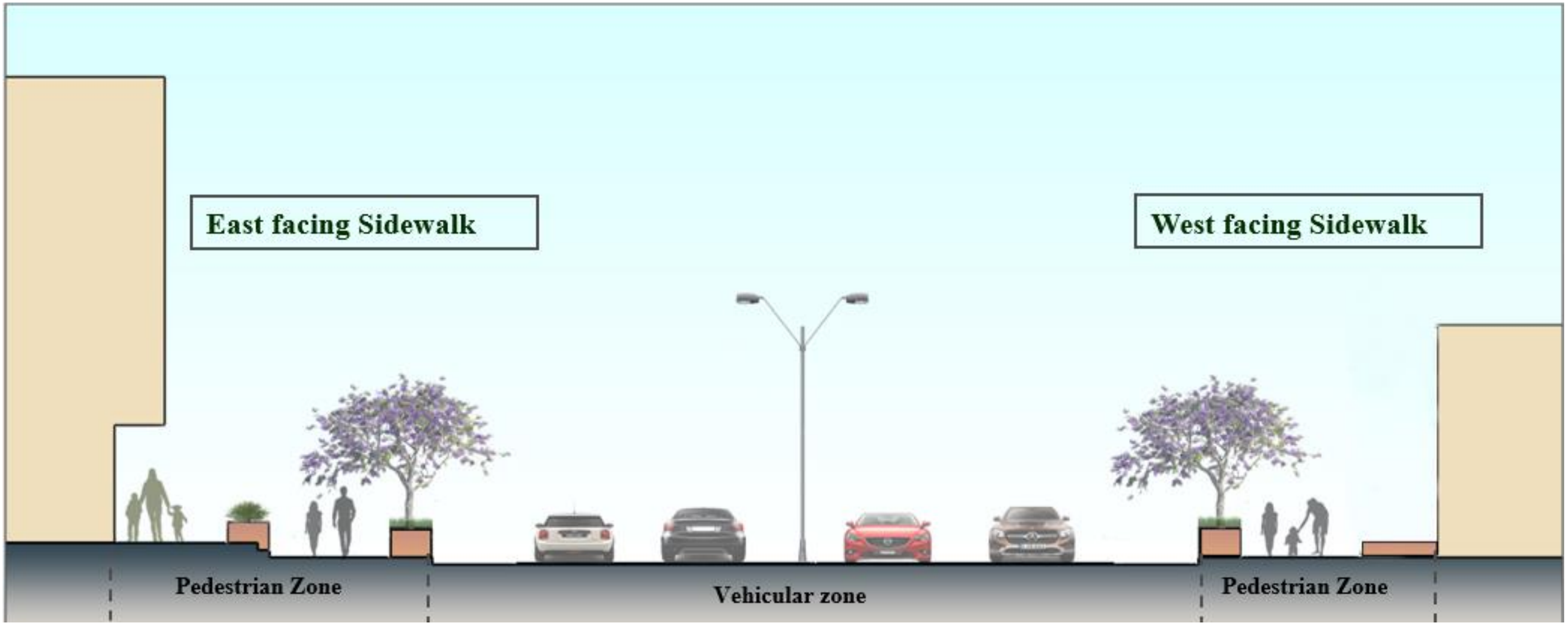


Figure 4-14 Section at X-X

The street consists of the vehicular zone and pedestrian zone. Vehicular zone consists of the 4 lanes. The sidewalks are on both sides. For convenience: they are named East facing sidewalk and West facing Sidewalk

4.6.2 Sidewalks in Durbarmarg

Sidewalks in Durbarmarg consists of building frontage zone. Pedestrian through zoena and Street furniture/curb zone. The pedestrian through zone is around 2.8 metres, curb zone is around 1 metres and building frontage varies from 2 to 2.5m. The figure below shows the east facing sidewalk and west facing sidewalk with their respective frontage zone, pedestrian through zone and street furniture/curb zone. There are few street furniture on east facing sidewalk whereas the west facing sidewalk does not have street furniture.

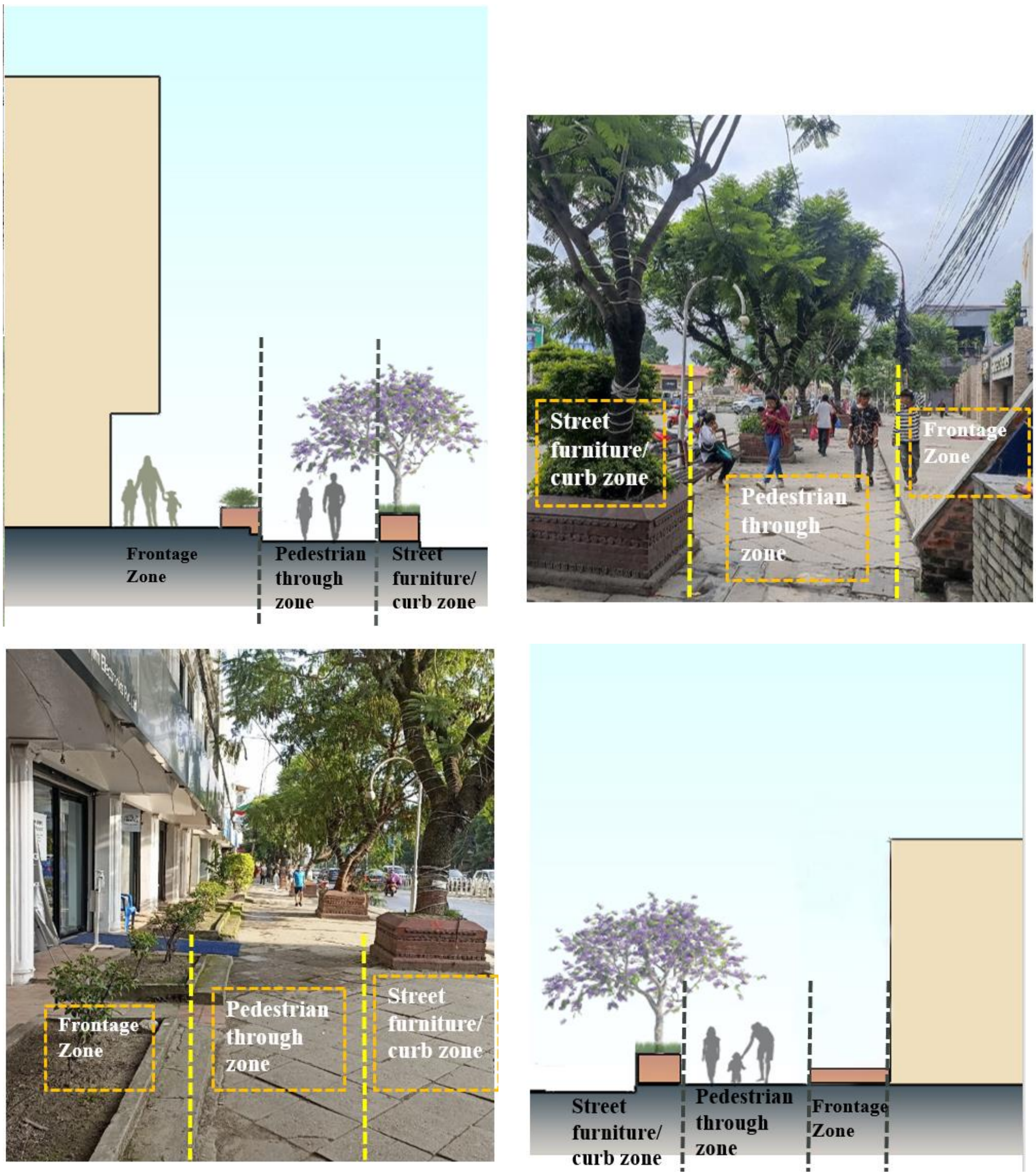


Figure 4-15 East facing and West facing Sidewalk *Picture Credit: Author*

4.6.3 Tree species in Sidewalks: Jacaranda Mimosifolia

Figure 4-16 Tree Spcies : Jacaranda Mimosifolia in Durbarmarg

Jacaranda mimosa is planted as the street tree in Durbarmarg. Over the last four decades, the spread of jacaranda has been consistent in Kathmandu. Rana aristocrats brought this plant to Kathmandu in the late nineteenth and early twentieth centuries, according to Nepali botanists and hostorians. Sur Shamsher Rana, a member of former Prime Minister Bir Shamsher's family, brought the plant to Nepal in the 1920s from Darjeeling or any hilly area of India, according to one historian with extensive knowledge of Nepalese plants.

He planted the flower in his private garden near the later location of Hotel Yak and Yeti in Durbarmarg, and it was the first jacaranda plant in Nepal. In his book, he also claims that King Tribhuwan planted the second jacaranda tree in Kathmandu. He planted it in front of the Narayanhiti Palace's southern gate.

Jacaranda is a deciduous tree with spreading branches and a light crown that can reach heights of 10 to 20 meters. The arched branches of the jacaranda form a canopy resembling an upturned umbrella. With its fern-like leaves that can grow up to 20 inches in length, the jacaranda tree makes an excellent shade (or street) tree. It makes an ideal street tree since it creates the spectacular sight in full bloom.

4.6.3.1 General information

Scientific name	Jacaranda mimosifolia
Common name	Jacaranda
Family	Bigoniaceae
Plant type	Flowering tree

Origin	Native to southern and central South America
Height	25-50ft
Spread	15-30ft
Soil type:	Sandy, well-drained

4.6.3.2 Favourable conditions for Jacaranda

Light

It needs at least 6 to 8 hours of sun per day for the best blooming. Smaller jacaranda trees can tolerate light shade if necessary, but a lack of sunlight can reduce the quantity and vibrancy of their blooms.

Soil

Jacaranda trees thrive in well-draining, medium-sandy soil with a slightly acidic pH. It tolerates clay and loamy soils but should not be planted in any mixture that is heavy, wet, or poorly draining. Waterlogged soil can increase the risk of root rot.

Temperature and Humidity

Some jacaranda trees can withstand cold weather (down to 20 degrees Fahrenheit), but this species does not thrive in climates with frequent freezing temperatures. This plant prefers heat and humidity, but it is susceptible to trunk scald in areas with high temperatures all year.

4.6.3.3 Foliage

Jacaranda has fern-like foliage which usually allows diffuse light to pass though, hence it is possible to grow grass under the tree. Jacaranda leaves and flowers can create litter when they drop and hence can make ground mess if they arenot swept up quickly, it can rot and cause the slimy slippery ground.

Figure 4-17 Flowers of Jacaranda
Source: askifas

Figure 4-18 Leaf of Jacaranda
Source: askifas

Leaf arrangement	Alternate
Leaf type	Bipinnately compound,odd-pinnately compound; made up of 20 secondary leaflets per primary leaflet
Leaf shape	Obovate,rhomboid
Leaf type and persistence	deciduous
Leaf blade length	9-18 inches, primary leaflets are 5 inces; secondary leaflets are ¼ inch
Leaf colour	green
Fall colour	No colour change
Flower colour	Lavender to violet purple
Flower characterisitics:	Very showy; lightly fragnant; emerges on numerous 12-18” long panicles
Flowering	Spring and Summer

4.6.3.4 Fruit

Fruit Shape	Round, disk-like capsule

Fruit length	3 inches
Fruit Covering	Dry or hard
Fruit colour	Brown
Fruit characterisitics	Doesnot attract wildlife;not showy; fruit/leaves a litter problem

Figure 4-19 Fruit- Jacaranda mimosifolia
Source: UF/ IFAS

Figure 4-20 Fruit Open- Jacaranda mimosifolia
Source: UF/IFAS

4.6.3.5 Trunk and branches

Trunk/branches	Branches droop; typically one trunk ;no thorns
Bark	Light brown, smooth, becoming blocky and rough with age
Breakage	Susceptible to breakage
Current year twig color	Gray,brown

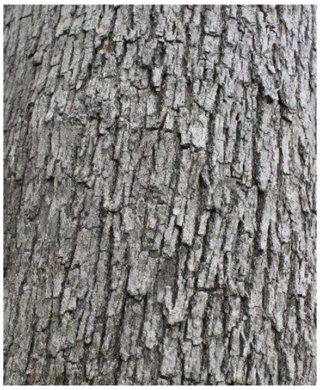


Figure 4-21 Jacaranda mimosifolia
Source: Gritta Hasing, UF/IFAS

4.6.4 Distance between trees:

The distance between trees is varying from 240” (6m) to 706” (18m) . The tree pit size is. 52” X 52”.

4.6.5 Canopy size and tree height

There were trees of various canopy size and height in the selected stretch. To approximately know the tree height, one of the person of height 67” (5’7”) stood next to the tree and the height of the tree was approximately calculated. Similarly to measure the canopy size, android phone app called ARuler was used.

Figure 4-22 Tree 1, Tree 2, Tree 3
Picture Credit: Author

	Tree 1	Tree 2	Tree 3
Tree height	22.4’ (6.8m)	13.5’(4.1m)	27.91’(8.5m)
Canopy Size	23.03’(7.01m)	10.05’(3.06m)	29.725’(9.06m)

4.6.6 Pavements

There are different kinds of pavements in the selected street section. It varies in the building frontage and in different street segments. Most of the pavers through pedestrian through zone are interlocking blocks and stone pavers.

Figure 4-23 Sidewalk pavement
Picture credit: Author

Figure 4-24 Different kinds of pavements along the sidewalks *Picture Credit: Author*

5 CHAPTER FIVE RESULTS AND ANALYSIS

5.1 Microclimatic measurement

The climatic parameters air temperature, relative humidity was measured with Kobo data logger for 12 days starting from June 29 2022 to July 10 2022. The device was calibrated with device on DHM (Department of Hydrology and Meteorology) and it was placed on the coordinates 27.7116667 N, 85.31747799E on site. Also the relative humidity and air temperature was taken next to every respondent by digital thermos-hygrometer HTC-2.

Figure 5-1 Digital Thermo-hygrometer HTC -2

Figure 5-2 Hobo MX series data logger
Source: onetemp.com.au

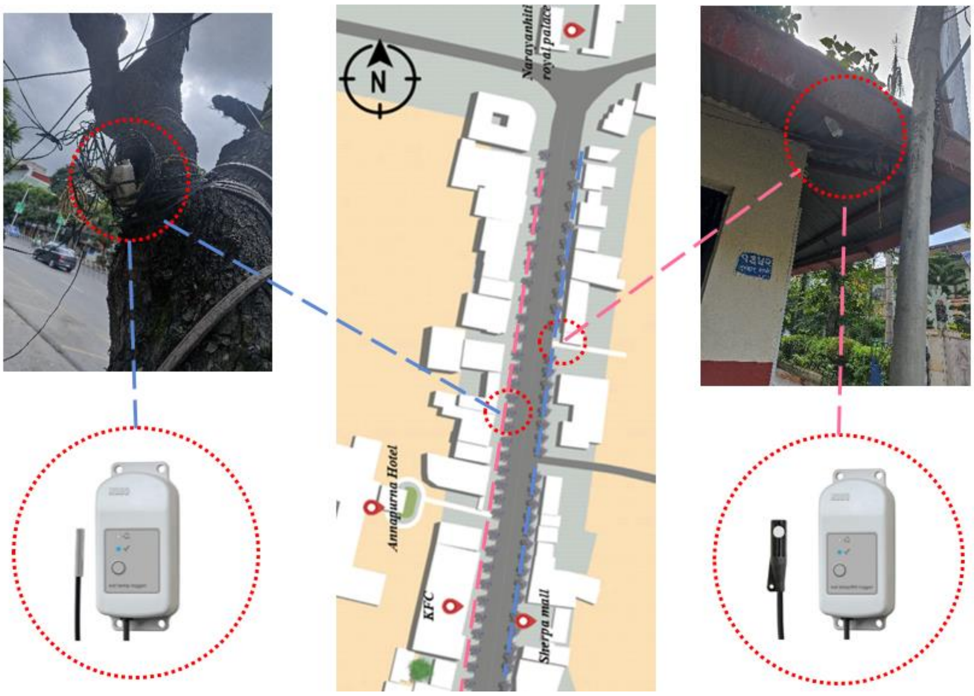


Figure 5-3 Location of data-loggers in Site

Temperature

The average daily temperature for 12 days of measurement is shown in the chart 5-1.

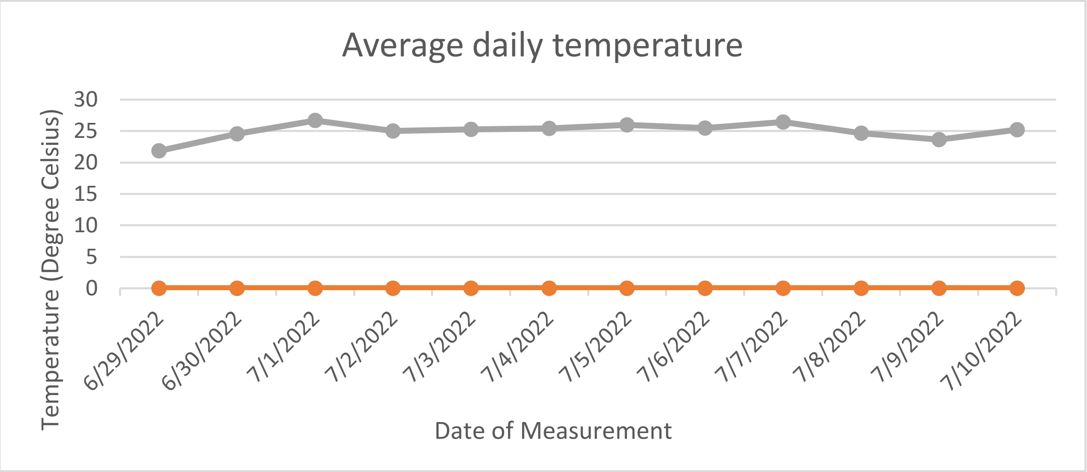


Figure 5-4 Average daily temperature for 12 days of measurement (June 29-July 10)

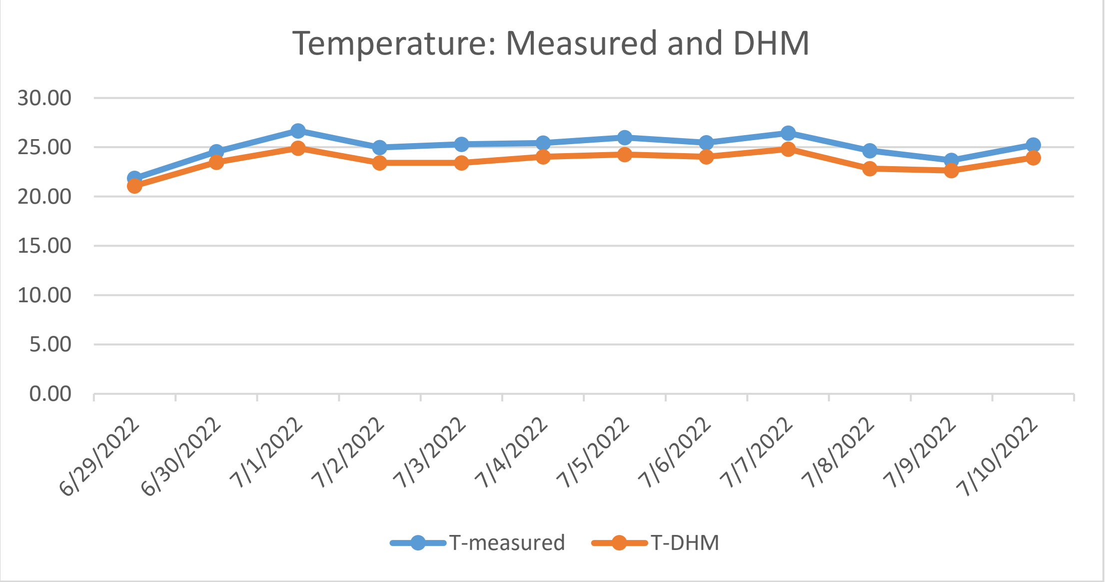


Figure 5-5 Average daily temperature for 12 days of measurement (June 29-July 10) (Measured and Department of Hydrology and Meterology)

The highest average daily temperature was on 7/1/2022 and 7/7/2022 with the value of 26.67 °C and 26.45 ° respectively. Between these two dates, 7/7/2022 was chosen for the simulation in Envi-met.

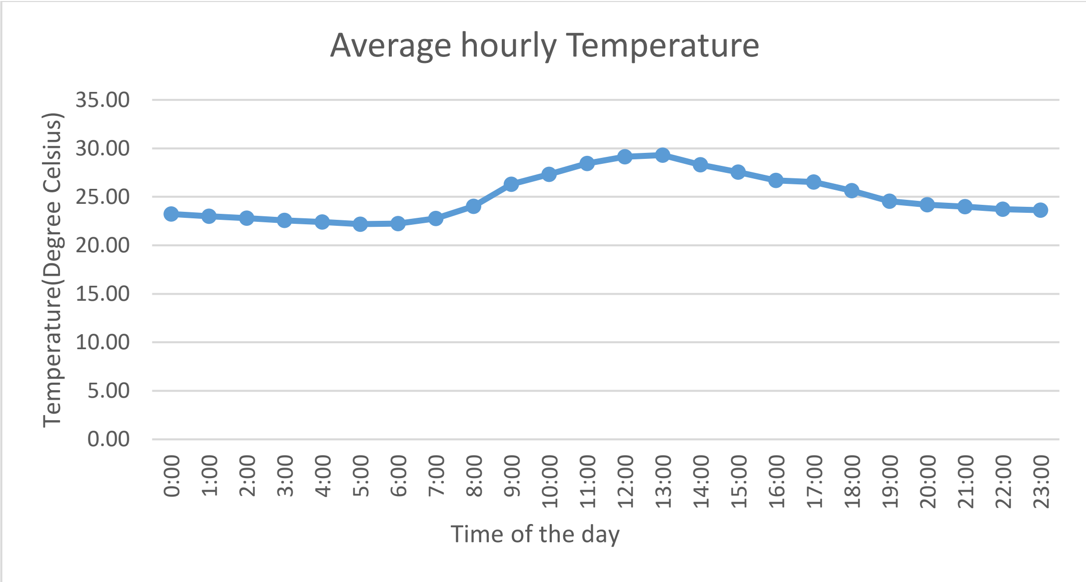


Figure 5-6 Average hourly temperature for 12 days of measurement

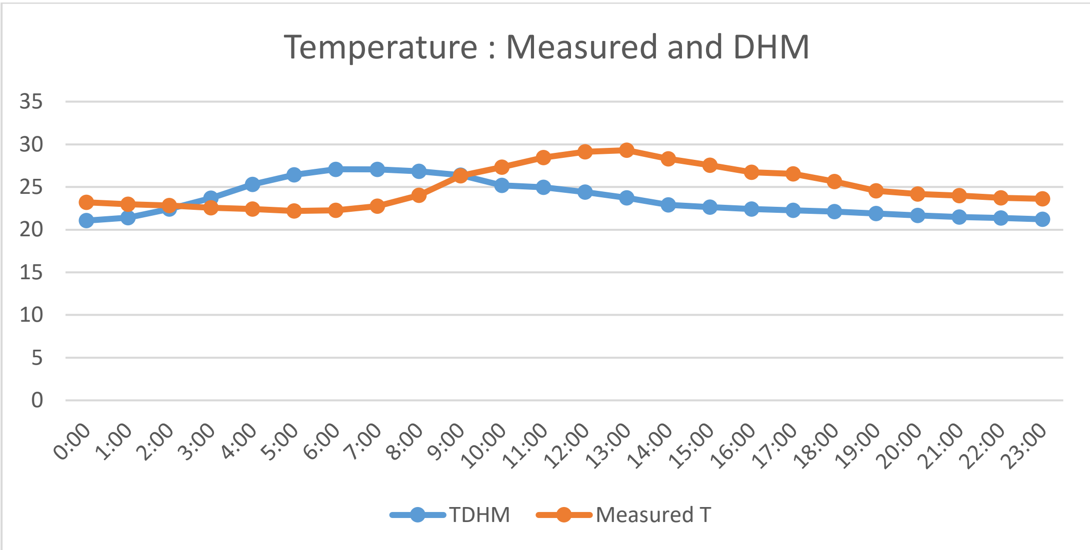


Figure 5-7 Average hourly temperature for 12 days of measurement (Measured and Department of Hydrology and Meterology)

The average hourly temperature for 12 days are shown in the chart 5-3. The maximum temperature was found on 1 pm with the value of 29.31 whereas the minimum temperature was found on 5 am with the value of 22.19.

Relative Humidity

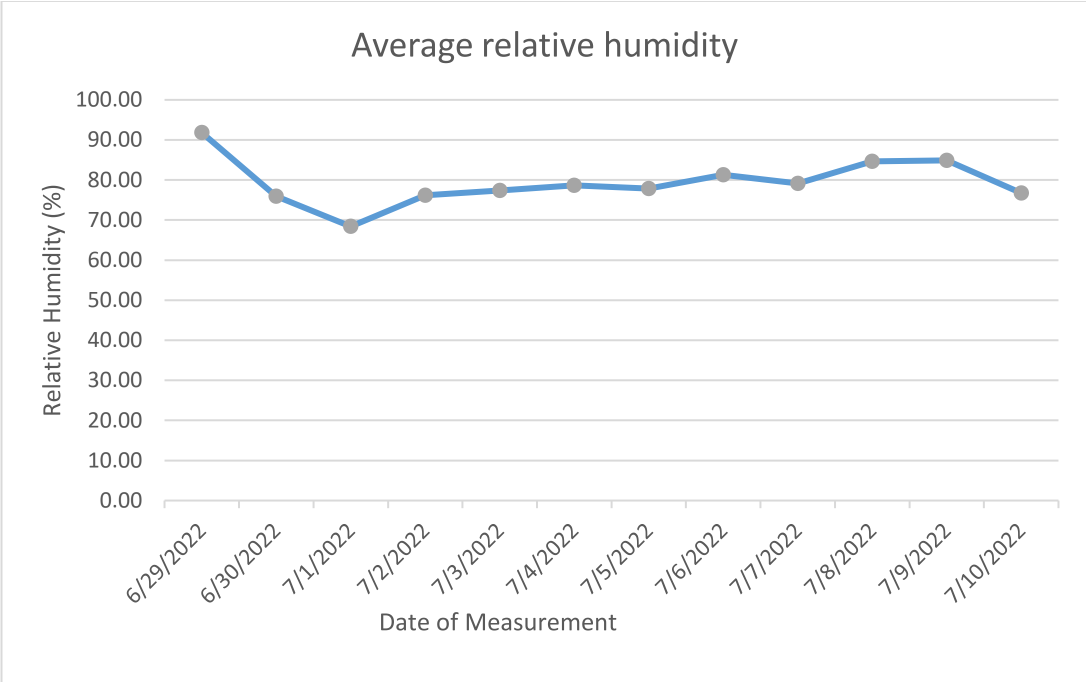


Chart 5-1 Average daily relative humidity for 12 days of measurement

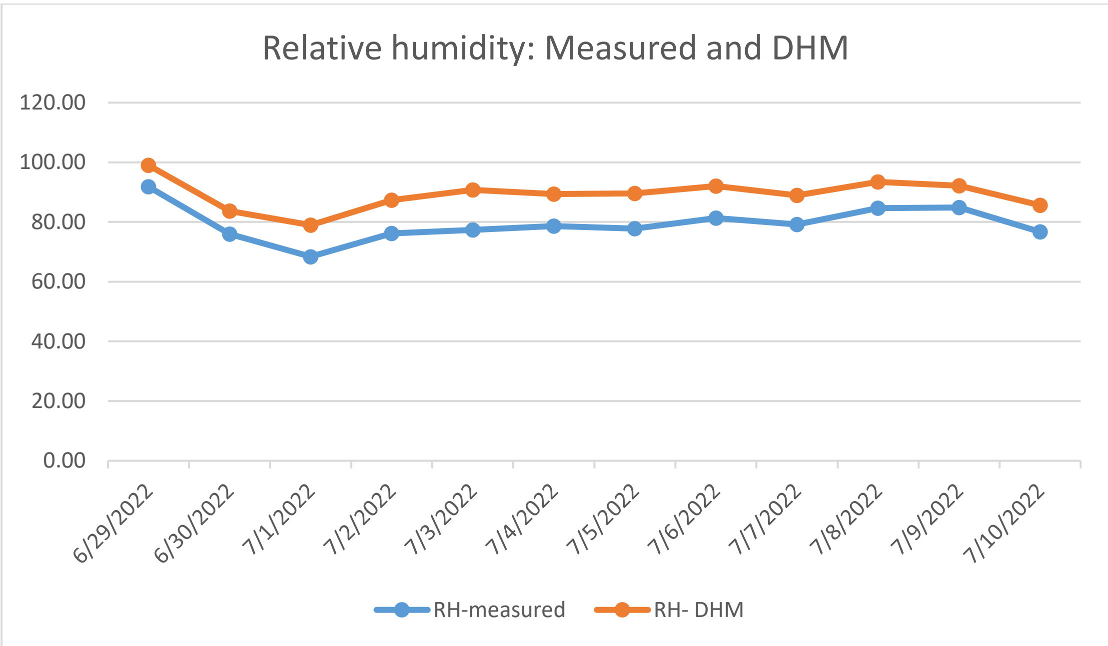


Figure 5-8 Average daily relative humidity for 12 days of measurement (Measured and Department of Hydrology and Meterology)

The graph above shows the average relative humidity of 12 days of measurement. The maximum relative humidity was recorded on 29th June 2022 with the value of 91.81 %.

The hourly average relative humidity for 12 days were shown in chart 5-6. The maximum hourly RH was found on 5 am with value of 89.78°C and the minimum hourly RH was found on 12 pm with value 61.62 %.

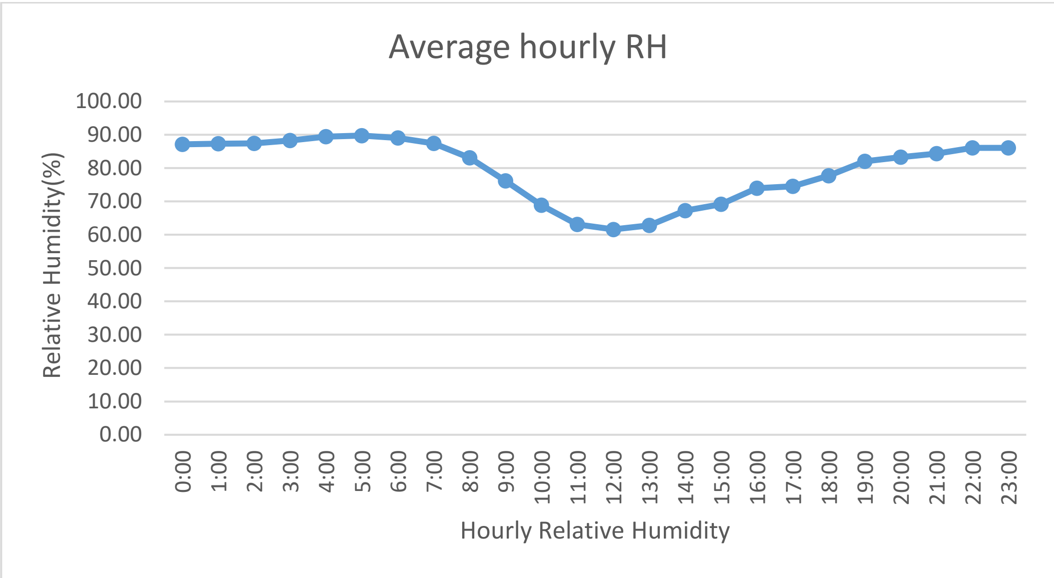


Chart 5-2 Average hourly relative humidity for 12 days of measurement

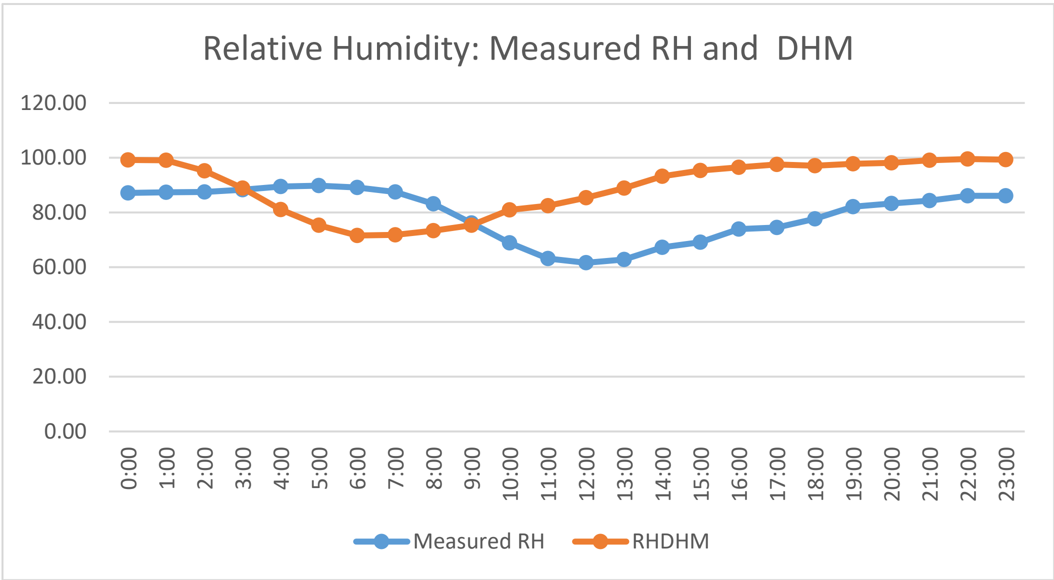


Figure 5-9 Average hourly relative humidity for 12 days of measurement (Measured and Department of Hydrology and Meterology)

5.2 Questionnaire Survey

The total number of respondents in survey was 36. The survey was done on the both sidewalks of the street. The questionnaire was divided into 6 parts where first part was to be filled by the surveyor by observation. The rest of the 5 parts consisted of demogrpahic details, purpose of visit, past thermal experience, thermal sensation, thermal comfort and thermal adaptability and preference for microclimate. Kobo Toolbox was used for the analysis of the data. The questionnaire sample is on the Appendix B.

Figure 5-10 Author doing the questionnaire survey

Picture Credit: Dikshya Shandilya

5.2.1 To be filled by surveyer's section

Survey time and date

The survey was done for almost 7 days on favourable climatic conditions. The no of people with the respective dates are shown in the table.

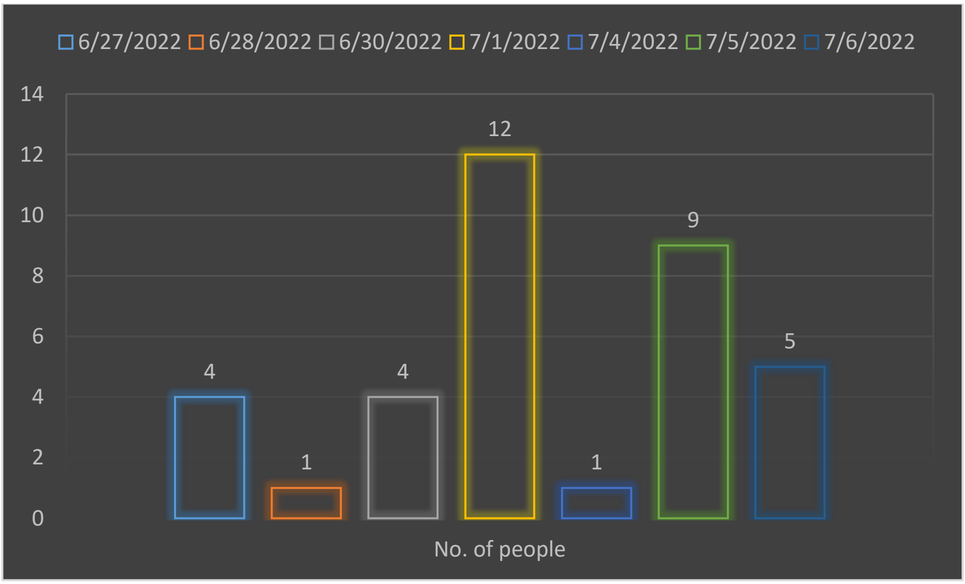


Figure 5-11 Date of Survey with no. of people surveyed.

Survey location

The survey was done both sidewalks. The number of people surveyed on east facing sidewalk and west facing sidewalk were 21 and 15 respectively.

Sidewalk	Frequency	Percentage
East facing Sidewalk	21	58.33
West facing Sidewalk	15	41.67

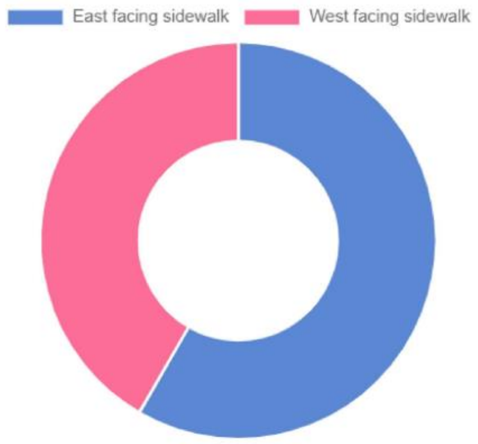


Chart 5-3 Survey Location

Sky Condition during survey

The chart shows the sky condition during the survey. The sky conditions during the survey were mostly clear/mostly sunny, partly cloudy/partly sunny, mostly cloudy. The frequency of people surveyed during these sky conditions are presented the table.

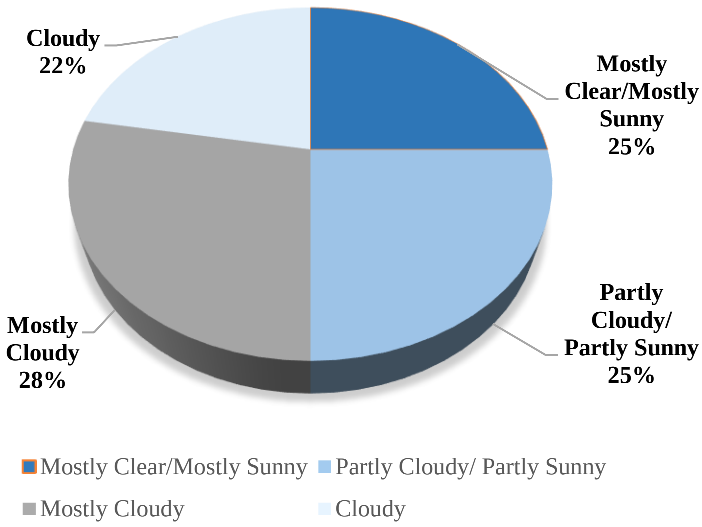
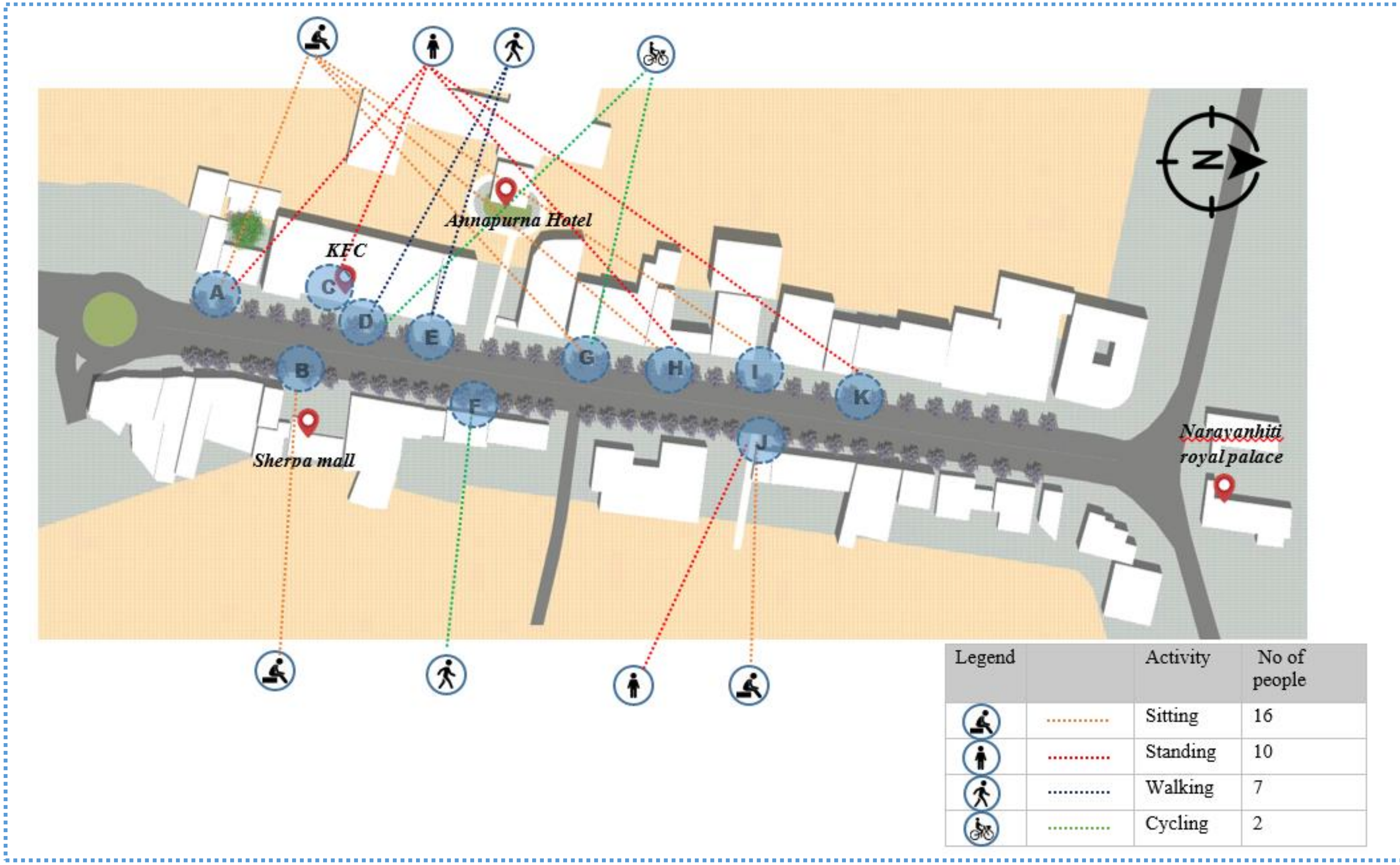


Chart 5-4 Sky condition during survey

Sky condition	Frequency	Percentage
Mostly Clear/Mostly Sunny	9.00	25
Partly Cloudy/ Partly Sunny	9.00	25
Mostly Cloudy	10.00	27.8
Cloudy	8.00	22.2

Activity mapping while surveying



Legend		Activity	No of people
	....	Sitting	16
	....	Standing	10
	....	Walking	7
	....	Cycling	2

Figure 5-12 Showing the different location of survey within the street section

Respondent’s type

The main target for this survey were pedestrians however people who spend their most time outdoors in the street like the vendors and guards were also surveyed.

Respondent	Frequency	Percent
Pedestrian	30.00	83.33
Vendor	2.00	5.56
Others (Security Guards	4.00	11.11

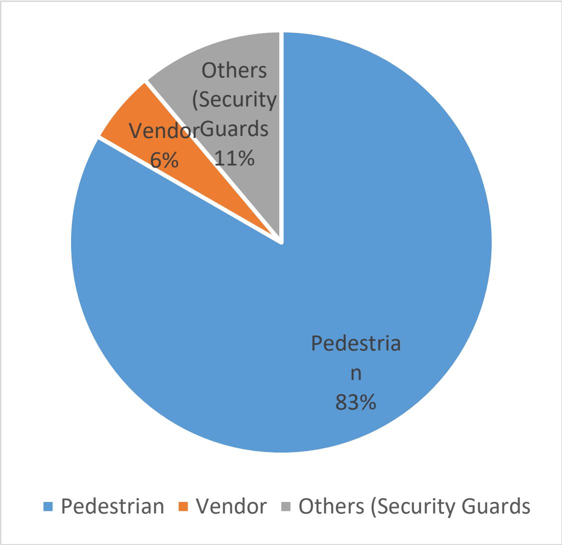


Chart 5-5 Respondent’s type during survey

5.2.2 Demographic details

Respondent’s Gender, Age and Weight

A person’s age, gender and his/weight also has influencing factors on their thermal comfort. Hence both male and female and adult with varying age groups were surveyed.

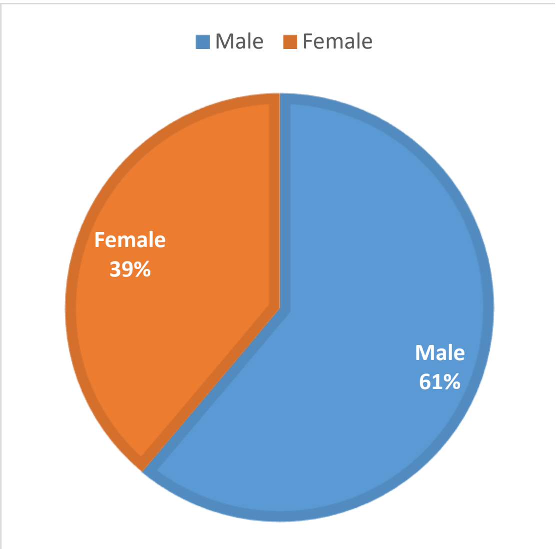


Chart 5-6 Respondents gender

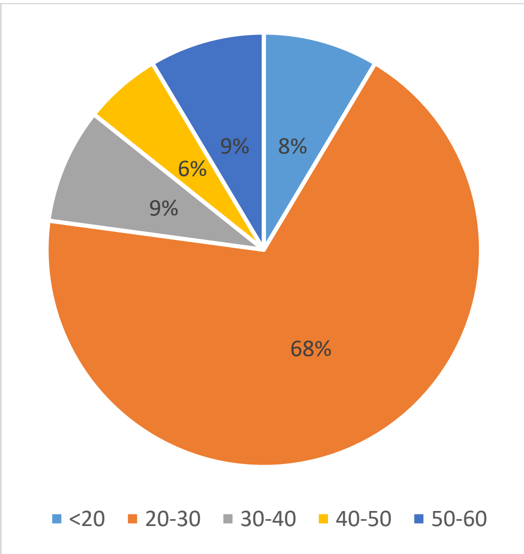


Chart 5-7 Respondents age

Gender	Frequency	Percent
Male	22	61.11
Female	14	38.89

Age	Frequency	Percentage
<20	3.00	8.33
20-30	24.00	66.67
30-40	3.00	8.33
40-50	2.00	5.56
50-60	3.00	8.33

Weight	Frequency	Percentage
40-50	7.00	19.44
50-60	10.00	27.78
60-70	10.00	27.78
70-80	8.00	22.22
80+	1.00	2.78

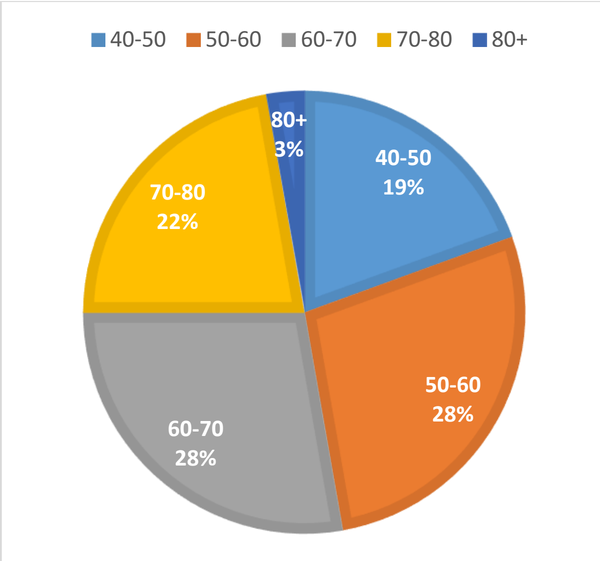


Chart 5-8 Respondent's weight

Reason for visiting this street

As mentioned earlier there is immense movement of people in this street. To speculate the reasons for visiting, this question was included. Most of the people surveyed visited this street for work. Entertainment/fun being the second reason of visit to this street.

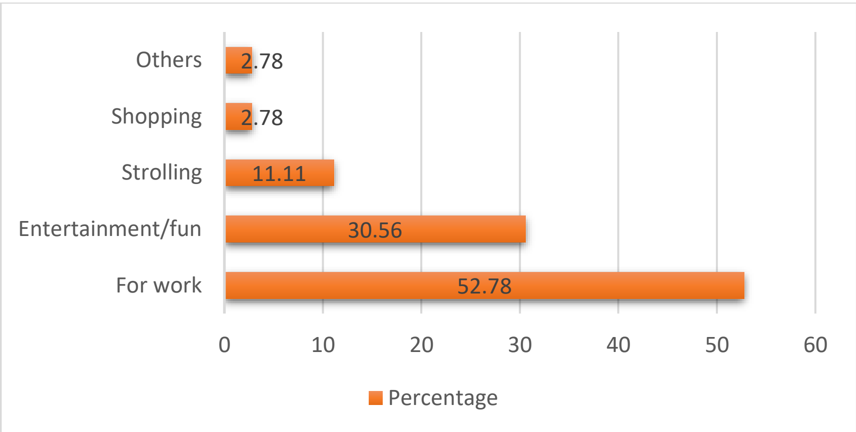


Chart 5-9 Reason for visitng the street

Reason	Frequency	Percentage
For work	19.00	52.78
Entertainment/fun	11.00	30.56
Strolling	4.00	11.11
Shopping	1.00	2.78
Others	1.00	2.78

Preferred side of street

36 % of the people surveyed prefered both sidewalks whereas 39% of people prefered east facing sidewalk.

Preferable side	Frequency	Percent
Sidewalk facing East	14.00	38.89
Sidewalk facing West	9.00	25
Both	13.00	36.11

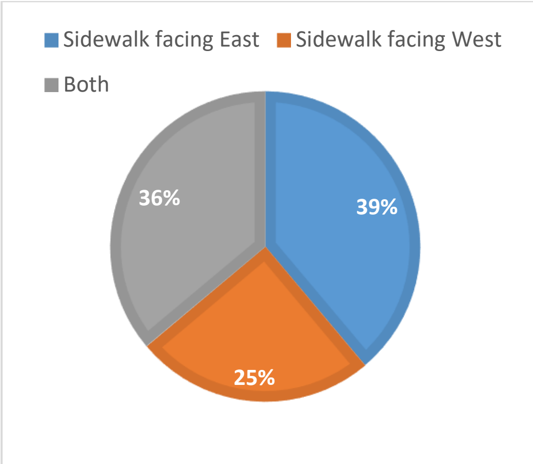


Chart 5-10 Preferred side of street

Reason to sit/stand/walk at the particular place

A major number of people chose to sit/stand/walk at the particular place due to tree cover.

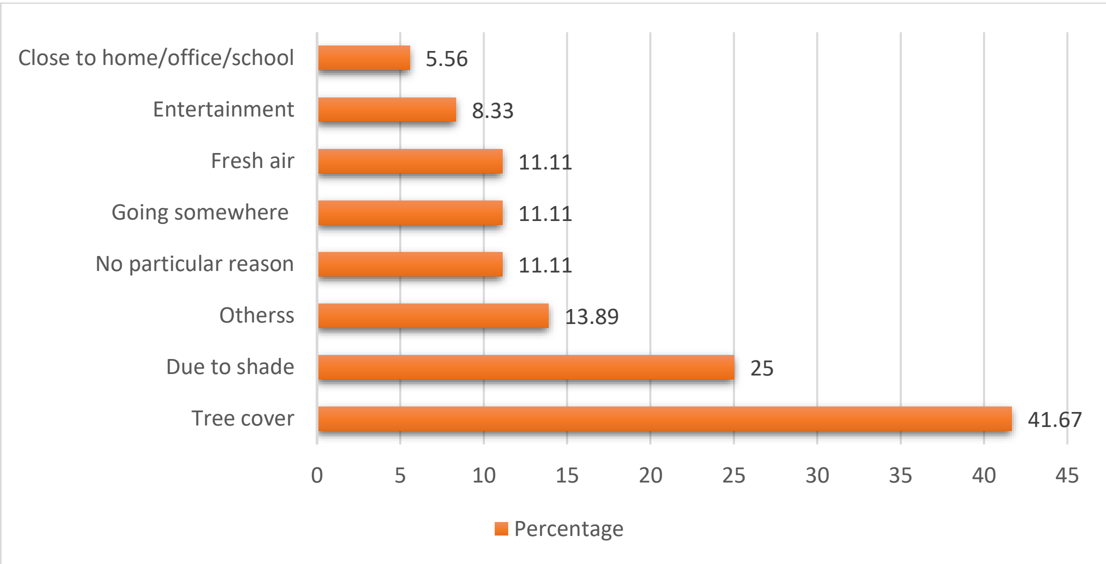


Chart 5-11 Reason to sit/stand/walk at the particular place

Reason	Frequency	Percentage
Tree cover	15.00	41.67
Due to shade	9.00	25
Otherss	5.00	13.89
No particular reason	4.00	11.11
Going somewhere	4.00	11.11
Fresh air	4.00	11.11
Entertainment	3.00	8.33
Close to home/office/school	2.00	5.56

Time and frequency of visit

Thermal comfort varies with the time of the day. To understand if there is relationship between the time of the day and no of people visiting, this question was included. 19 of the people visited the street between 10 am to 2pm.

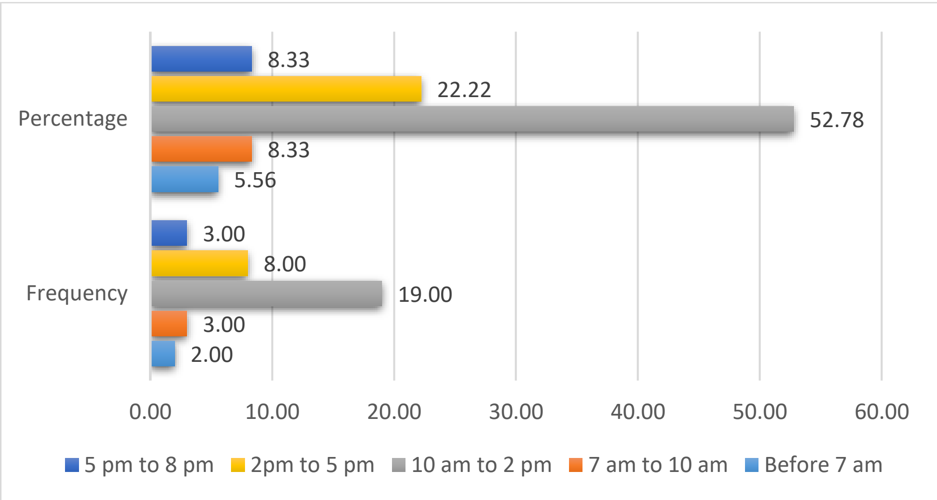


Chart 5-12 Time of the visit

Time of the day	Frequency	Percentage
Before 7 am	2.00	5.56
7 am to 10 am	3.00	8.33
10 am to 2 pm	19.00	52.78
2pm to 5 pm	8.00	22.22
5 pm to 8 pm	3.00	8.33

Similarly to understand how often people visit in this street, this question was

Frequency		Percentage
Daily	10	27.78
Rarely	9	25
Monthly	8	22.22
Few times a week	7	19.44
Weekly	2	5.56

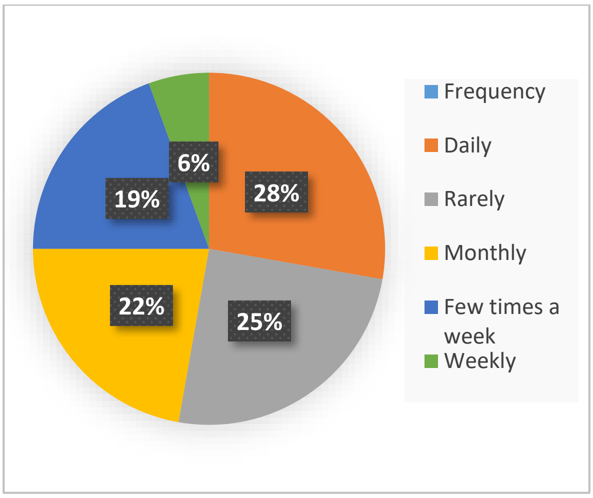


Chart 5-13 Frequency of visit

included. 28% of the pople visited street daily. 25% of the surveyed people visited the street rarely.

Heat from the pavement

A majority of people around 63.89% of people feels heat from the pavement.

Value	**Freq.**	**Percentage**
Yes	23	63.89
No	13	36.11

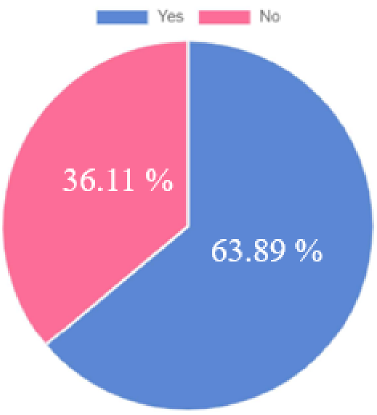


Chart 5-14 Heat from the pavement

5.2.3 Past thermal experience

What were you doing in the past 15 min prior to the survey?

Activity	Frequency	Percentage
Walking	11.00	30.56
Driving (2-wheelers)	10.00	27.78
Sitting	8.00	22.22
Standing	6.00	16.67
Driving (4-wheelers)	1.00	2.78
Working	1.00	2.78

Others	3.00	8.33

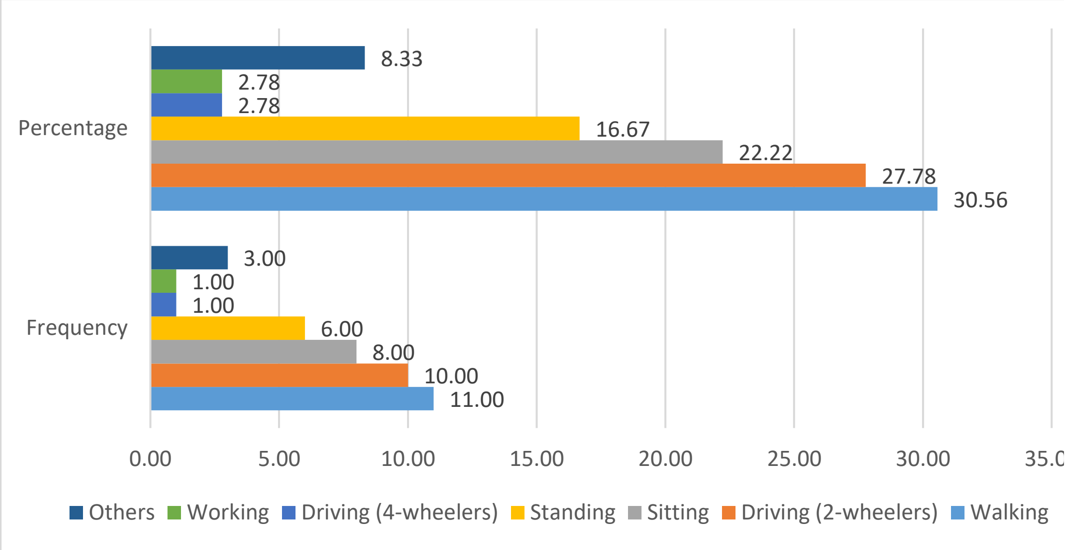


Chart 5-15 Activity level prior to the survey

5.2.4 Thermal sensation

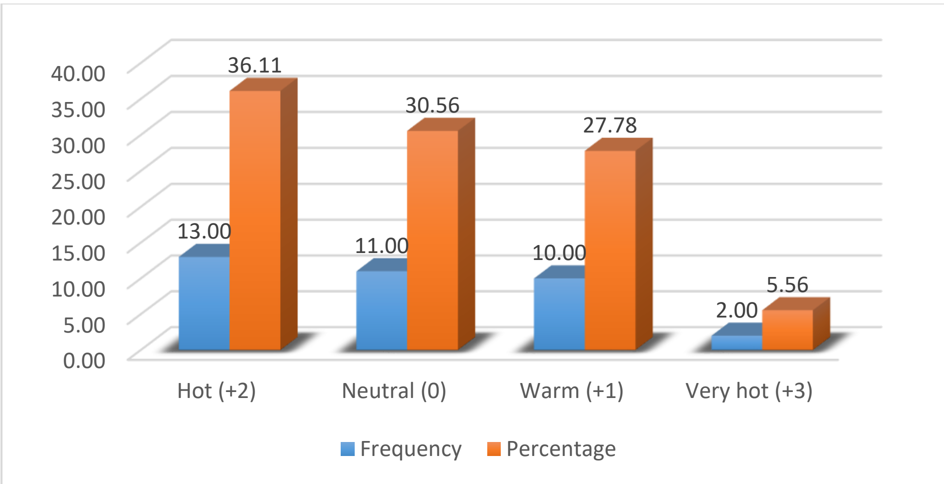


Chart 5-16 Thermal Sensation Votes

Thermal Sensation	Frequency	Percentage
Hot (+2)	13.00	36.11
Neutral (0)	11.00	30.56
Warm (+1)	10.00	27.78
Very hot (+3)	2.00	5.56

13 out of 36 people felt hot, 2 people felt very hot, 10 people felt warm whereas the rest 11 people felt neutral. The thermal sensation votes are shown in the chart 5-23.

Skin condition

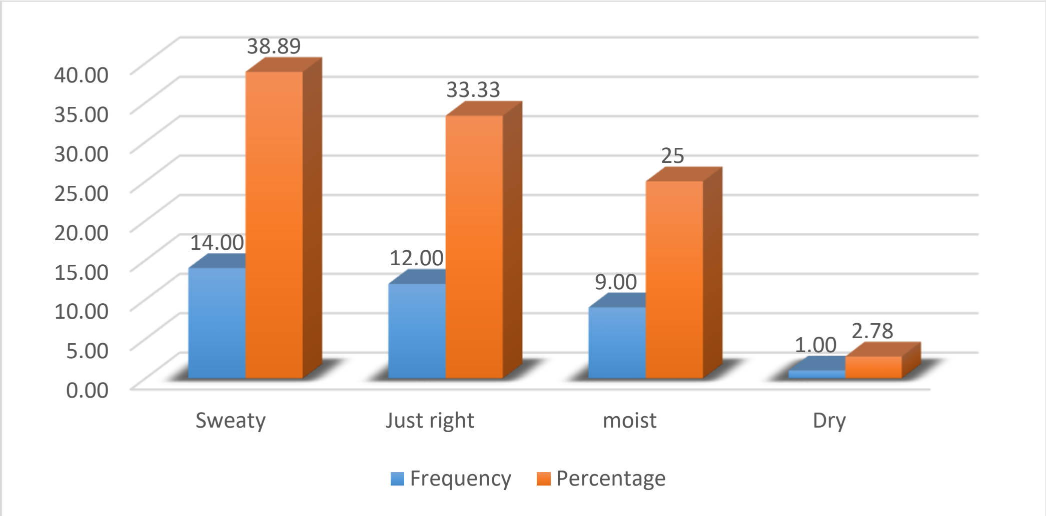


Chart 5-17 Skin Condition

Skin Condition	Frequency	Percentage
Sweaty	14.00	38.89
Just right	12.00	33.33
moist	9.00	25
Dry	1.00	2.78

5.2.5 Preference for microclimate

To understand the preference for the microclimate and whether the respondents want the change in their microclimate, this question was placed in the survey.

Air temperature

Air temperature	No pf people	Percentage
Cooler (-1)	25.00	69.44
No change (0)	11.00	30.56

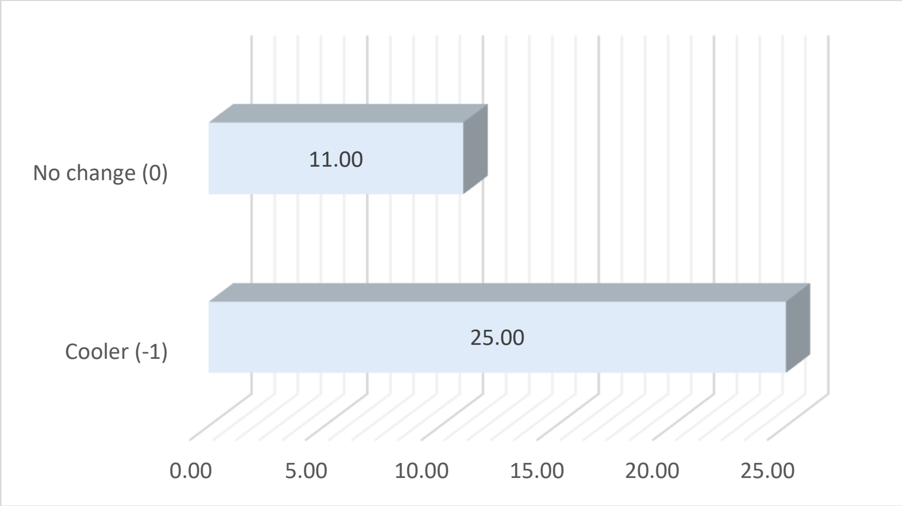


Chart 5-18 Preference for air temperature

Sun

Sun	Frequency	Percentage
Weaker Sun (-1)	21.00	58.33
No change (0)	15.00	41.67

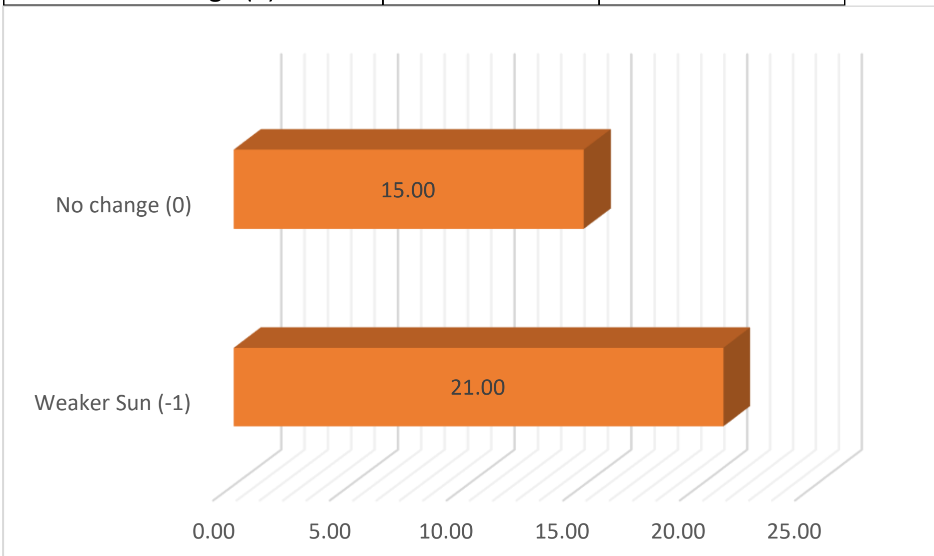


Chart 5-19 Preference for Sun

Wind

Wind	Frequency	Percentage
No change	20.00	55.55
Stronger wind (+1)	16.00	44.45

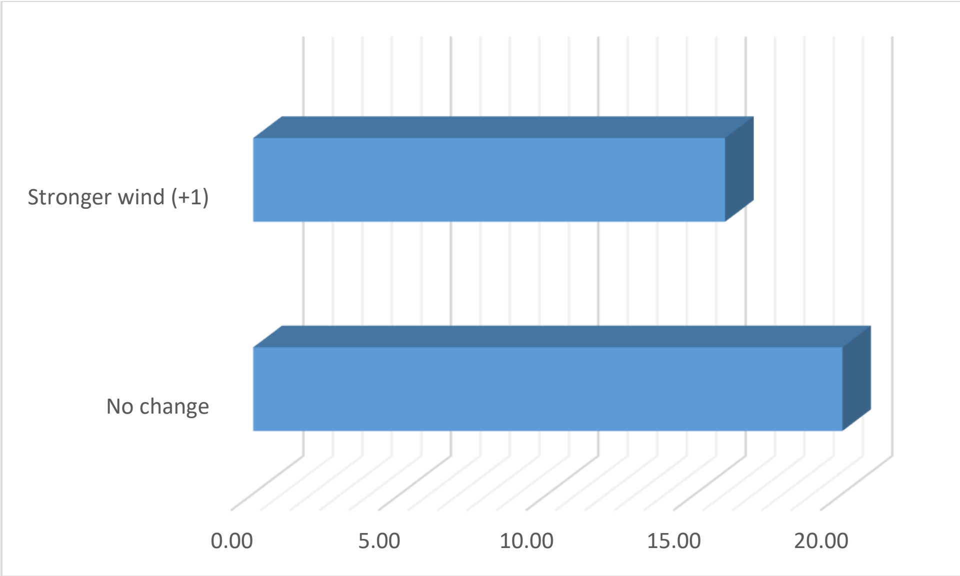


Chart 5-20 Preference for wind

Relative Humidity

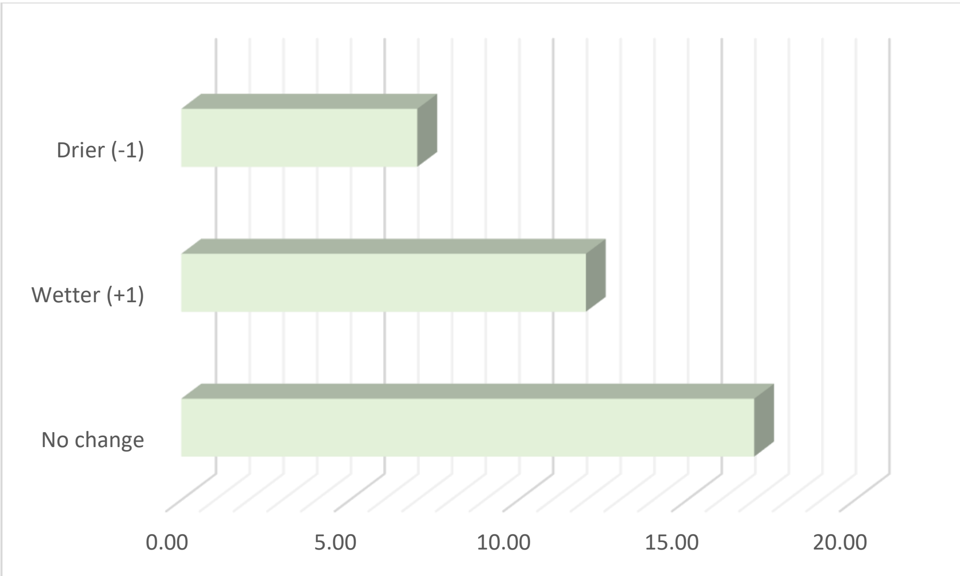


Chart 5-21 Preference for Relative humidity

Relative Humidity	Frequency	Percentage
No change	17.00	47.22
Wetter (+1)	12.00	33.33
Drier (-1)	7.00	19.44

5.3 Simulation with ENVI-met

The simulation was done in ENVI-met 5.03. A stretch of 150m was selected for the simulation since the lite version of software has limited domain size of 50 X50 X30.

5.3.1 Simulation day

The simulation day is chosen as 7/7/2022. The chart 5-3 shows the average hourly temperature for the day for both east and west facing sidewalk. The chart 5-4 shows the hourly temperature for east and west facing sidewalk separately.

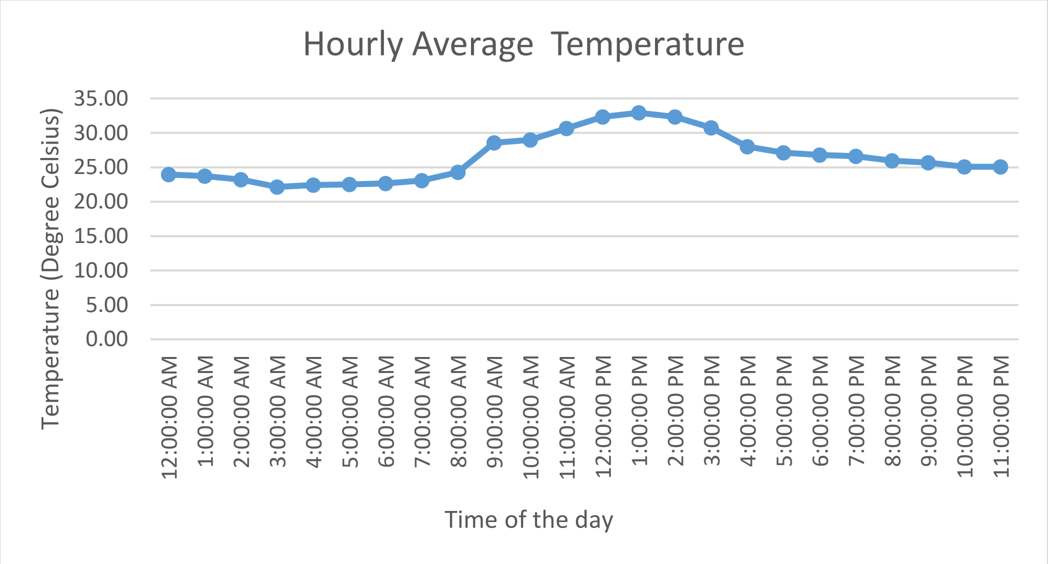


Figure 5-13 Hourly Average temperature of 7/7/2022 of east facing and west facing sidewalk

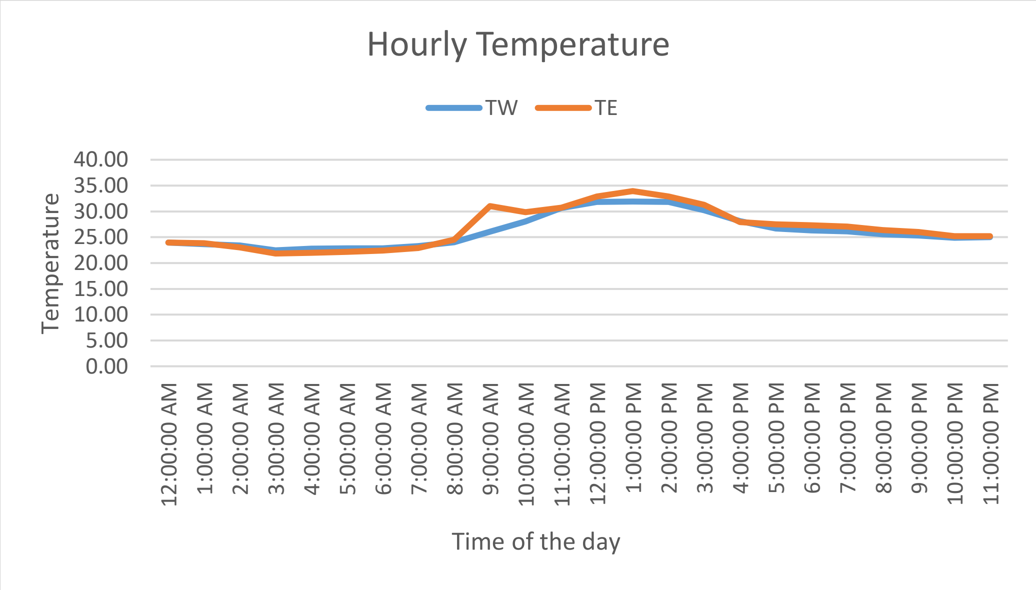


Figure 5-14 Hourly Temperature for 7/7/2022 on east facing and west facing sidewalk

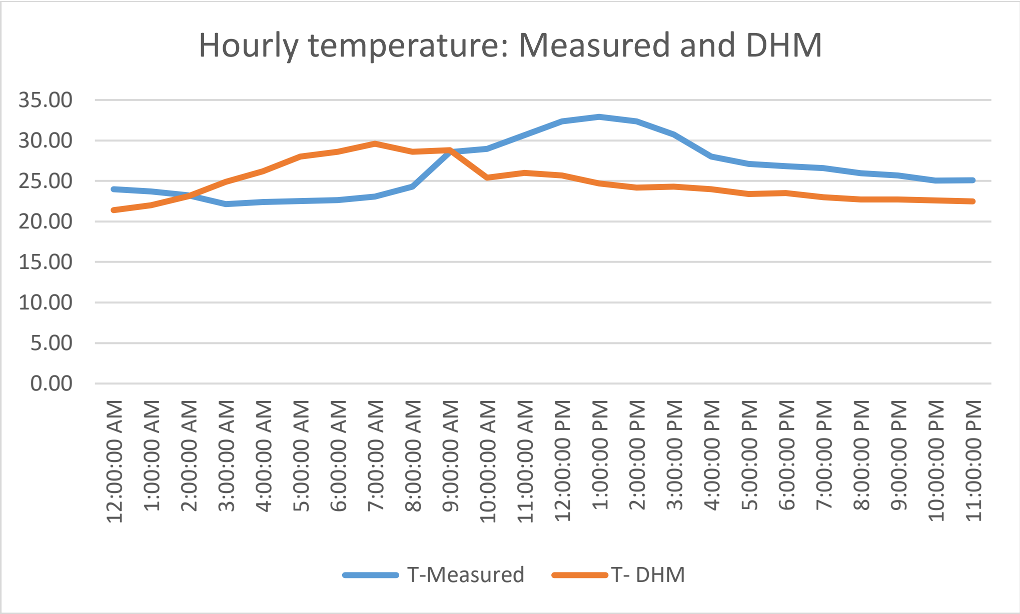


Figure 5-15 Hourly Average temperature of 7/7/2022 (Measured and Department of Meteorology and Hydrology)

The chart 5-6 shows the relative humidity of the chosen simulation day. It is maximum at 3 am and minimum at 12 pm.

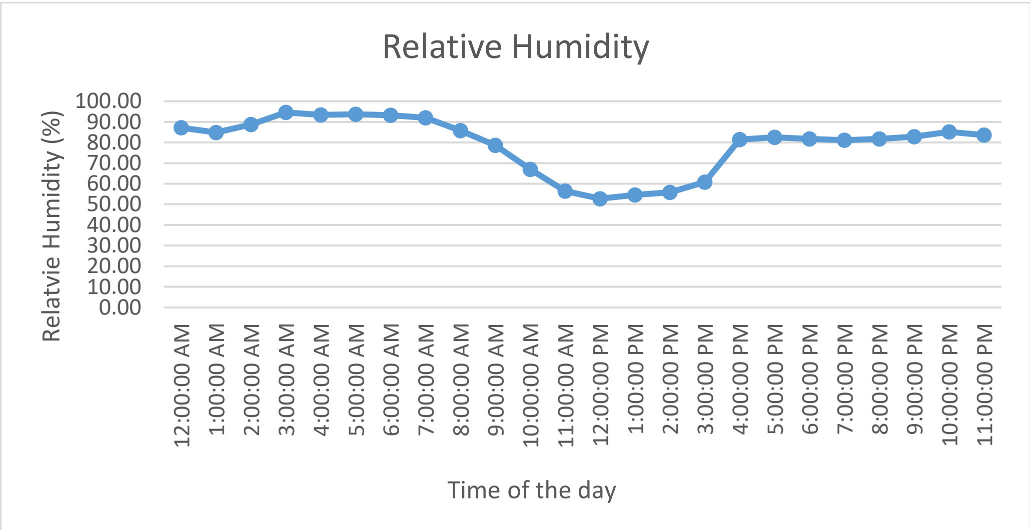


Figure 5-16 Hourly Relative Humidity for 7/7/2022

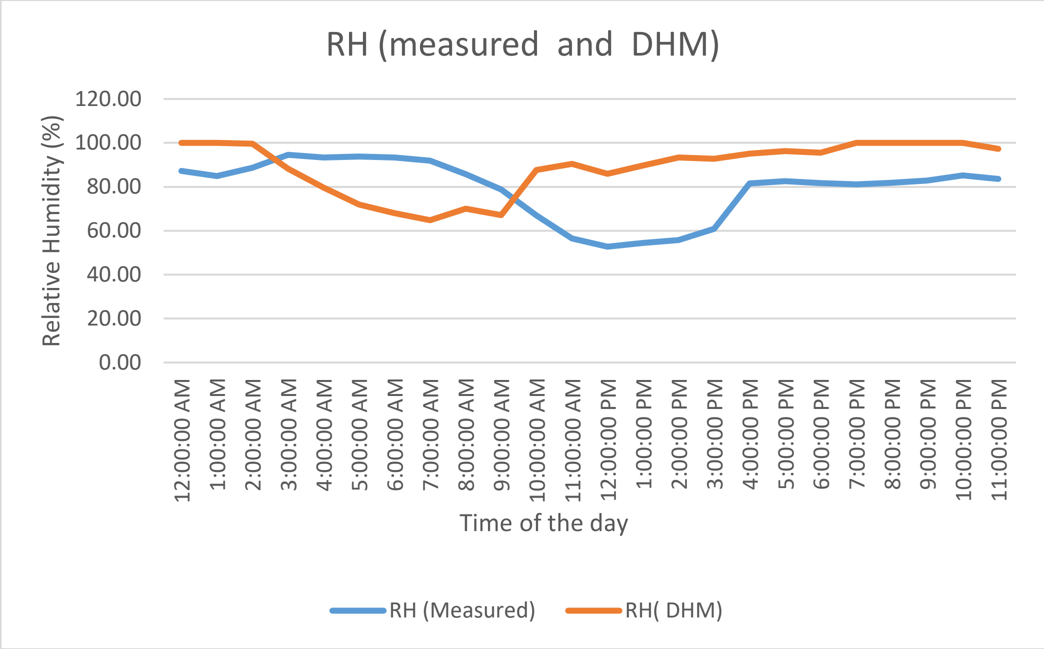


Figure 5-17 Hourly Relative Humidity for 7/7/2022 (Measured and Department of Meteorology and Hydrology)

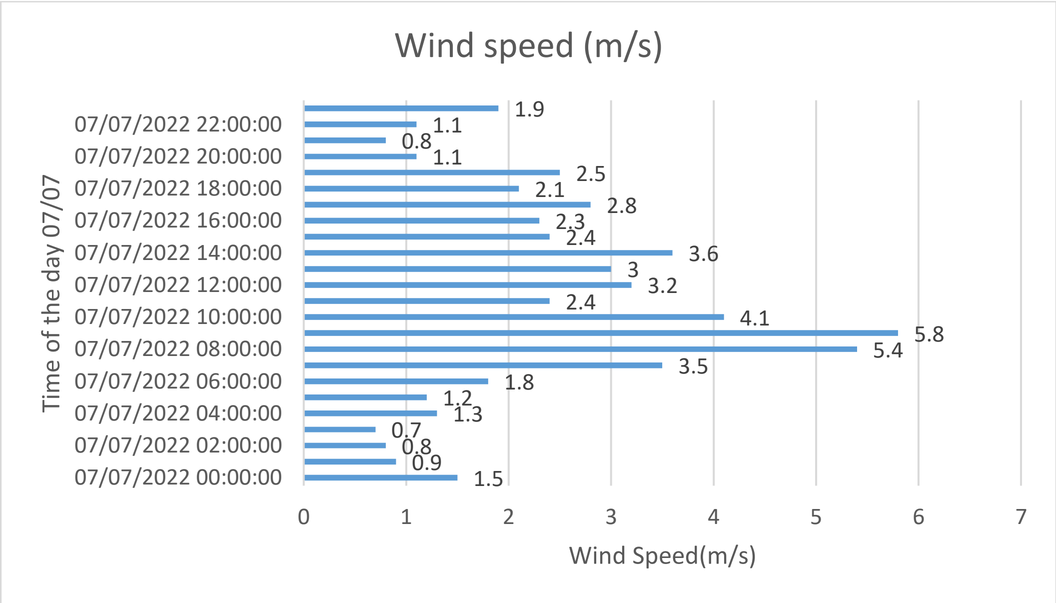


Figure 5-18 Hourly Average Wind Speed of 7/72022 *Source: Department of hydrology and Meteorology*

The wind speed data for the particular day is taken from department of hydrology and Meteorology. The average wind speed for the day is 2.34 m/s.

5.3.2 Simulation scenarios

Different scenarios are created by changing the parameters like the orientation, no. of planting strips, spacing between trees, leaf area density and the pavement materials. The summary of scenarios is presented in the table below.

Table 5-1 Summary of Different Scenarios for Simulation

S.N	Scenarios	Trees	Pavement
1	BC: Base Case Scenario	Low LAD trees	Concrete pavement dirty/used
2.	O1: Orientation changed to EW	Same as base case	Same as base case
3.	V1: Low Leaf Area Density trees(LAD) changed to High LAD	High LAD trees	Same as base case
4.	V2: Trees Canopy (3m) and height (5) changed.	High LAD trees	Same as base case
5.	V3: Trees Canopy (13m) and height (15m) changed.	High LAD trees	Same as base case
6.	V4: Median with trees introduced in between road	High LAD trees	Same as base case
7	P1: Pavement material same as BC	No trees	Same as base case
8	P2:Pavement material changed	No trees	Light coloured concrete
9	P3:Pavement material changed	No trees	Dark coloured Concrete
10	P4: Pavement material changed	No trees	Interlocking concrete blocks
11	P5: Pavement material changed	No trees	Porous concrete

12	P6: Pavement material changed	No trees	Red brick
13	P7: Pavement material changed	No trees	Flagstone
14	P8: Pavement material changed	No trees	Limestone
15	P9: Pavement material changed	No trees	Coloured Asphalt
16	V1P1: Pavement and vegetation parameter changed.	High LAD trees (9m X 10m)	Pavement same as base case
17	V1P2: Pavement and vegetation parameter changed.	High LAD trees (9m X 10m)	Light color Concrete
18.	V1P5: Pavement and vegetation parameter changed.	High LAD trees (9m X 10m)	Porous Concrete
19.	V1P7: Pavement and vegetation parameter changed.	High LAD trees (9m X 10m)	Flagstone

5.3.3 Simulation Model

As the Envi-met 5.03 Lite version has model size limitation up to the 50 X50x30 grids, the portion of the street below is selected for the simulation.

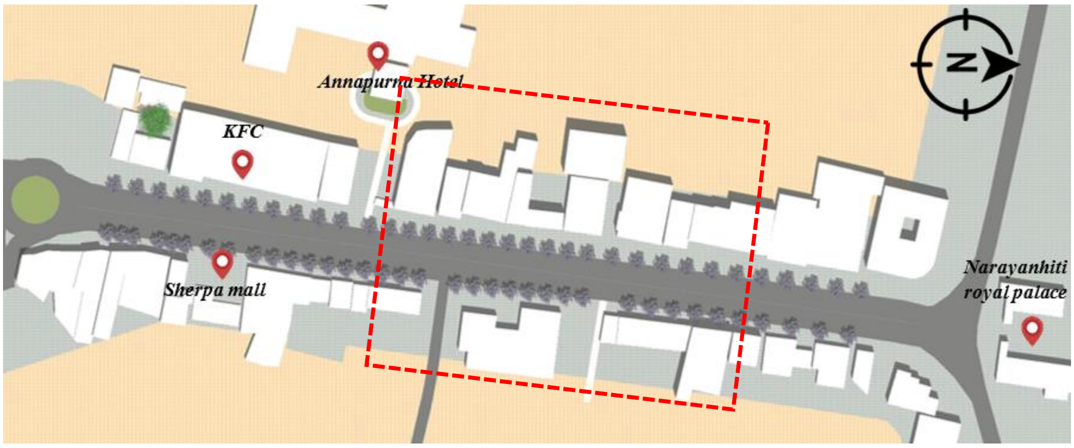


Figure 5-19 Part of the street section taken for simulation

The model size in domain is 38 X 50 X 15 with dx 3 m dy 3m and dy 3m. The north is tilted 8 degree towards left with the grid north. The model location is set as 27.712611N, 85.317972E.

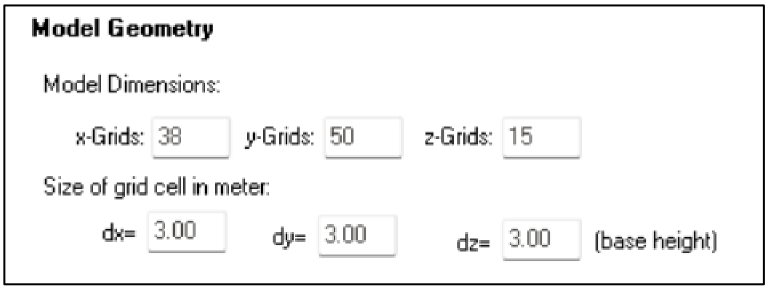


Figure 5-20 Model Geometry in ENVI-met 5.03

5.3.4 Simple forcing

The simulation is done for 12 hours starting from 7 am in the morning for 7/7/2022. For the simulation, simple forcing of the data has been done. The hourly temperatures of the simulation day has been manually adjusted.

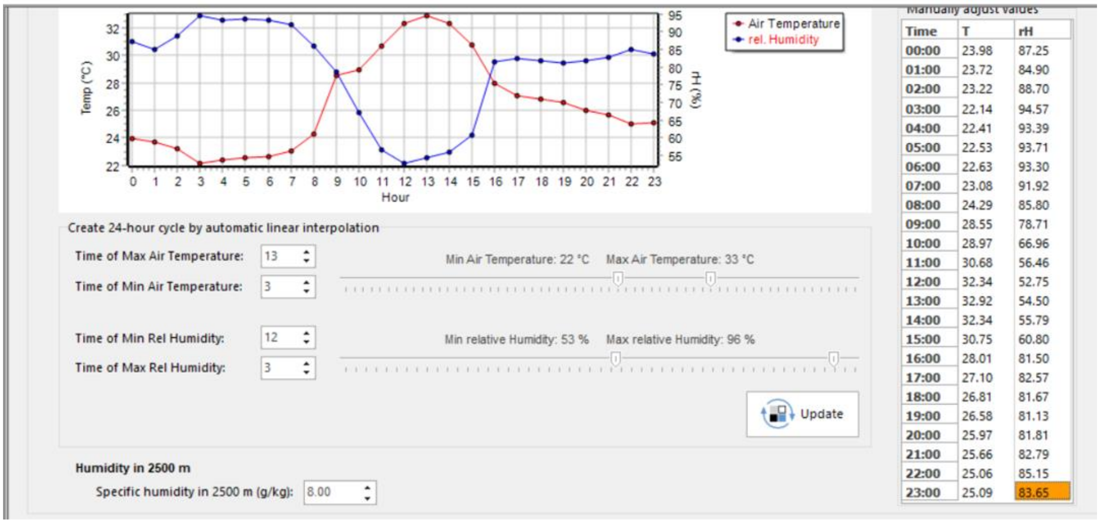


Figure 5-21 Meteorological conditions for simple forcing

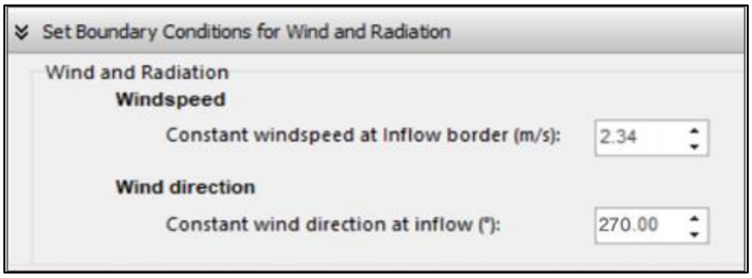


Figure 5-22 Boundary conditions for wind and radiation

Scenario 1: BC: Base Case Scenario

The base case materials are shown in the table below:

COMPONENTS	BUILDING WALLS	BUILDING ROOF	PAVEMENT	TREES
MATERIALS	Brick walls	Concrete case dense	Concrete pavement used/dirty	Jacaranda Mimosifolia

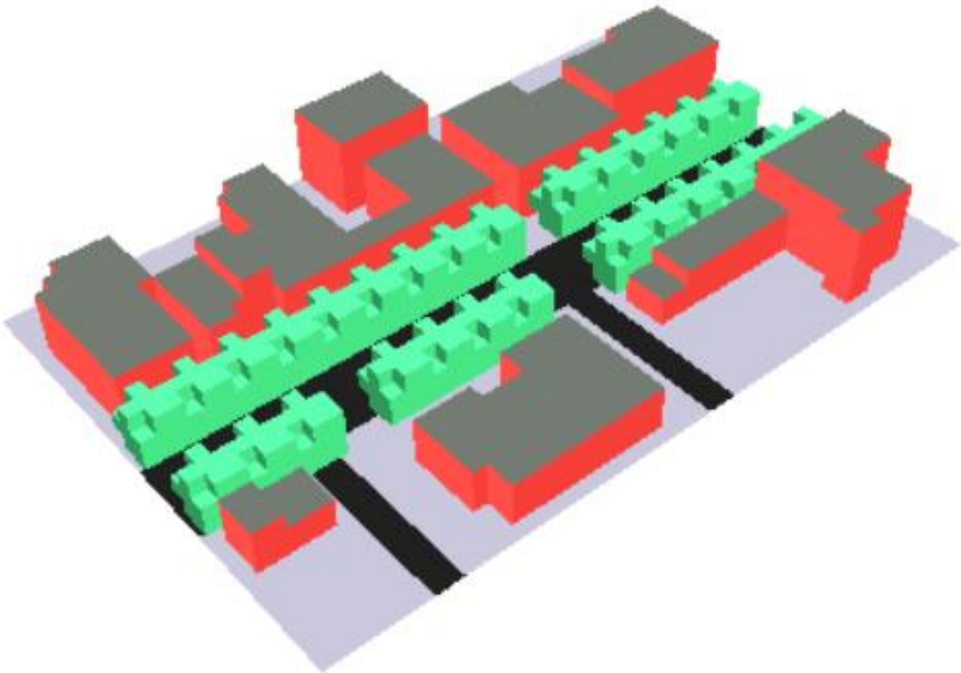


Figure 5-23 3D model of Base Case Scenario

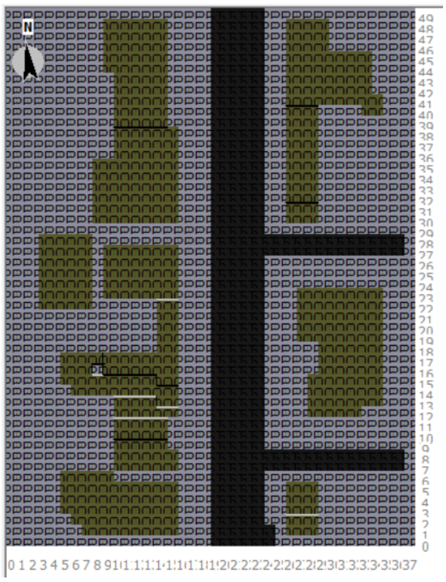


Figure 5-24 2D model on ENVI-met showing surface and building

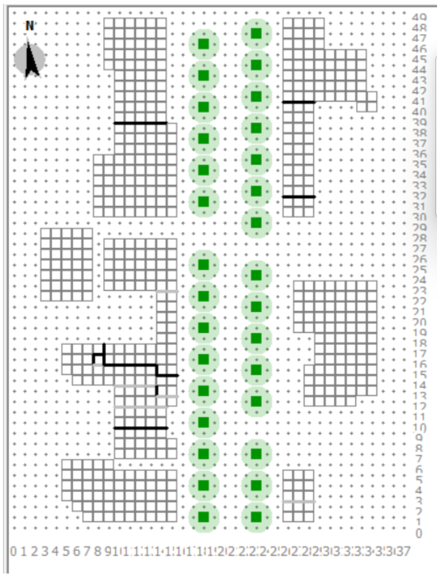


Figure 5-25 2D model on ENVI-met showing building and vegetation

Name: Pavement (Concrete), used/ dirty
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.30000
Emissivity	0.90000

Name: Asphalt Road
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.20000
Emissivity	0.90000

Database-ID: [0100B2]
Name: Default Brick: burned
Color:

Parameter	Value
Default Thickness	0.30000
Absorption	0.60000
Transmission	0.00000
Reflection	0.40000
Emissivity	0.90000
Specific Heat	650.00000
Thermal Conductivity	0.44000
Density	1500.00000

Name: Concrete: cast dense
Color:

Parameter	Value
Default Thickness	0.30000
Absorption	0.70000
Transmission	0.00000
Reflection	0.30000
Emissivity	0.90000

Figure 5-26 Properties of the assigned materials to the model

5.3.5 Simulation Results

Air temperature

The air temperature rises from the morning and reaches the peak in the afternoon and gradually decreases in the evening. The hourly mean temperature is analysed and shown in the figure 5-18.

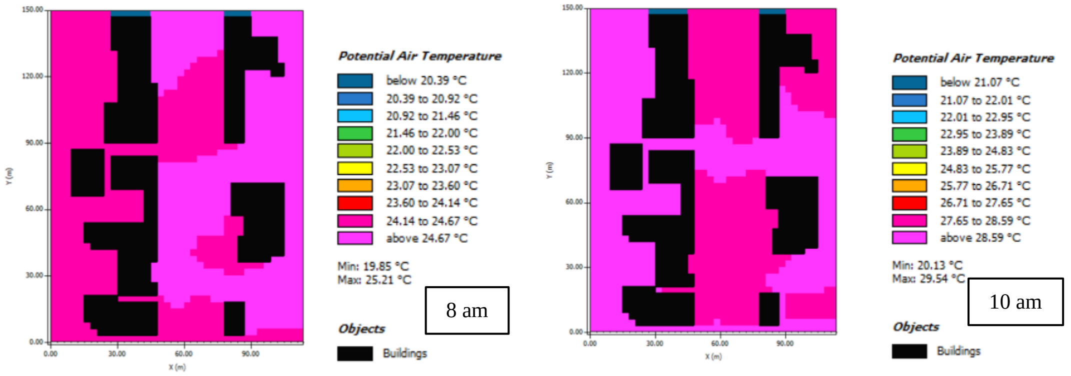


Chart 5-22 Potential air temperature for 8 am and 10 am in Scenario 1: Base Case Scenario

The figure above shows the potential air temperature at 8 am and 10 am. The temperature varies between 24.14 ° C and 24.67 ºC at 8 am whereas the temperature varies between 27.65 ºC and 28.59 ºC at 10 am.

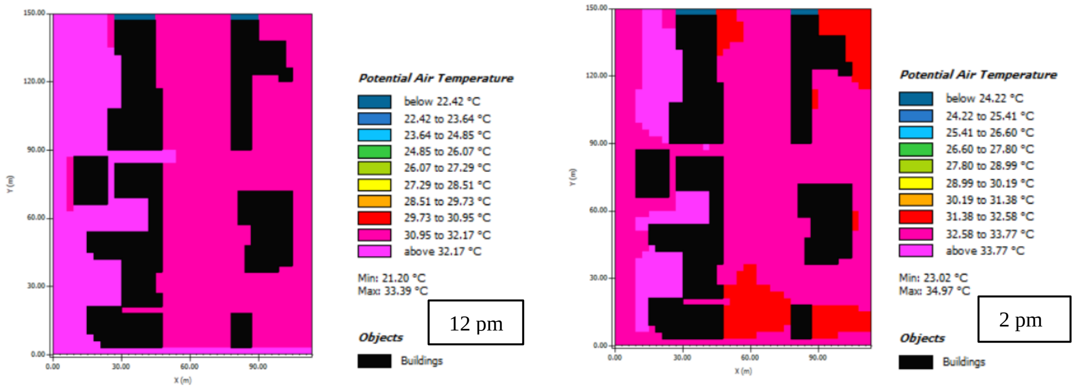


Chart 5-23 Potential air temperature for 12 pm and 2 pm in Scenario 1: Base Case Scenario

The chart above shows the potential air temperature at 12 pm and 2 pm. The temperature varies between 30.95 ºC to 32.17 ºC at 12 pm whereas the temperature fluctuates between 31.38 ºC and 33.77 ºC.

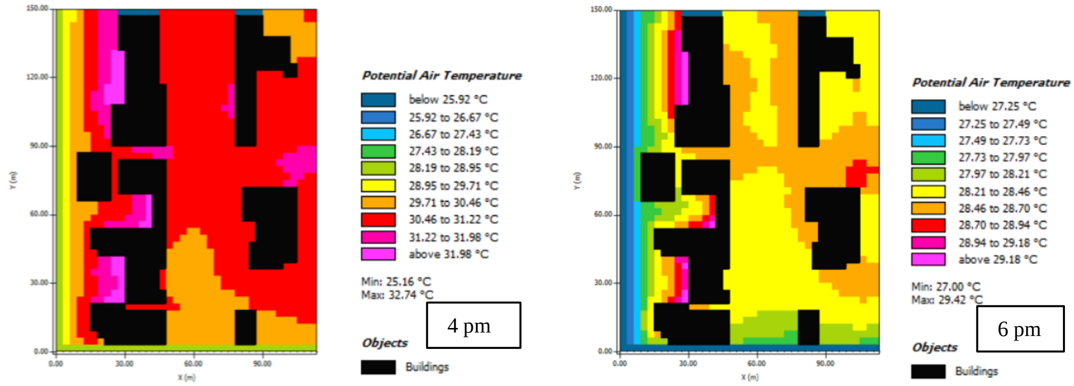


Chart 5-24 Potential air temperature for 4 pm and 6 pm in Scenario 1: Base Case Scenario

The temperature fluctuates between 29.71 ºC to 31.22ºC at 4 pm whereas the temperature varies between 28.21 ºC to 28.70 ºC at 6 pm.

The figure below shows the variation of temperature throughout the day for the east facing and west facing sidewalk. There is no significant difference in the air temperature in both sidewalks as per the graph.

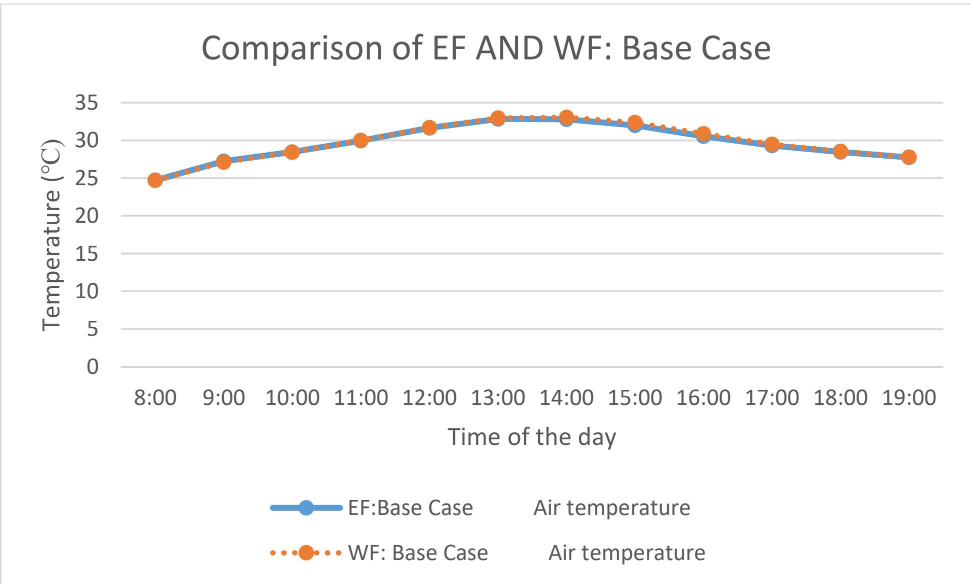


Figure 5-27 Air temperature in East and West Facing Sidewalk

Mean radiant temperature

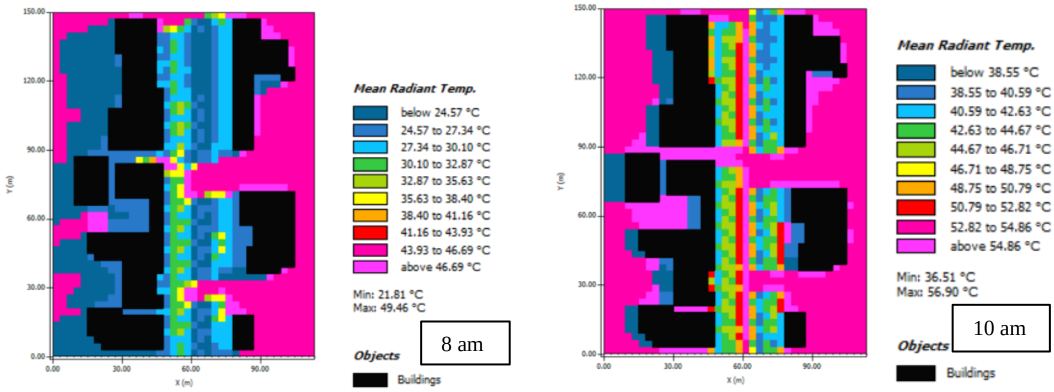


Chart 5-25 Mean Radiant temperature at 8 am and 10 am in Scenario 1: Base Case Scenario

The mean radiant temperature varies from 24.57 °C to 46.69 °C within the sidewalks at 8 am and 38.55 °C to 54.86°C at 10 am.

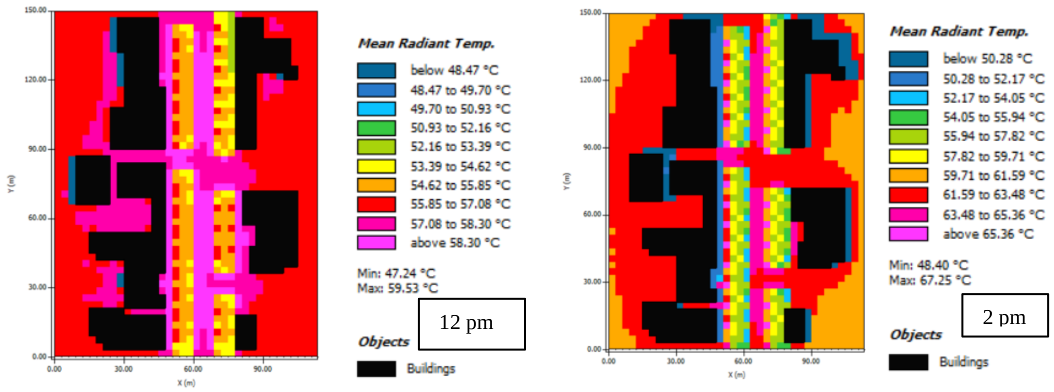


Chart 5-26 Mean Radiant temperature at 12 pm and 2 pm in Scenario 1: Base Case Scenario

The mean radiant temperature varies from 53.39°C to 58.30°C across sidewalks at 12 pm whereas it varies from 54.05 °C to 65.36 at 2pm.

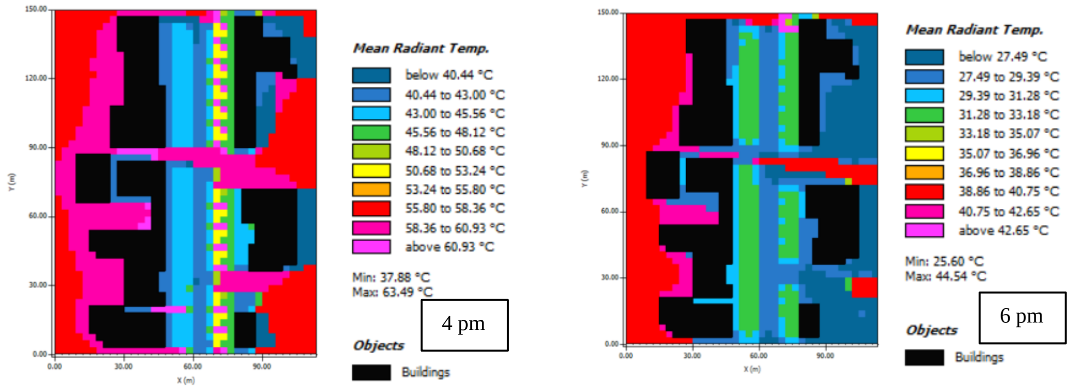


Chart 5-27 Mean Radiant temperature at 4 pm and 6 pm in Scenario 1: Base Case Scenario

The mean radiant temperature varies from 40.44°C to 60.93°C within sidewalks at 4pm and it fluctuates from 27.49 °C to 33.18°C at 6 pm.

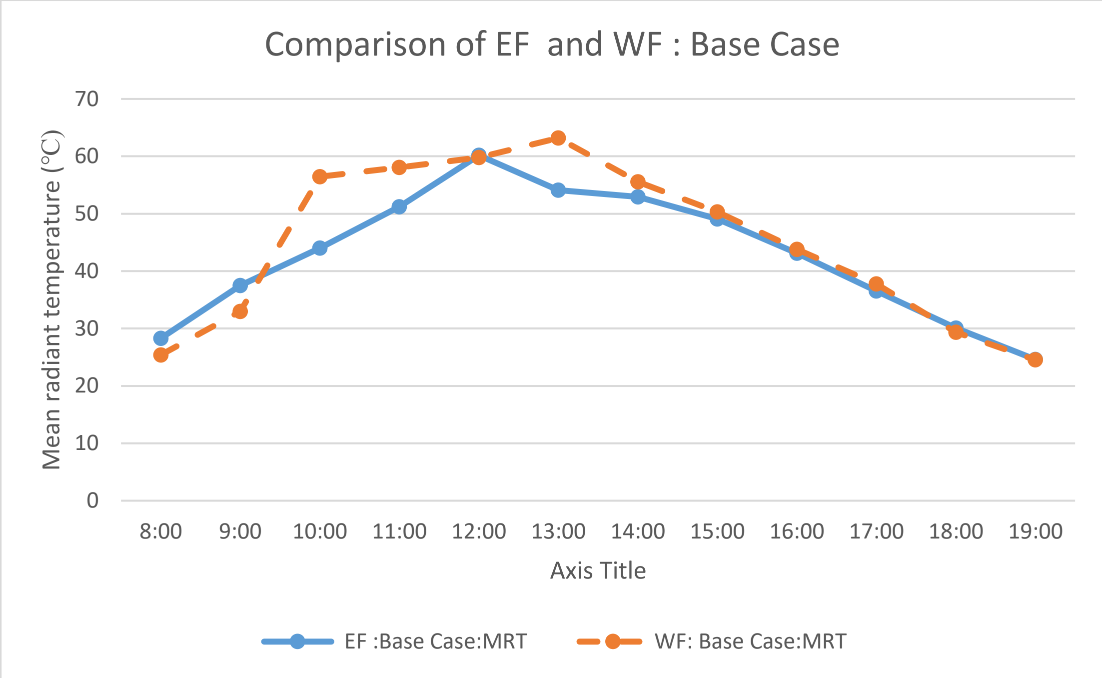


Figure 5-28 Comparison of Mean radiant temperature of East and West facing sidewalk for: Base Case

The graph above shows the mean radiant temperature variation within the day for the east and west facing sidewalk. As per the graph, the mean radiant temperature decreases during the morning hours and increases after 9 am in the morning and the value becomes same as east facing Sidewalk a 12 pm and again increases around 1 pm in the morning.

Scenario 2: O1: Orientation changed to EW

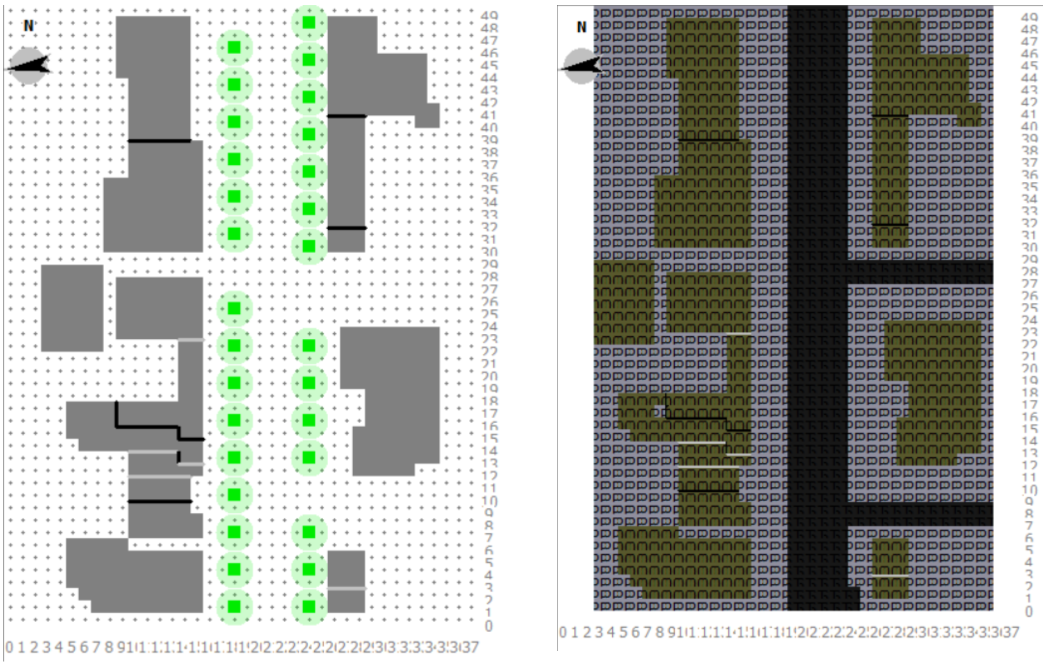


Figure 5-29 2D model in Envi-met of Scenario O1: Orientation changed to EW.

The scenario 4 is created by changing the orientation of the site from NS to EW.

Air temperature

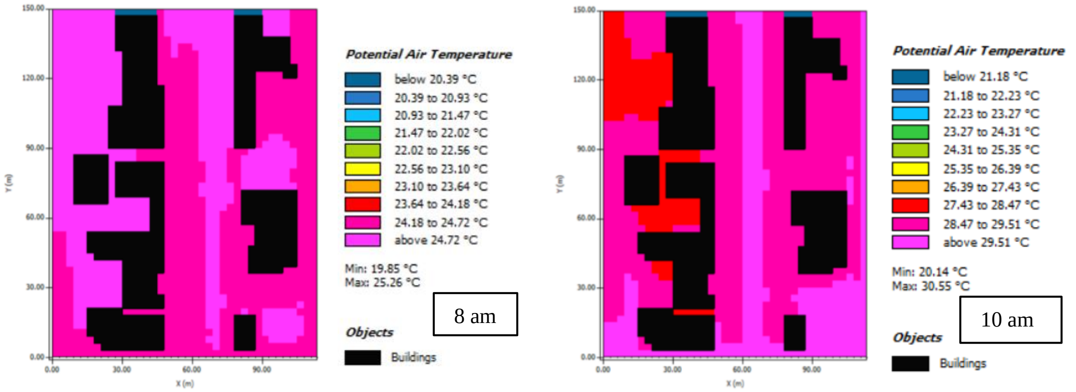


Chart 5-28 Potential air temperature for 8 am and 10 am in Scenario O1: Orientation changed to EW.

The figure above shows the potential air temperature at 8 am varies between 24.18℃ and 24.72℃ at 8 am. At 10 am it increases up to 28.47℃ and fluctuates up to 29.51℃.

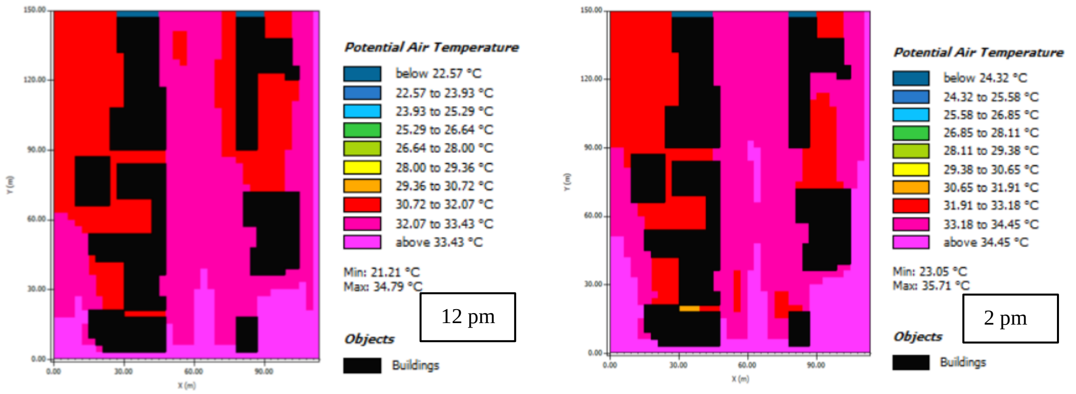


Chart 5-29 Potential air temperature for 12 pm and 2 pm in Scenario O1: Orientation changed to EW.

The figure shows that the air temperature ranges from 32.07℃ and 33.43℃ at 12 pm whereas the temperature gradually increases and fluctuates between 33.18 ℃ and 34.45℃.

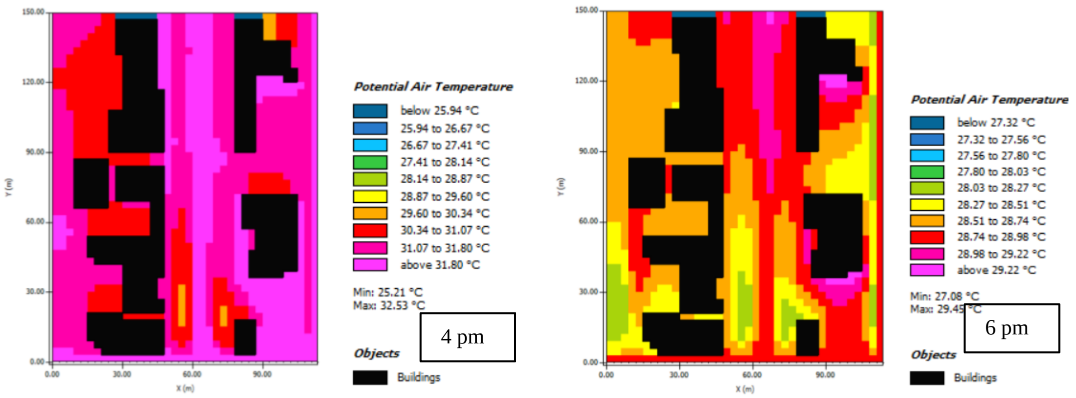


Chart 5-30 Potential air temperature for 2 pm and 4 pm in Scenario O1: Orientation changed to EW.

The figure shows that the air temperature ranges from 31.07℃ and 31.80℃ at 4 pm The temperature gradually decreases and fluctuates between 28.27 ℃ and 28.51℃ at west whereas the temperature is slightly more in east it might be because the wind flows from the same direction.

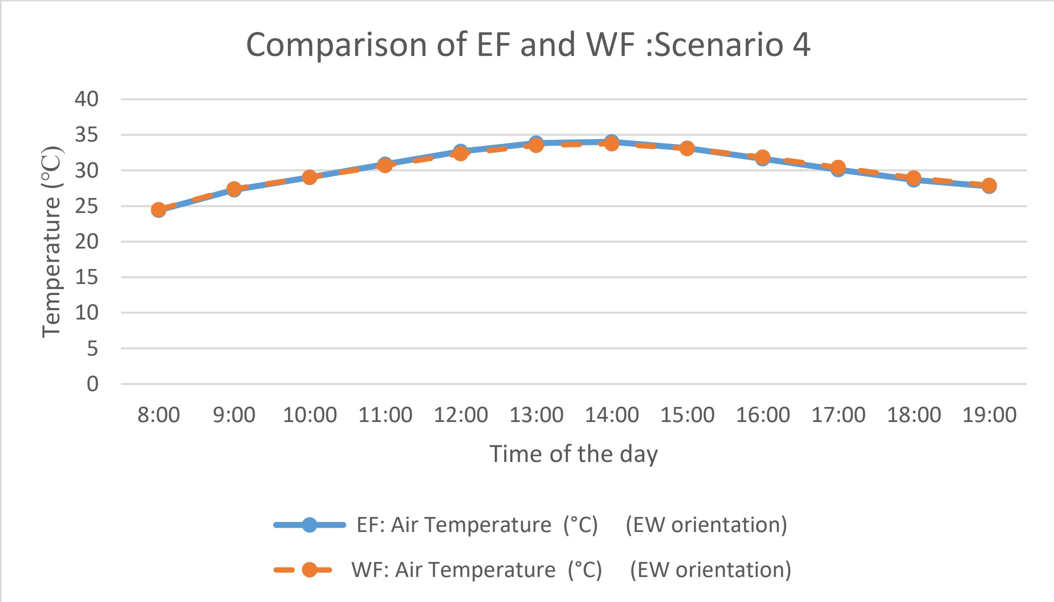


Figure 5-30 Comparison of air temperature of east and west facing Sidewalk: Orientation changed to EW.

The figure 5-57 shows the variation in air temperature throughout the day for east and west facing sidewalk. There is no significant difference between the both sidewalks in terms of air temperature.

Mean Radiant temperature

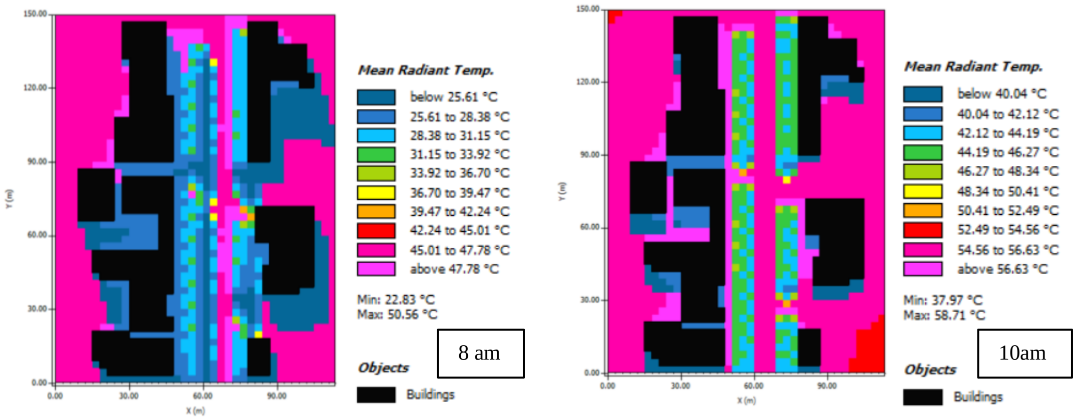


Chart 5-31 Mean radiant temperature for 8 am and 10 am in Scenario O1: Orientation changed to EW.

The mean radiant temperature fluctuates from 25.61℃ to 28.38 ℃ within the sidewalks at 8 am and at 10 am it increases to 42.27℃.

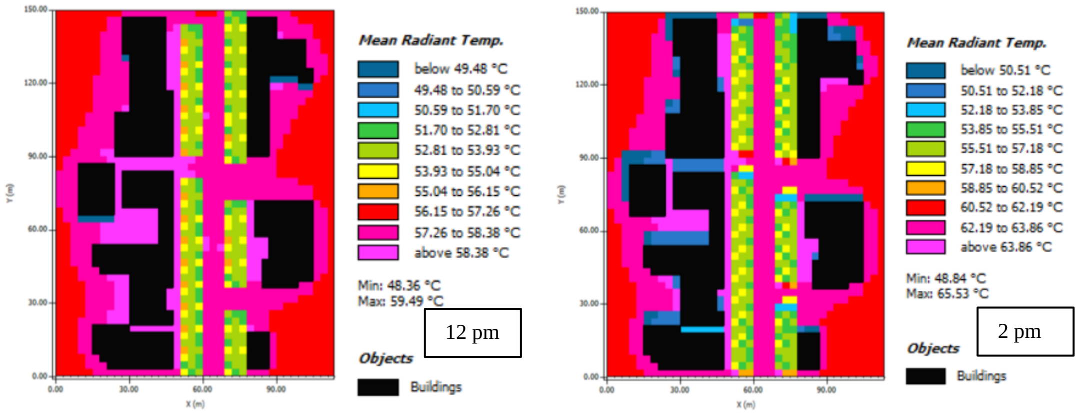


Chart 5-32 Mean radiant temperature for 12 pm and 2 pm in Scenario O1: Orientation changed to EW.

The mean radiant temperature fluctuates between 52.81 ℃ to 58.38 ℃ at 12 pm within the sidewalks and it varies between 55.51 ℃ and 63.86 ℃ at 2 pm.

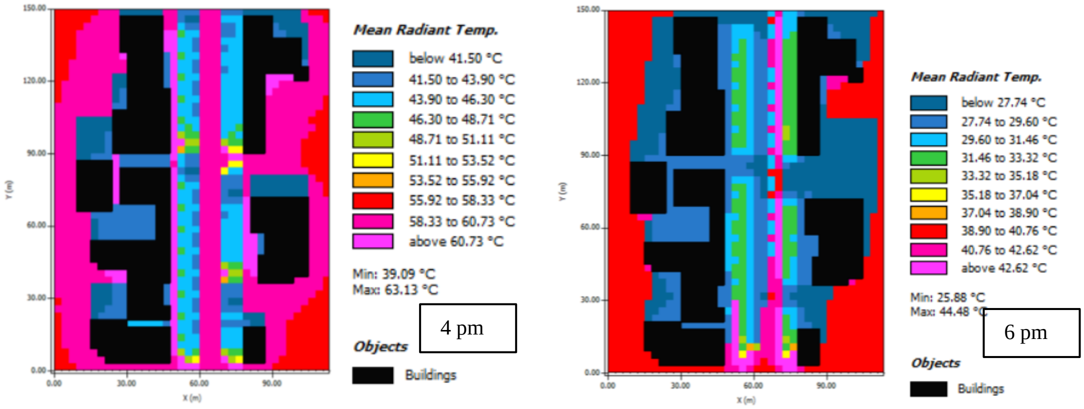


Chart 5-33 Mean radiant temperature for 4 pm and 6pm in Scenario O1: Orientation changed to EW.

The mean radiant temperature fluctuates between 43.90 ℃ to 60.73 ℃ at 4 pm within the sidewalks and it varies between 27.74 ℃ and 33.32 ℃ at 6 pm

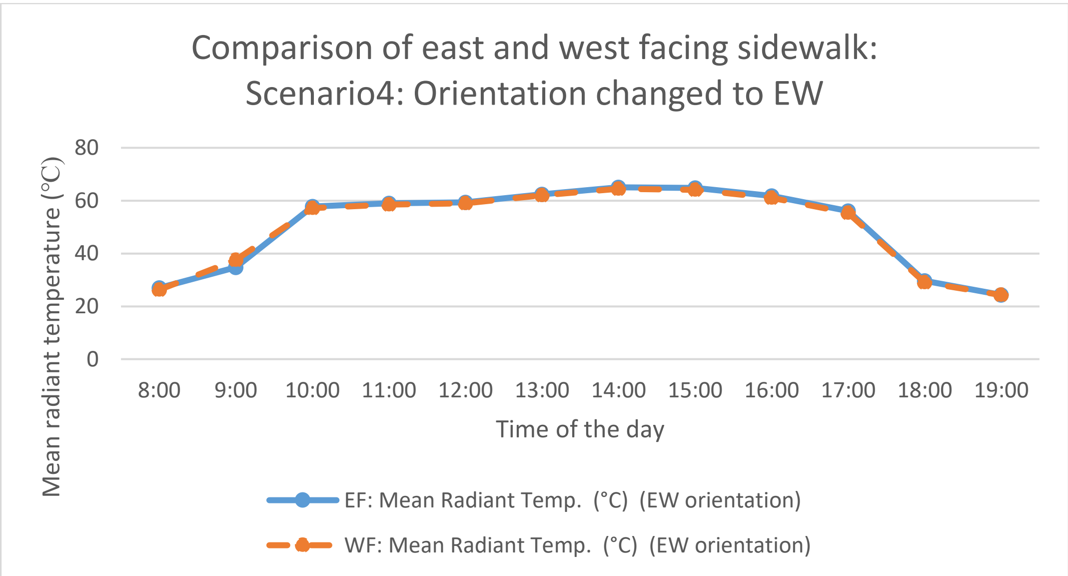


Figure 5-31 Comparison of east and west facing Sidewalk: Orientation changed to EW.

The south facing sidewalk has slightly more mean radiant temperature than north facing sidewalk except at 9 am in the morning.

Scenario 3: V1: Low leaf area index changed to High leaf area index

Air temperature

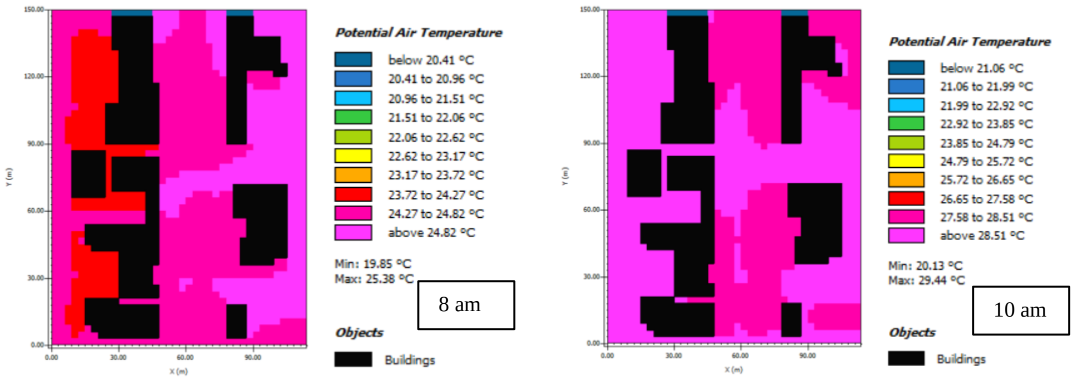


Chart 5-34 Potential air temperature for 8 am and 10 am in Scenario V1: Low leaf area index changed to high leaf area index

The figure above shows the potential air temperature at 8 am varies between 23.72°C and 24.82°C at 8 am. At 10 am it increases up to 27.58°C and fluctuates up to 28.51°C.

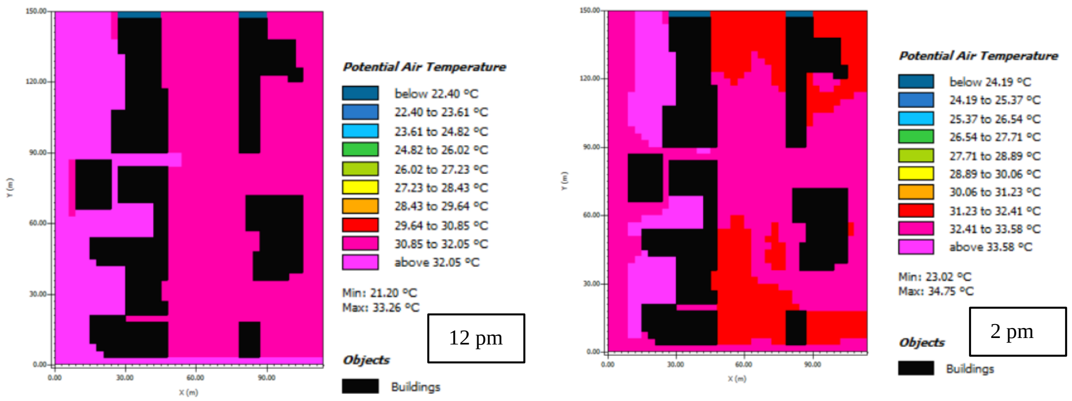


Chart 5-35 Potential air temperature for 12 pm and 2 pm in Scenario V1: Low leaf area index changed to high leaf area index

The figure above shows the potential air temperature at 8 am varies between 30.85°C and 32.05°C at 8 am. At 10 am it increases up to 31.23°C and fluctuates up to 33.58°C.

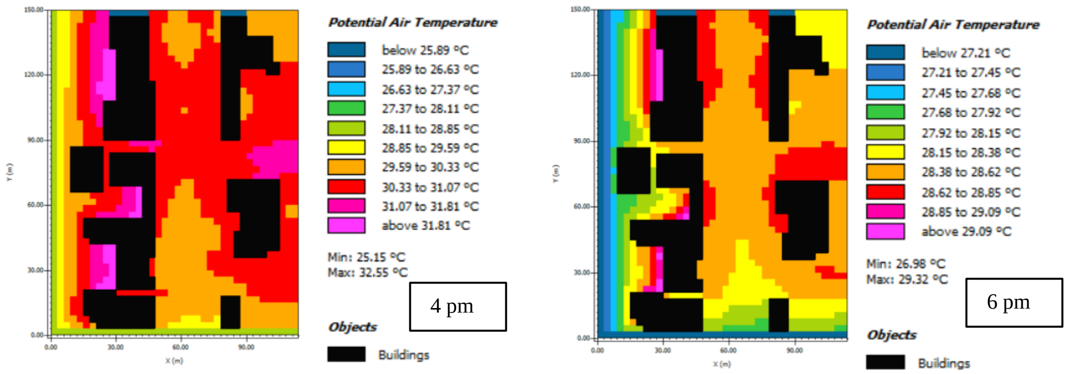


Chart 5-36 Potential air temperature for 4 pm and 6 pm in Scenario V1: Low leaf area index changed to high leaf area index

The figure shows that the air temperature ranges from 29.59℃ and 30.33℃ at 4 pm The temperature gradually decreases and fluctuates between 28.38 ℃ and 28.62℃ at 6pm.

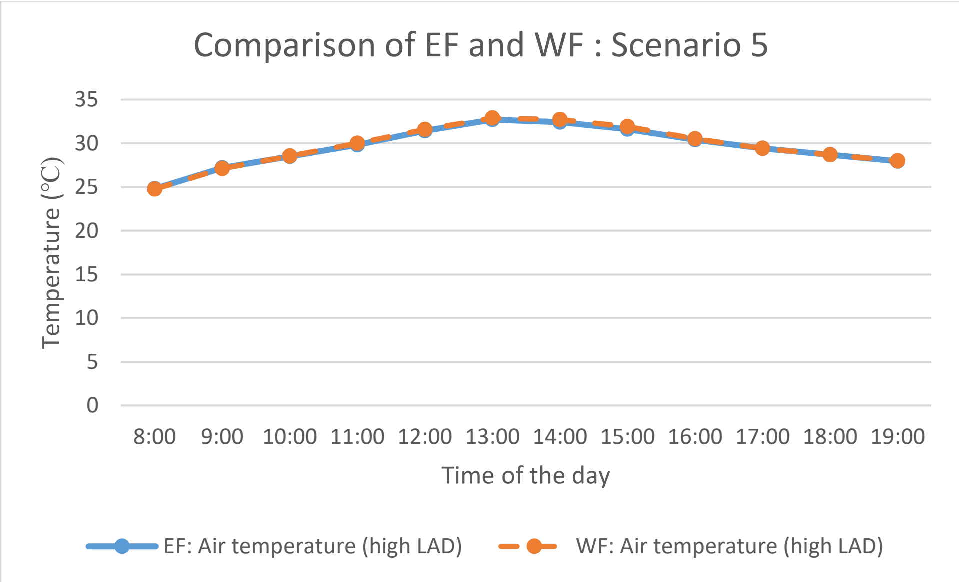


Figure 5-32 Comparison of potential air temperature of east facing and west facing Sidewalk for scenario 5: Changing low leaf area index to high leaf area index.

The figure 5-65 shows the variation in air temperature throughout the day for east and west facing sidewalk. There is no significant difference between the both sidewalks in terms of air temperature.

Mean Radiant temperature

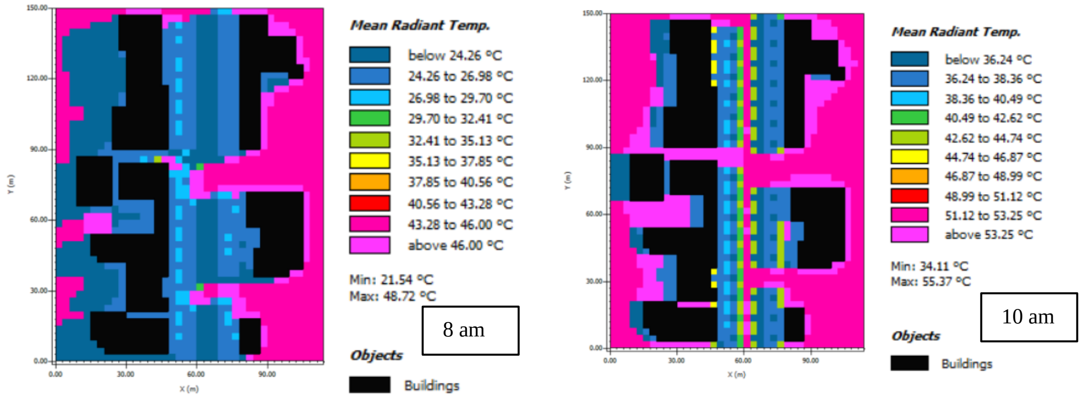


Chart 5-37 Mean radiant temperature for 8 am and 10 am in Scenario V1: Low leaf area index changed to high leaf area index

The mean radiant temperature fluctuates from 24.26℃ to 26.98 ℃ within the sidewalks at 8 am and at 10 am it increases to 36.24℃.

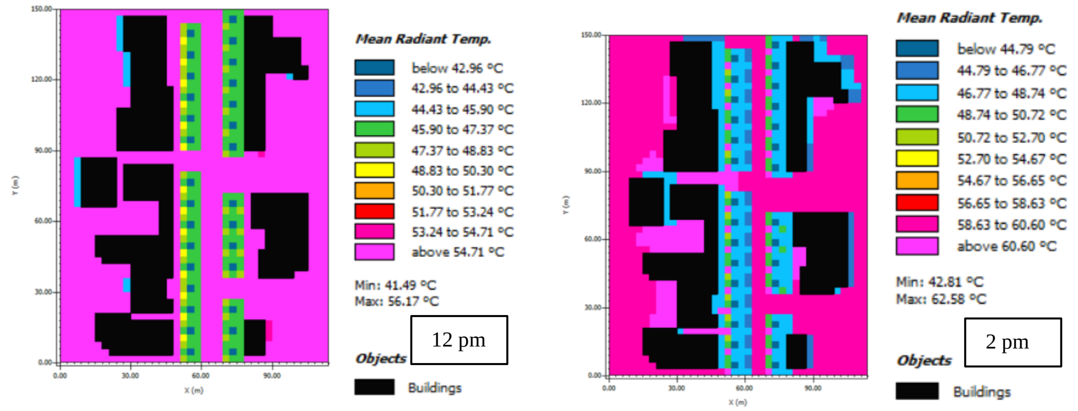


Chart 5-38 Mean radiant temperature for 12 pm and 2 pm in Scenario V1: Low leaf area index changed to high leaf area index

The mean radiant temperature is 45.90℃ at trees whereas it is above 54.71℃ at sidewalks at 12 pm. At 2 pm, the mean radiant temperature varies from 46.77 ℃to 48.74℃.

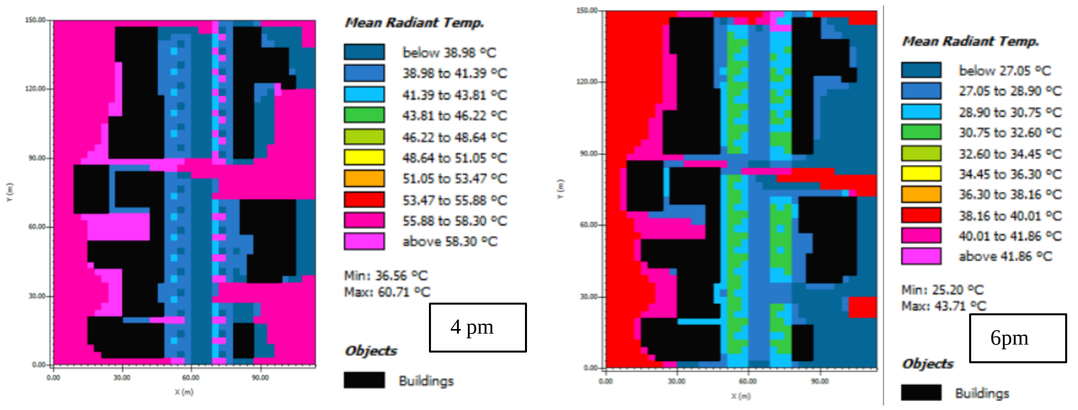


Chart 5-39 Mean radiant temperature for 4 pm and 6 am in Scenario V1: Low leaf area index changed to high leaf area index

The mean radiant temperature fluctuates from 39.98℃ to 41.39℃ at 4 pm. At 2 pm, the mean radiant temperature varies from 27.05 ℃ to 30.75 ℃.

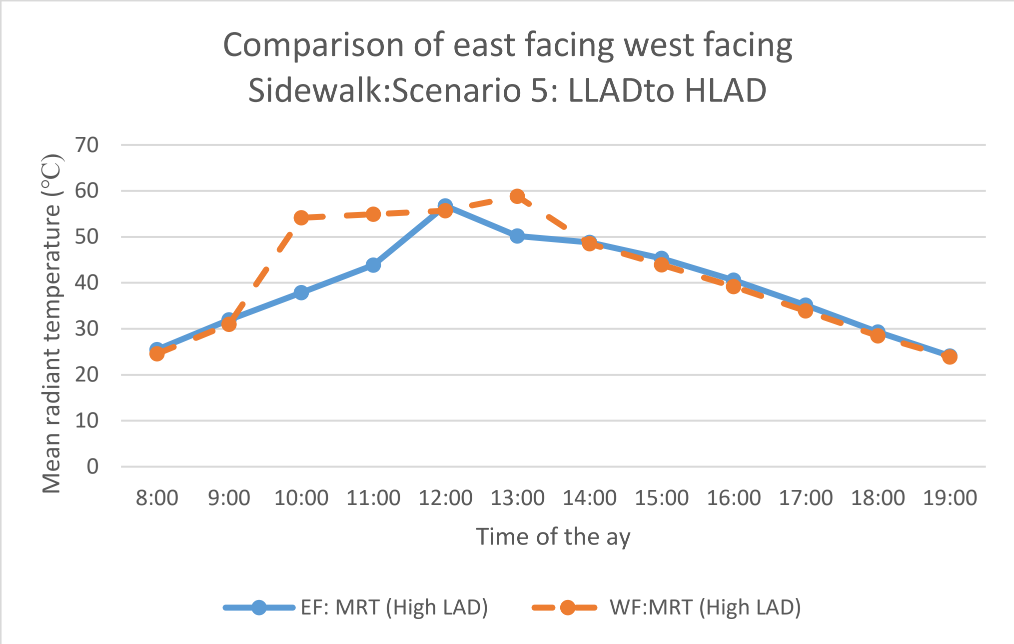


Figure 5-33 Comparison of mean radiant temperature of east facing and west facing Sidewalk for scenario 5: Changing low leaf area index to high leaf area index.

The graph above shows that the mean radiant temperature for west facing sidewalk is more at the time of 10 am to 11 am and also at 1pm.

Scenario 4: V2: High LAD Trees Canopy (3m) and height (5m) changed.

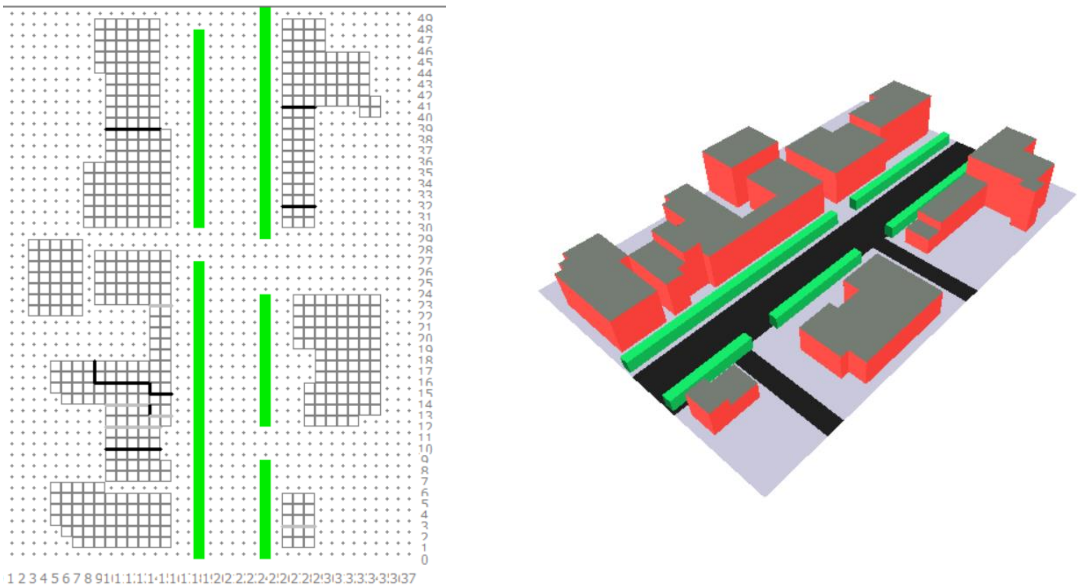


Figure 5-34 2D model in Envi-met of Scenario V2: High LAD Trees Canopy (3m) and height (5m) changed.

This scenario is created by changing the canopy size of tree to 3m and height to 5m and spacing between trees reduced to 3m.

Air temperature

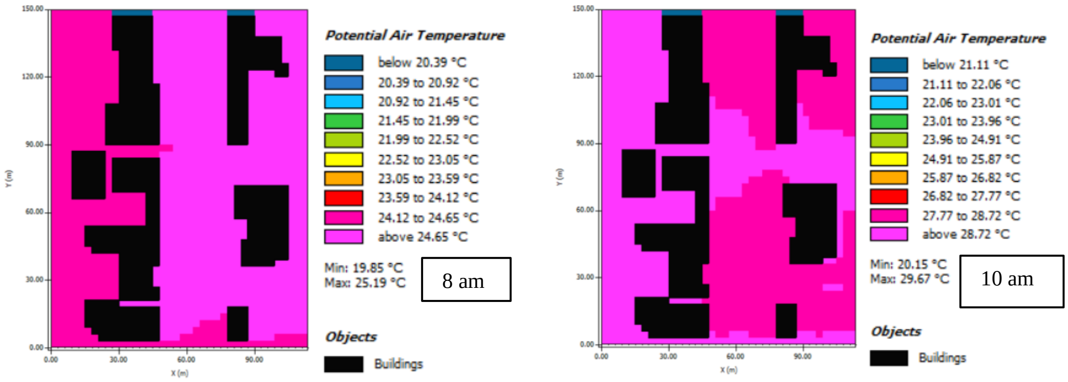


Chart 5-40 Potential temperature for 8 am and 10 am in Scenario V2: High LAD Trees Canopy (3m) and height (5m) changed.

The figure above shows the potential air temperature at 8 am and 10 am. The temperature varies between 24.12 ° C and 24.65 ºC at 8 am whereas the temperature varies between 27.77 ºC and 28.72 ºC at 10 am.

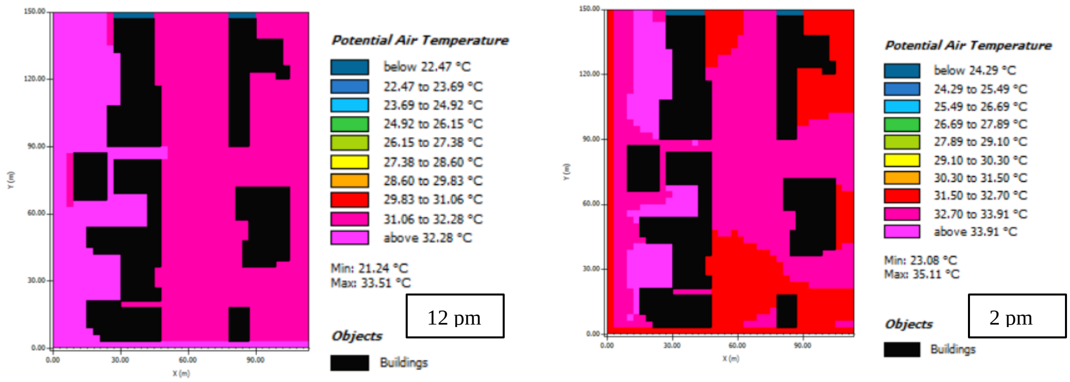


Chart 5-41 Potential temperature for 12 pm and 2 pm in Scenario V2: High LAD Trees Canopy (3m) and height (5m) changed.

The chart above shows the potential air temperature at 12 pm and 2 pm. The temperature varies between 31.06 ºC to 32.28 ºC at 12 pm whereas the temperature fluctuates between 31.50 ºC and 33.91 ºC.

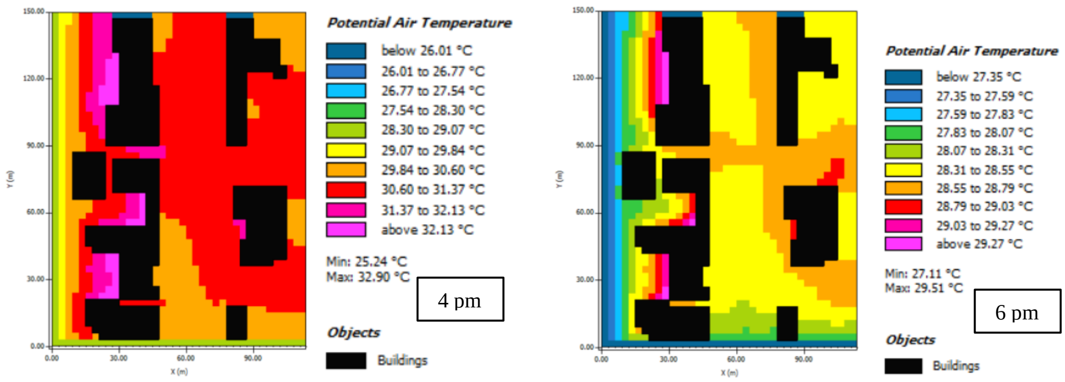


Chart 5-42 Potential temperature for 4 pm and 6 pm in Scenario V2: High LAD Trees Canopy (3m) and height (5m) changed.

The temperature fluctuates between 29.84 ºC to 31.37ºC at 4 pm whereas the temperature varies between 28.31 ºC to 28.79 ºC at 6 pm.

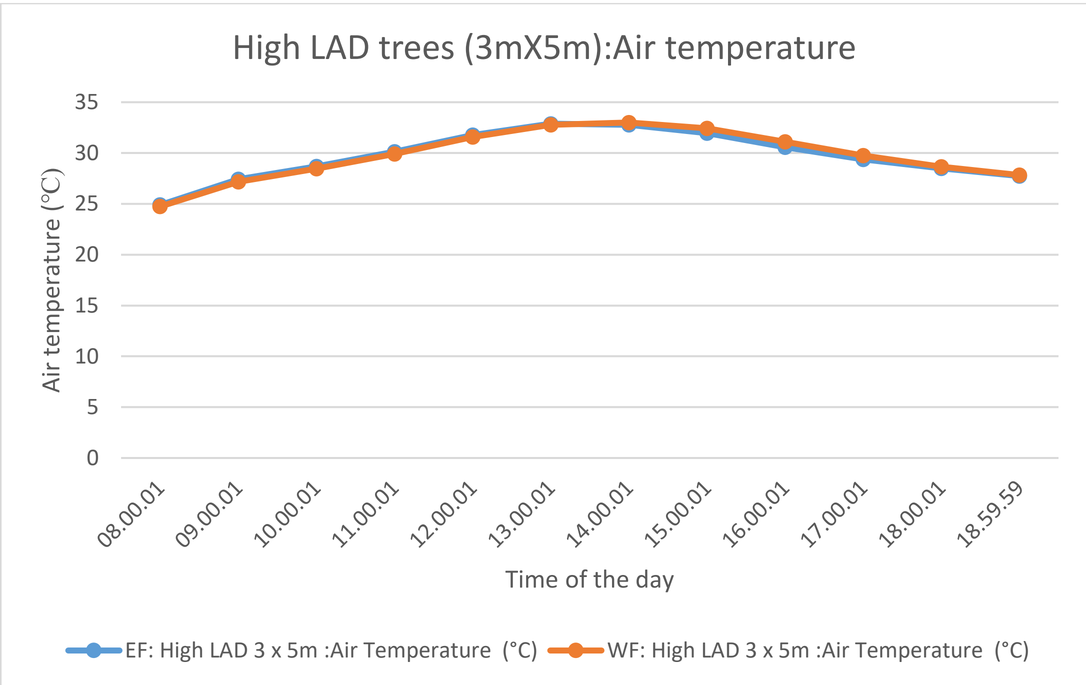


Figure 5-35 Comparison of potential air temperature for Scenario 4: V2 for east and west facing sidewalks

The figure shows the potential air temperature for the scenario 4: V2 throughout the day for the east and west facing sidewalk. There is no significant difference in the potential air temperature as seen in the graph.

Mean radiant temperature

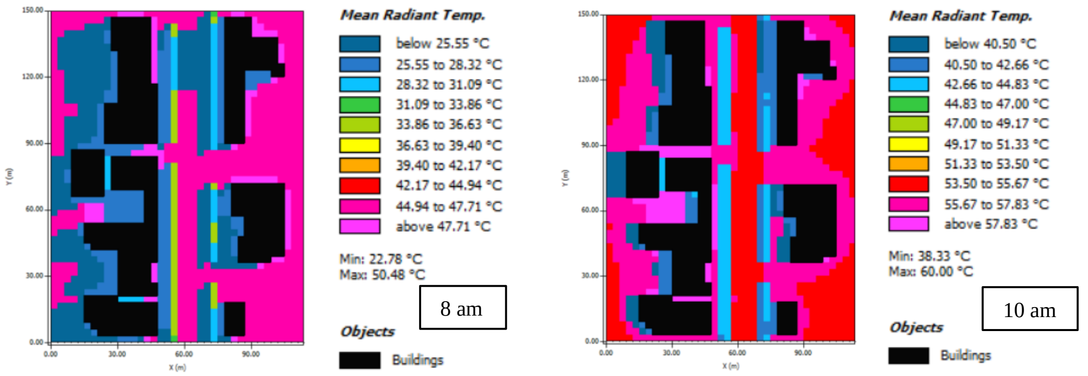


Chart 5-43 Mean radiant temperature for 8 am and 10 am in Scenario V2: High LAD Trees Canopy (3m) and height (5m) changed.

The mean radiant temperature varies from 25.55 °C to 28.32 °C within the sidewalks at 8 am and 40.55 °C to 55.67°C at 10 am.

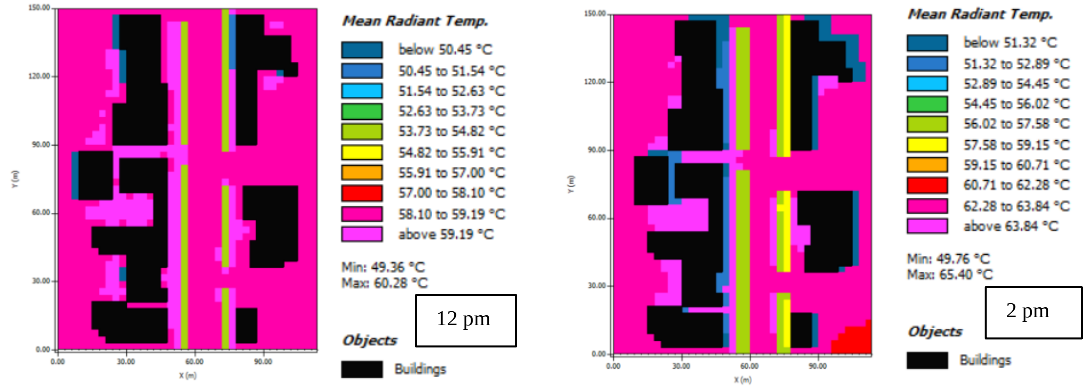


Chart 5-44 Mean radiant temperature for 12 pm and 2 pm in Scenario V2: High LAD Trees Canopy (3m) and height (5m) changed.

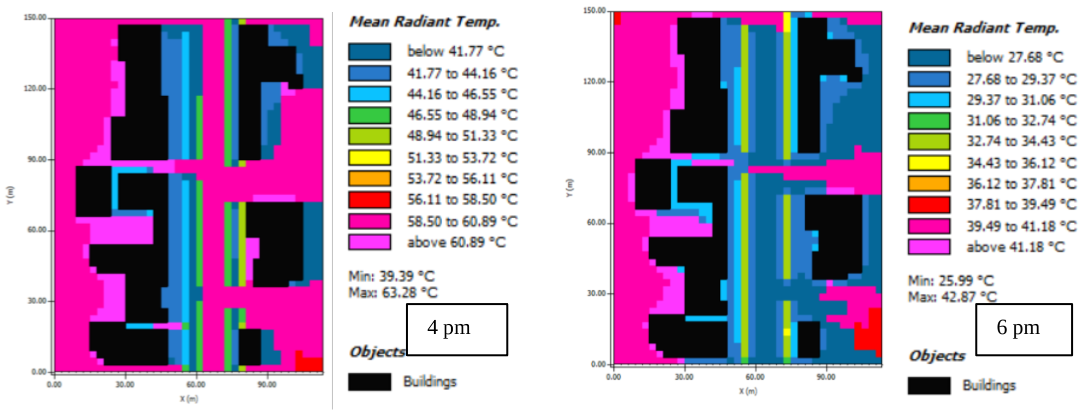


Chart 5-45 Mean radiant temperature for 4 pm and 6 pm in Scenario V2: High LAD Trees Canopy (3m) and height (5m) changed.

The mean radiant temperature varies from 58.10°C to 59.19°C across sidewalks at 12 pm whereas it varies from 57.58°C to 63.84 at 2pm.The mean radiant temperature varies from 41.77°C to 60.89°C within sidewalks at 4pm and it fluctuates from 27.68 °C to 31.06°C at 6 pm.

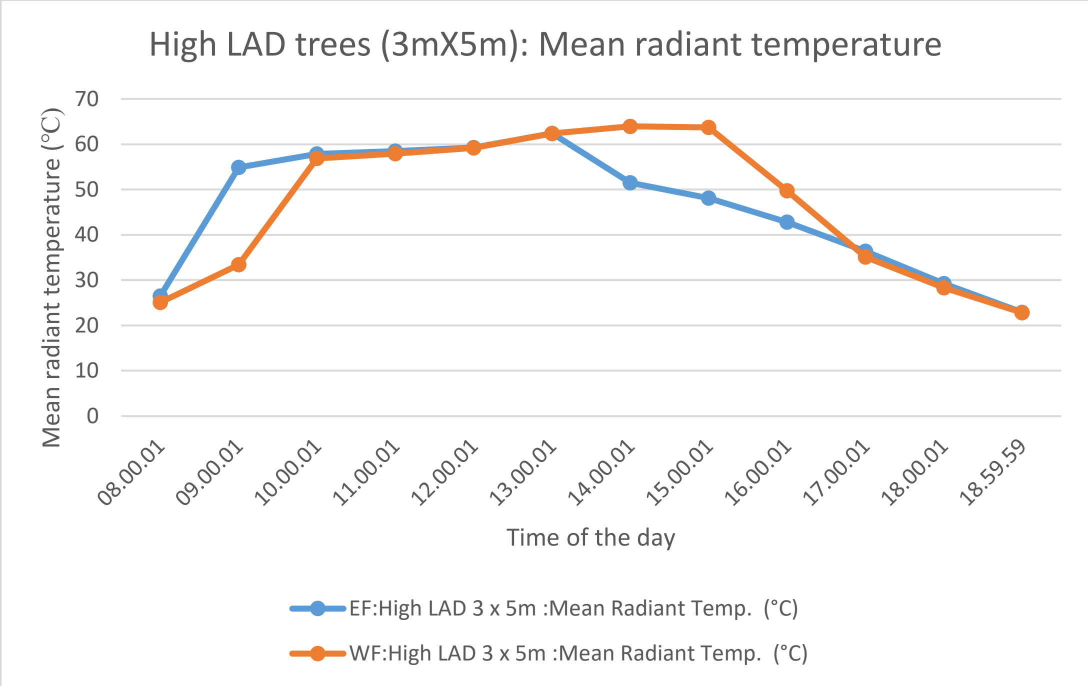


Figure 5-36 Comparison of Mean radiant temperature for Scenario 4: V2 for east and west facing sidewalks

The figure shows the mean radiant temperature for the scenario for the both east and west facing Sidewalk. As per the graph, the mean radiant temperature during the morning hours is more in east facing sidewalk whereas during the period of 1pm to 4pm, the mean radiant temperature in west facing sidewalk is more.

Scenario 5: V3: High LAD Trees Canopy (13m) and height (15m) changed.

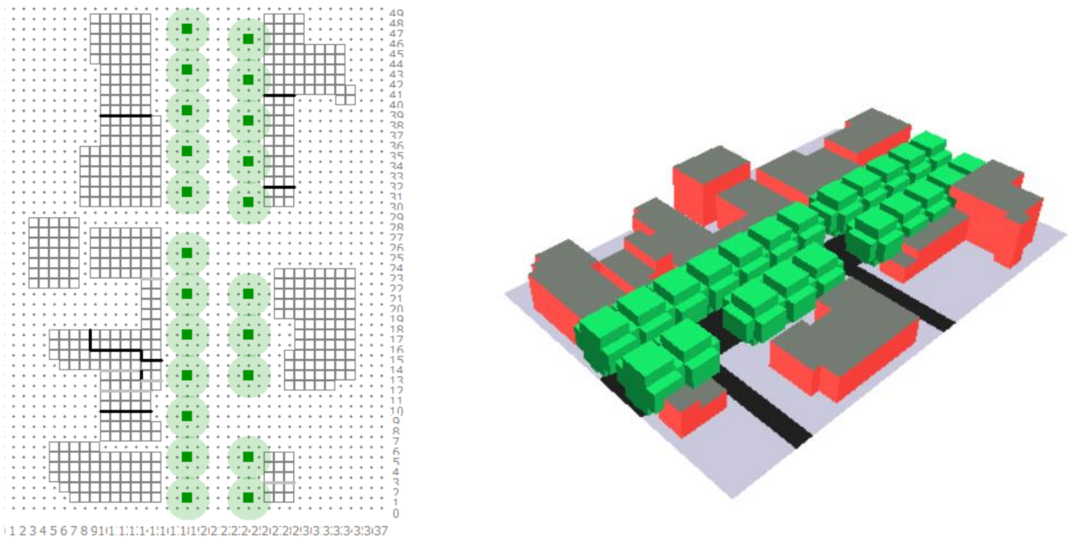


Figure 5-37 2D model in Envi-met of Scenario V3: High LAD Trees Canopy (13m) and height (15m) changed.

This scenario is created by changing the tree canopy size to 13m and tree height to 15m and spacing 12m. The following charts shows the air temperature and mean radiant temperature for this scenario.

Air temperature

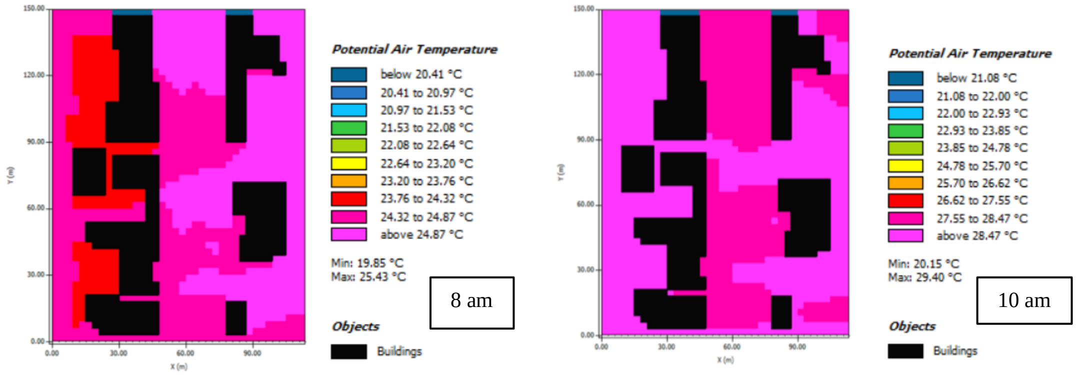


Chart 5-46 Potential air temperature for 8 am and 10 am in V3: High LAD Trees Canopy (13m) and height (15m) changed.

The figure above shows the potential air temperature at 8 am varies between 24.32°C and 24.87°C at 8 am. At 10 am it increases up to 27.55°C and fluctuates up to 28.47°C.

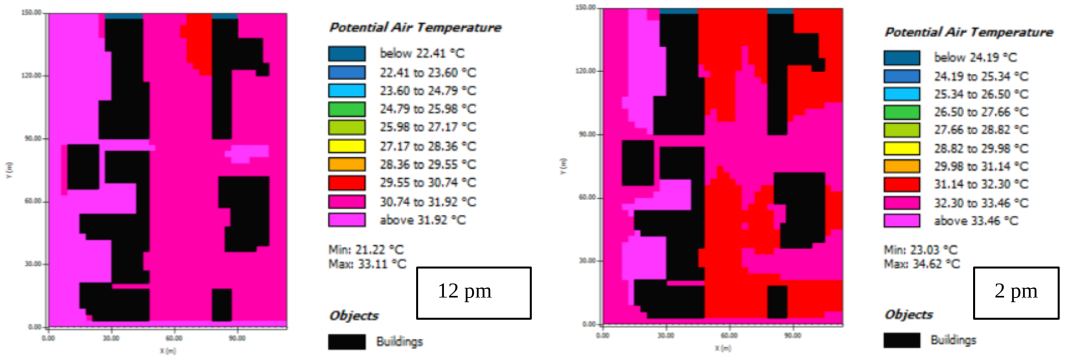


Chart 5-47 Potential air temperature for 12 pm and 2 pm in V3: High LAD Trees Canopy (13m) and height (15m) changed.

The figure above shows the potential air temperature at 12 pm varies between 29.55°C and 30.74°C. At 2 pm it increases up to 31.14°C and fluctuates up to 33.46°C.

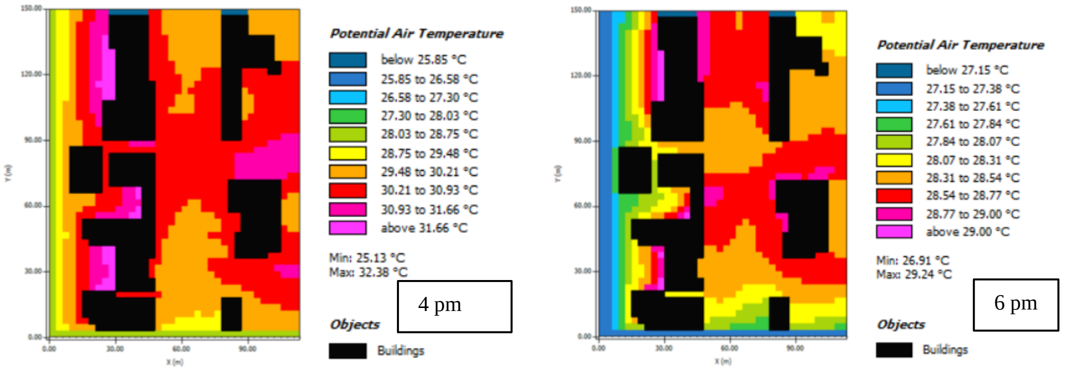


Chart 5-48 Potential air temperature for 4 pm and 6 pm in V3: High LAD Trees Canopy (13m) and height (15m) changed.

As per the figure above, the potential air temperature at 4 pm varies between 29.48℃ and 30.39℃. At 6 pm it decreases up to 28.54℃ and fluctuates between 28.54℃ and 28.77℃.

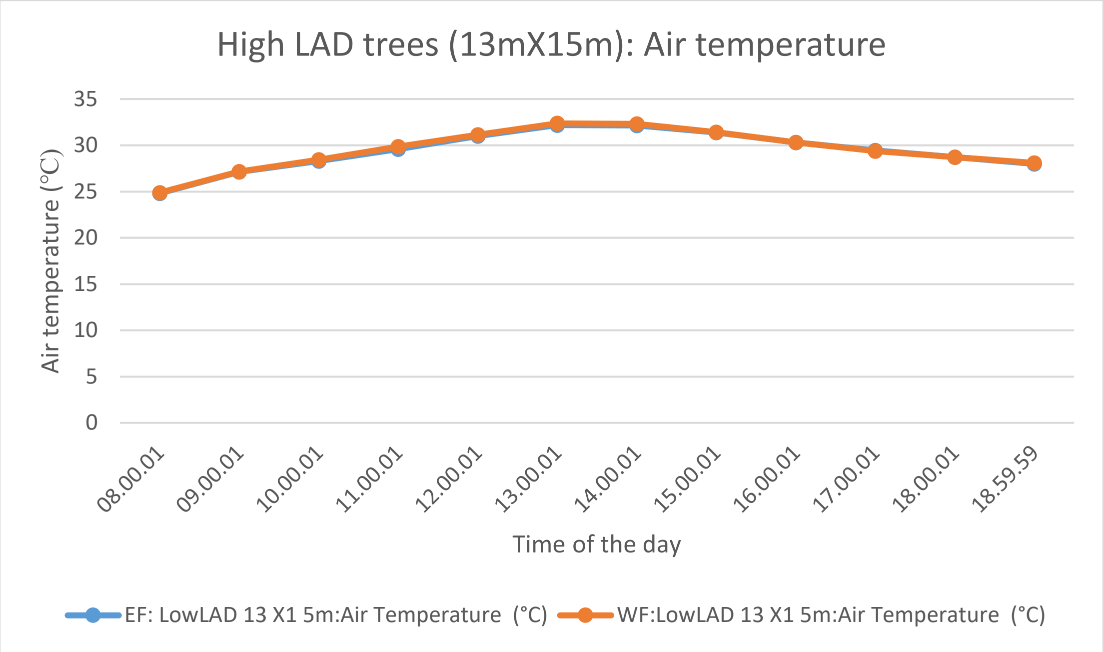


Figure 5-38 Comparison of Potential temperature for Scenario 5: V3 for east and west facing sidewalks

The figure shows the potential air temperature for the scenario throughout the day for east and west facing sidewalk. As per the graph, there is no significant difference in the air temperature throughout the day for both sidewalks.

Mean radiant temperature

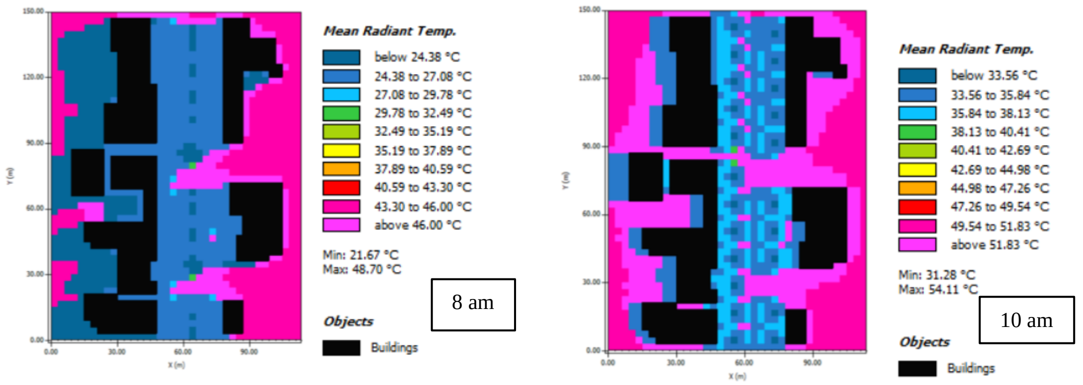


Chart 5-49 Mean radiant temperature for 8 am and 10 am in V3: High LAD Trees Canopy (13m) and height (15m) changed.

The mean radiant temperature varies between 24.38℃ and 27.08℃ at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 33.56℃ and 38.13 ℃.

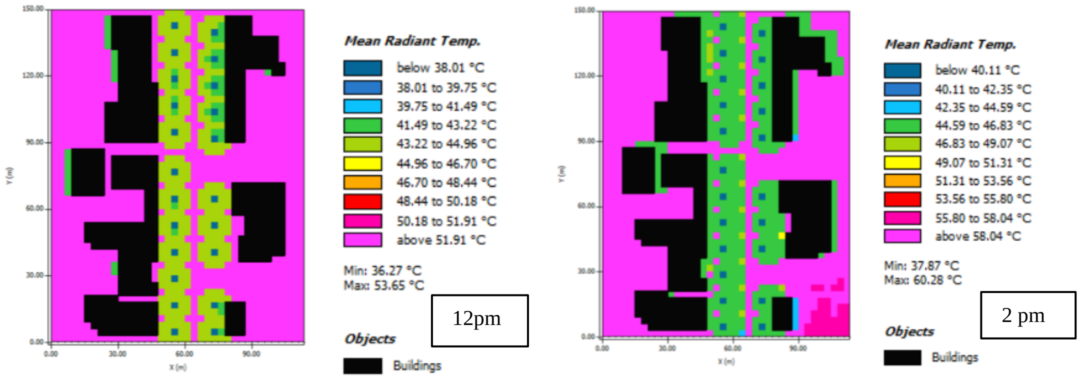


Chart 5-50 Mean radiant temperature for 12 pm and 2 pm in V3: High LAD Trees Canopy (13m) and height (15m) changed.

The mean radiant temperature varies between 43.22°C and 46.70 °C at 12 pm within the sidewalks. At 2 pm the mean radiant temperature increases and varies between 44.59°C and 49.07 °C.

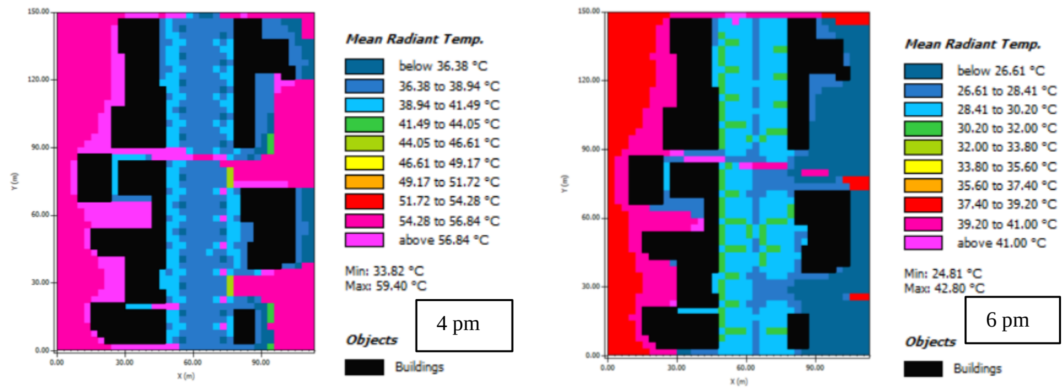


Chart 5-51 Mean radiant temperature for 4 pm and 6 pm in V3: High LAD Trees Canopy (13m) and height (15m) changed.

The mean radiant temperature fluctuates from 36.38°C to 41.49°C at 4 pm. At 6 pm, the mean radiant temperature varies from 28.41 °C to 30.20 °C.

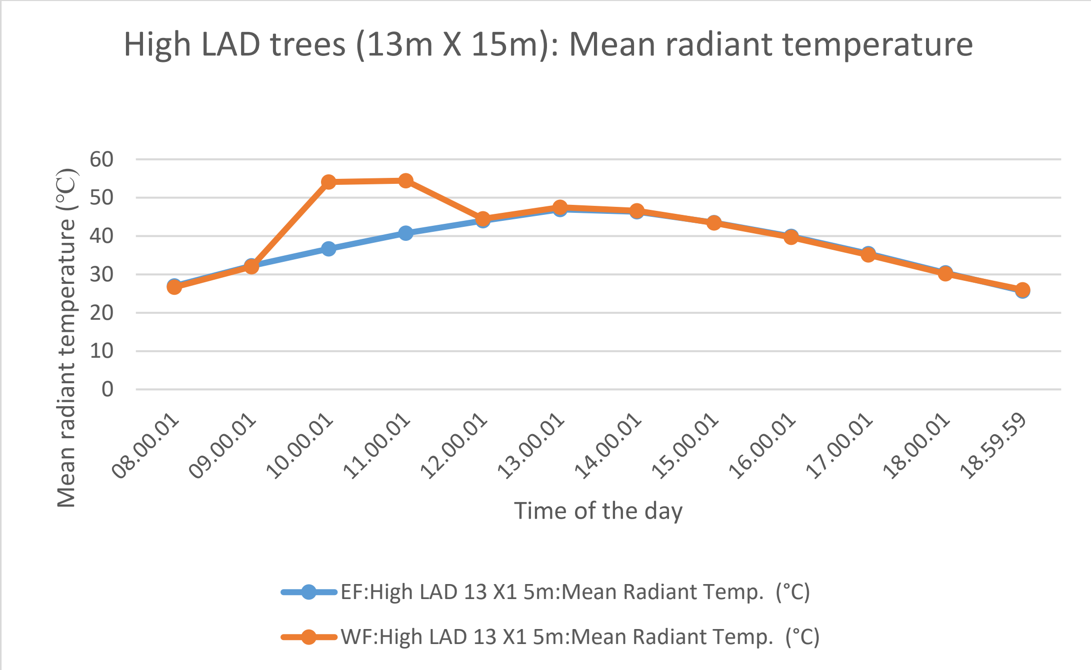


Figure 5-39 Comparison of Mean radiant for Scenario 5: V3 for east and west facing sidewalks

The figure shows the mean radiant temperature difference for the east and west facing sidewalk throughout the day. The mean radiant temperature for the west facing sidewalk is more from time of 10 am and 11 am.

Scenario 6: V4: Median with trees introduced in between road

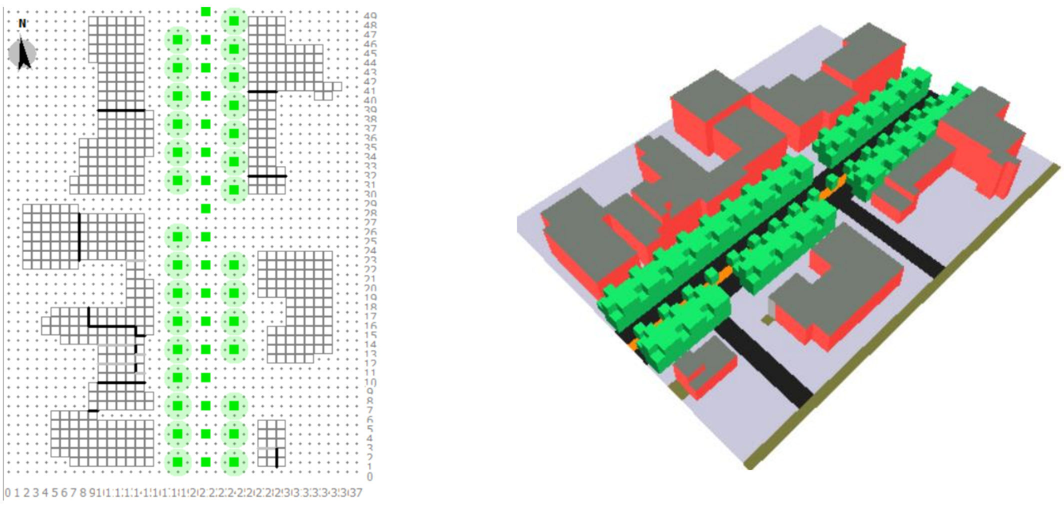


Figure 5-40 2D and 3D model in ENVI-met of Scenario 6: V4: Adding trees in median

This scenario is created by adding 5m trees in the median of the road in scenario 5 having High LAD trees.

Air temperature

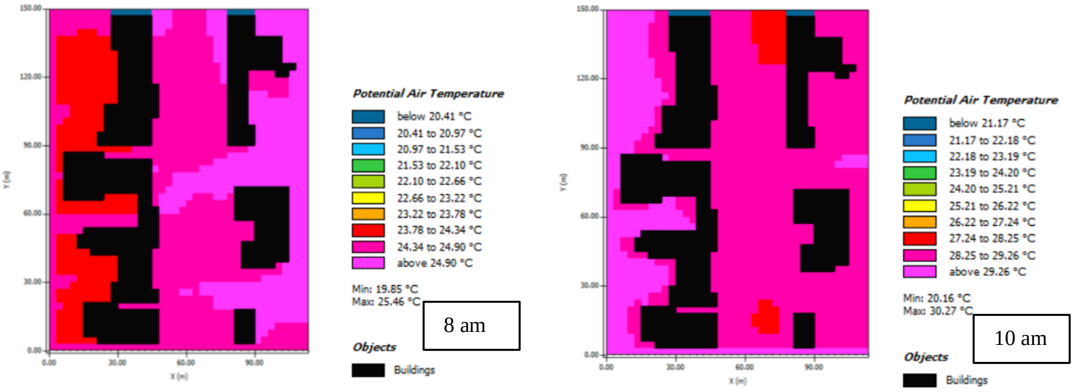


Chart 5-52 Potential air temperature for 8 am and 10 am in Scenario 6: Adding trees in median.

The figure above shows the potential air temperature at 8 am varies between 24.34°C and 24.90°C at 8 am. At 10 am it increases up to 28.25°C and fluctuates up to 28.25°C.

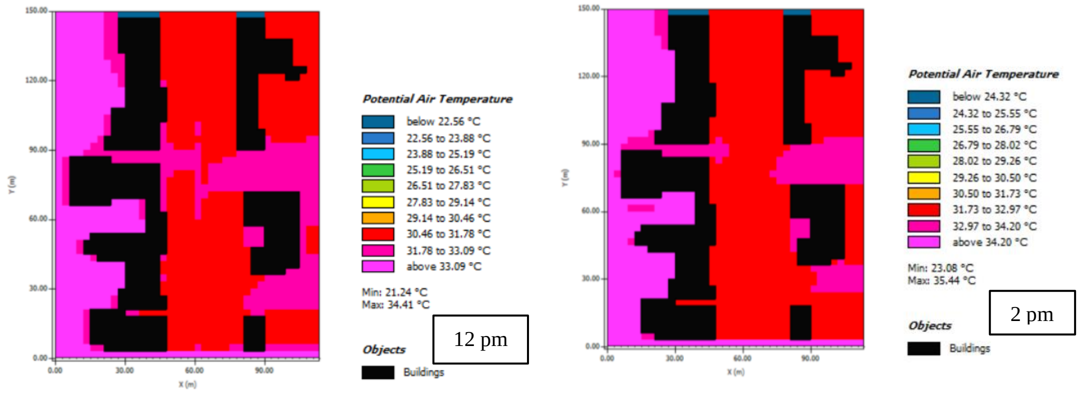


Chart 5-53 Potential air temperature for 12 pm and 2 pm in Scenario 6: Adding trees in median.

The figure above shows the potential air temperature at 12 pm varies between 30.46°C and 31.78°C. At 2 pm it increases up to 31.73°C and fluctuates up to 32.97°C.

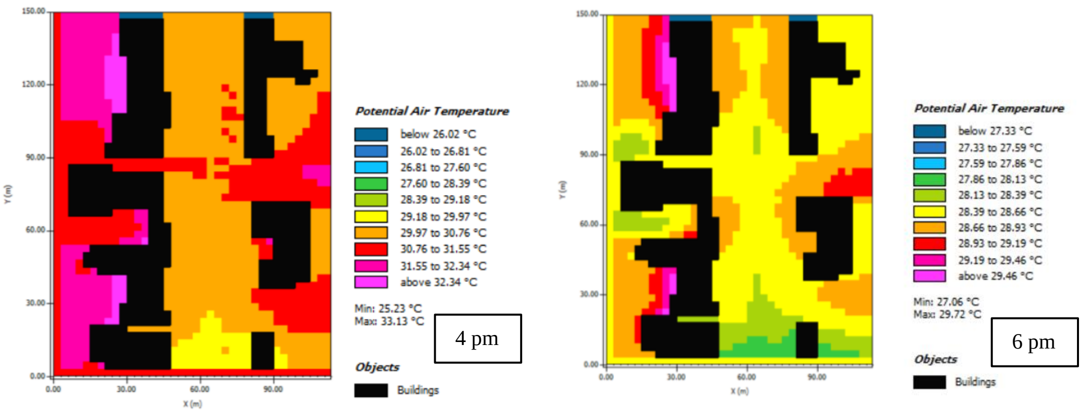


Chart 5-54 Potential air temperature for 4 pm and 6 pm in Scenario 6: Adding trees in median.

As per the figure above, the potential air temperature at 4 pm varies between 29.97°C and 30.76°C. At 6 pm it decreases up to 28.39°C and fluctuates between 28.39°C and 28.66°C.

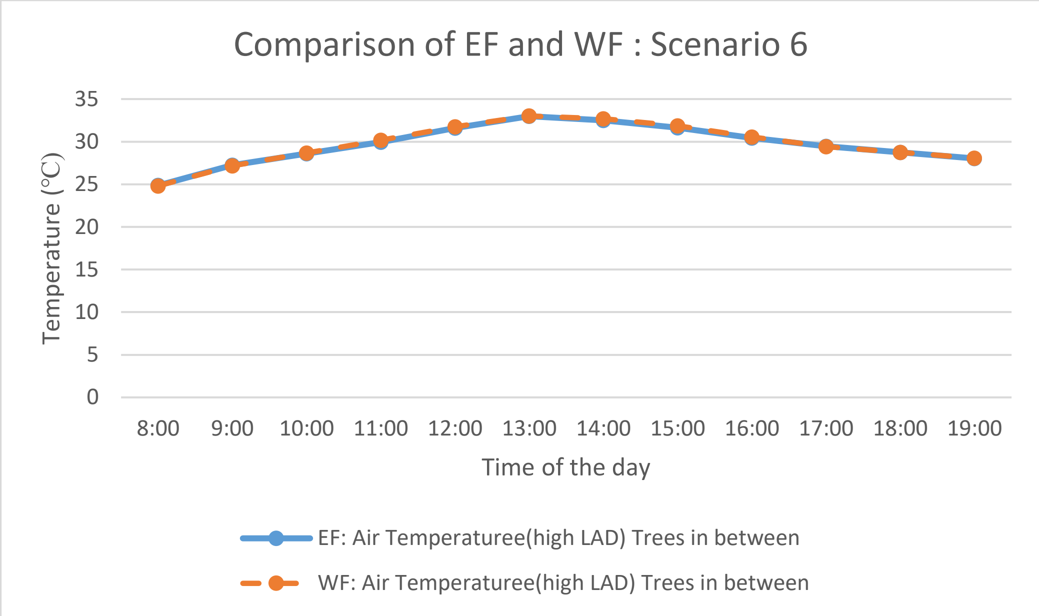


Figure 5-41 Comparison of potential air temperature of east facing and west facing Sidewalk for scenario 6: Adding trees in median.

The graph shows the potential air temperature variation throughout the day for east facing and west facing sidewalk. There is no significant difference in air temperature as seen in the graph for the scenario 6.

Mean Radiant temperature

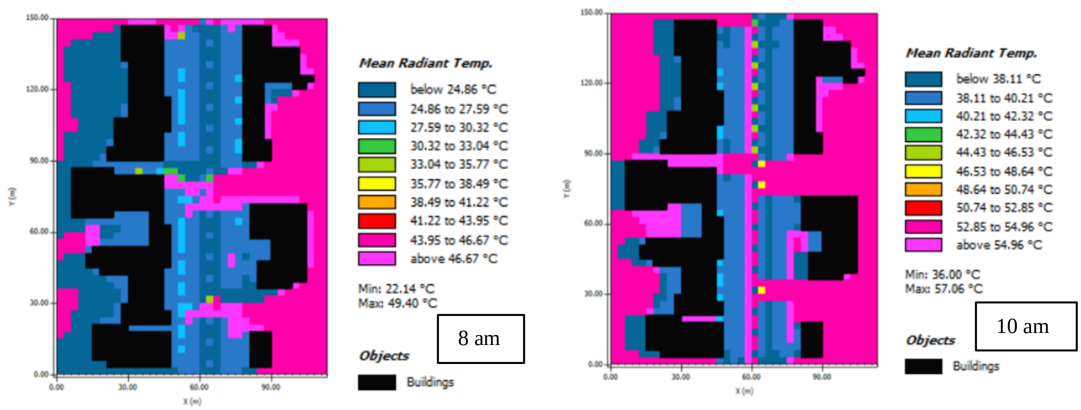


Chart 5-55 Mean radiant temperature for 8 am and 10 am in Scenario 6: Adding trees in median

The mean radiant temperature varies between 24.86°C and 27.59°C at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 38.11°C and 40.21 °C.

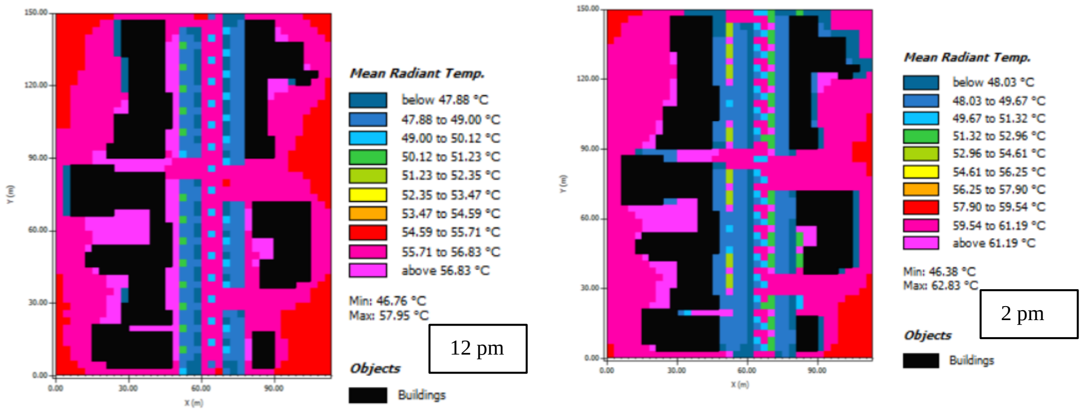


Chart 5-56 Mean radiant temperature for 12 pm and 2 pm in Scenario 6: Adding trees in median

The mean radiant temperature varies between 47.88℃ and 56.83 ℃ at 12 pm within the sidewalk. At 2 pm the mean radiant temperature increases and varies between 48.03℃ and 49.67 ℃.

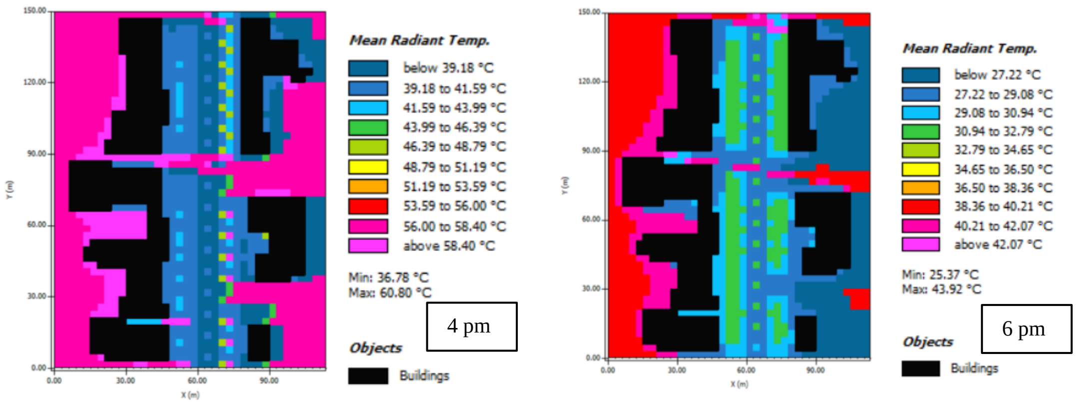


Chart 5-57 Mean radiant temperature for 4 pm and 6 pm in Scenario 6: Adding trees in median

The mean radiant temperature fluctuates from 39.18℃ to 41.59℃ at 4 pm. At 6 pm, the mean radiant temperature varies from 29.08 ℃ to 32.79 ℃.

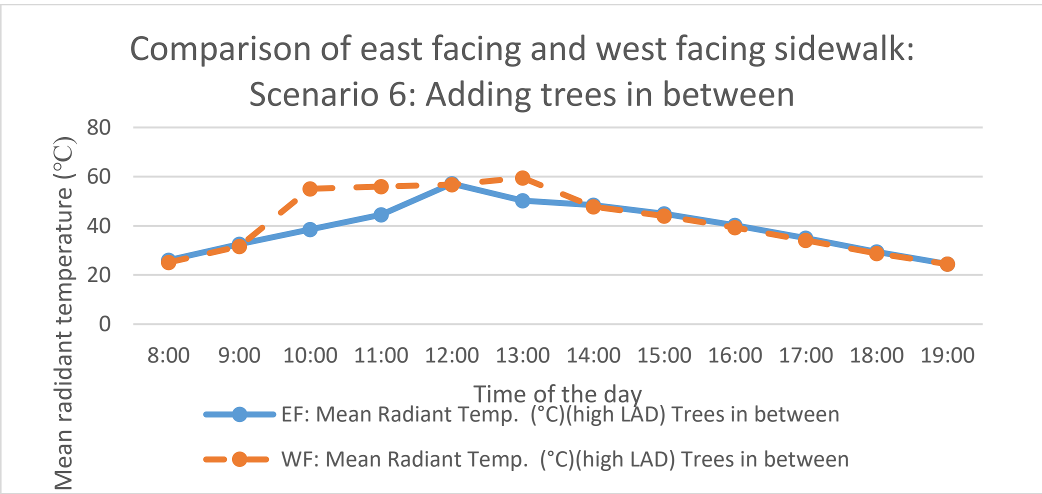


Figure 5-42 Comparison of mean radiant temperature of east facing and west facing Sidewalk for Scenario 6: Adding trees in between.

The graph above shows the mean radiant temperature variation throughout the day for the East facing and west facing Sidewalk. The mean radiant temperature in west facing sidewalk is slightly higher at 10 am, 11am and 1 pm.

Scenario 7: P1: Pavement material same as BC (Without trees)

The scenario 3 is created by removing the trees in ENVI-met.

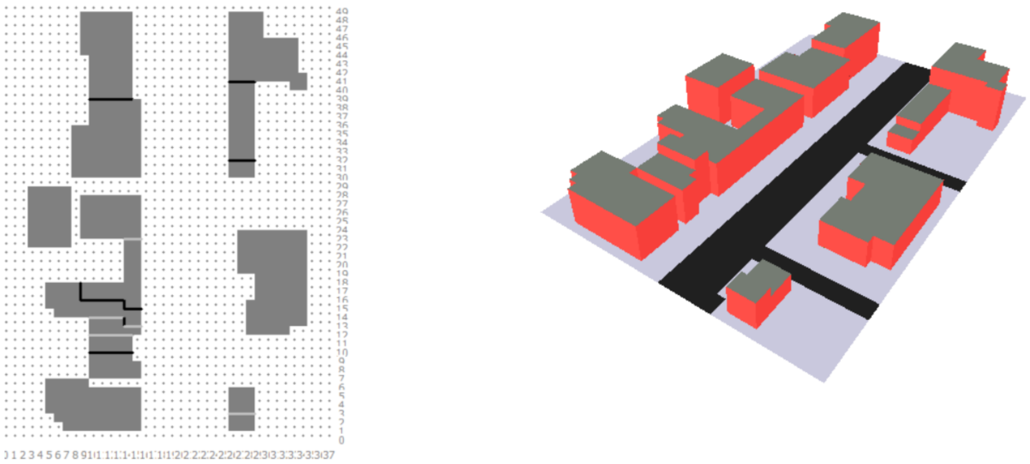


Figure 5-43 2d and 3D model of Scenario 3: without trees

Air temperature

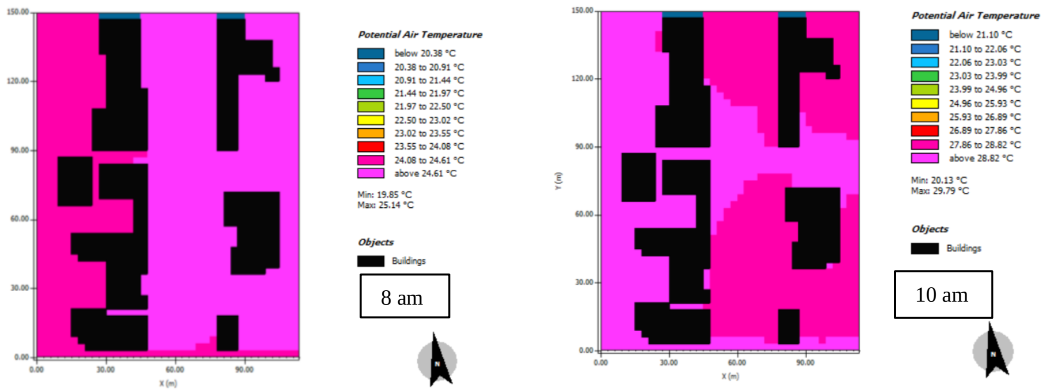


Chart 5-58 Potential air temperature for 8 am and 10 am in Scenario 7: P1: Without trees

The temperature ranges from 25.08 ºC to 24.61 ºC at 8 am. It gradually increases to 26.89 and fluctuates between 26.89 ºC to 28.82 ºC.

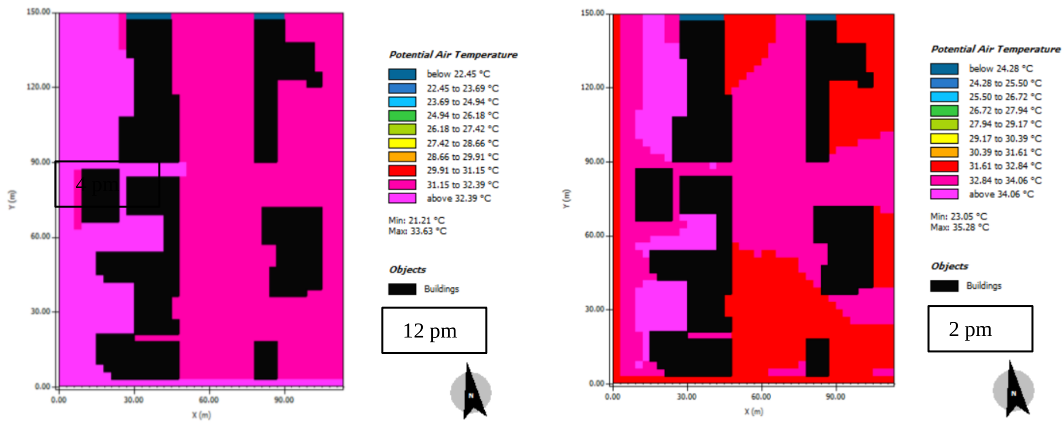


Chart 5-59 Potential air temperature for 12 pm and 2 pm in Scenario 7: P1: Without trees

The temperature is between 29.91 ºC to 31.15 ºC at 12 am and gradually increases between 31.61 ºC to 34.06 ºC.

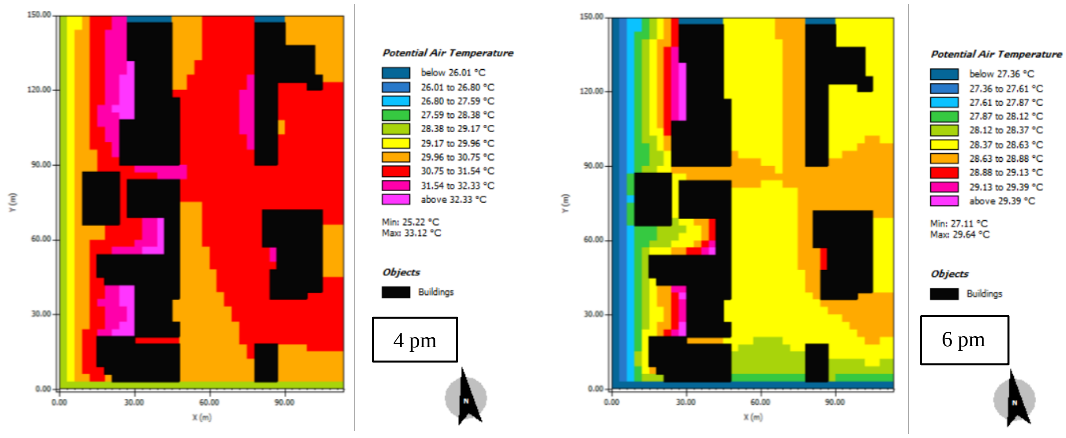


Chart 5-60 Potential air temperature for 4 pm and 6 pm in Scenario 7: P1: Without trees

The temperature ranges between 30.75 ºC to 31.54 ºC at 4 pm in the evening and decreases up to 28.37 and varies to 28.63.

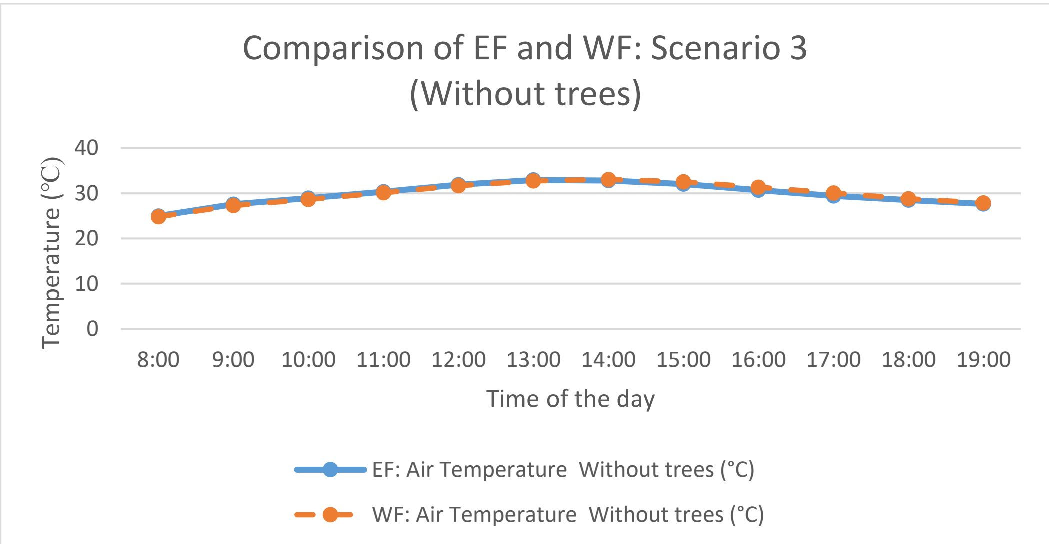


Figure 5-44 Air temperature in East and West facing Sidewalk in Scenario 7: P1: (Without trees)

The above figure shows the variation in air temperature throughout the day for east and west facing sidewalk. There is no significant difference between the both sidewalks in terms of air temperature.

Mean radiant temperature

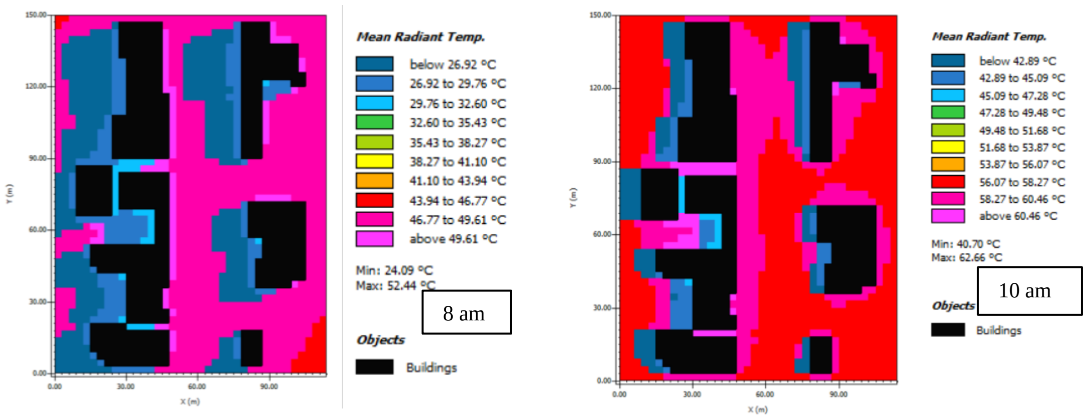


Chart 5-61 Mean radiant temperature for 8 am and 10 am in Scenario 7: P1: No trees

The mean radiant temperature is 49.61°C at 8 am in sidewalks except for the part where shadows fall on ground in west facing sidewalk where the temperature is below 26.92 °C. At 10 am the temperature increases up to 58.27 °C and varies between 58.27°C to 60.46 °C.

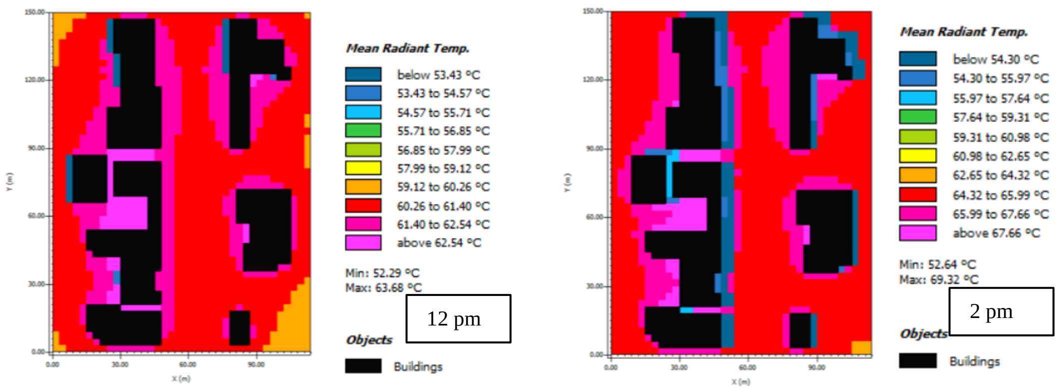


Chart 5-62 Mean radiant temperature for 12 pm and 2 pm in Scenario 7: P1: No trees

The mean radiant temperature fluctuates between 60.26 °C to 62.54 °C at 12 pm within the sidewalks and it varies between 54.30 °C and 67.66 °C at 2 pm.

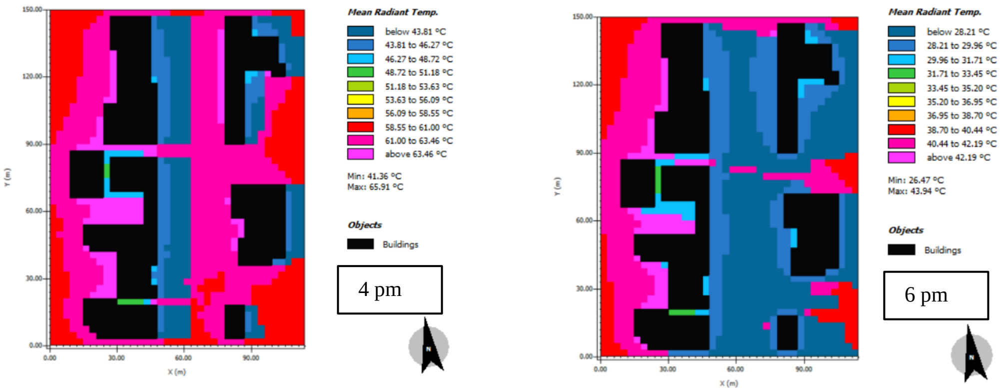


Chart 5-63 Mean radiant temperature for 4 pm and 6 pm in Scenario 7: P1: No trees

The mean radiant temperature is 43.81℃ in east facing sidewalk at 4 pm and it is 63.46℃ at west facing sidewalk. At 6 pm the mean radiant temperature decreases and varies between 28.21℃ and 29.96 ℃.

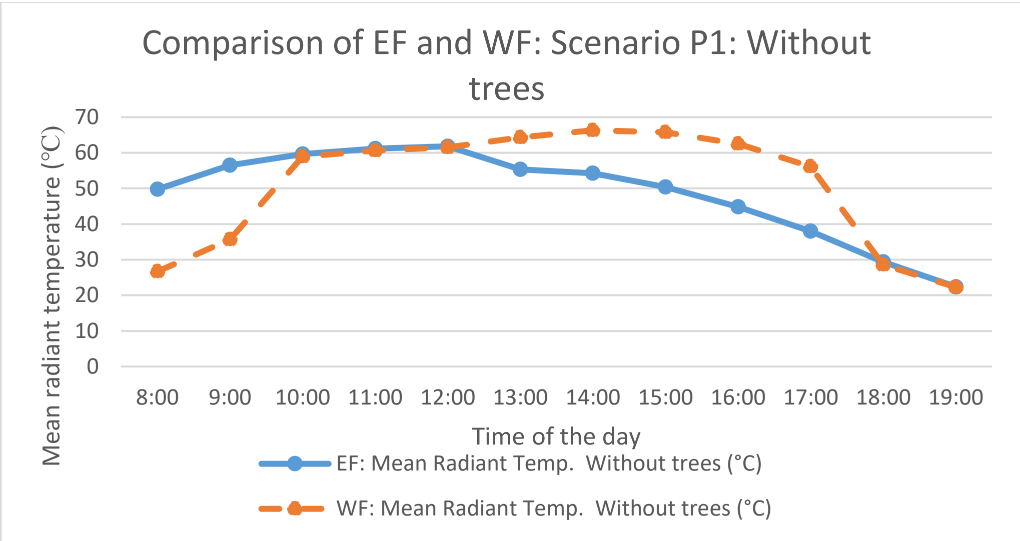


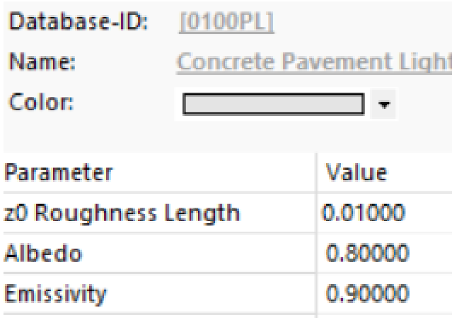
Figure 5-45 Comparison of mean radiant temperature of East facing and west facing sidewalk for scenario 7: P1:Without trees

The figure shows that the mean radiant temperature in west facing sidewalk is less in the morning than east facing sidewalk whereas the MRT increases during the time 1 pm -5 pm in west facing sidewalk.

Scenario 8: P2: Pavement changed to light colored concrete

From the literature it is evident that the light colour material reflects more sunlight and hence are known as cool pavements. The light coloured concrete having albedo value 0.8 and emissivity 0.9 is used for this scenario.

The material is from the default settings of envimet.



Database-ID: [0100PL]
Name: Concrete Pavement Light
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.80000
Emissivity	0.90000

Figure 5-46 Properties of material in envimet

Air temperature

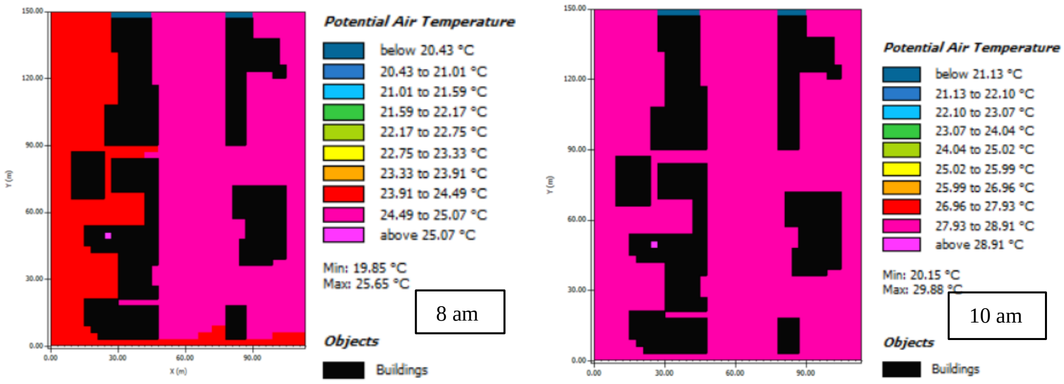


Chart 5-64 Potential air temperature for 8 am and 10 am in Scenario 8: P2: Pavement changed to light colored concrete.

As per the figure above, the potential air temperature at 8 am varies between 24.49°C and 25.07°C at 8 am. At 10 am it increases up to 27.93°C.

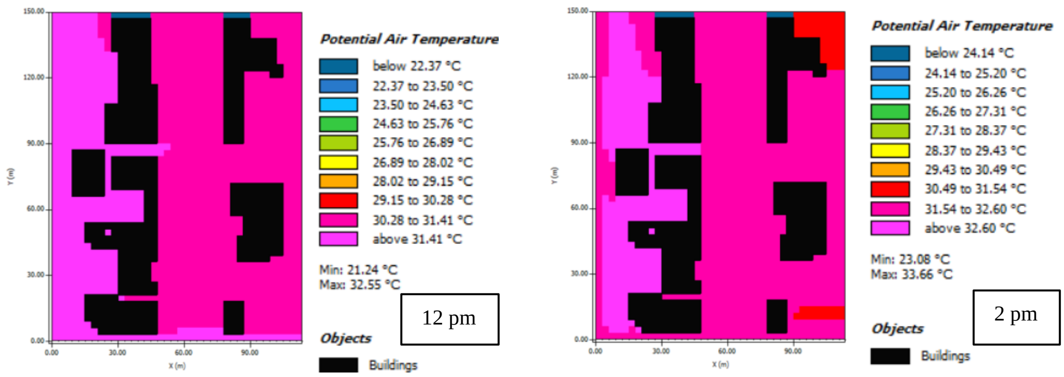
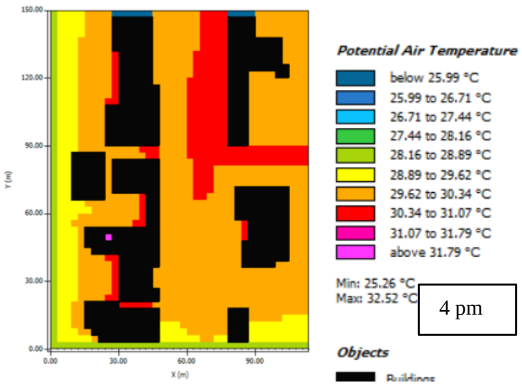


Chart 5-65 Potential air temperature for 12 pm and 2 pm in Scenario 8: P2: Pavement changed to light colored concrete.

The temperature varies between 29.15°C and 31.41°C at 12 pm and increases and varies between 31.54°C and 32.60 °C at 2 pm.



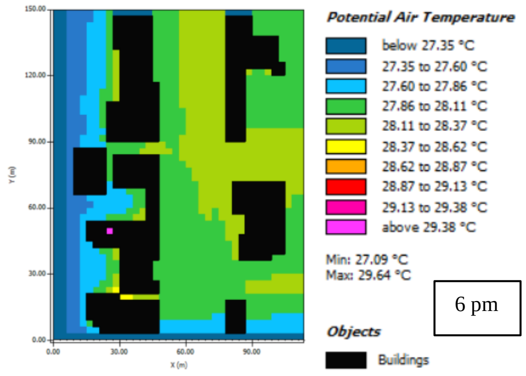


Chart 5-66 Potential air temperature for 4 pm and 6 pm in Scenario 8: P2: Pavement changed to light colored concrete.

The potential air temperature fluctuates from 29.40℃ to 30.01℃ at 4 pm and gradually it decreases and reaches up to 28.15 ℃ within some parts of sidewalk at 6 pm in the evening.

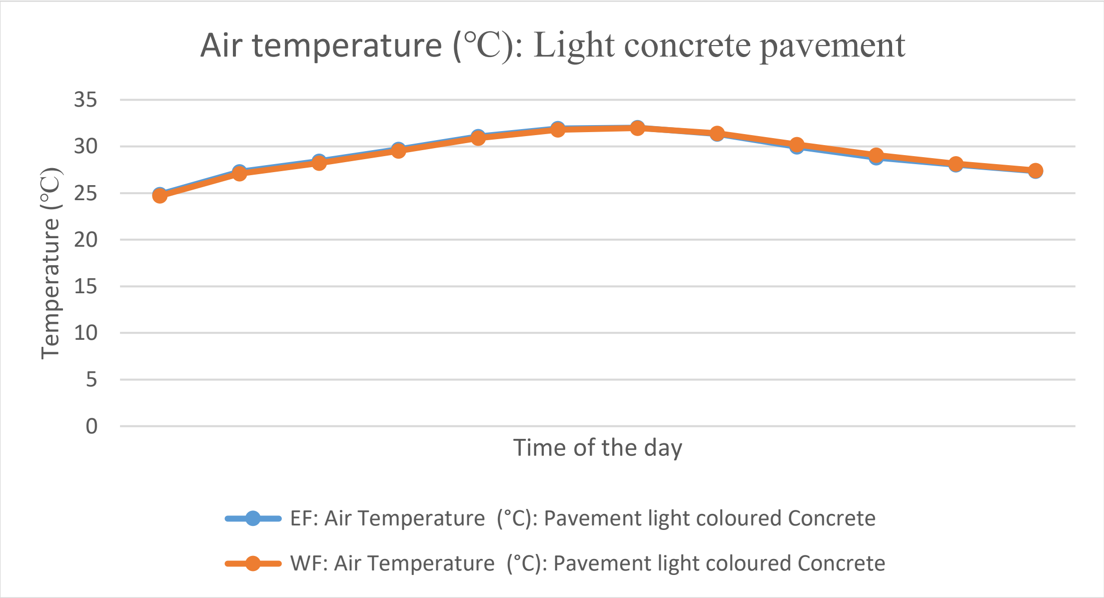


Figure 5-47 Comparison of Potential air temperature of East facing and west facing sidewalk for 8: P2: Pavement changed to light colored concrete.

The figure shows the potential air temperature for the scenario within the day for the east and west facing sidewalk. There is no significant difference between the both sidewalks in terms of air temperature.

Mean radiant temperature

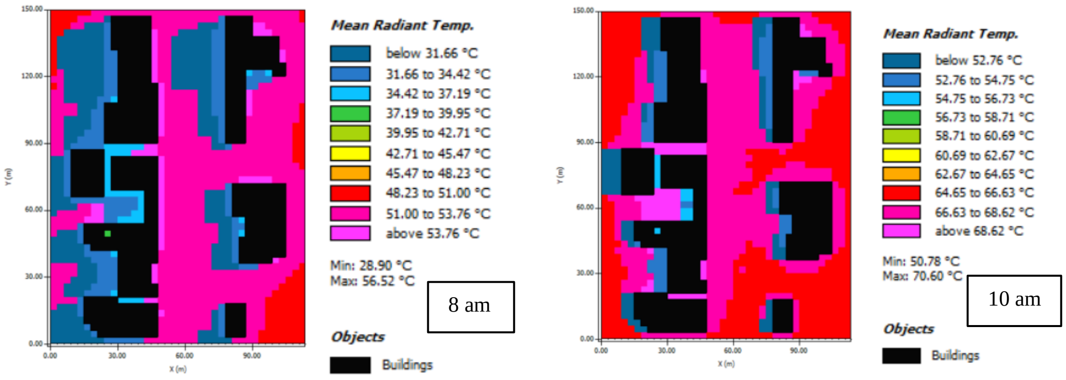


Chart 5-67 Mean radiant temperature for 8 am and 10 am in Scenario 8: P2: Pavement changed to light colored concrete.

The mean radiant temperature varies between 31.66℃ and 53.766℃ at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 64.65℃ and 68.62 ℃.

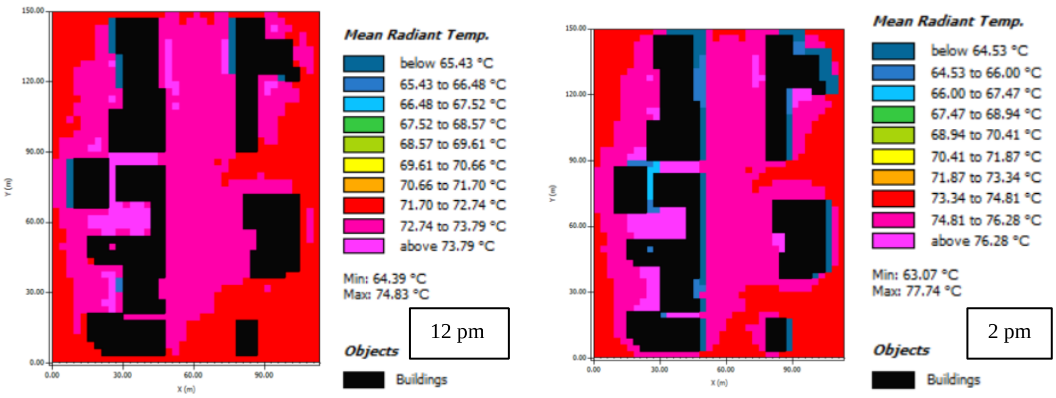


Chart 5-68 Mean radiant temperature for 12pm and 2pm in Scenario 8: P2: Pavement changed to light colored concrete.

The mean radiant temperature varies between 72.74℃ and 73.79 ℃ at 12 pm within the sidewalk. At 2 pm the mean radiant temperature increases and varies between 74.81℃ and 76.28 ℃.

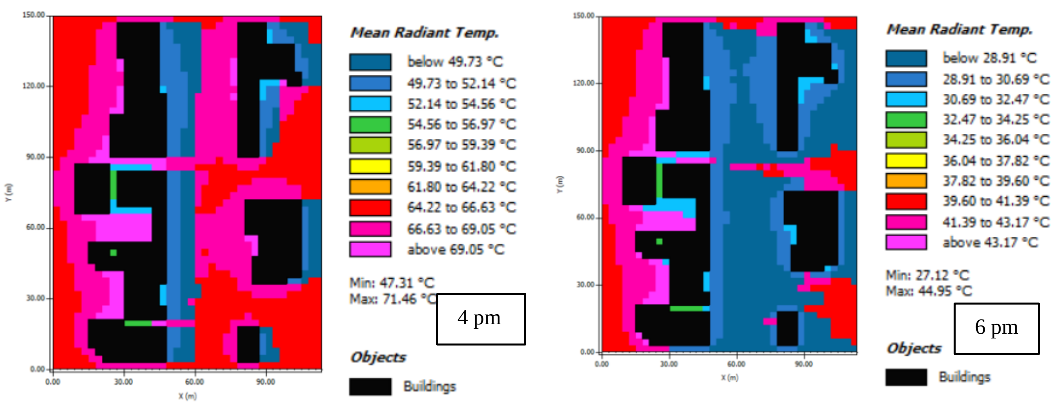


Chart 5-69 Mean radiant temperature for 4pm and 6pm in Scenario 8: P2: Pavement changed to light colored concrete.

The mean radiant temperature fluctuates from 49.73℃ to 64.22℃ at 4 pm. At 6 pm, the mean radiant temperature varies from 28.91℃ to 30.69 ℃.

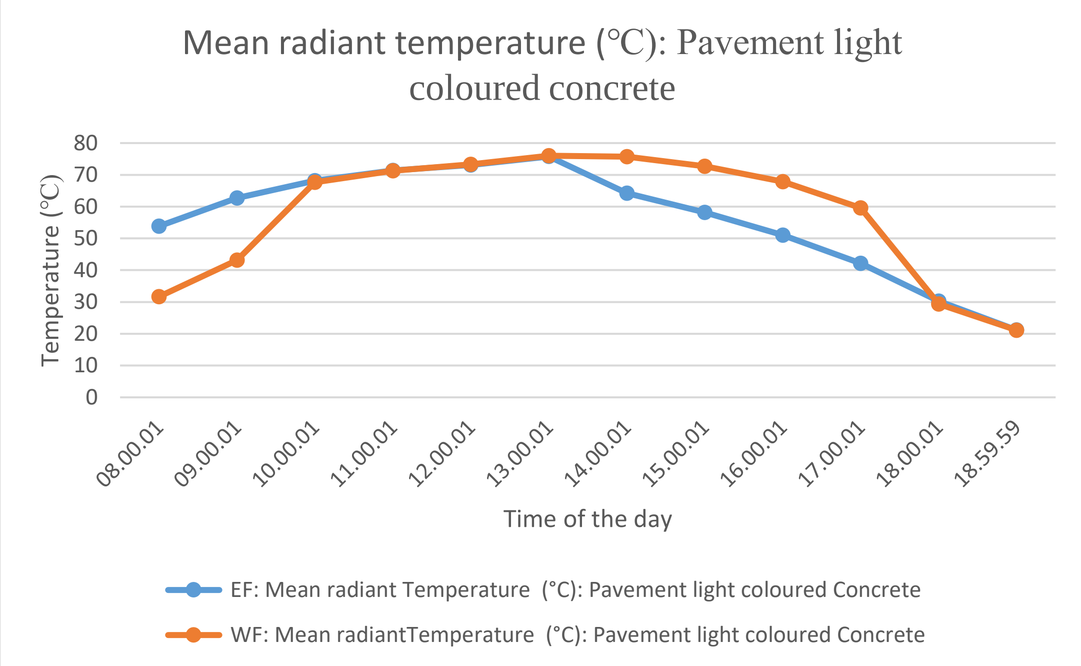


Figure 5-48 Comparison of mean radiant temperature of east facing and west facing Sidewalk for Scenario 8: P2: Pavement material changed to light concrete.

The graph above shows the mean radiant temperature variation throughout the day for the East facing and west facing Sidewalk. The mean radiant temperature in east facing sidewalk is higher during morning hours and less than that of west facing sidewalk between the time interval of 14pm to 17pm.

Scenario 9: P3: Pavement changed to Dark colored concrete

The dark coloured concrete having albedo value 0.2 and emissivity 0.9 is used for this scenario. The material is from the default settings of Envi-met 5.03.

Database-ID: [0000PD]
Name: Concrete Pavement Dark
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.20000
Emissivity	0.90000
ExtraID	0
Surface is irrigated	False
Water: Mixing Coefficient	0.00100
Water: Turbidity/Extinction	2.10000

Figure 5-49

Air temperature

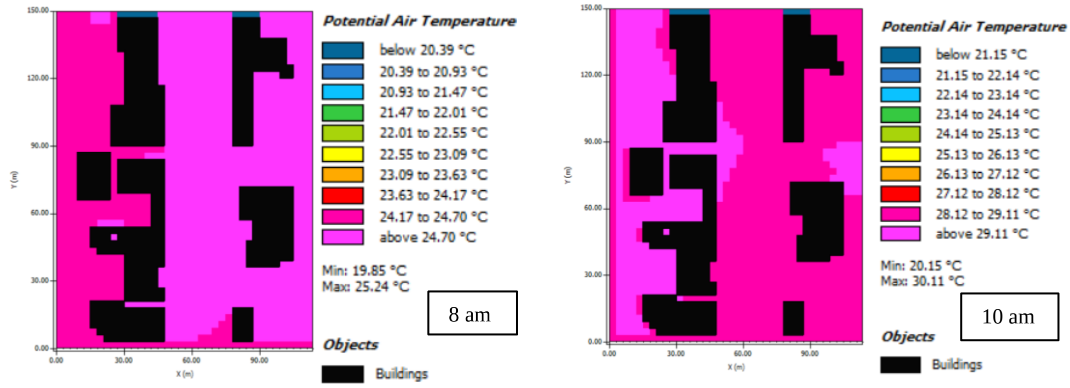


Chart 5-70 Air temperature for 8 am and 10 am in Scenario 9: P3: Pavement changed to Dark colored concrete.

As per the figure above, the potential air temperature at 8 am varies between 24.17°C and 24.70°C at 8 am. At 10 am it increases up to 29.11°C.

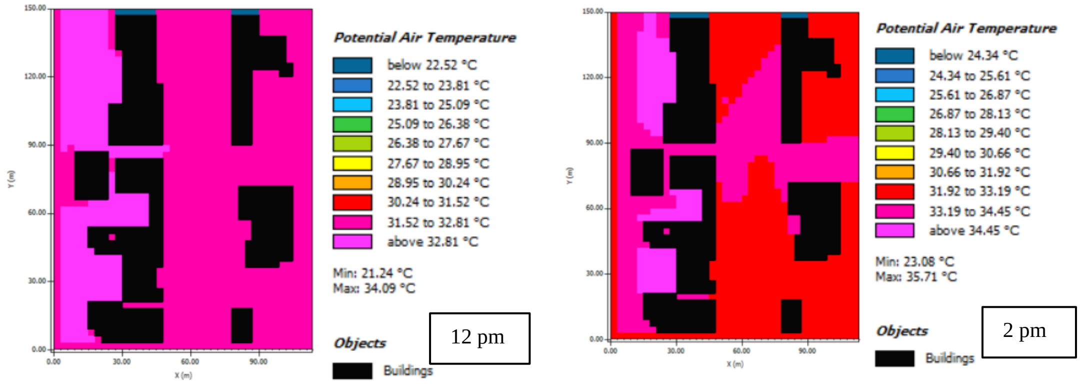


Chart 5-71 Air temperature for 12pm and 2pm in Scenario 9: P3: Pavement changed to Dark colored concrete.

The temperature varies between 31.52°C and 32.81°C at 12 pm and increases and varies between 31.92°C and 34.45°C at 2 pm.

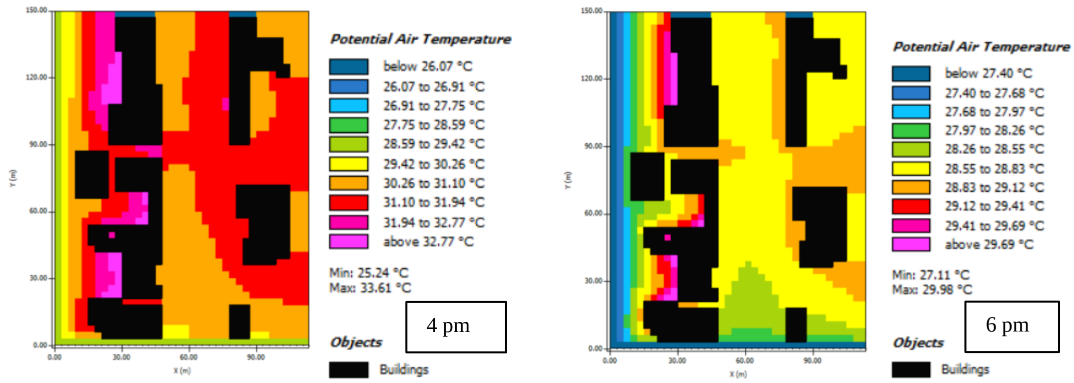


Chart 5-72 Air temperature for 4 pm and 6 pm in Scenario 9: P3: Pavement changed to Dark colored concrete.

The potential air temperature fluctuates from 30.26℃ to 31.94℃ at 4 pm and gradually it decreases and reaches up to 28.55 ℃ to 28.83℃ within some parts of sidewalk at 6 pm in the evening.

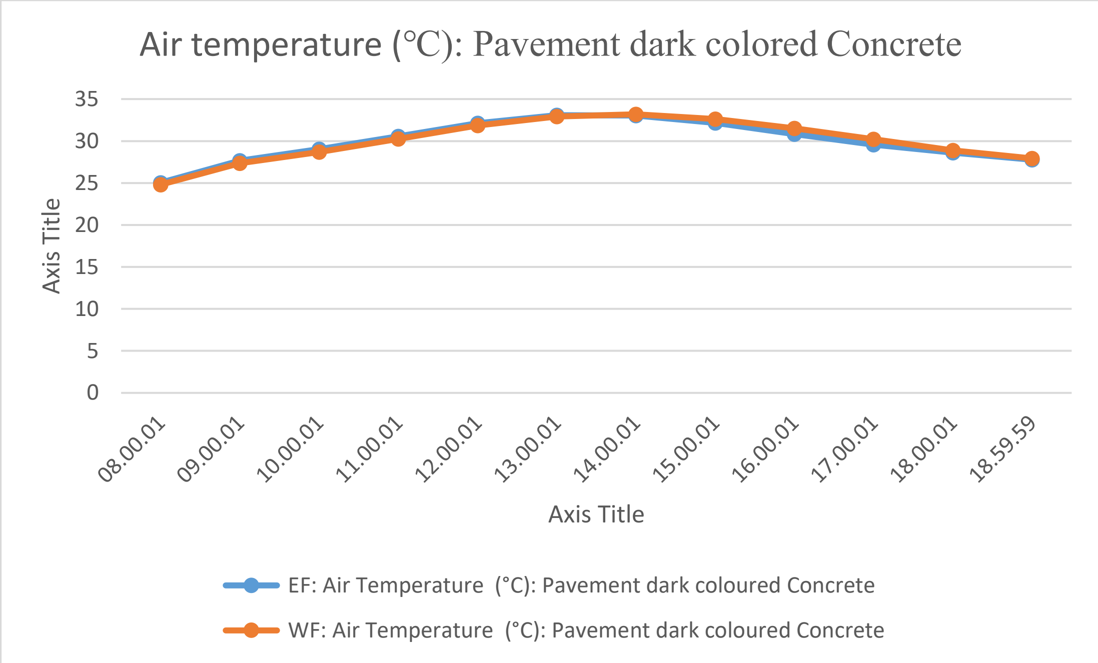


Figure 5-50 Comparison of Potential air temperature of East facing and west facing sidewalk for Scenario 9: P3: Pavement changed to Dark colored concrete.

The figure shows the potential air temperature for the scenario within the day for the east and west facing sidewalk. There is no significant difference between the both sidewalks in terms of air temperature.

Mean radiant temperature

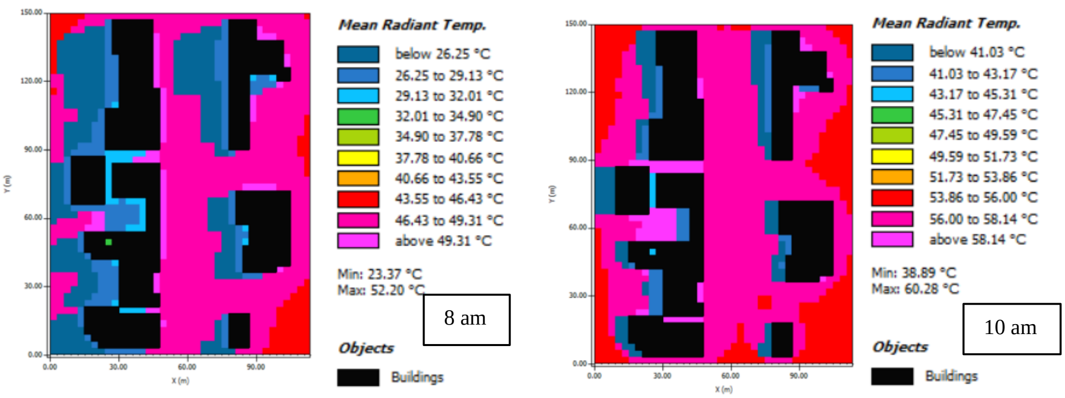


Chart 5-73 Mean radiant temperature for 8 am and 10 am in Scenario 9: P3: Pavement changed to Dark colored concrete.

The mean radiant temperature varies between 26.25℃ and 46.43℃ at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 41.03℃ and 58.14℃.

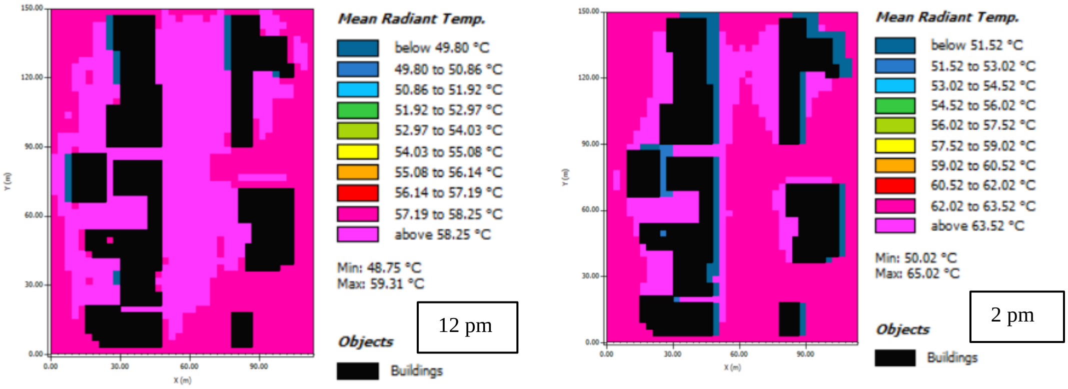


Chart 5-74 Mean radiant temperature for 12 pm and 2 pm in Scenario 9: P3: Pavement changed to Dark colored concrete.

The mean radiant temperature varies between 57.19℃ and 58.25 ℃ at 12 pm within the sidewalk. At 2 pm the mean radiant temperature increases and varies between 62.02℃ and 63.52 ℃.

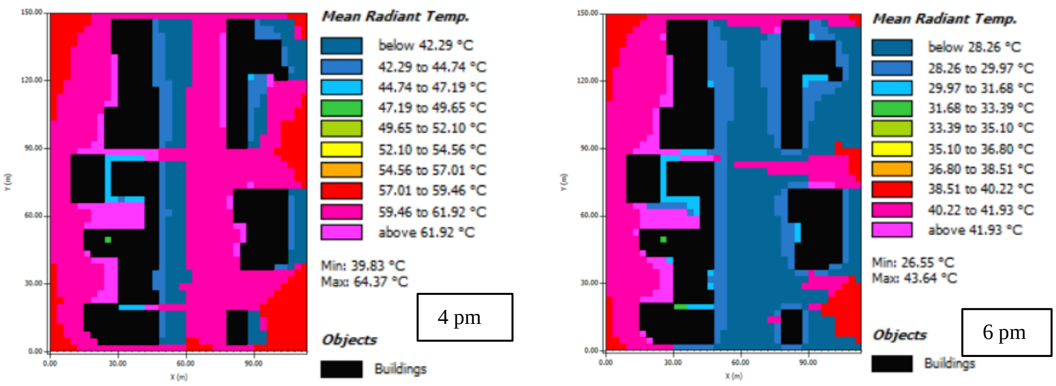


Chart 5-75 Mean radiant temperature for 4 pm and 6 pm in Scenario 9: P3: Pavement changed to Dark colored concrete.

The mean radiant temperature fluctuates from 42.29℃ to 59.46℃ at 4 pm. At 6 pm, the mean radiant temperature varies from 28.26 ℃ to 29.97 ℃.

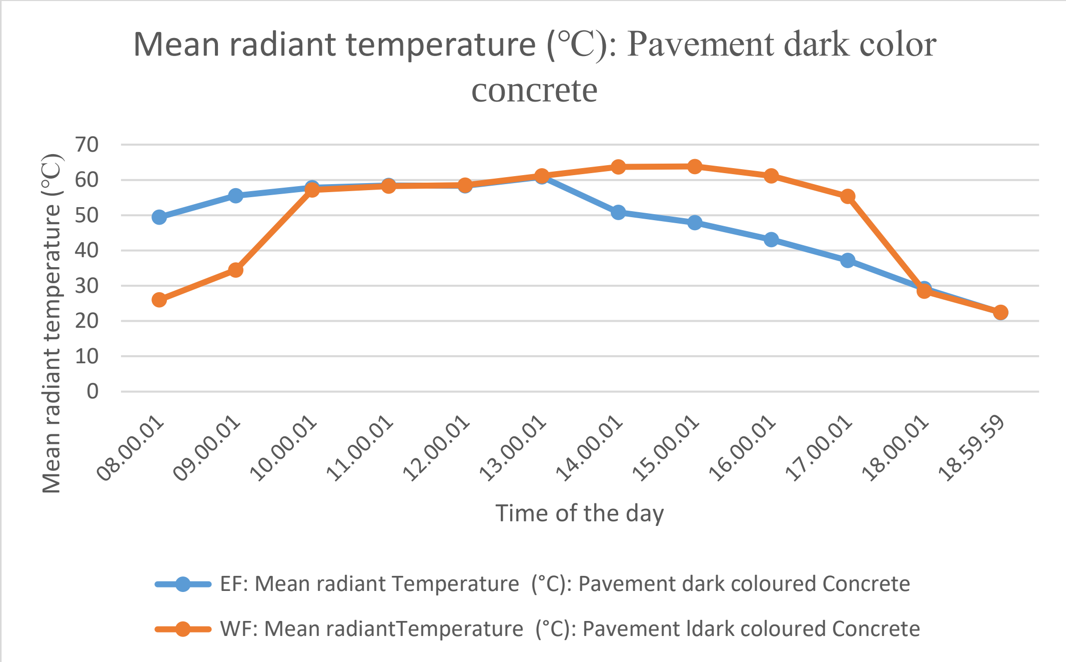


Figure 5-51 Comparison of Mean radiant temperature of East facing and west facing sidewalk for Scenario 9: P3: Pavement changed to Dark colored concrete.

The graph above shows the mean radiant temperature variation throughout the day for the East facing and west facing Sidewalk. The mean radiant temperature in east facing sidewalk is higher during morning hours and less than that of west facing sidewalk between the time interval of 14pm to 17pm.

Scenario 10: P4: Pavement changed to interlocking concrete blocks

This scenario is created by changing the pavement material to the permeable interlocking concrete blocks. The albedo value of the material is 0.5 and the thermal emissivity if 0.9. Since the permeable pavements are considered as cool pavements, the material is tested for the simulation.

Database-ID: [0100PC]
Name: interlocking permeable concrete blocks
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.50000
Emissivity	0.90000
ExtraID	0
Surface is irrigated	False
Water: Mixing Coefficient	0.00100
Water: Turbidity/Extinction	2.10000

Figure 5-52 Properties of material in Envi-met

Air temperature

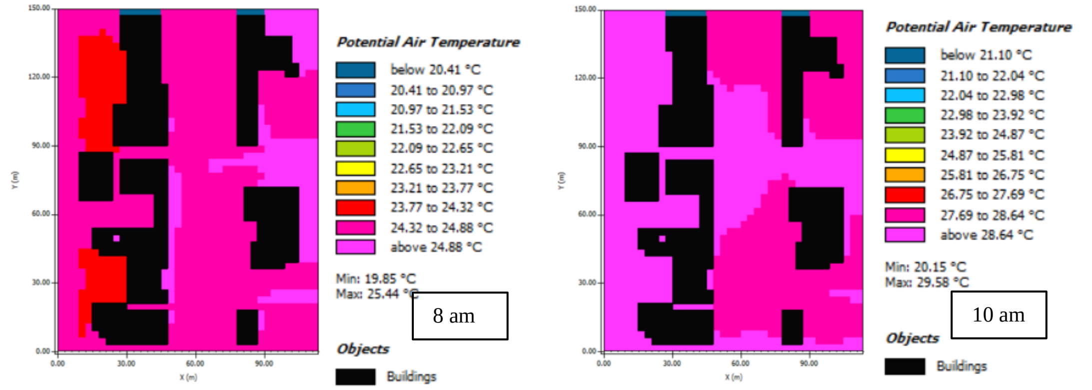


Chart 5-76 Air temperature for 8 am and 10 am in Scenario 10: P4: Pavement changed to Interlocking concrete blocks

The figure above shows the potential air temperature at 8 am varies between 24.32℃ and 24.88℃ at 8 am. At 10 am it increases up to 27.69℃ and varies between 27.69℃ and 28.64℃.

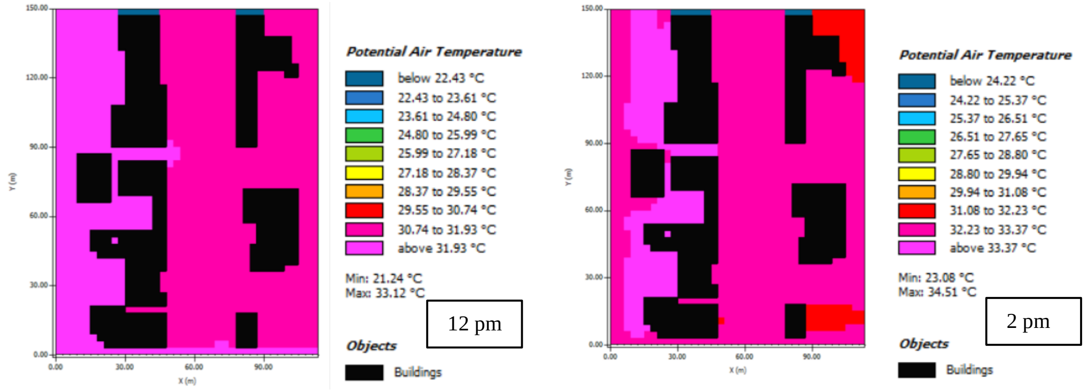


Chart 5-77 Air temperature for 12 pm and 2 pm in Scenario 10: P4: Pavement changed to Interlocking concrete blocks

The temperature varies between 30.74℃ and 31.93℃ at 12 pm and increases and varies between 32.23℃ and 33.37℃ at 2 pm.

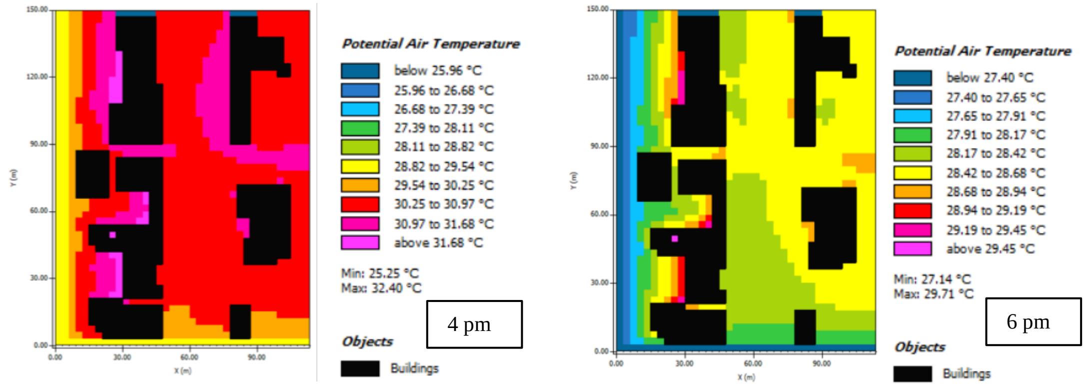


Chart 5-78 Air temperature for 4 pm and 6 pm in Scenario 10: P4: Pavement changed to Interlocking concrete blocks

The potential air temperature fluctuates from 30.25℃ to 30.97℃ at 4 pm and gradually it decreases and reaches up to 28.17 ℃ to 28.68℃ at 6 pm in the evening.

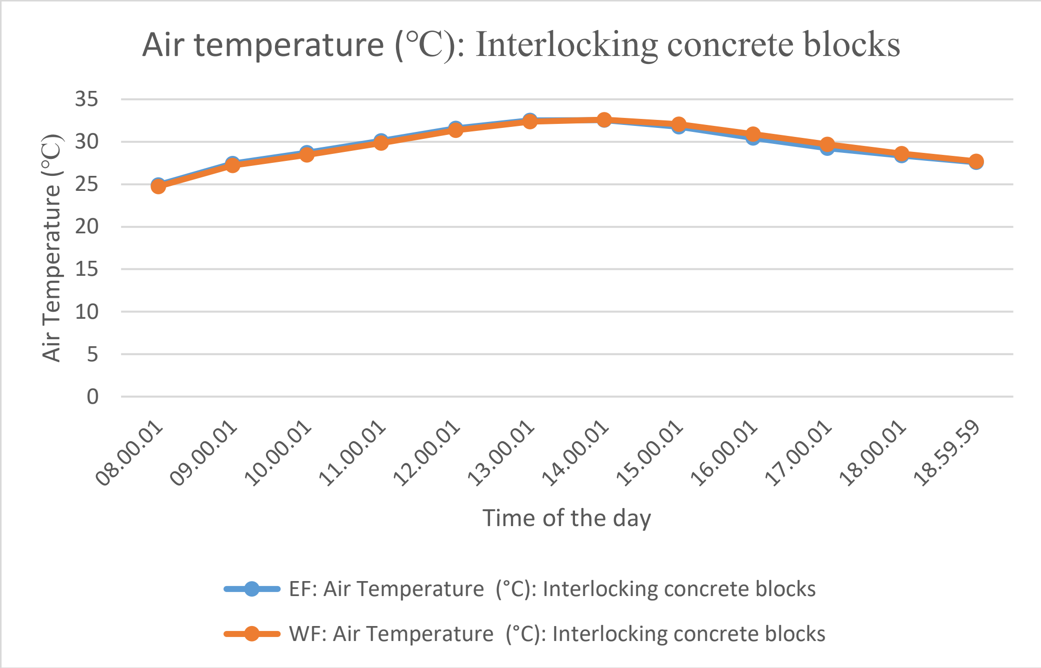


Figure 5-53 Comparison of Air temperature of East facing and west facing sidewalk for Scenario 10: P4: Pavement changed to Interlocking concrete blocks.

The graph shows the potential air temperature of east and west facing Sidewalk for Scenario. There is no significant difference in the air temperature as per the graph between two sidewalks.

Mean radiant temperature

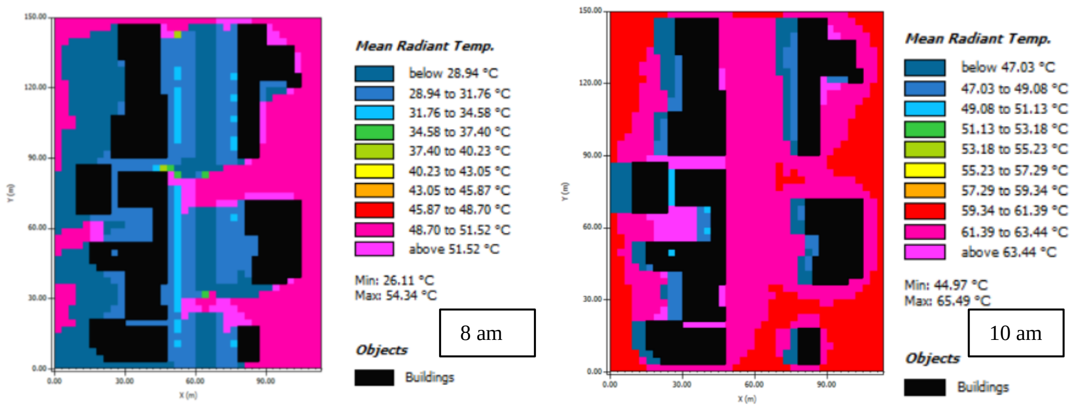


Chart 5-79 Mean radiant temperature for 8 am and 10 am in Scenario 10: Pavement changed to permeable interlocking concrete blocks.

The mean radiant temperature varies between 28.94℃ and 31.76℃ at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 59.34℃ and 63.44℃.

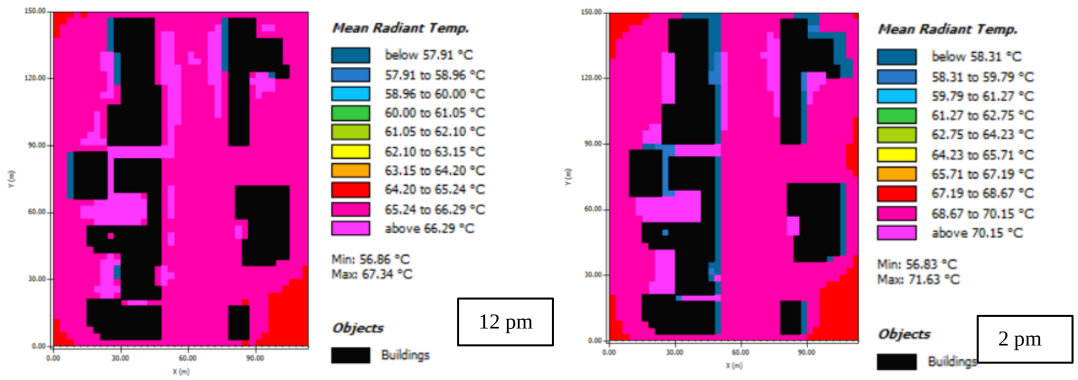


Chart 5-80 Mean radiant temperature for 12pm and 2pm in Scenario 10: Pavement changed to permeable interlocking concrete blocks.

The mean radiant temperature varies between 65.24℃ and 66.29 ℃ at 12 pm within the sidewalk. At 2 pm the mean radiant temperature increases and varies between 68.67℃ and 70.15 ℃.

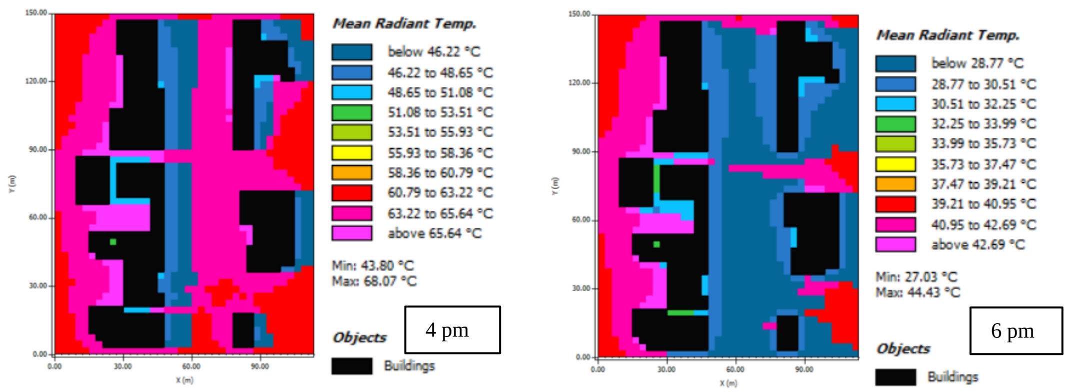


Chart 5-81 Mean radiant temperature for 4pm and 6pm in Scenario 10: Pavement changed to permeable interlocking concrete blocks.

The mean radiant temperature fluctuates from 46.22℃ to 60.97℃ at 4 pm. At 6 pm, the mean radiant temperature varies from 28.77 ℃ to 30.51 ℃.

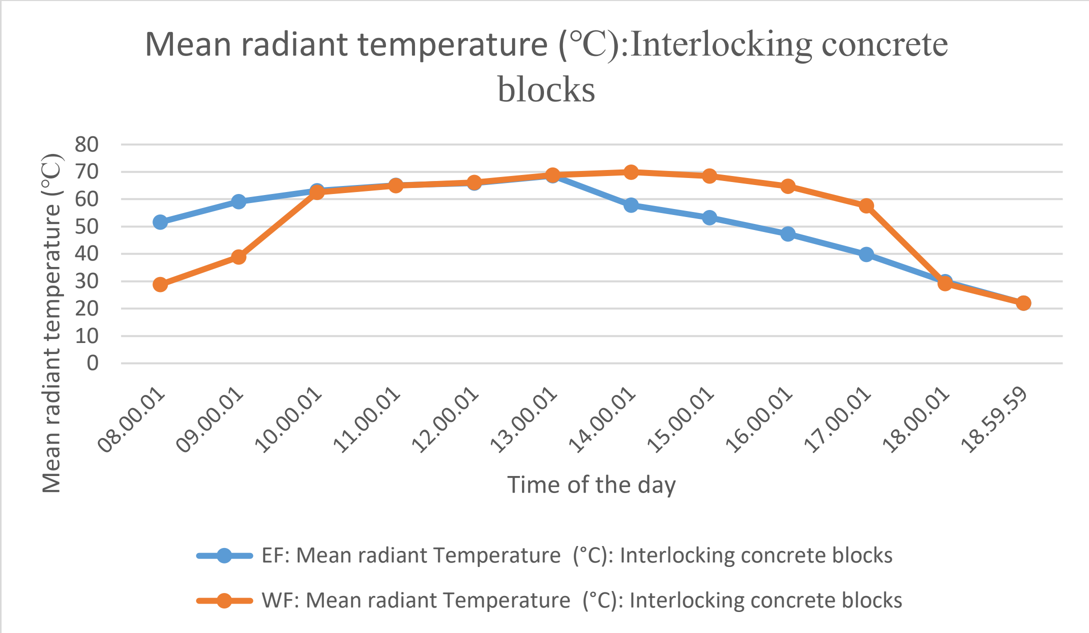


Figure 5-54 Comparison of Mean radiant temperature of East facing and west facing sidewalk for Scenario 10: P4: Pavement changed to Interlocking concrete blocks.

The graph above shows the mean radiant temperature variation throughout the day for the East facing and west facing Sidewalk. The mean radiant temperature in east facing sidewalk is higher during morning hours and less than that of west facing sidewalk between the time interval of 14pm to 17pm.

Scenario 11: P5: Pavement changed to Porous Concrete

This scenario is created by changing the pavement material to the Porous concrete. The albedo value for the material is 0.3 and the emissivity is 0.9. The simulation results for the scenario P4 is shown below in terms of the air temperature and mean radiant temperature.

Database-ID: [010PPC]
Name: pervious concrete
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.30000
Emissivity	0.90000
ExtraID	0
Surface is irrigated	False
Water: Mixing Coefficient	0.00100
Water: Turbidity/Extinction	2.10000

Figure 5-55 Properties of material in ENVI-met

Air temperature

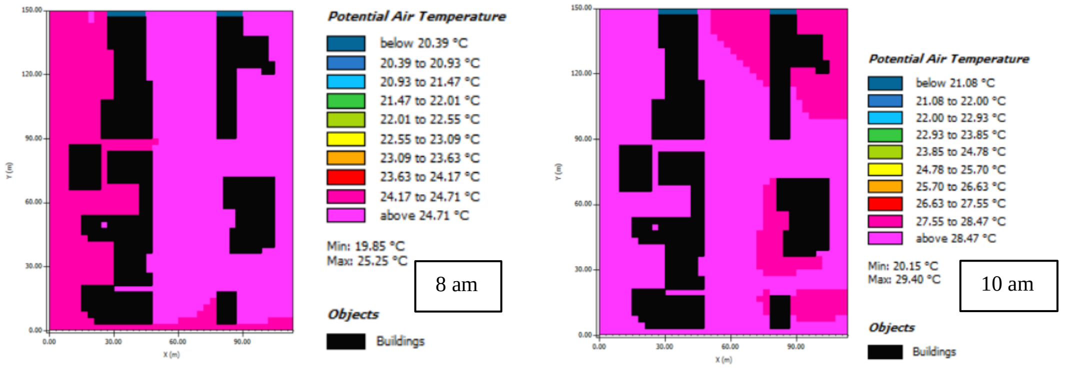


Chart 5-82 Air temperature for 8 am and 10 am in Scenario 11: P5: Pavement changed to Porous Concrete

The potential air temperature at 8 am varies between 24.17°C and 24.71°C at 8 am. At 10 am it increases up to 28.47°C as shown in the charts.

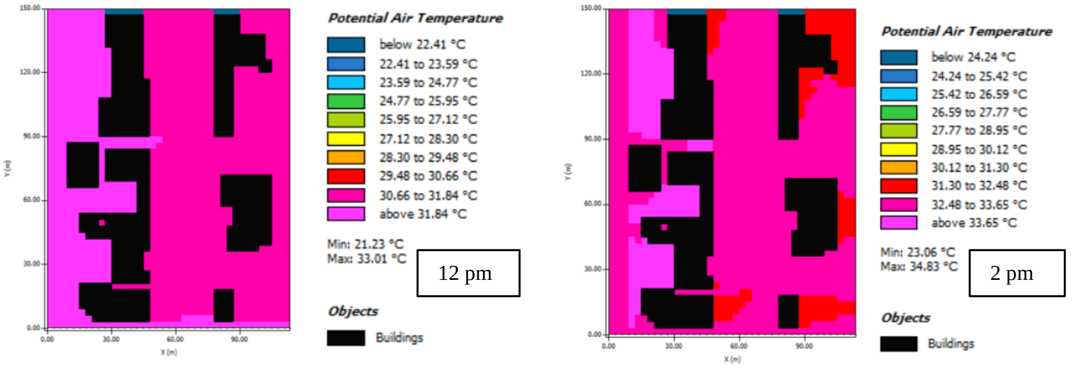


Chart 5-83 Air temperature for 12 pm and 2 pm in Scenario 11: P5: Pavement changed to Porous Concrete

As per the figure above, the potential air temperature at 8 am varies between 30.66°C and 31.84°C at 8 am. At 10 am it increases up to 33.65°C.

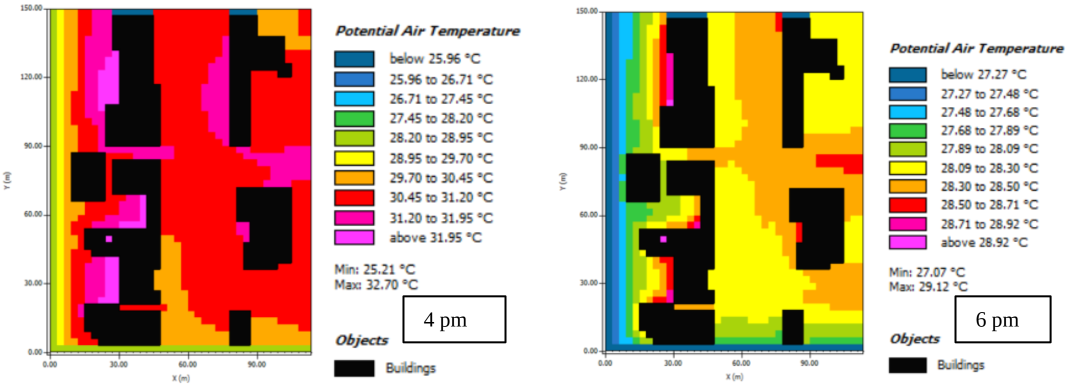


Chart 5-84 Air temperature for 4 pm and 6 pm in Scenario 11: P5: Pavement changed to Porous Concrete

The potential air temperature fluctuates from 30.25°C to 30.97°C at 4 pm and gradually it decreases and reaches up to 28.09 °C to 28.50°C at 6 pm in the evening.

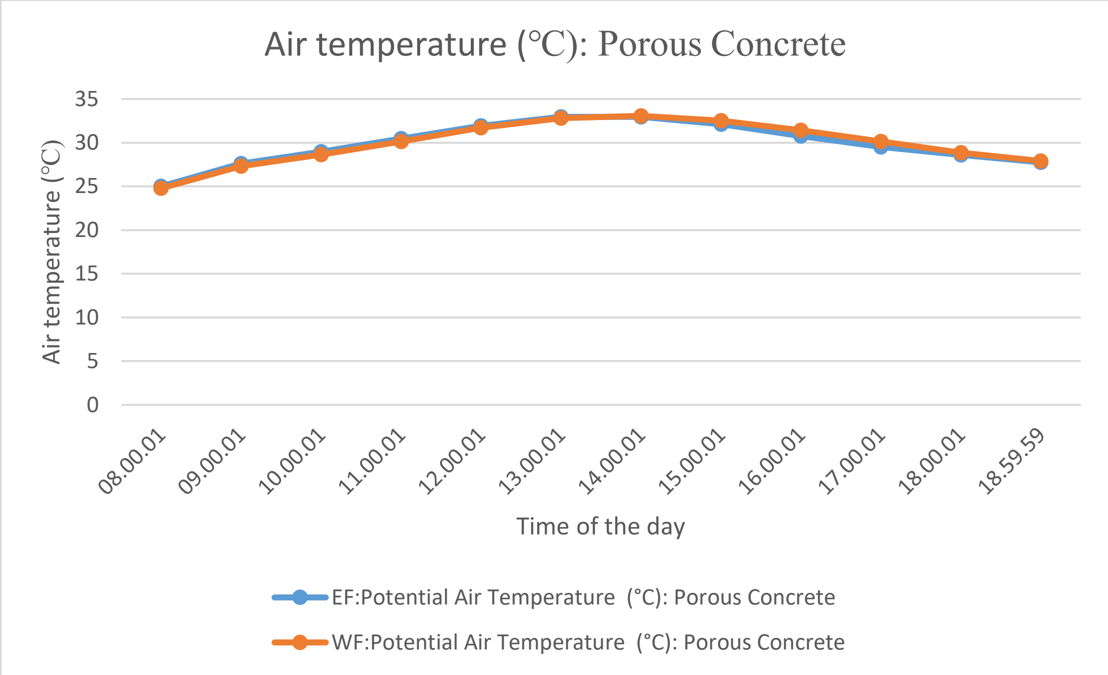


Figure 5-56 Comparison of Air temperature of East facing and west facing sidewalk for Scenario 11: P5: Pavement changed to Porous Concrete.

The graph shows the potential air temperature of east and west facing Sidewalk for Scenario. There is no significant difference in the air temperature as per the graph between two sidewalks.

Mean radiant temperature

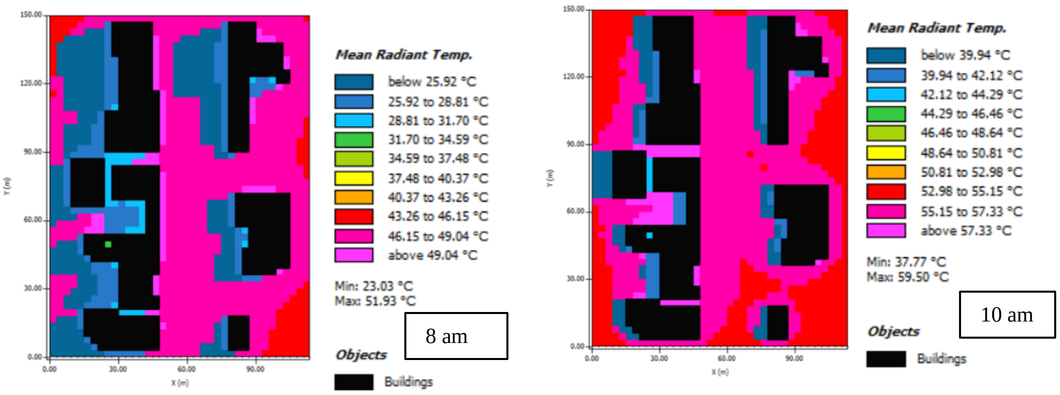


Chart 5-85 Mean radiant temperature for 8 am and 10 am in Scenario 11: P5: Pavement changed to Porous Concrete

The mean radiant temperature varies between 25.92℃ and 46.15℃ at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 55.15℃ and 57.33℃.

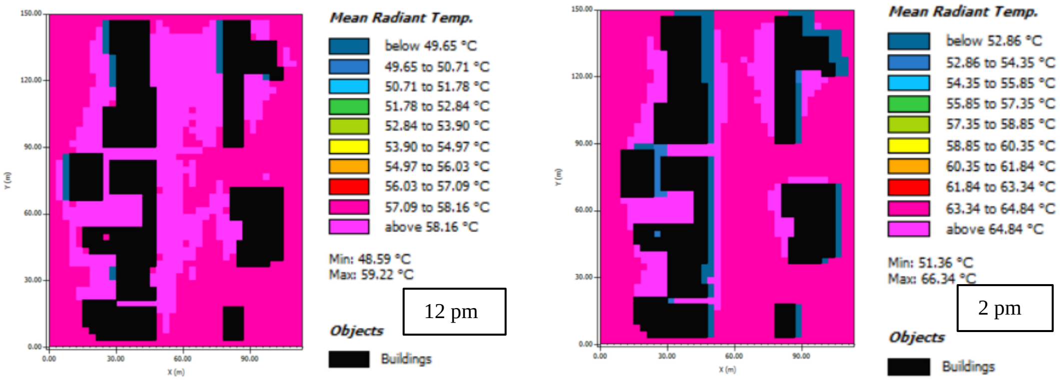


Chart 5-86 Mean radiant temperature for 12 pm and 2 pm in Scenario 11: P5: Pavement changed to Porous Concrete

The mean radiant temperature varies between 56.03℃ and 58.16℃ at 12 pm within the sidewalk. At 10 am the mean radiant temperature increases and varies between 61.84℃ and 64.84℃.

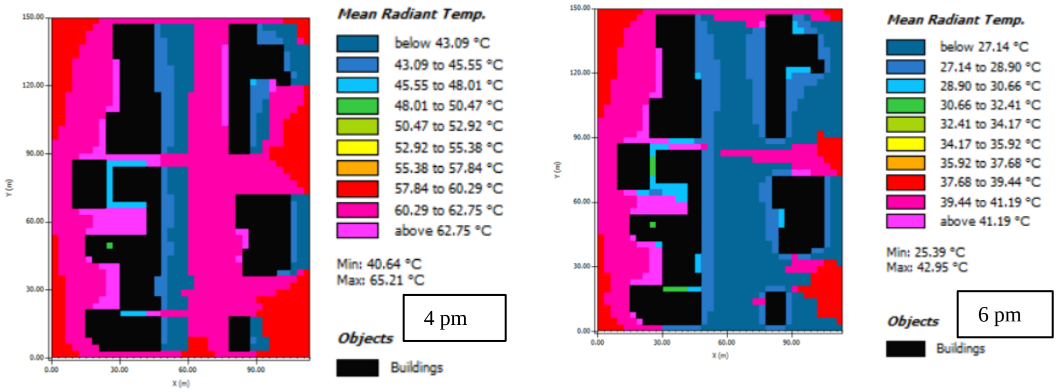


Chart 5-87 Mean radiant temperature for 4 pm and 6 pm in Scenario 11: P5: Pavement changed to Porous Concrete

The mean radiant temperature varies between 43.09℃ and 60.29℃ at 4 pm within the sidewalk. At 6 pm the mean radiant temperature increases and varies between 27.14℃ and 28.90℃.

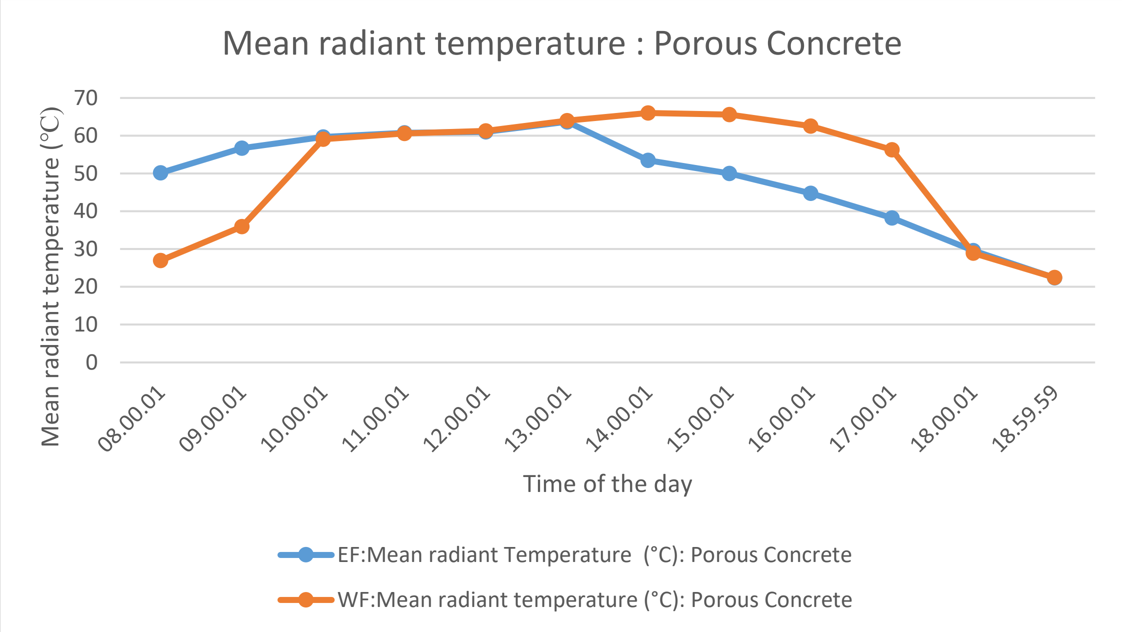
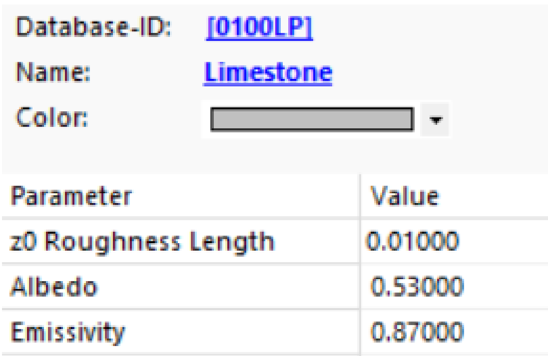


Figure 5-57 Comparison of Mean radiant temperature of East facing and west facing sidewalk for Scenario 11: P5: Pavement changed to Porous Concrete.

The graph above shows the mean radiant temperature variation throughout the day for the East facing and west facing Sidewalk. The mean radiant temperature in east facing sidewalk is higher during morning hours and less than that of west facing sidewalk between the time interval of 14pm to 17pm.

Scenario 12: P6: Pavement material changed to limestone

This scenario is created by changing the pavement material to the limestone. The albedo value for the material is 0.53 and the emissivity is 0.87. The simulation results for the scenario 9 is shown below in terms of the air temperature and mean radiant temperature.


Database-ID: [0100LP]
Name: Limestone
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.53000
Emissivity	0.87000

Figure 5-58 Properties of material in Envimet

Air temperature

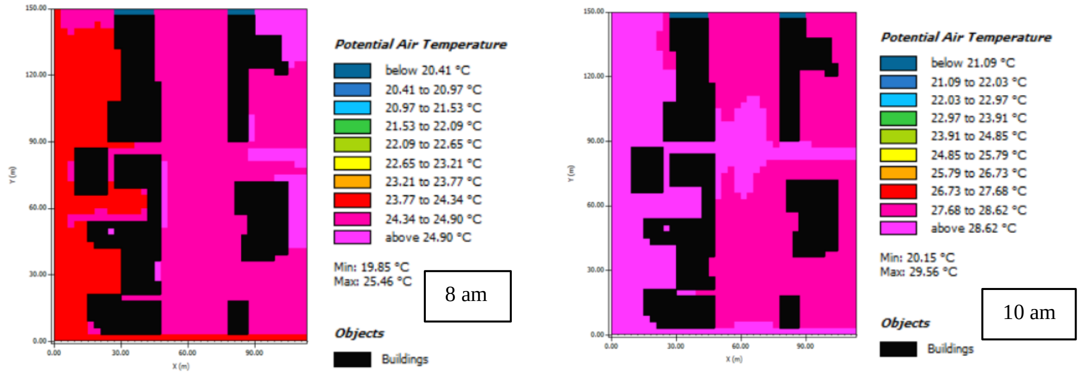


Figure 5-59 Potential air temperature for 8 am and 10 am in Scenario 12: P6: Pavement changed to limestone

As per the figure above, the potential air temperature at 8 am varies between 24.34°C and 24.90°C at 8 am. At 10 am it increases up to 28.62°C.

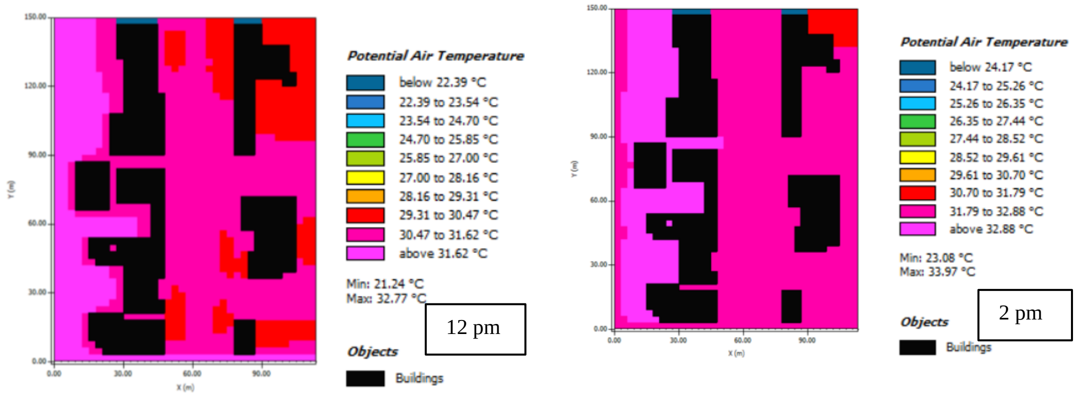


Figure 5-60 Potential air temperature for 12 pm and 2 pm in Scenario 12: P6: Pavement changed to limestone

The temperature varies between 29.31°C and 31.62°C at 12 pm and increases and varies between 31.79°C and 32.88°C at 2 pm.

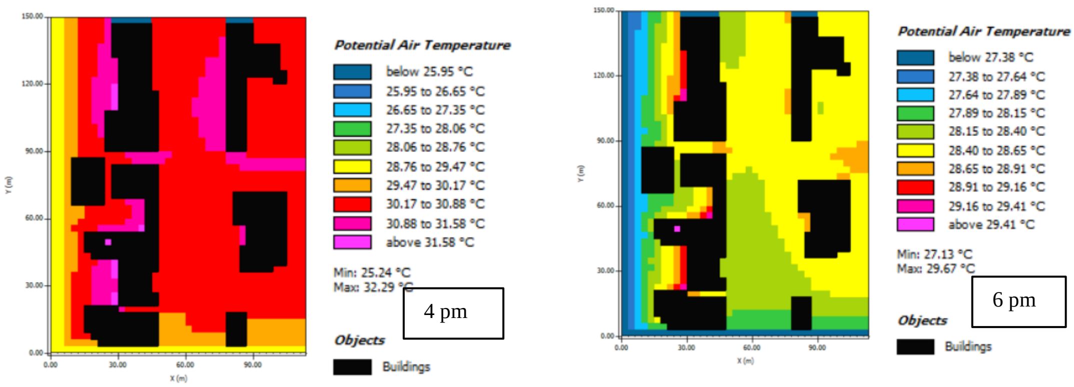


Figure 5-61 Potential air temperature for 4 pm and 6 pm in Scenario 12: P6: Pavement changed to limestone

The potential air temperature fluctuates from 30.17°C to 30.88°C at 4 pm and gradually it decreases and reaches up to 28.15 °C to 28.65°C at 6 pm in the evening.

The graph below shows the potential air temperature of east and west facing Sidewalk for Scenario 9. There is no significant difference in the air temperature as per the graph between two sidewalks.

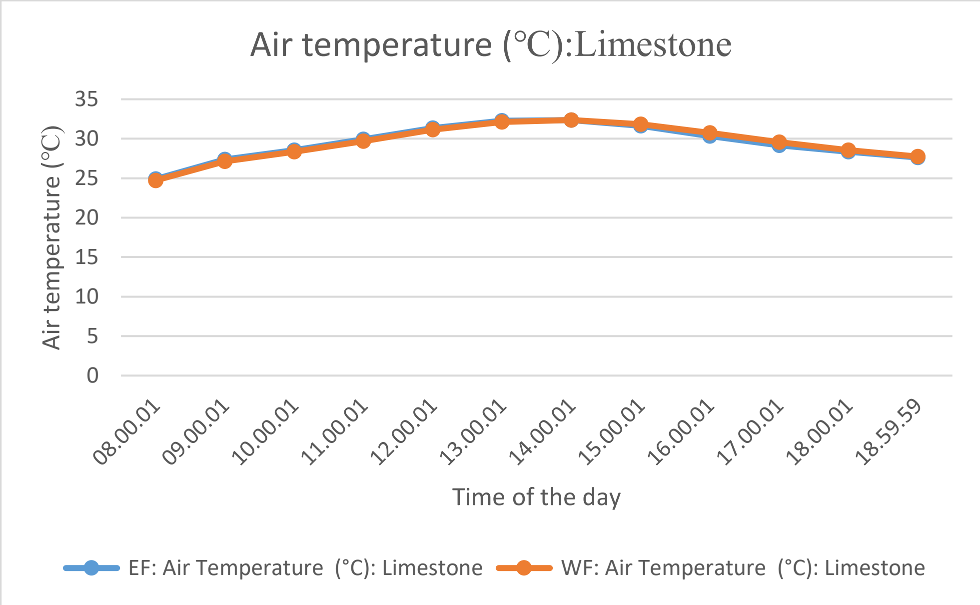


Figure 5-62 Comparison of potential air temperature for east and west facing sidewalk for scenario 12: Pavement material changed to limestone.

Mean radiant temperature

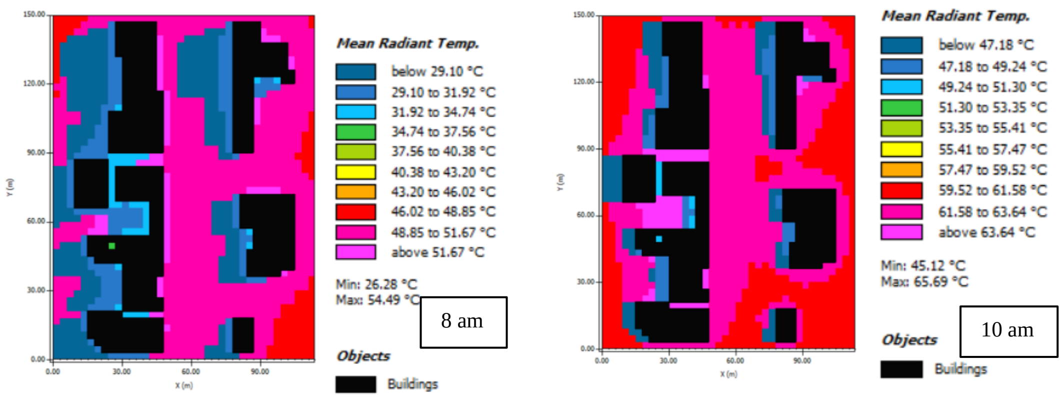


Figure 5-63 Mean radiant temperature for 8 am and 10 am in Scenario 12: Pavement changed to Limestone

The mean radiant temperature varies between 29.10℃ and 48.85℃ at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 59.92℃ and 61.58℃.

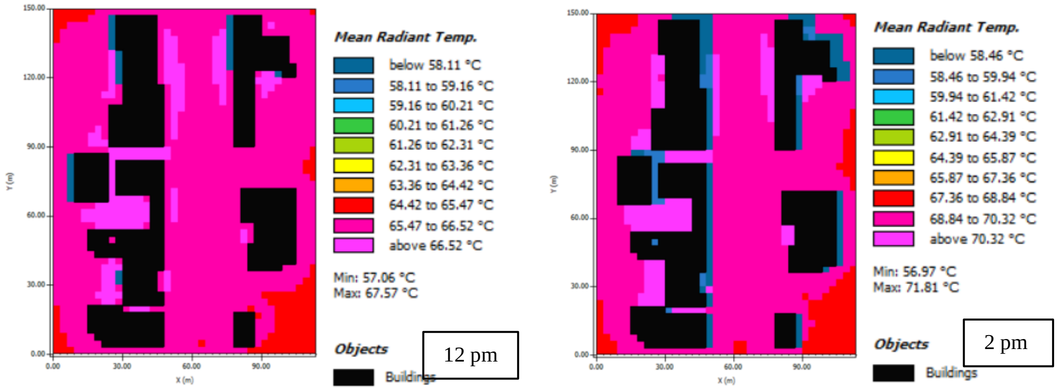


Figure 5-64 Mean radiant temperature for 12 pm and 2 pm in Scenario 12: P6: Pavement changed to limestone

The mean radiant temperature varies between 65.47℃ and 66.52 ℃ at 12 pm within the sidewalk. At 2 pm the mean radiant temperature increases and varies between 68.84℃ and 70.32 ℃.

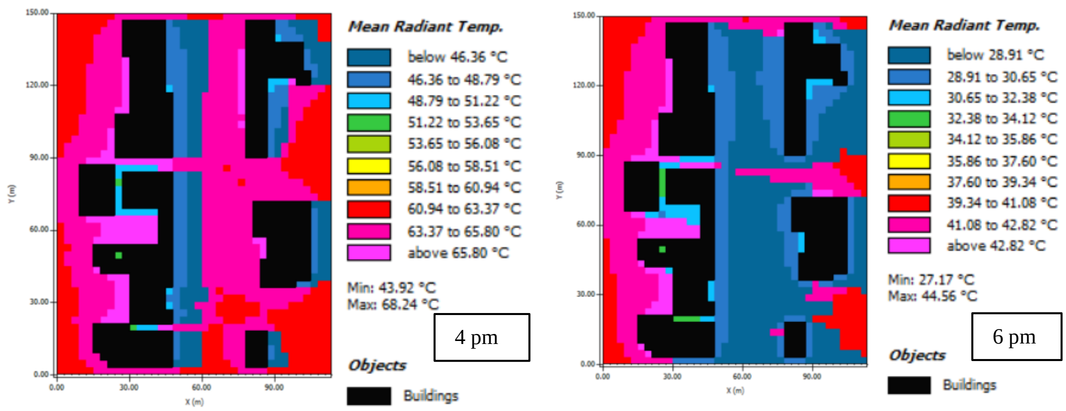


Figure 5-65 Mean radiant temperature for 4 pm and 6 pm in Scenario12: P6: Pavement changed to limestone.

The mean radiant temperature fluctuates from 46.36℃ to 63.37℃ at 4 pm. At 6 pm, the mean radiant temperature varies from 28.91 ℃ to 30.65 ℃.

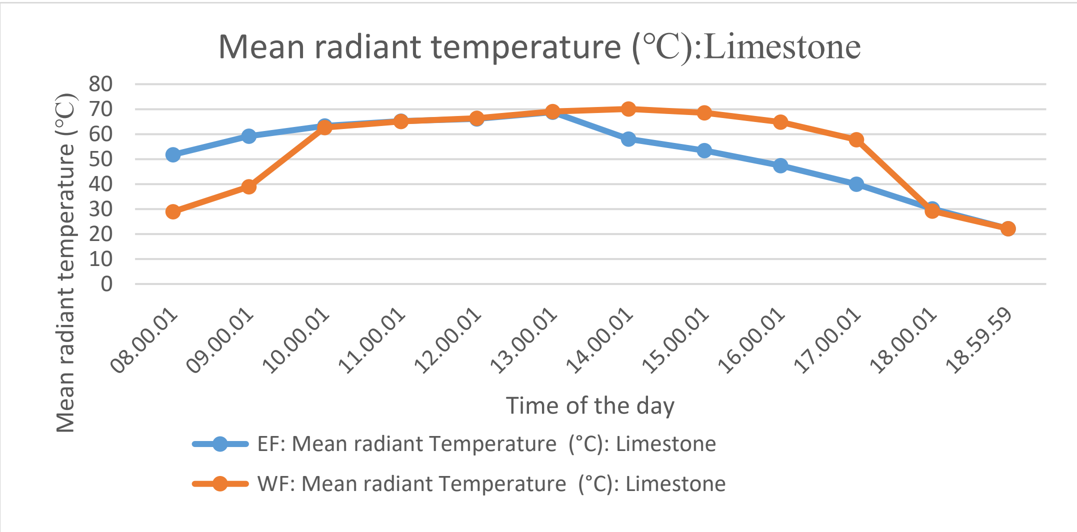


Figure 5-66 Comparison of Mean radiant temperature for east and west facing sidewalk for scenario 12: Pavement material changed to limestone.

The graph above shows the mean radiant temperature variation throughout the day for the East facing and west facing Sidewalk. The mean radiant temperature in east facing sidewalk is higher during morning hours and less than that of west facing sidewalk between the time interval of 14pm to 17pm.

Scenario 13: P7: Pavement changed to flagstone pavers

This scenario is created by changing the pavement material to the flagstone. The albedo value and emissivity for the flagstone is 0.24 and 0.925 respectively.

Database-ID: [0100FP]
Name: Flagstone pavers
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.24000
Emissivity	0.92500
ExtraID	0
Surface is irrigated	False
Water: Mixing Coefficient	0.00100
Water: Turbidity/Extinction	2.10000

Figure 5-67 Properties of material in ENVI-met

Air temperature

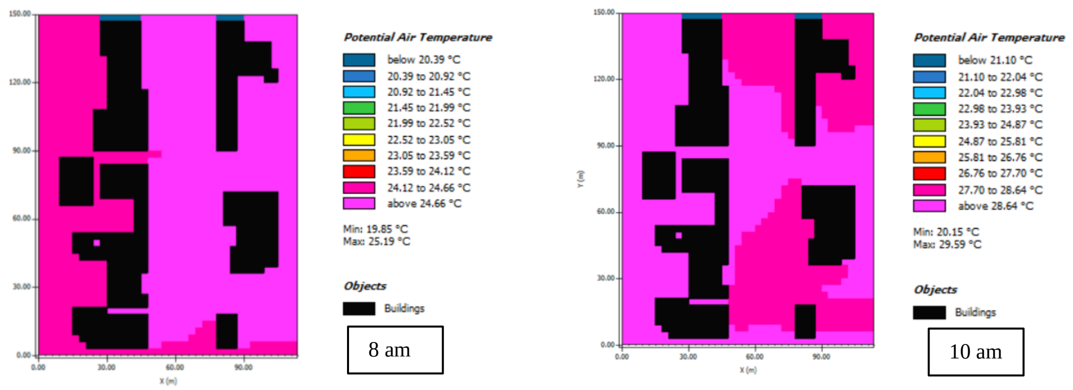


Chart 5-88 Air temperature for 8 am and 10 am in Scenario 13: P7: Pavement changed to flagstone.

As per the figure above, the potential air temperature at 8 am varies between 24.12℃ and 24.66℃ at 8 am. At 10 am it increases up to 28.64℃.

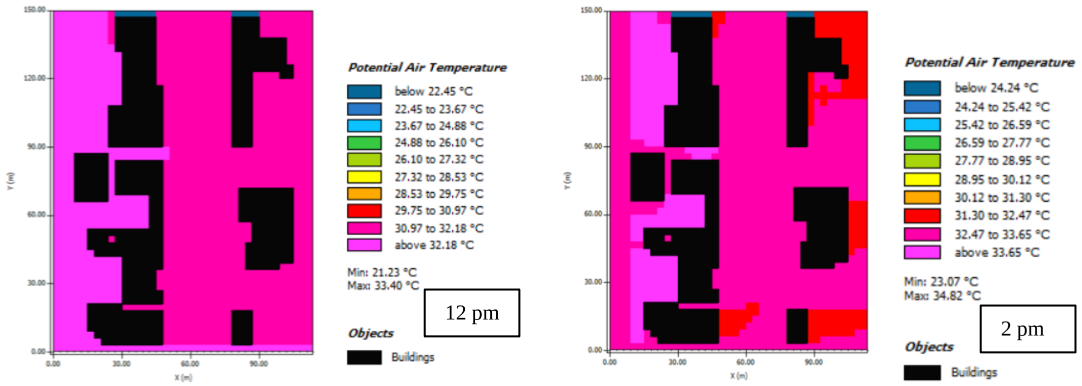


Chart 5-89 Air temperature for 12 pm and 2 pm in Scenario 13: P7: Pavement changed to flagstone.

As per the figure above, the potential air temperature at 12pm varies between 30.97℃ and 32.18℃ at 8 am. At 2 pm it increases up to 33.65℃.

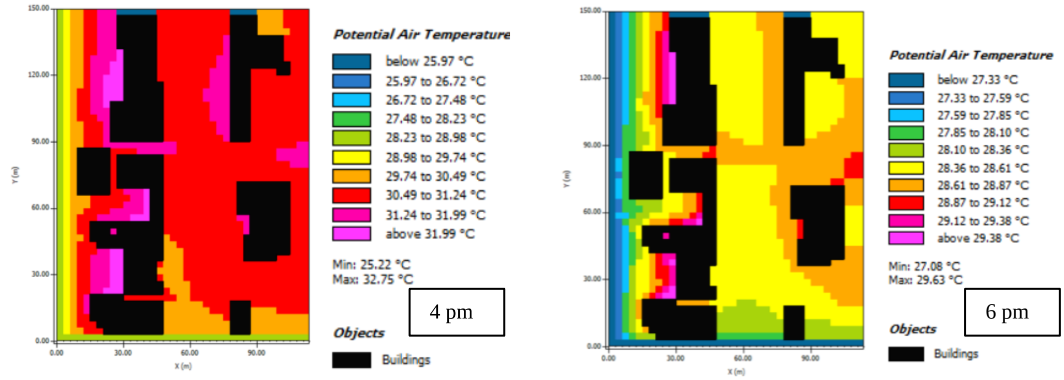


Chart 5-90 Air temperature for 4 pm and 6 pm in Scenario 13: P7: Pavement changed to flagstone.

The potential air temperature fluctuates from 29.74℃ to 31.24℃ at 4 pm and gradually it decreases and reaches up to 28.36 ℃ to 28.87℃ at 6 pm in the evening.

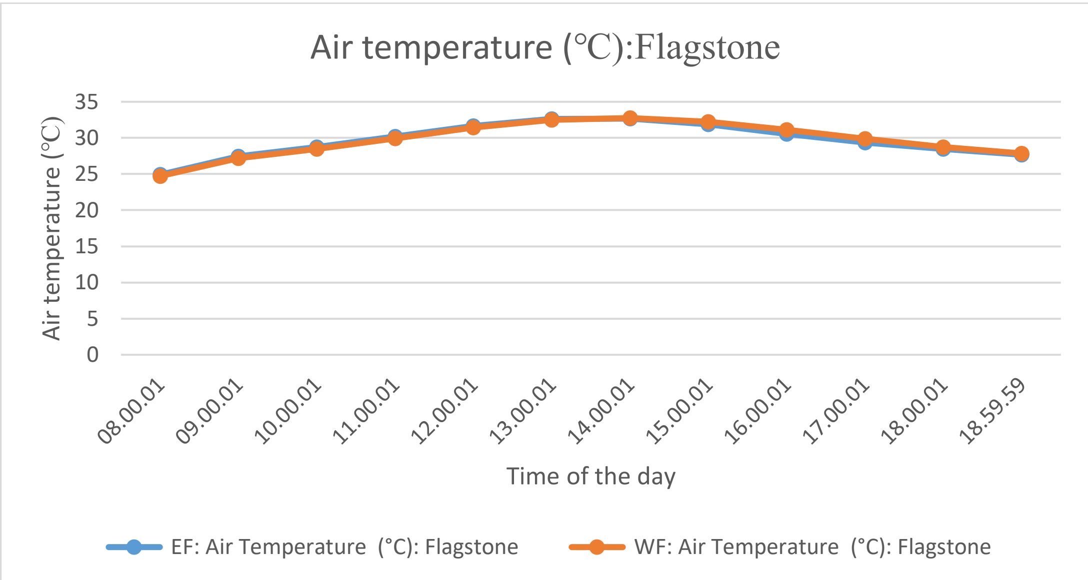


Figure 5-68 Comparison of Air temperature for east and west facing sidewalk for scenario 13: P7: Pavement material changed to limestone.

The graph shows the potential air temperature of east and west facing Sidewalk for Scenario P7. There is no significant difference in the air temperature as per the graph between two sidewalks.

Mean radiant temperature

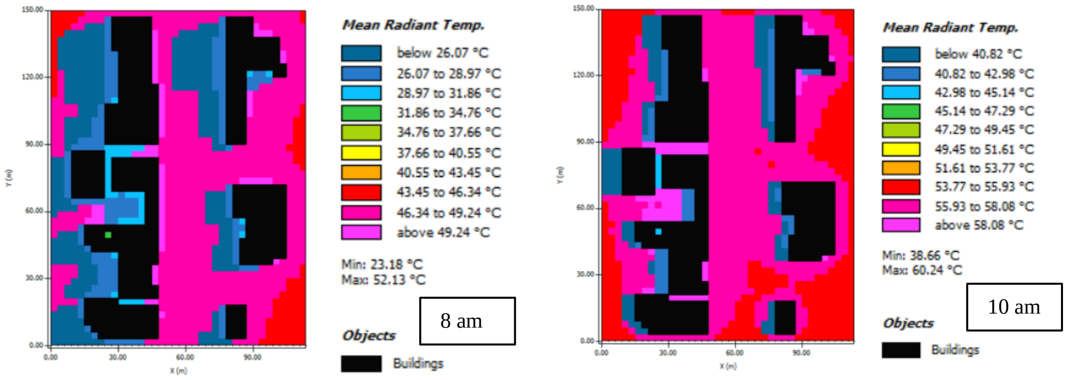


Chart 5-91 Mean radiant temperature for 8 am and 10 am in Scenario 13: P7: Pavement changed to flagstone.

The mean radiant temperature varies between 26.07°C and 46.34°C at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 55.93°C and 58.08°C.

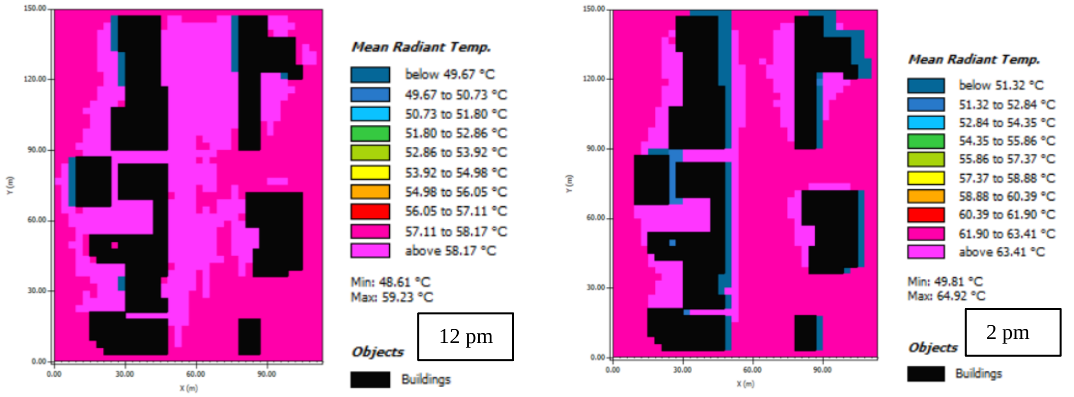


Chart 5-92 Mean radiant temperature for 12 pm and 2 pm in Scenario 13: P7: Pavement changed to flagstone.

The mean radiant temperature varies between 57.11°C and 58.17°C at 12 pm within the sidewalk. At 2pm the mean radiant temperature increases and varies between 61.90°C and 63.41°C.

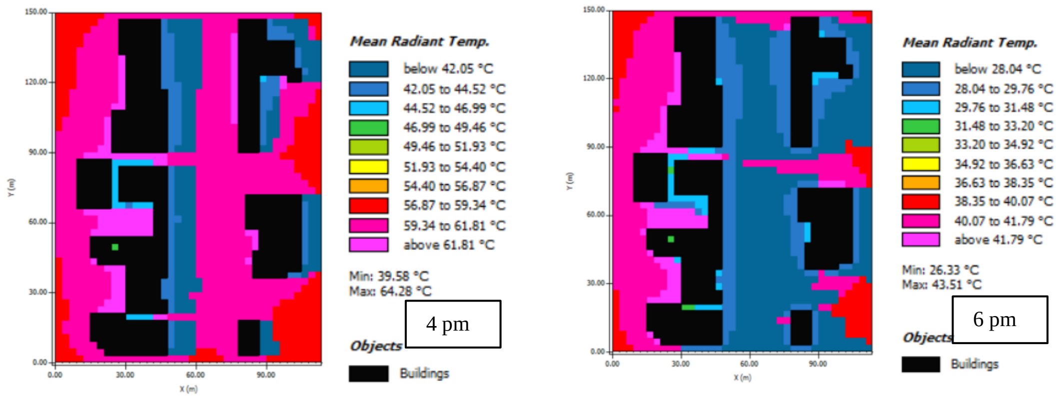


Chart 5-93 Mean radiant temperature for 4 pm and 6 pm in Scenario 13: P7: Pavement changed to flagstone.

The mean radiant temperature varies between 42.05℃ and 59.34℃ at 4 pm within the sidewalk. At 6pm the mean radiant temperature increases and varies between 28.04℃ and 29.76℃.

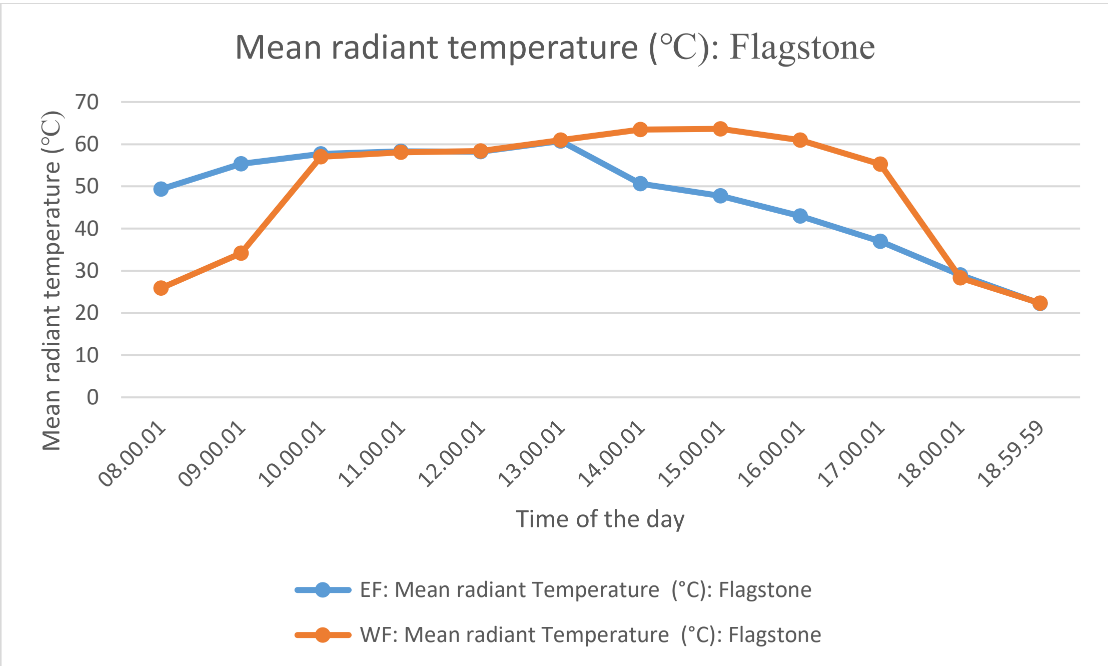
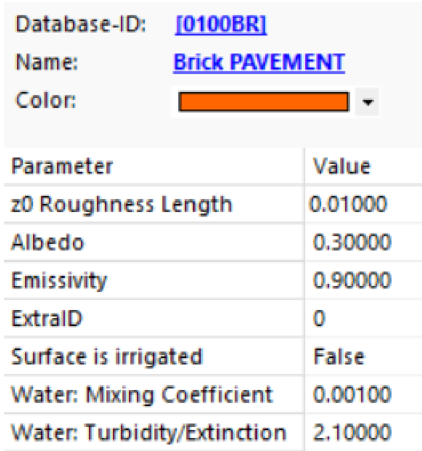


Figure 5-69 Mean radiant temperature for Flagstone as pavers for East and West facing Sidwalk

The graph above shows the mean radiant temperature variation throughout the day for the East facing and west facing Sidewalk. The mean radiant temperature in east facing sidewalk is higher during morning hours and less than that of west facing sidewalk between the time interval of 14pm to 17pm.

Scenario 14: P8: Pavement changed to Red brick pavers

This scenario is created by changing the pavement material to brick pavers. The albedo value and emissivity of the brick is 0.3 and 0.9 respectively.



Database-ID: [0100BR]
Name: Brick PAVEMENT
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.30000
Emissivity	0.90000
ExtraID	0
Surface is irrigated	False
Water: Mixing Coefficient	0.00100
Water: Turbidity/Extinction	2.10000

Figure 5-70 Properties of material in ENVI-met

Air temperature

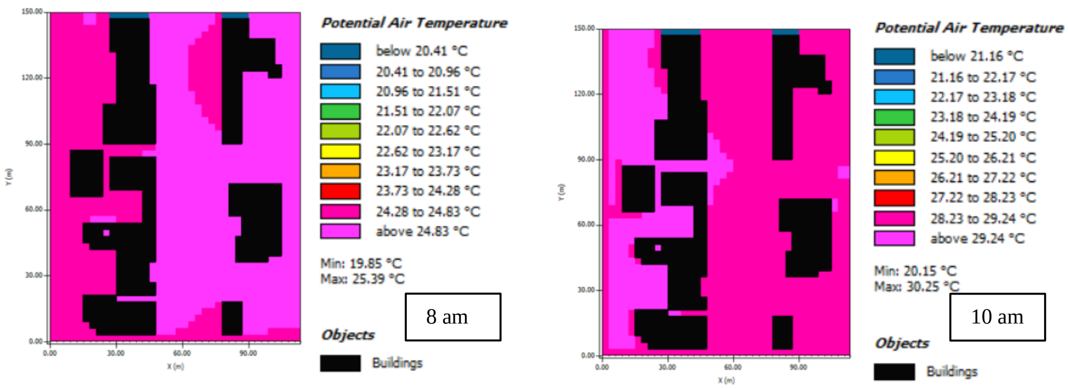


Chart 5-94 Potential air temperature at 8 am and 10 am for Scenario P8: Pavement changed to bricks

The potential air temperature varies between 24.17℃ and 24.71℃ at 8 am. At 10 am it increases up to 28.47℃ as shown in the charts.

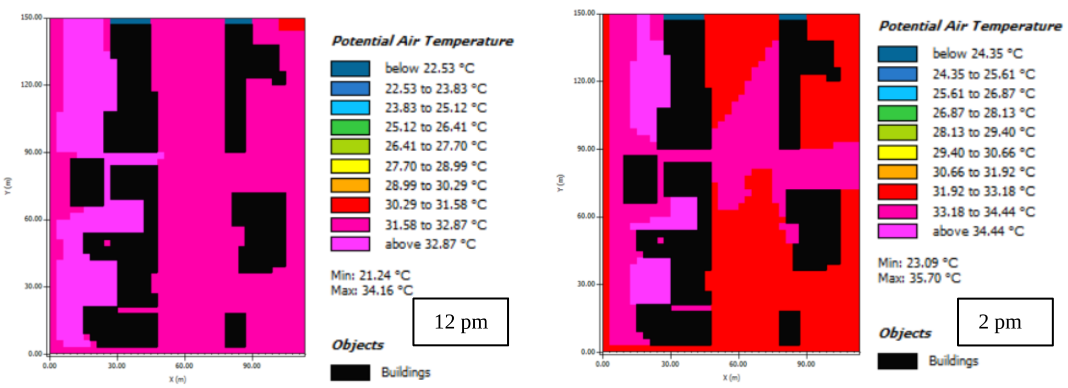


Chart 5-95 Potential air temperature at 12 pm and 2 pm for Scenario P8: Pavement changed to bricks

The potential air temperature at 12 pm varies between 31.58℃ and 32.87℃. At 2 pm it increases up to 33.18℃ as shown in the charts.

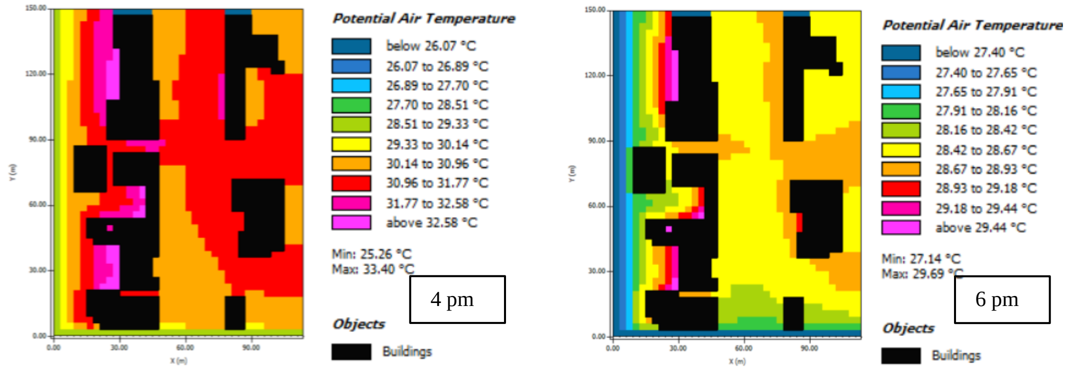


Chart 5-96 Potential air temperature at 4 pm and 6 pm for Scenario P8: Pavement changed to bricks

The potential air temperature at 4pm varies between 31.58℃ and 32.87℃. At 6 pm it increases up to 33.18℃ as shown in the charts.

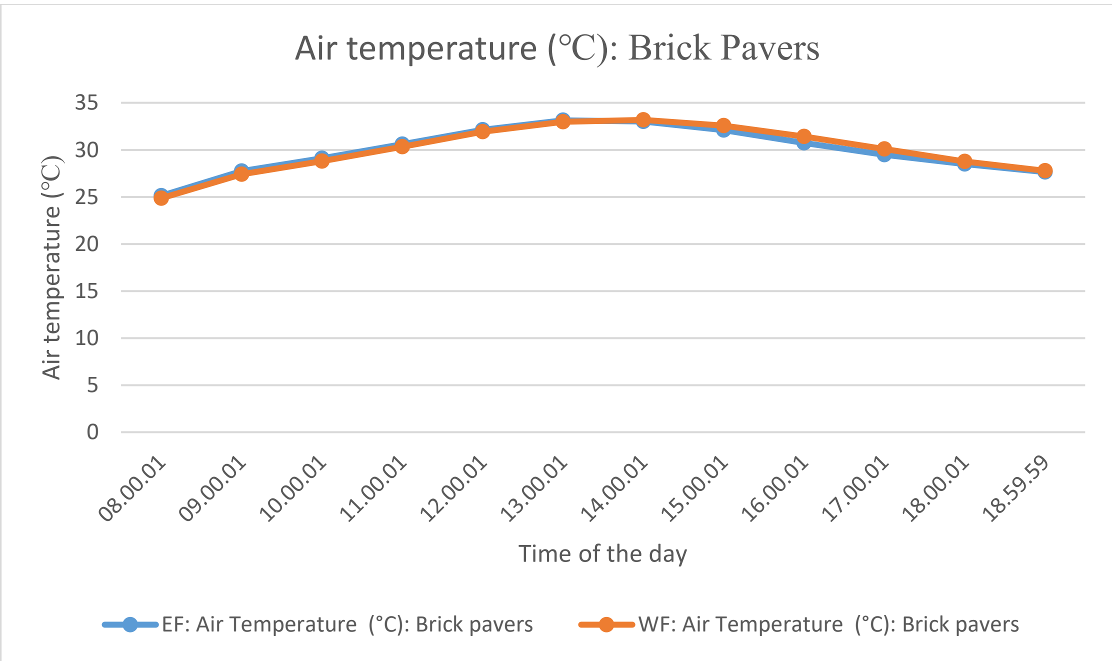


Figure 5-71 Comparison of potential air temperature for brick pavers for East and West facing Sidewalk

The graph shows the potential air temperature of east and west facing Sidewalk for Scenario P8. There is no significant difference in the air temperature as per the graph between two sidewalks.

Mean radiant temperature

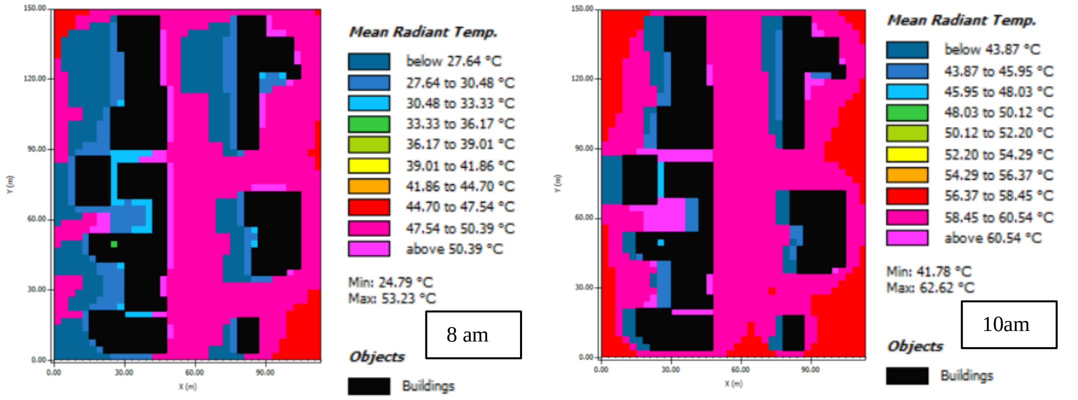


Chart 5-97 Mean radiant temperature at 8 am and 10 am for Scenario P8: Pavement changed to bricks

The mean radiant temperature varies between 27.64℃ and 50.39℃ at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 43.87℃ and 58.45℃.

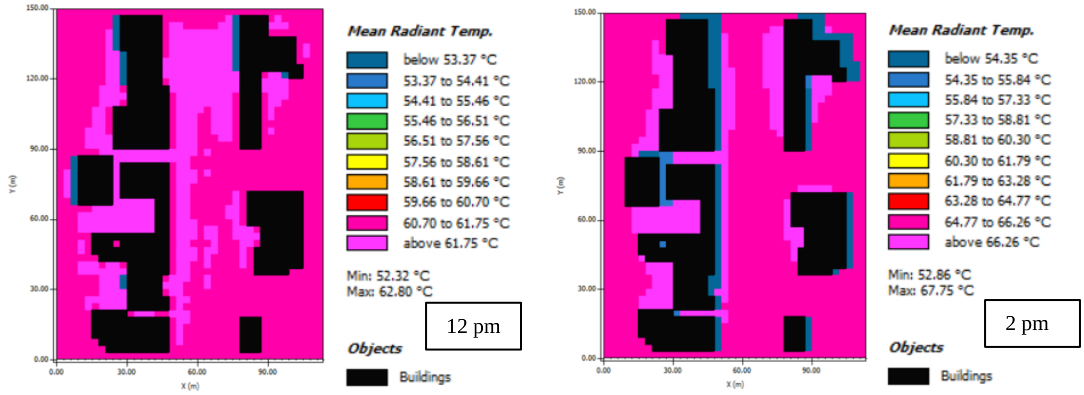


Chart 5-98 Mean radiant temperature at 12 pm and 2 pm for Scenario P8: Pavement changed to bricks

The mean radiant temperature varies between 59.66℃ and 61.75℃ at 12 pm within the sidewalk. At 2 pm the mean radiant temperature increases and varies between 64.77℃ and 66.26℃.

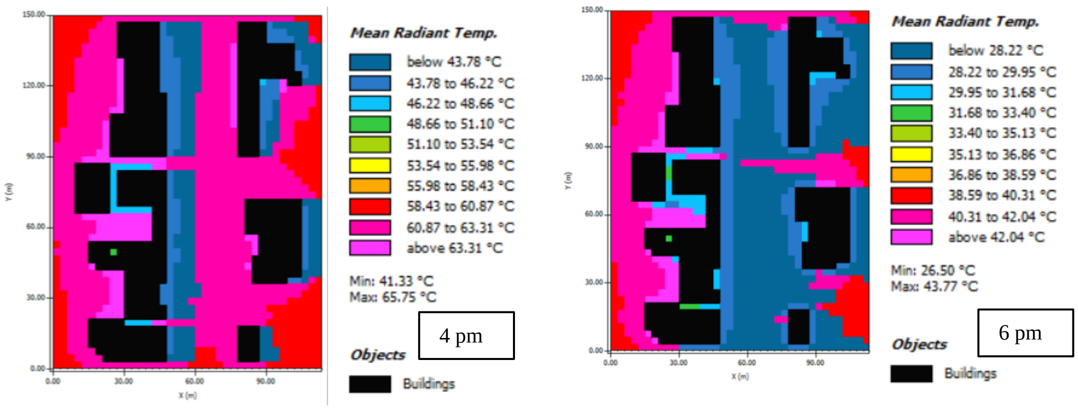


Chart 5-99 Mean radiant temperature at 4 pm and 6 pm for Scenario P8: Pavement changed to bricks

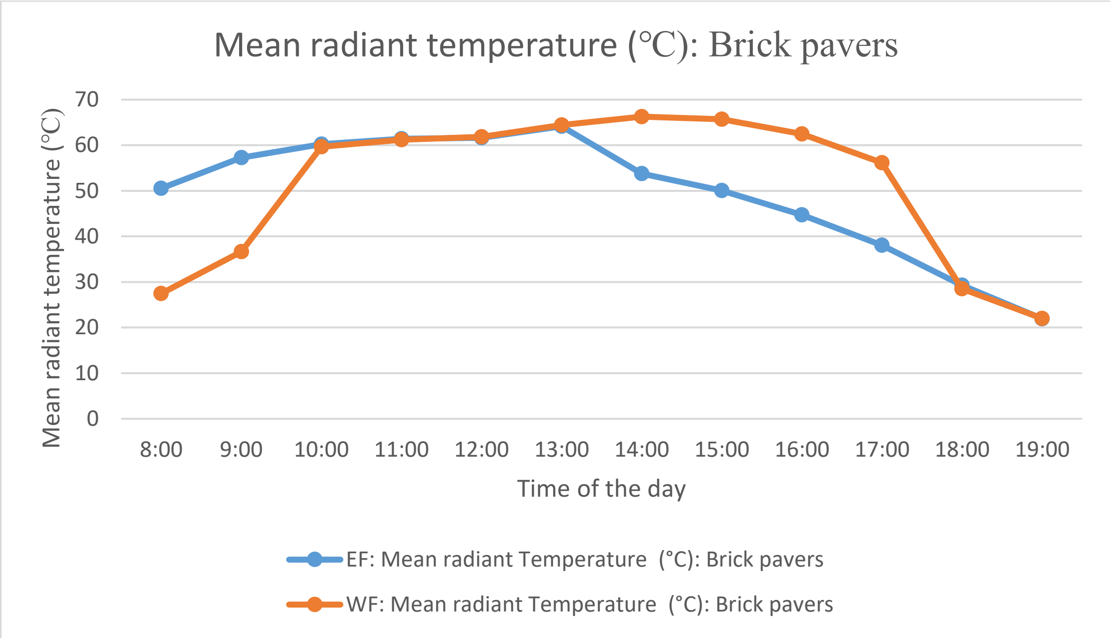
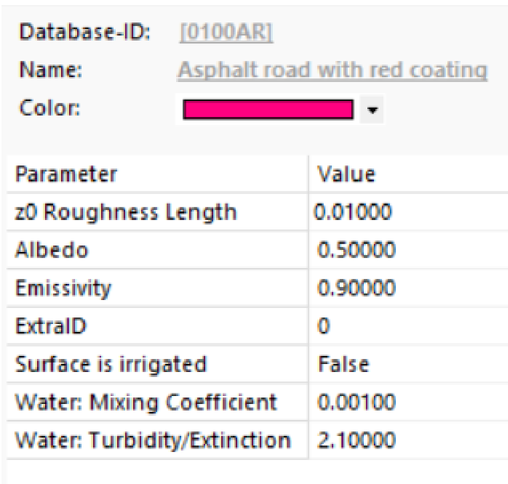


Figure 5-72 Comparison of Mean radiant temperature for brick pavers for East and West facing Sidewalk

The graph above shows the mean radiant temperature variation throughout the day for the East facing and west facing Sidewalk. The mean radiant temperature in east facing sidewalk is higher during morning hours and less than that of west facing sidewalk between the time interval of 14pm to 17pm.

Scenario 15: P9: Pavement changed to Asphalt with red coating

This scenario is created by changing the regular asphalt to the asphalt with red coating. The albedo value is increased to 0.5 and the emissivity is 0.9.



Database-ID: [0100AR]
Name: Asphalt road with red coating
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.50000
Emissivity	0.90000
ExtraID	0
Surface is irrigated	False
Water: Mixing Coefficient	0.00100
Water: Turbidity/Extinction	2.10000

Figure 5-73

Air temperature

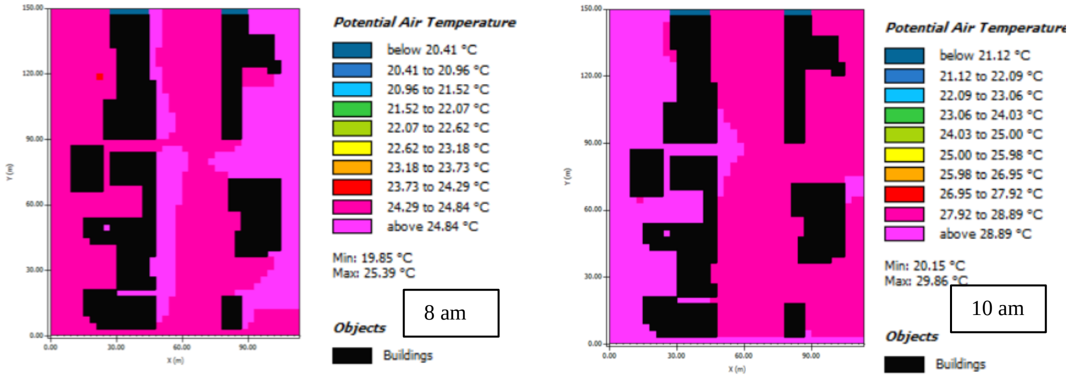


Chart 5-100 Air temperature at 8 am and 10 am for Scenario P9: Asphalt changed to colored Asphalt

As per the figure above, the potential air temperature varies between 24.29°C and 24.84°C at 8 am. At 10 am it increases up to 27.92°C.

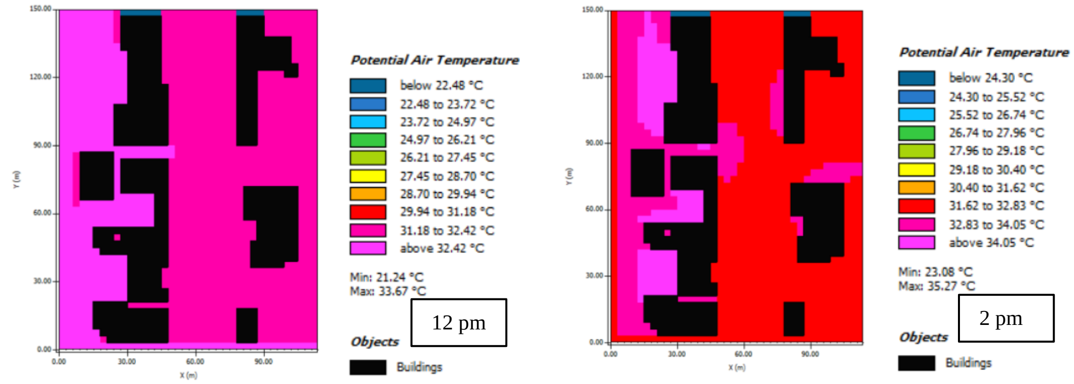


Chart 5-101 Air temperature at 12pm and 2 pm for Scenario P9: Asphalt changed to colored Asphalt

As per the figure above, the potential air temperature at 12 pm varies between 31.18°C and 32.42°C. At 2pm it increases up to 31.62°C.

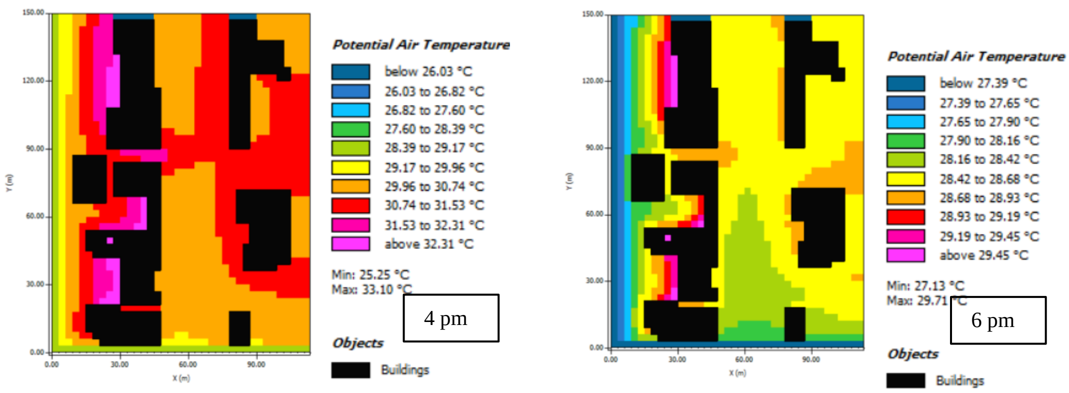


Chart 5-102 Air temperature at 4 pm and 6 pm for Scenario P9: Asphalt changed to colored Asphalt

As per the figure above, the potential air temperature at 8 am varies between 29.96°C and 31.53°C at 4 pm. At 6 pm it increases and varies between 28.16°C and 28.68°C.

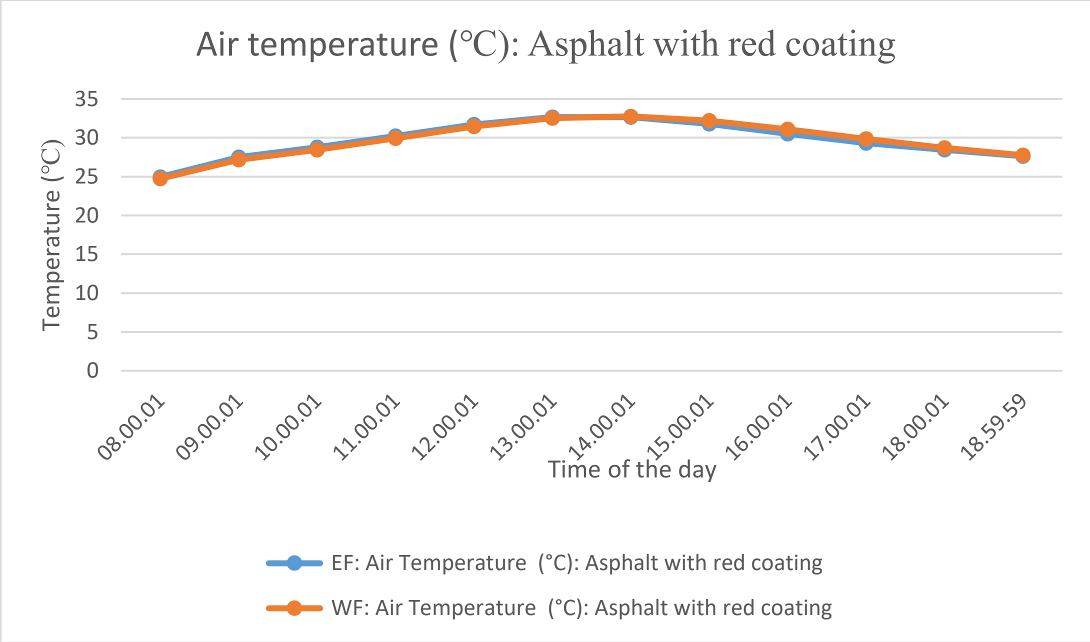


Figure 5-74 Comparison of potential air temperature for Scenario 15 for East and West facing Sidewalk

The graph shows the potential air temperature of east and west facing Sidewalk for Scenario 15. There is no significant difference in the air temperature as per the graph between two sidewalks.

Mean radiant temperature

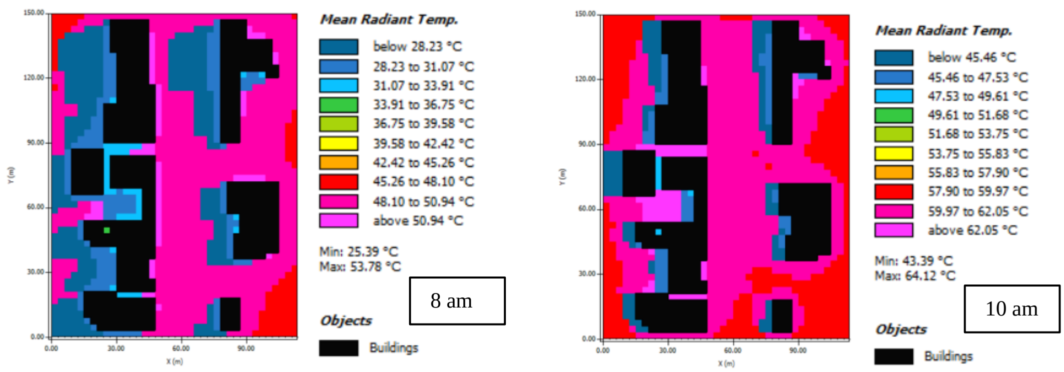


Chart 5-103 Mean radiant temperature at 8 am and 10 am for Scenario P9: Asphalt changed to colored Asphalt

The mean radiant temperature varies between 28.23℃ and 48.10℃ at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 59.97℃ and 62.05℃.

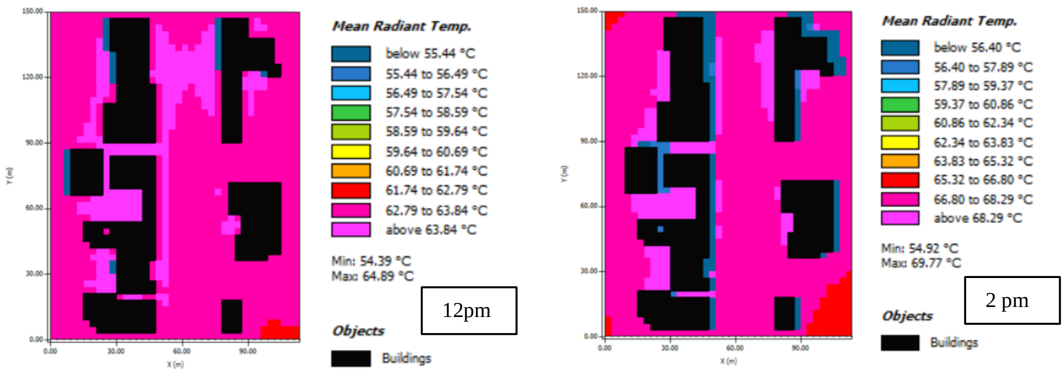


Chart 5-104 Mean radiant temperature at 12 pm and 2 pm for Scenario P9: Asphalt changed to colored Asphalt

The mean radiant temperature varies between 62.79℃ and 63.84℃ at 12 pm within the sidewalk. At 2 pm the mean radiant temperature increases and varies between 66.80℃ and 68.29℃.

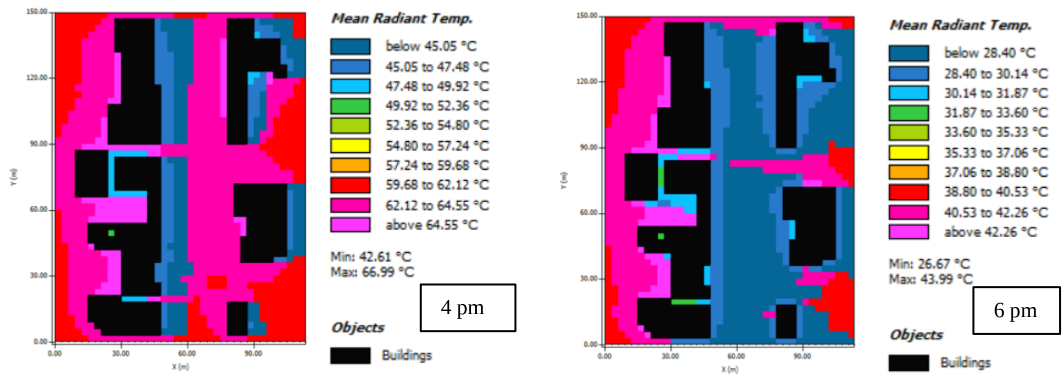


Chart 5-105 Mean radiant temperature at 4 pm and 6 pm for Scenario P9: Asphalt changed to colored Asphalt

The mean radiant temperature varies between 45.05℃ and 62.12℃ at 4 pm within the sidewalk. At 6 pm the mean radiant temperature increases and varies between 28.40℃ and 30.14℃.

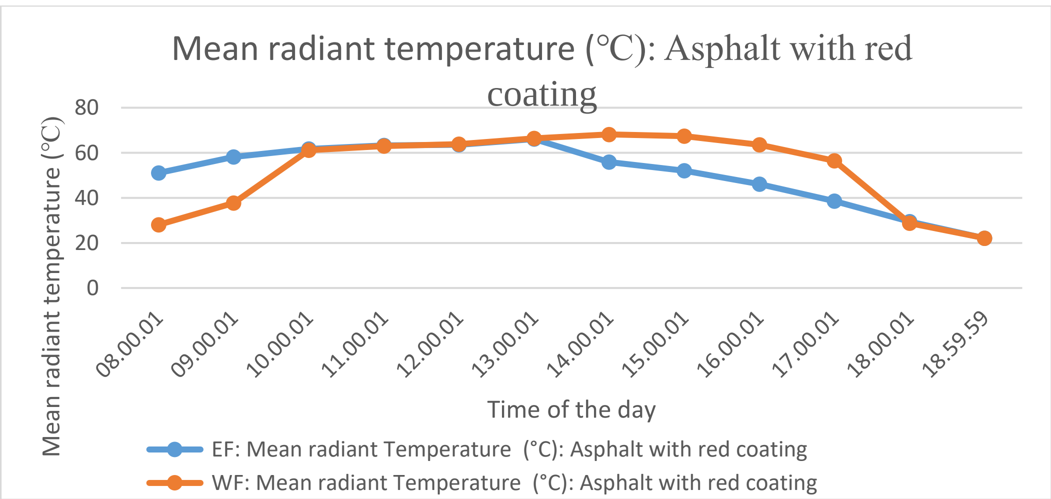


Figure 5-75 Comparison of Mean radiant temperature for Scenario 15 for East and West facing Sidewalk

The graph above shows the mean radiant temperature variation throughout the day for the East facing and west facing Sidewalk. The mean radiant temperature in east facing sidewalk is higher during morning hours and less than that of west facing sidewalk between the time interval of 14pm to 17pm.

Scenario 16: V1P2: High LAD trees (9m X 10m) and pavement light color concrete.

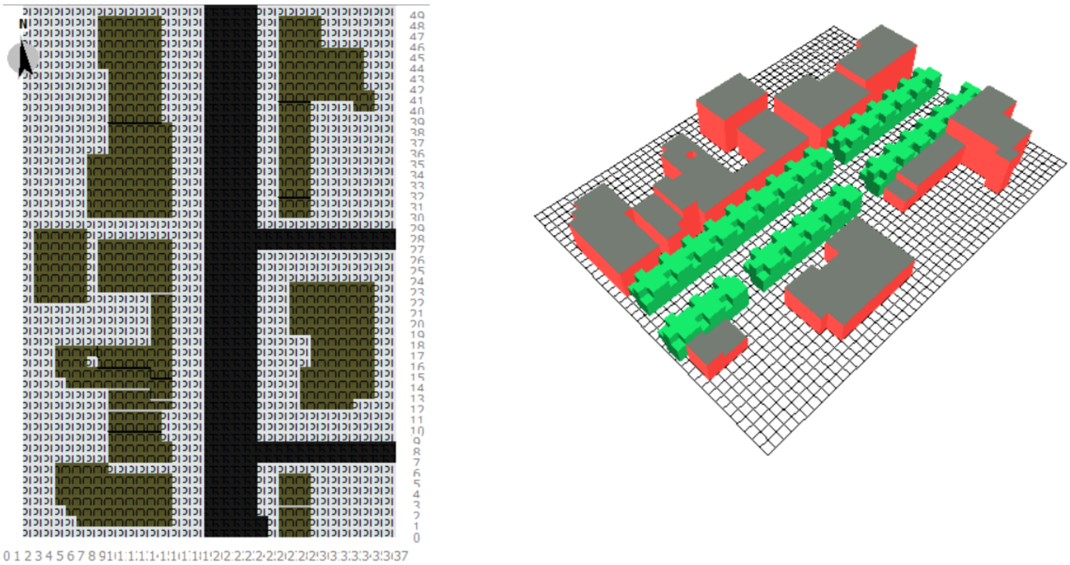
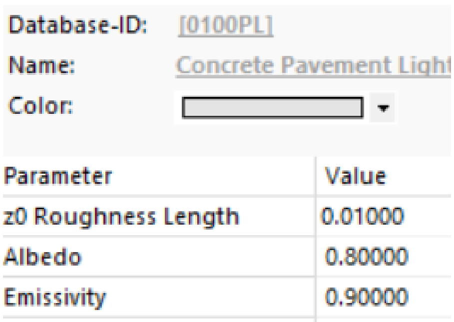


Figure 5-76 2D and 3D model in ENVI-met of Scenario 16: High LAD trees (9m X 10m) Pavement light color concrete

This scenario is created by changing the pavement material to light color concrete.

From the literature it is evident that the light colour material reflects more sunlight and hence are known as cool pavements. The light coloured concrete having albedo value 0.8 and emissivity 0.9 is used for this scenario.

The material is from the default settings of envimet.



Database-ID: [0100PL]
Name: Concrete Pavement Light
Color:

Parameter	Value
z0 Roughness Length	0.01000
Albedo	0.80000
Emissivity	0.90000

Figure 5-77 Properties of material in envimet

Air temperature

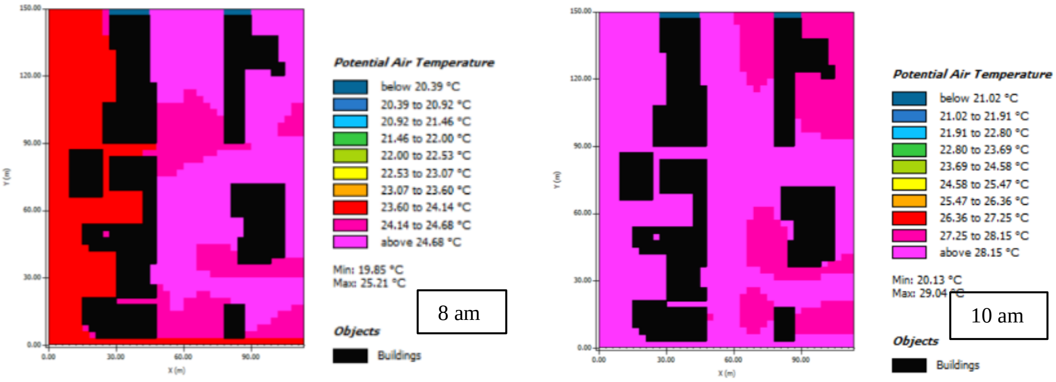


Chart 5-106 Potential air temperature for 8 am and 10 am in Scenario 16: Pavement changed to light colored concrete.

As per the figure above, the potential air temperature at 8 am varies between 23.60°C and 24.68°C at 8 am. At 10 am it increases up to 28.15°C.

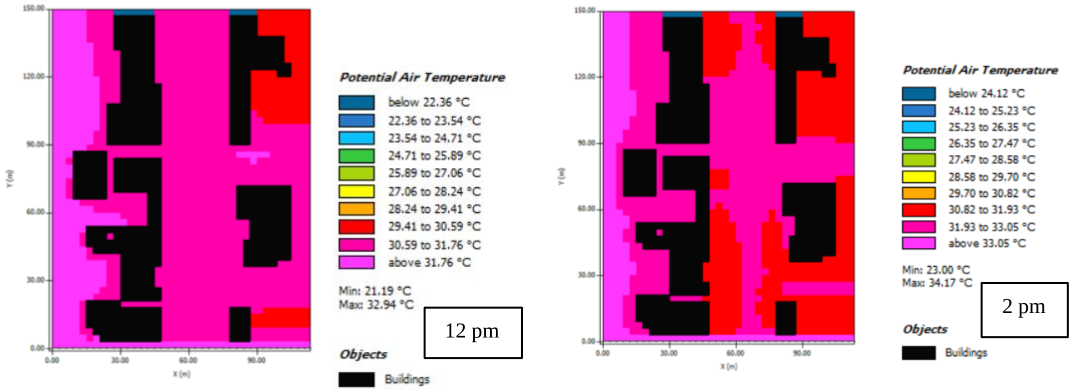


Chart 5-107 Potential air temperature for 12 pm and 2 pm in Scenario 16: Pavement changed to light colored concrete.

The temperature varies between 30.59°C and 31.76°C at 12 pm and increases and varies between 30.82°C and 33.05 °C at 2 pm.

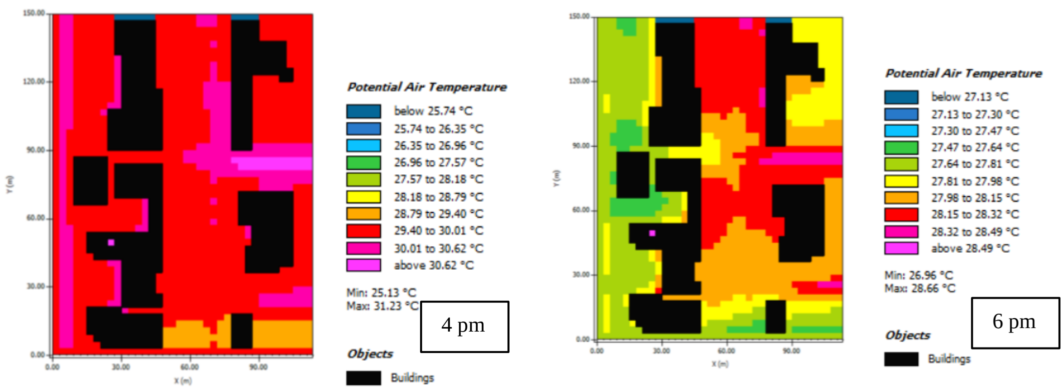


Chart 5-108 Potential air temperature for 4 pm and 6 pm in Scenario 16: Pavement changed to light colored concrete.

The potential air temperature fluctuates from 29.40℃ to 30.01℃ at 4 pm and gradually it decreases and reaches up to 28.15 ℃ within some parts of sidewalk at 6 pm in the evening.

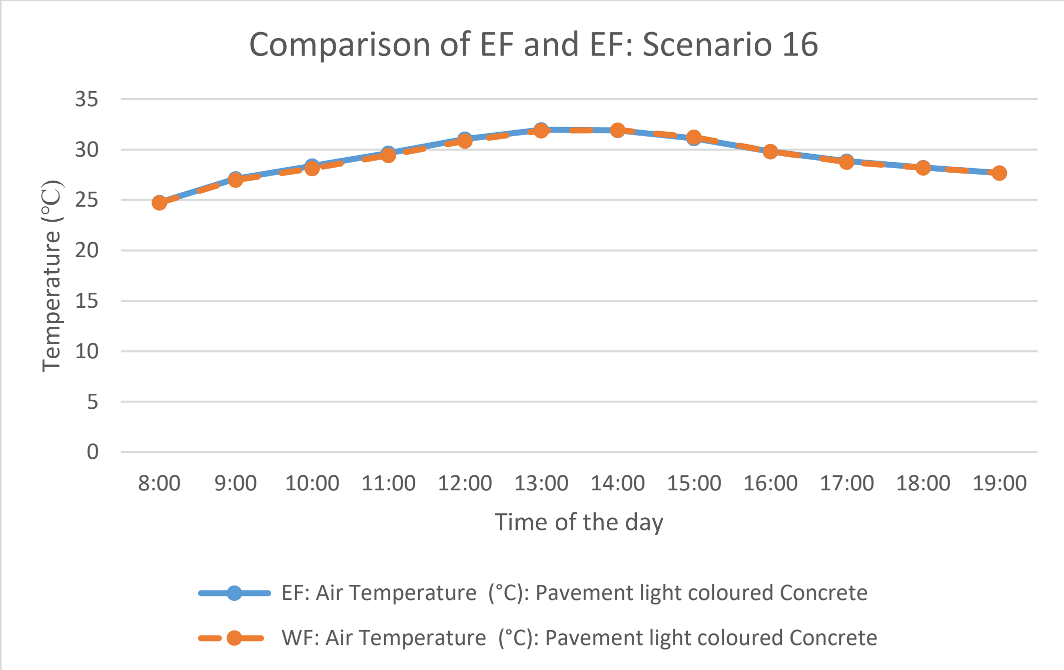


Figure 5-78 Comparison of potential air temperature of east and west facing Sidewalk: Scenario 16: Changing pavement material to light color concrete.

The graph shows the potential air temperature of east and west facing Sidewalk for Scenario 16. There is no significant difference in the air temperature as per the graph between two sidewalks.

Mean radiant temperature

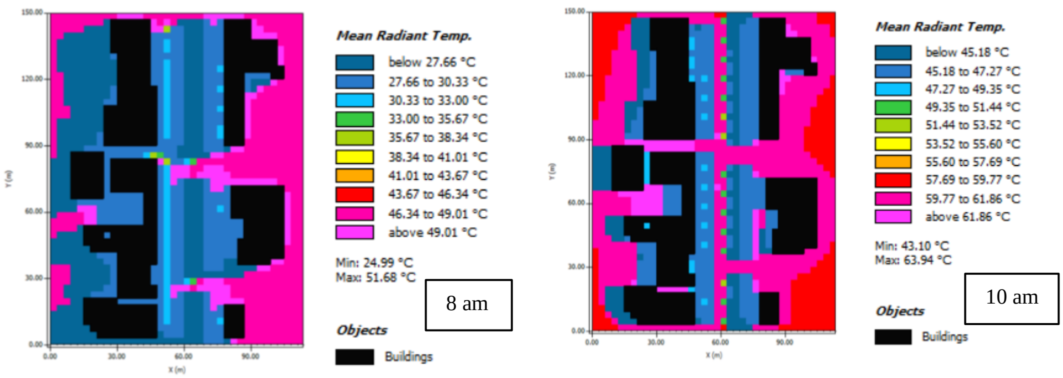


Chart 5-109 Mean radiant temperature for 8 am and 10 am in Scenario 16: Pavement changed to light colored concrete.

The mean radiant temperature varies between 27.66℃ and 30.33℃ at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 45.18℃ and 47.27 ℃.

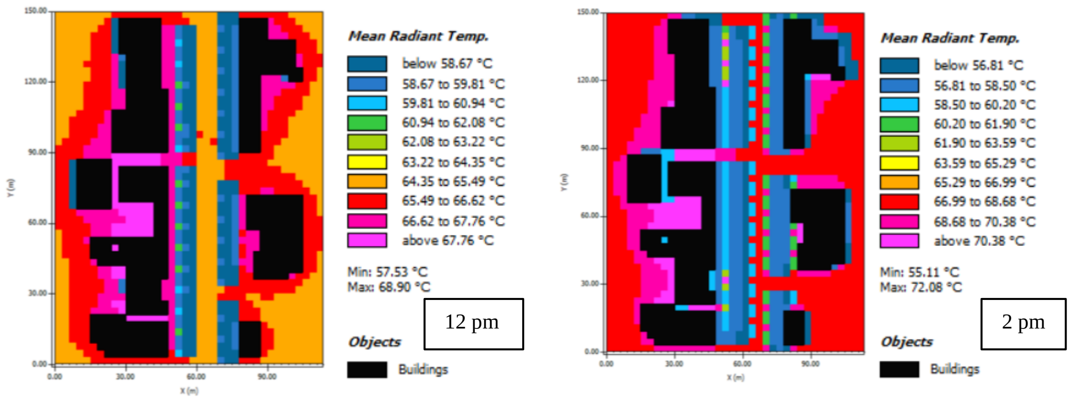


Chart 5-110 Mean radiant temperature for 12pm and 2pm in Scenario `16: Pavement changed to light colored concrete.

The mean radiant temperature varies between 58.67℃ and 64.25 ℃ at 12 pm within the sidewalk. At 2 pm the mean radiant temperature increases and varies between 56.81℃ and 58.50 ℃.

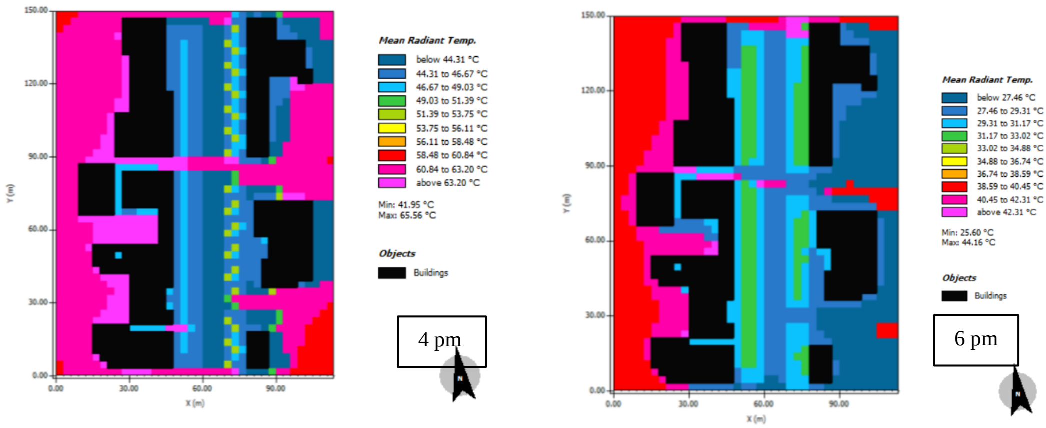


Chart 5-111 Mean radiant temperature for 4pm and 6pm in Scenario 16: Pavement changed to light colored concrete.

The mean radiant temperature fluctuates from 44.31℃ to 49.03℃ at 4 pm. At 6 pm, the mean radiant temperature varies from 27.46 ℃ to 33.02 ℃.

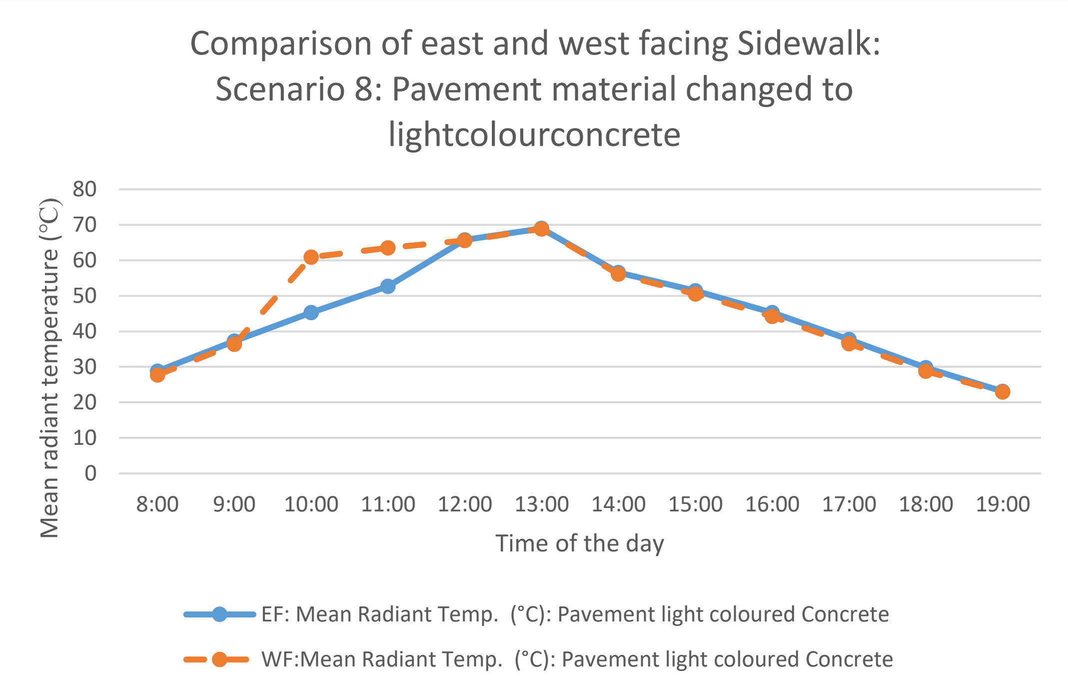


Figure 5-79 Comparison of mean radiant temperature of east facing and west facing Sidewalk for Scenario 16: Pavement material changed to light concrete.

The graph above shows the mean radiant temperature variation throughout the day for the East facing and west facing Sidewalk. The mean radiant temperature in west facing sidewalk is slightly higher at 10 am and 11 am.

Scenario 17: V1P2: High LAD trees (9m X 10m) and pavement porous concrete.

This scenario is created by changing the pavement material to porous concrete.

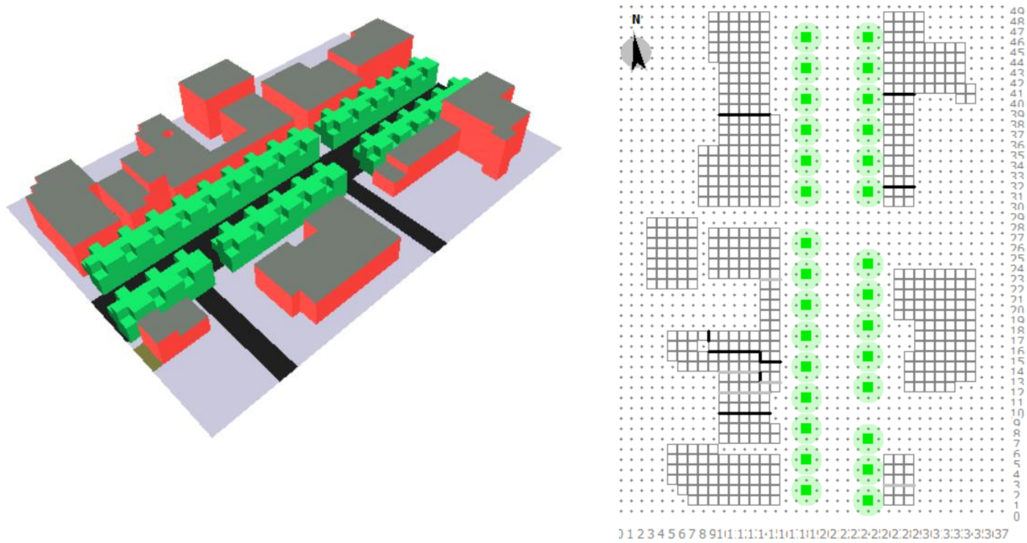


Figure 5-80 2D and 3D model in ENVI-met of Scenario 17: High LAD trees (9m X 10m) Pavement porous concrete

Air temperature

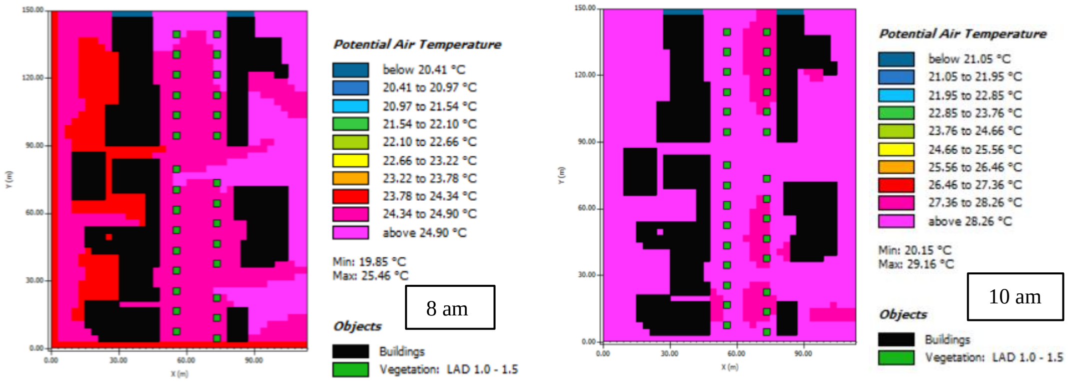


Chart 5-112 Potential air temperature for 8 am and 10 am in Scenario 17: High LAD trees (9m X 10m) Pavement porous concrete.

As per the figure above, the potential air temperature at 8 am varies between 24.34°C and 24.90°C at 10 am. At 10 am it increases up to 28.26°C.

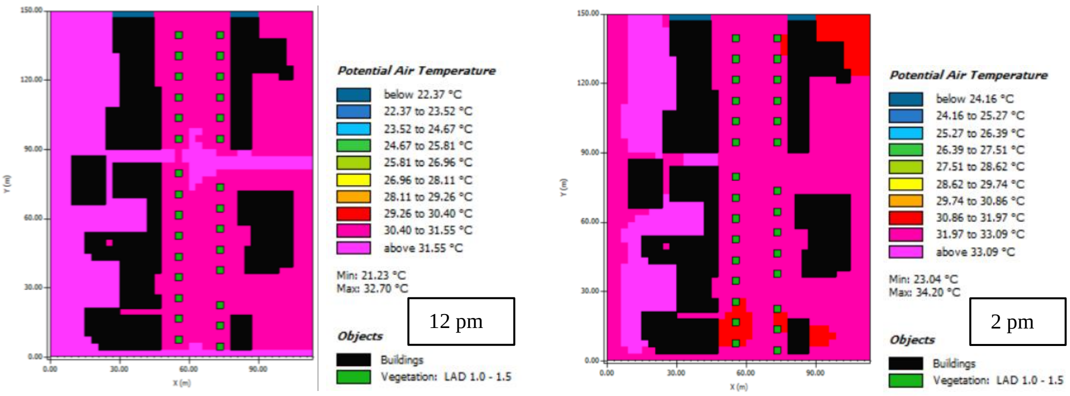


Chart 5-113 Potential air temperature for 12 pm and 2 pm in Scenario 17: High LAD trees (9m X 10m) Pavement porous concrete.

The potential air temperature at 12 pm varies between 30.40°C and 31.55°C and it increases from 31.97°C to 33.09°C.

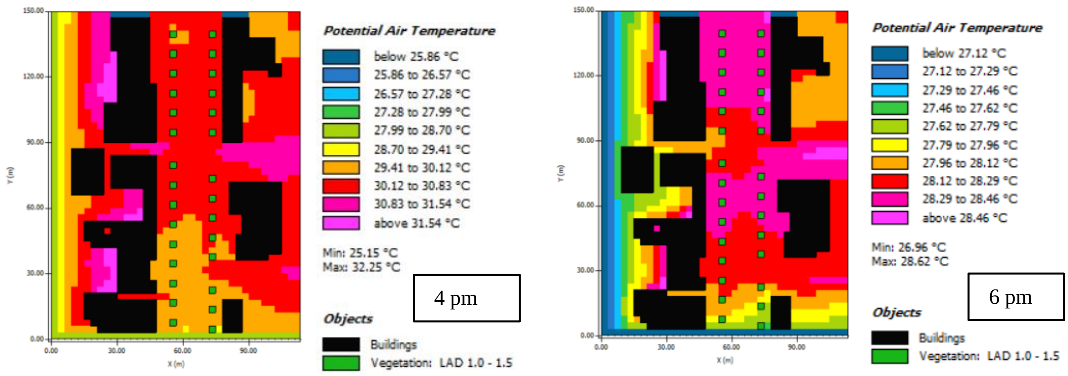


Chart 5-114 Potential air temperature for 4 pm and 6 pm in Scenario 17: High LAD trees (9m X 10m) Pavement porous concrete.

The potential air temperature at 4 pm varies between 29.41°C and 30.83°C and it increases from 27.62°C to 28.46°C.

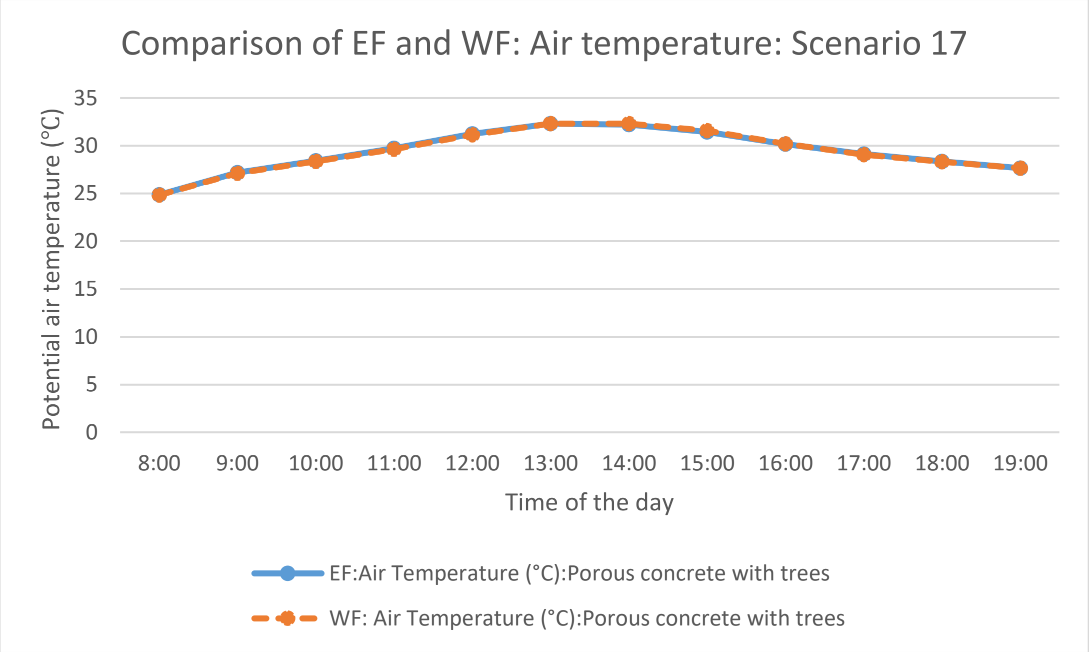


Figure 5-81 Comparison of potential air temperature of East and West facing Sidewalk for Scenario 17: High LAD trees (9m X 10m) Pavement porous concrete

The figure shows the potential air temperature across the both east facing and west facing sidewalks for the Scenario 17: High LAD trees (9m X 10m) pavement porous concrete. As per the figure there is no significant difference in the potential air temperature in east and west facing sidewalk for the scenario 17.

Mean Radiant Temperature

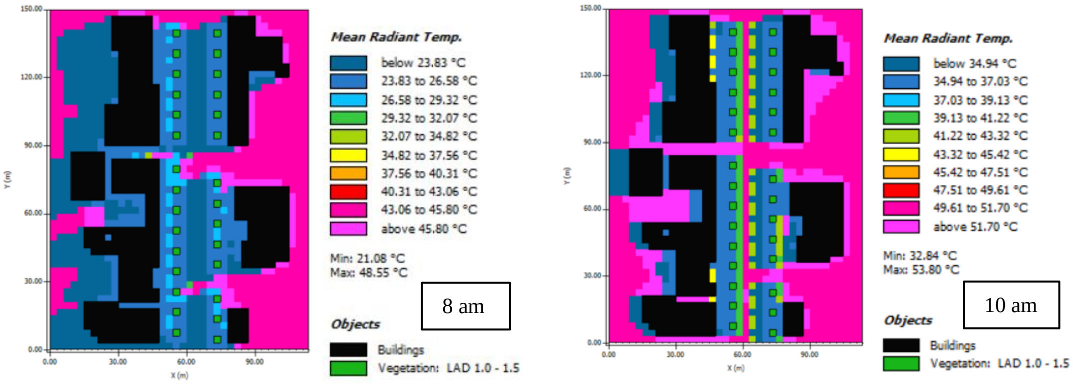


Chart 5-115 Mean radiant temperature for 8 am and 10 am in Scenario 17: High LAD trees (9m X 10m) Pavement porous concrete.

The mean radiant temperature varies between 23.83℃ and 29.32℃ at 8 am within the sidewalk. At 10 am the mean radiant temperature increases and varies between 34.94℃ and 37.03 ℃.

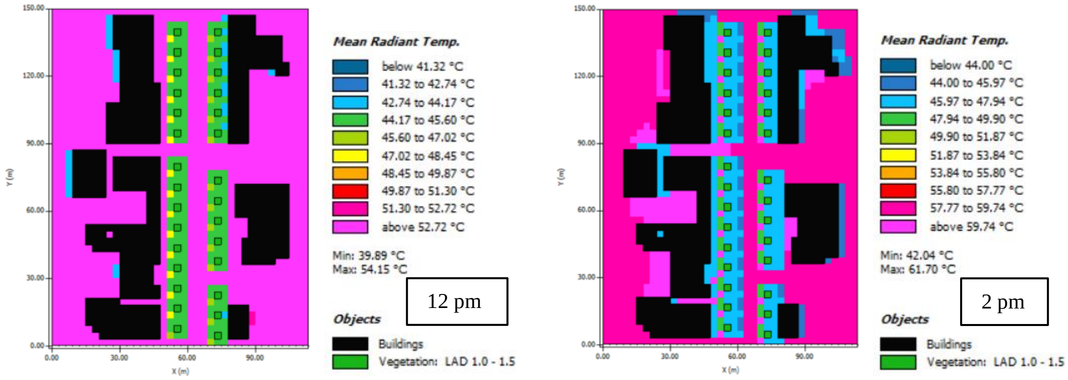


Chart 5-116 Mean radiant temperature for 8 am and 10 am in Scenario 17: High LAD trees (9m X 10m) Pavement porous concrete.

The mean radiant temperature increases and varies between 45.60℃ to 52.72℃ within sidewalks at 12 pm. At 2 pm the mean radiant temperature further increases and varies between 45.97℃ to 47.94℃.

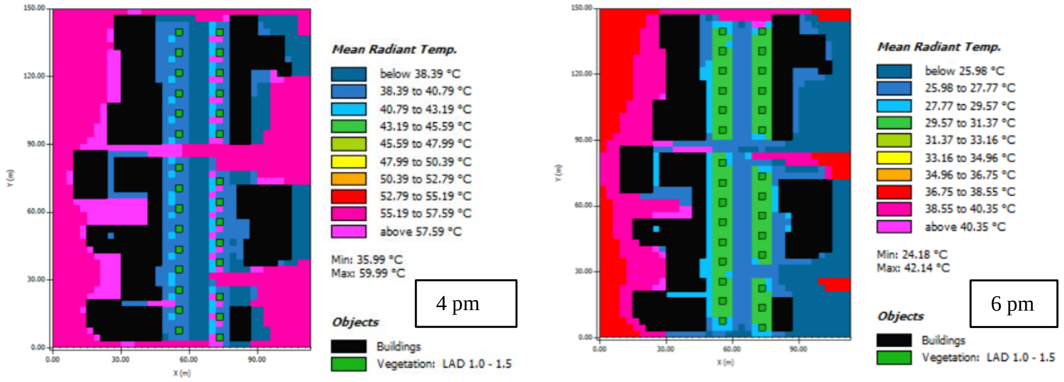


Chart 5-117 Mean radiant temperature for 8 am and 10 am in Scenario 17: High LAD trees (9m X 10m) Pavement porous concrete.

The mean radiant temperature gradually decreases and varies from 38.39℃ to 40.79 ℃ at 6 pm and further decreases up to 31.37℃ at 8 pm.

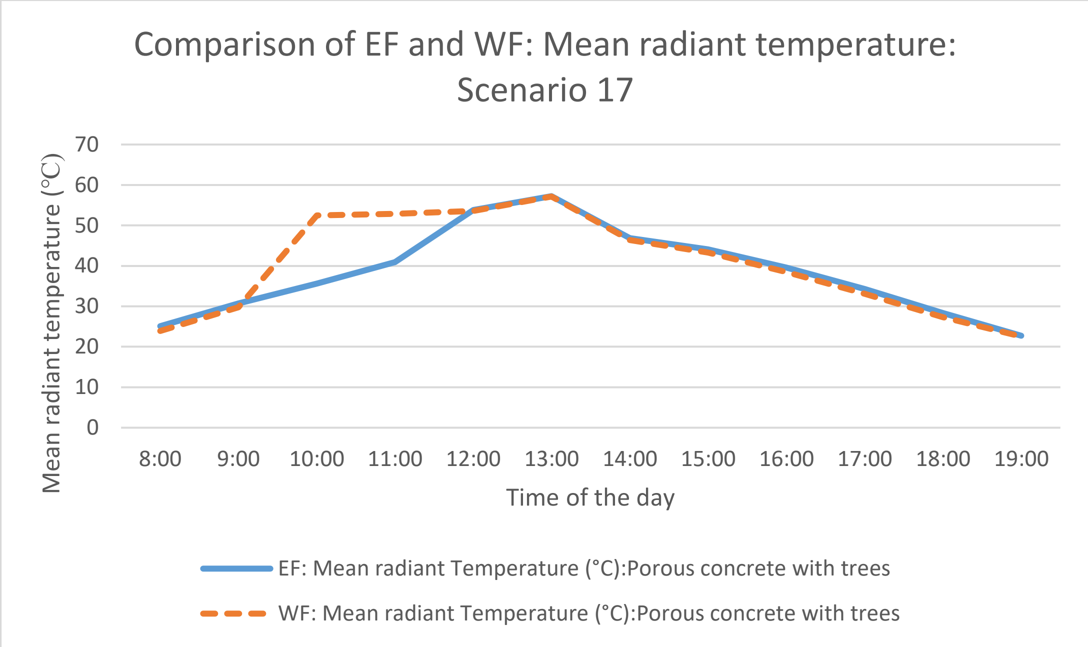


Figure 5-82 Comparison of Mean radiant temperature of East and West facing Sidewalk for Scenario 17: High LAD trees (9m X 10m) Pavement porous concrete

The graph shows the mean radiant temperature for the both sidewalks for the scenario 17 and as per the graph MRT is slightly lower in west facing sidewalk during morning hours and at 10 am and 11 am in the morning it is more than east facing sidewalk and is same as east facing sidewalk throughout the day.

Scenario 18: V1P2: High LAD trees (9m X 10m) and pavement red brick pavers.

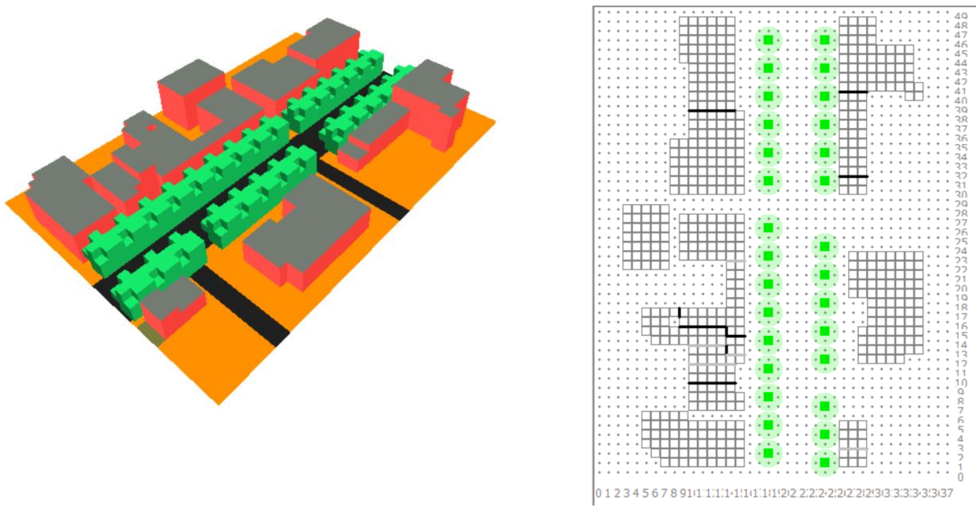


Figure 5-83 2D and 3D model in ENVI-met of Scenario 17: High LAD trees (9m X 10m) Pavement red bricks.

Air temperature

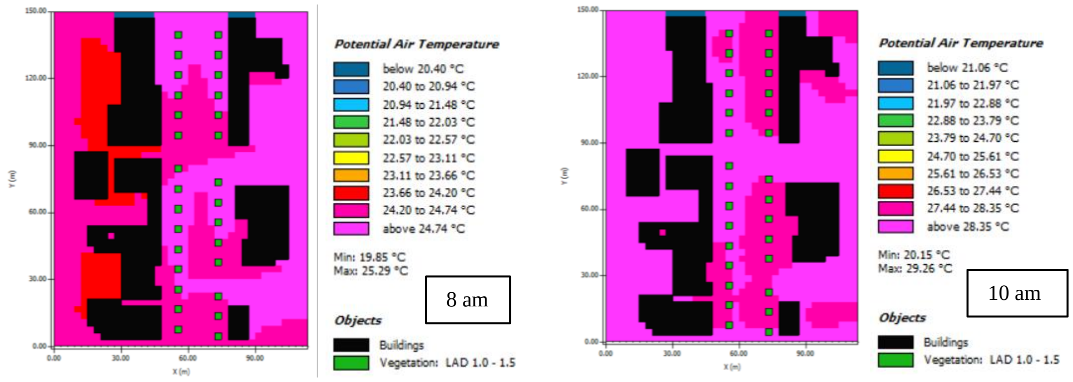


Chart 5-118 Potential air temperature for 8 am and 10 am in Scenario 18: High LAD trees (9m X 10m) Pavement red brick.

The potential air temperature varies between 24.20°C to 24.74°C at 8 am and it gradually increases up to 28.35°C at 10 am in the morning within the sidewalks.

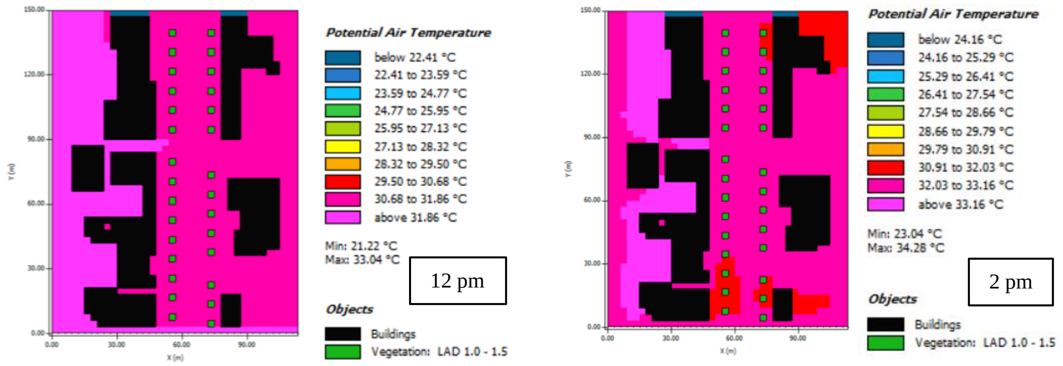


Chart 5-119 Potential air temperature for 12 pm and 2 pm in Scenario 18: High LAD trees (9m X 10m) Pavement red bricks.

The charts shows the potential air temperature variation within sidewalks at 12 pm and 2 pm in the afternoon. The potential air temperature reaches maximum 31.86°C at 12 pm and it gradually increases and reaches up to 33.16°C at 2 pm.

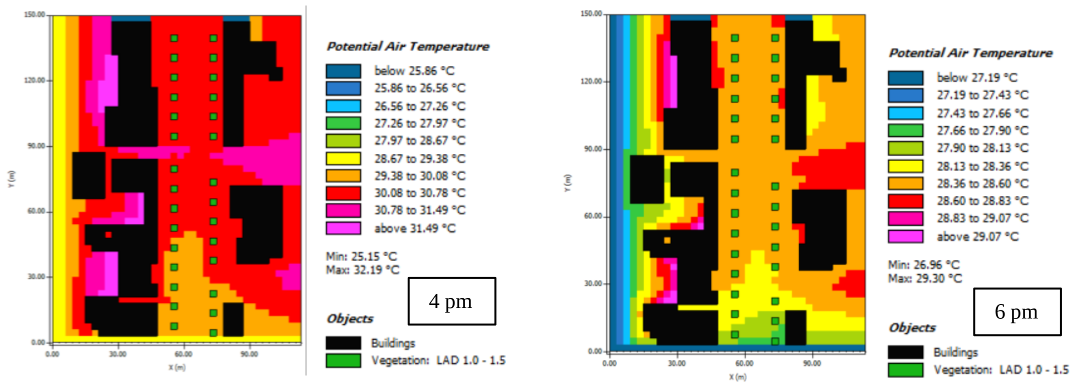


Chart 5-120 Potential air temperature for 4 pm and 6 pm in Scenario 18: High LAD trees (9m X 10m) Pavement red brick.

The potential air temperature decreases by the evening. At 4 pm, it decreases varies between 29.38℃ and 30.78℃ and at 6 pm it further decreases up to 28.36℃ within most parts of the sidewalks.

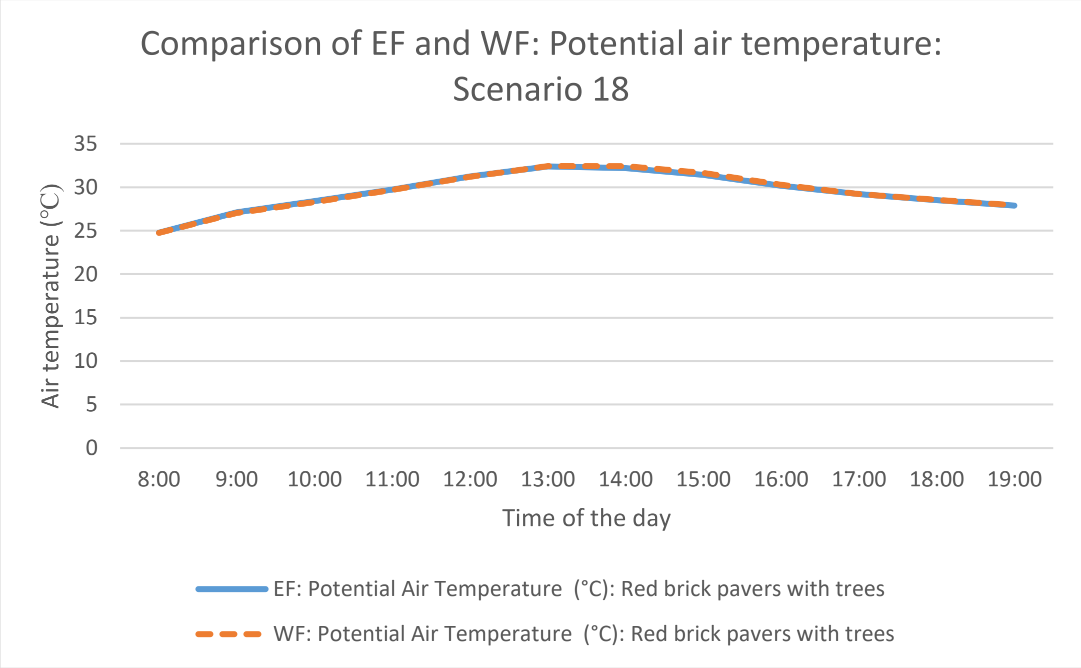


Figure 5-84 Comparison of potential air temperature of East and West facing Sidewalk for Scenario 18: High LAD trees (9m X 10m) Pavement red brick.

The figure shows the potential air temperature across the both east facing and west facing sidewalks for the Scenario 18: High LAD trees (9m X 10m) pavement porous concrete. As per the figure there is no significant difference in the potential air temperature in east and west facing sidewalk for the scenario 18.

Mean Radiant temperature

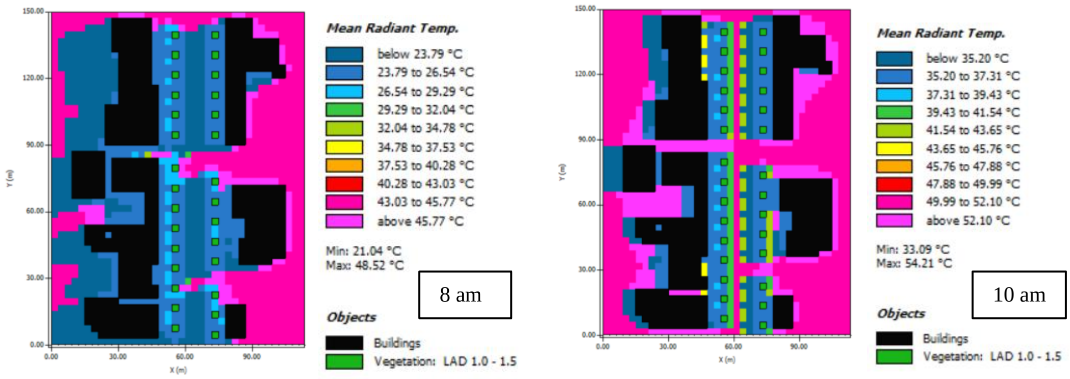


Chart 5-121 Mean radiant temperature for 8 am and 10 am in Scenario 18: High LAD trees (9m X 10m) Pavement red brick.

The mean radiant temperature at 8 am is between the range of 23.79℃ to 29.29℃ within sidewalks and it gradually increases and ranges from 35.20℃ to 41.54℃ within the both sidewalks.

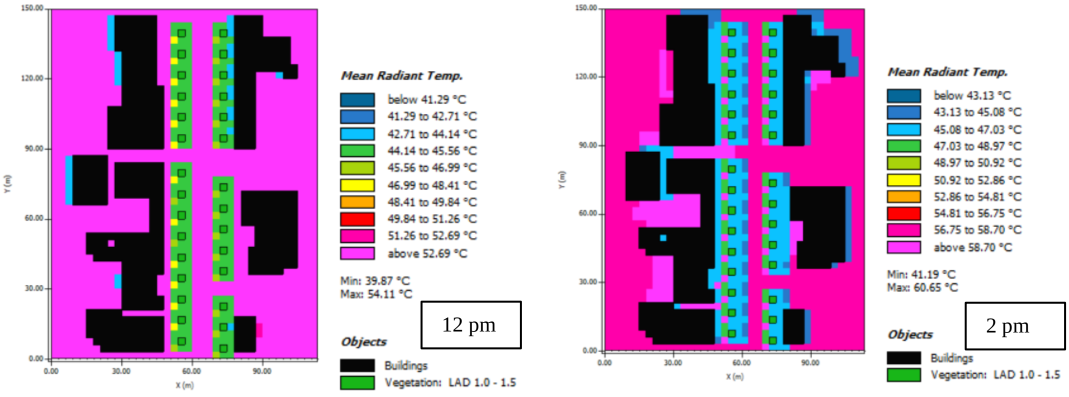


Chart 5-122 Mean radiant temperature for 12 pm and 2 pm in Scenario 18: High LAD trees (9m X 10m) Pavement red brick.

The charts shows the mean radiant temperature at 12 pm and 2 pm in the afternoon. As per the charts, the mean radiant temperature 45.56℃ to 51.26℃ within the sidewalks at 12 pm and at 2 pm, the temperature ranges from 45.08℃ to 47.03℃.

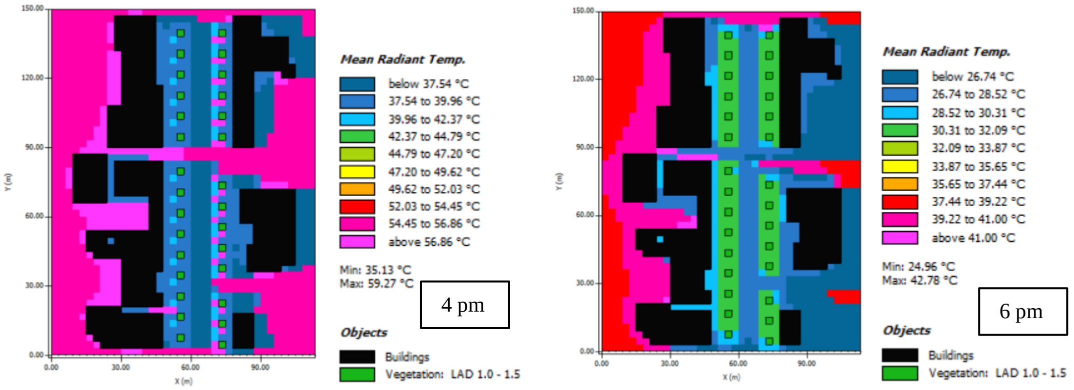


Chart 5-123 Mean radiant temperature for 4 pm and 6 pm in Scenario 18: High LAD trees (9m X 10m) Pavement red brick.

The mean radiant temperature decreases to the range of 37.54℃ to 39.96℃ within most parts of the sidewalks at 4 pm and at 6 pm it further decreases to the range of 32.09℃ and 33.87℃.

The graph shows the mean radiant temperature for the both sidewalks for the scenario 18 and as per the graph MRT is slightly lower in west facing sidewalk during morning hours and at 10 am and 11 am in the morning it is more than east facing sidewalk and is same as east facing sidewalk throughout the day.

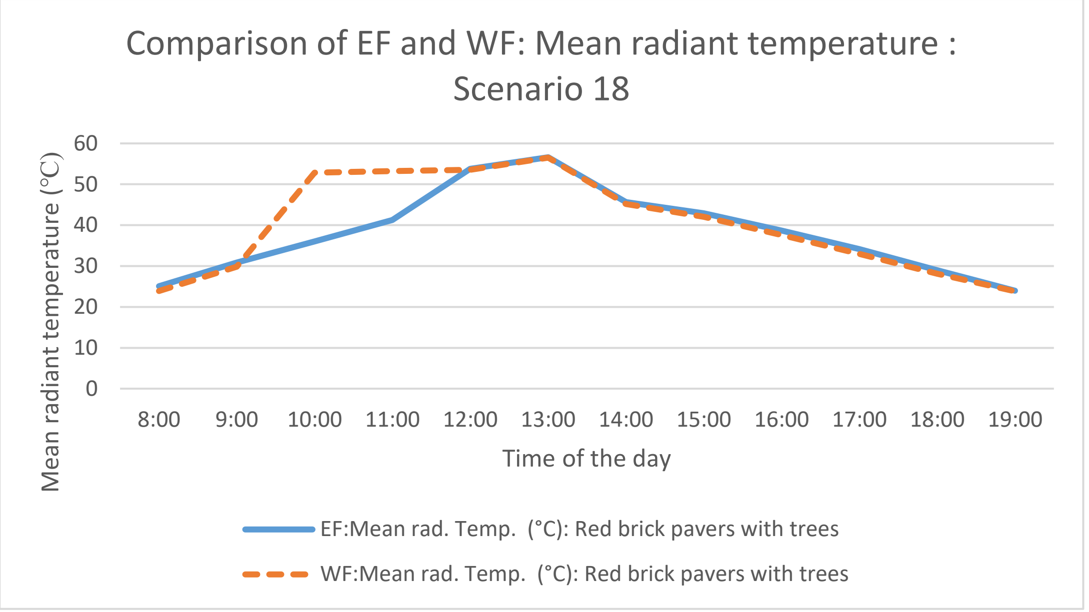


Figure 5-85 Comparison of Mean radiant temperature of East and West facing Sidewalk for Scenario 18: High LAD trees (9m X 10m) Pavement red brick.

The figure shows the mean radiant temperature for east and west facing sidewalk for Scenario 18: High LAD trees (9m X 10m) Pavement red bricks. The mean radiant temperature in west facing sidewalk is more at 10 am and 11 am in the morning than east facing sidewalk.

5.1 Comparison of Scenarios

5.1.1 Comparison of Scenario BC (Base Case) and Scenario O1 (Orientation EW)

The scenario O1 is created by changing the orientation from the NS to EW. The above figure shows the potential air temperature for the base case Scenario and Scenario O1 (Orientation changed to EW). The temperature is higher in EW orientation than the North South orientation by the max difference of 0.9 °C at 2 pm in the afternoon

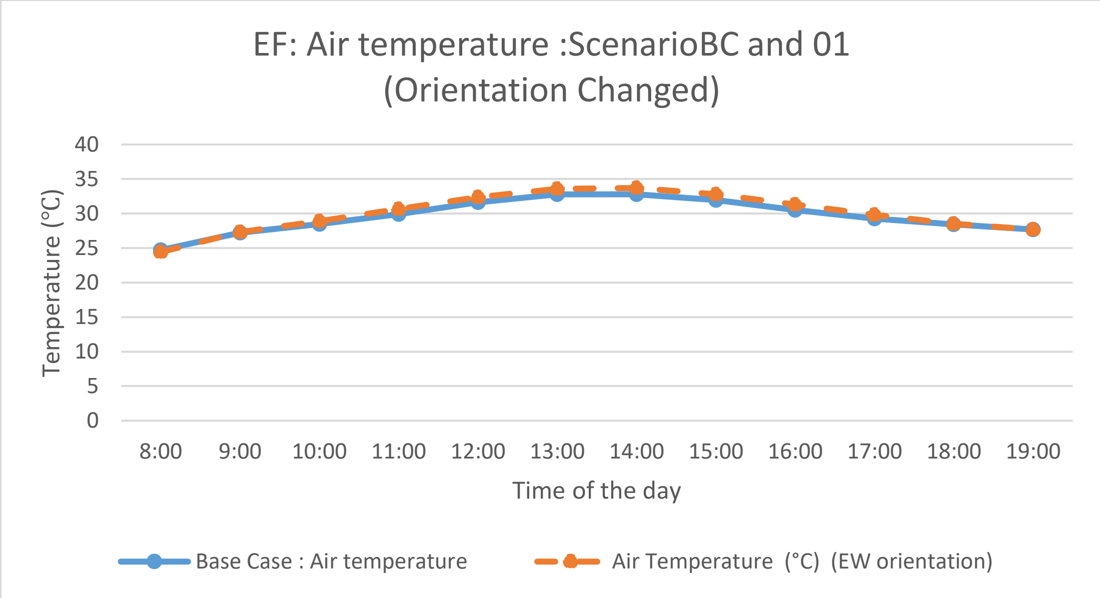


Figure 5-86 Comparison of Potential air temperature of Scenario BC (base case), Scenario O1 (Changing Orientation) for East facing Sidewalk

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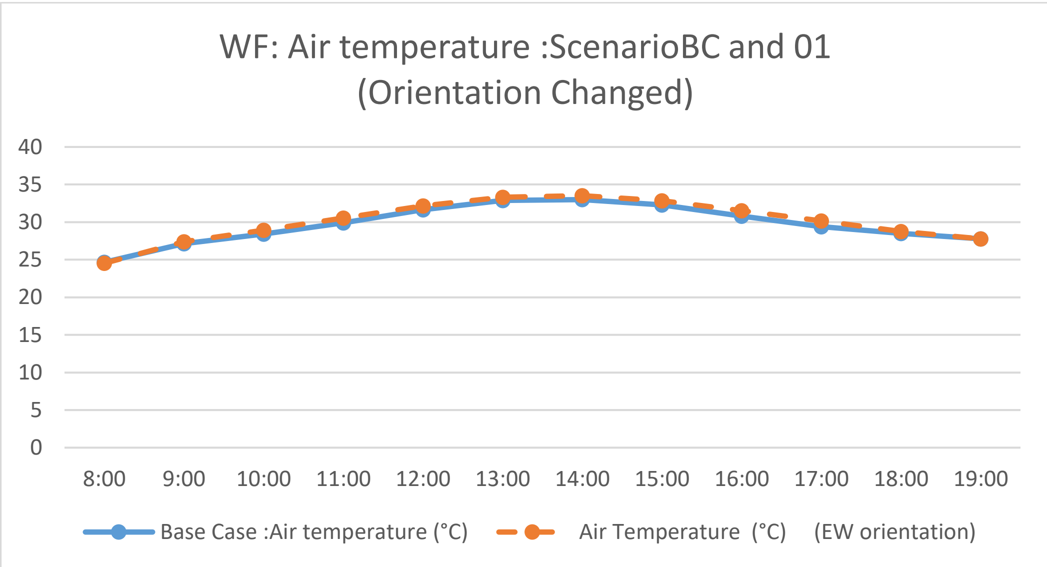


Figure 5-87 Comparison of Potential air temperature of Scenario1 (base case), Scenario 4 (Changing Orientation) for West facing Sidewalk

The above figure shows the potential air temperature for the base case Scenario and Scenario O1 (Orientation changed to EW) for the west facing sidewalk. The temperature is higher in EW orientation than the North South orientation by the max difference of 0.724 °C at 4 pm in the afternoon.

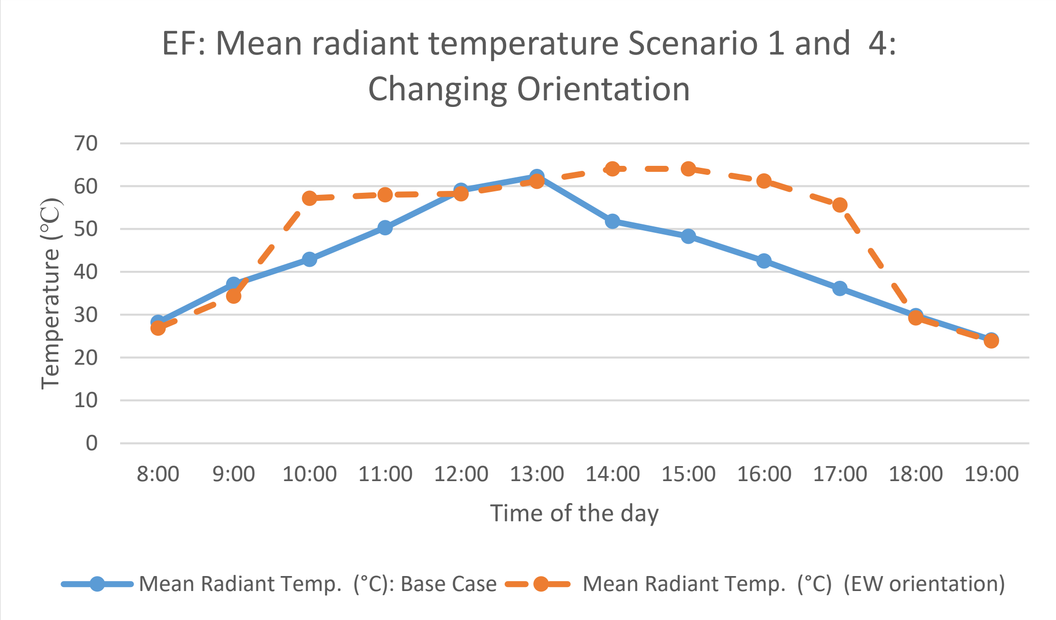


Figure 5-88 Comparison of mean radiant temperature by changing orientation (NS-EW) for east facing Sidewalk

The mean radiant temperature of EW orientation is lower in the morning at 8 and 9 am by approx. 1℃. And higher during day time. At 12 pm and 1 pm, MRT is less than NS orientation by approx. 1℃. During most part of the day the MRT is higher in EW orientation than NS orientation.

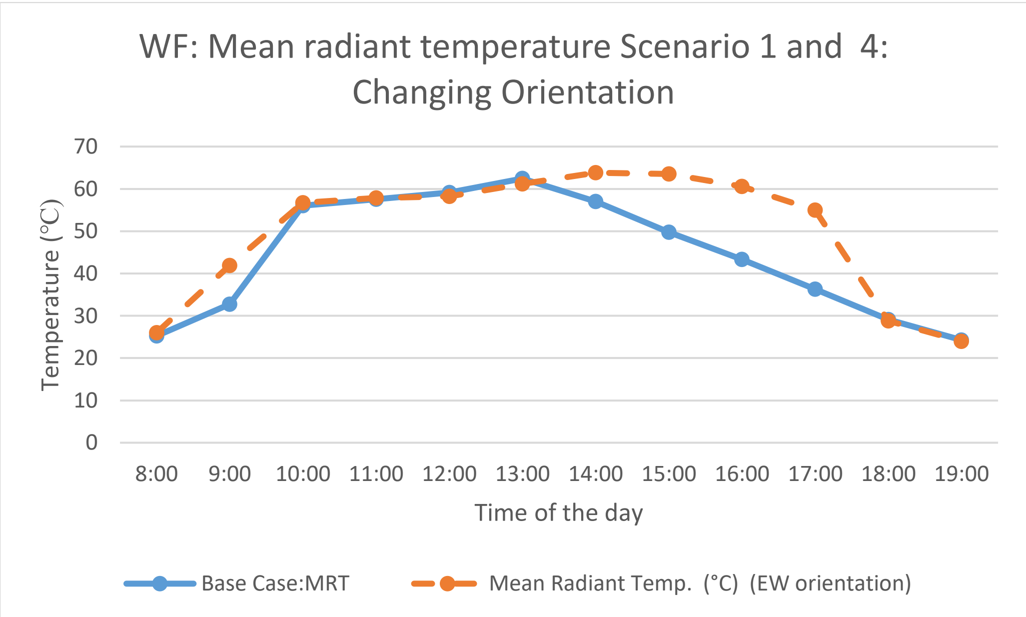


Figure 5-89 Comparison of mean radiant temperature by changing orientation (NS-EW) for West facing Sidewalk

The figure shows the mean radiant temperature by changing orientation to EW for West facing sidewalk. The mean radiant temperature is higher for the most part of the day except at 12 pm and 1 pm in the afternoon. The mean radiant temperature difference is highest during 5 pm in the evening

5.1.2 Comparison of BC (Base Case), V1, V2, V3, V4

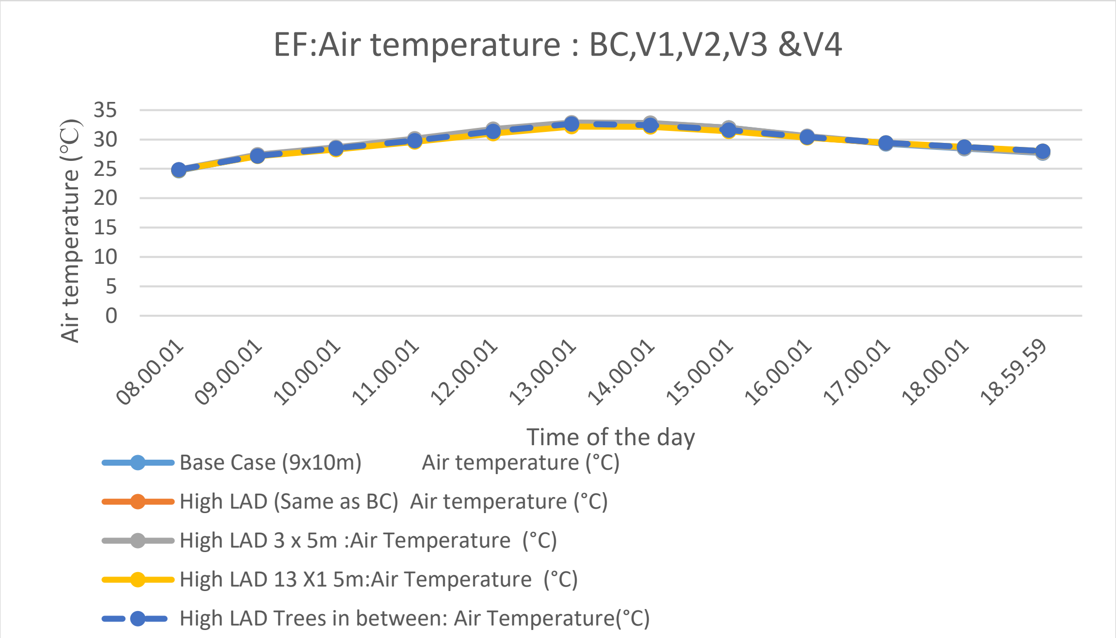


Figure 5-90 Comparison of Potential air temperature by changing the leaf area density , canopy size and tree height and adding trees in median in east facing sidewalk

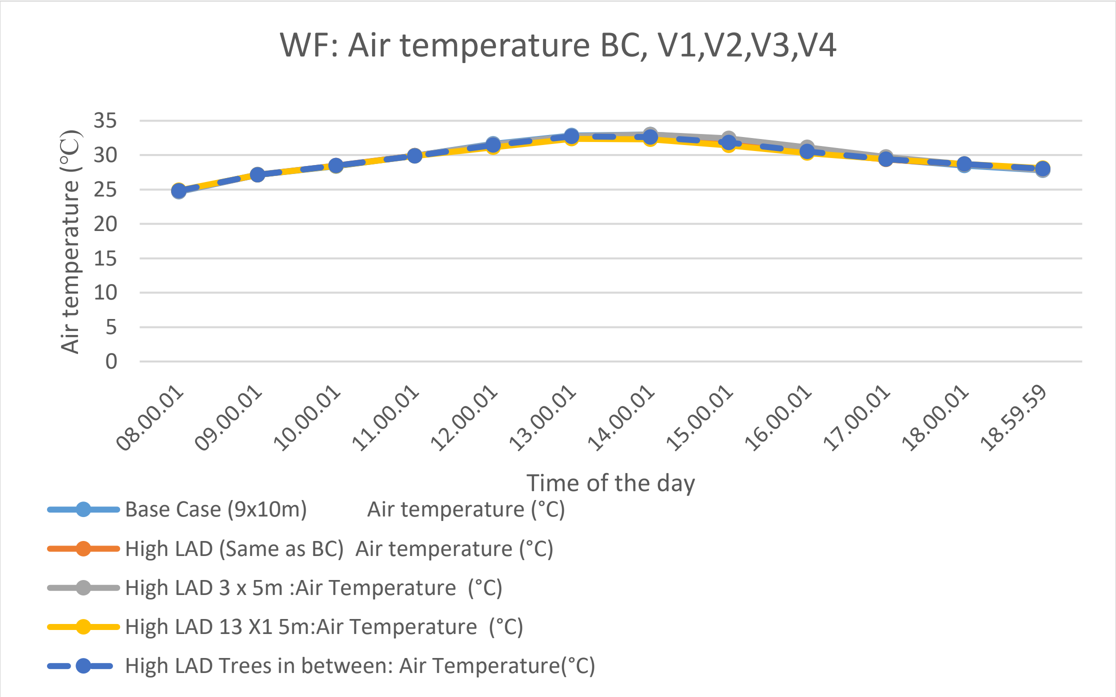


Figure 5-91 Comparison of Potential air temperature by changing the leaf area density , canopy size and tree height and adding trees in median in West facing sidewalk

The figures show the potential air temperature for the scenarios V1 (Low LAD changed to High LAD), V2 (Tree changed from 9 X10m to 3 X 5m), V3 (Tree changed from 9 X10m to 13 X 15m), V4 (Adding 3X5 m trees in median in between the road) for both east and west facing Sidewalk. The figures shows that there is no significant difference in the air temperature among these scenarios.

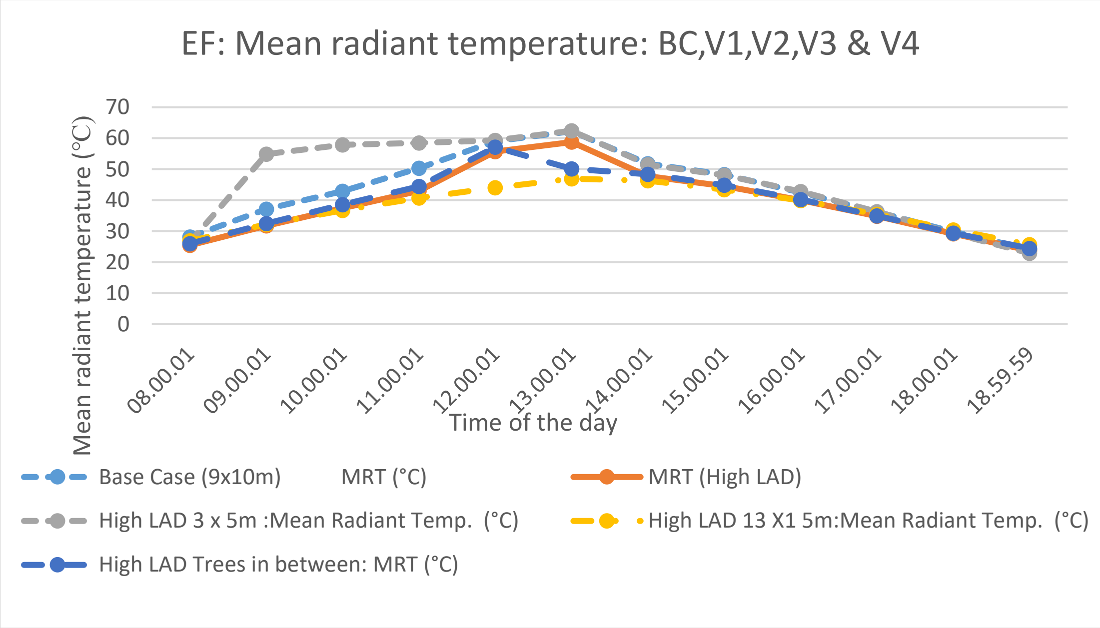


Figure 5-92 Comparison of Mean radiant temperature by changing the leaf area density , canopy size and tree height and adding trees in median in east facing sidewalk

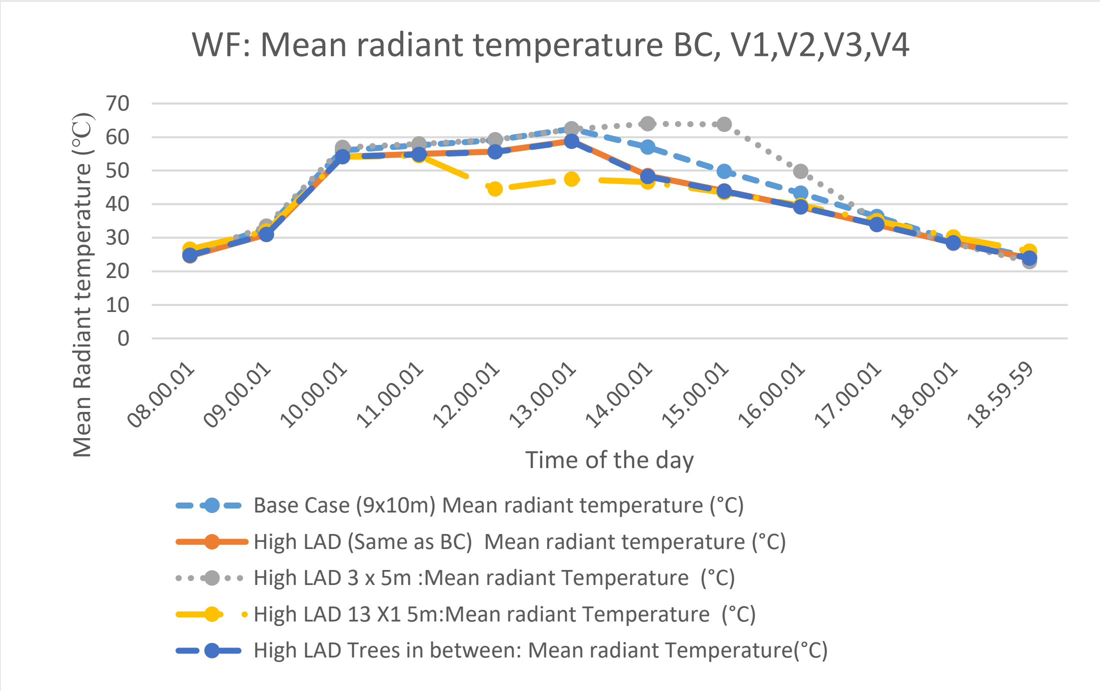


Figure 5-93 Comparison of Mean radiant temperature by changing the leaf area density , canopy size and tree height and adding trees in median in west facing sidewalk

The figures show the Mean radiant temperature for the scenarios V1 (Low LAD changed to High LAD), V2 (Tree changed from 9 X10m to 3 X 5m), V3 (Tree changed from 9 X10m to 13 X 15m), V4 (Adding 3X5 m trees in median in between the road) for both east and west facing Sidewalk.

In east facing sidewalk, the Mean radiant temperature decreases by average 3.34℃ when changing from low LAD to high LAD. When changing the tree canopy assize and height to 3m and 5m (High LAD) respectively, mean radiant temperature increases by 6.4℃ and when changing the tree canopy size and height to 13m and 15 m (High LAD) respectively, the mean radiant temperature decreases by 1.9 ℃. Adding the trees in the median did not show any significant difference in the mean radiant temperature in the sidewalks.

In west facing sidewalk, the Mean radiant temperature decreases by average 2.9℃ when changing from low LAD to high LAD. When changing the tree canopy assize and height to 3m and 5m (High LAD) respectively, mean radiant temperature increases by 5.1℃ and when changing the tree canopy size and height to 13m and 15 m (High LAD) respectively, the mean radiant temperature decreases by 1.4 ℃. Adding the trees in the median did not show any significant difference in the mean radiant temperature in the sidewalks.

5.1.3 Comparison of Base Case (BC), P1, P2, P3, P4, P5, P6, P8, P9

The figures show the potential air temperature by changing the pavement materials in east and west facing sidewalk. The pavement materials replaced in base case scenario are interlocking concrete blocks, brick pavers, porous concrete, flagstone, limestone, light concrete pavement, dark colored concrete and changing the asphalt to colored Asphalt.

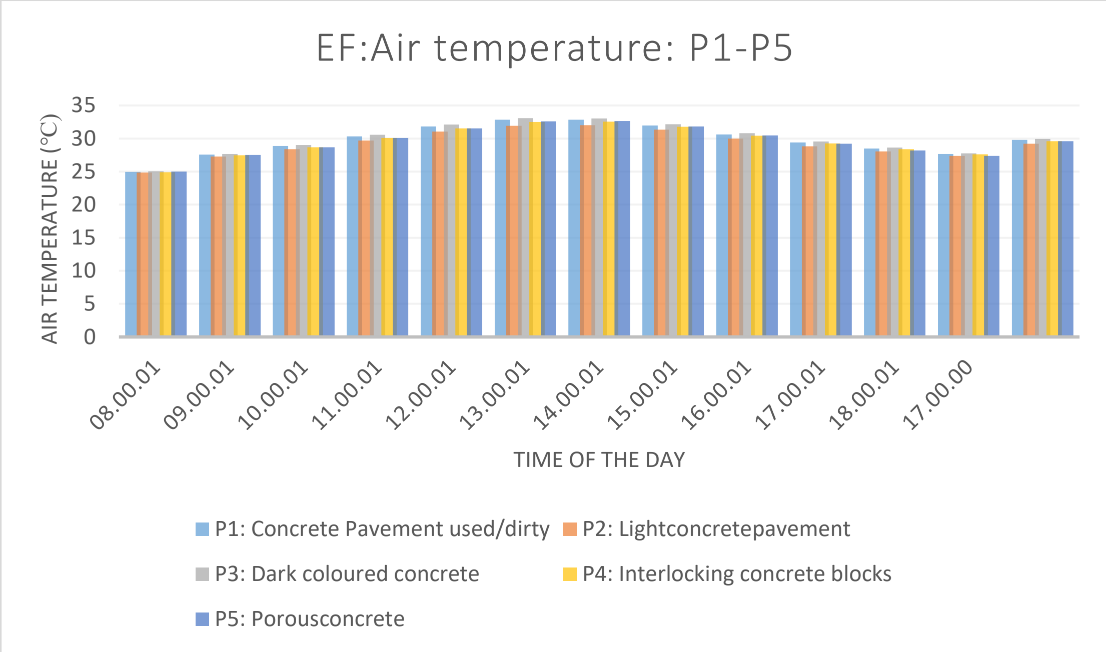


Figure 5-94 Comparison of Potential air temperature by changing pavements (Light color , dark color concrete, interlocking concrete blocks, porous concrete) in East facing Sidewalk.

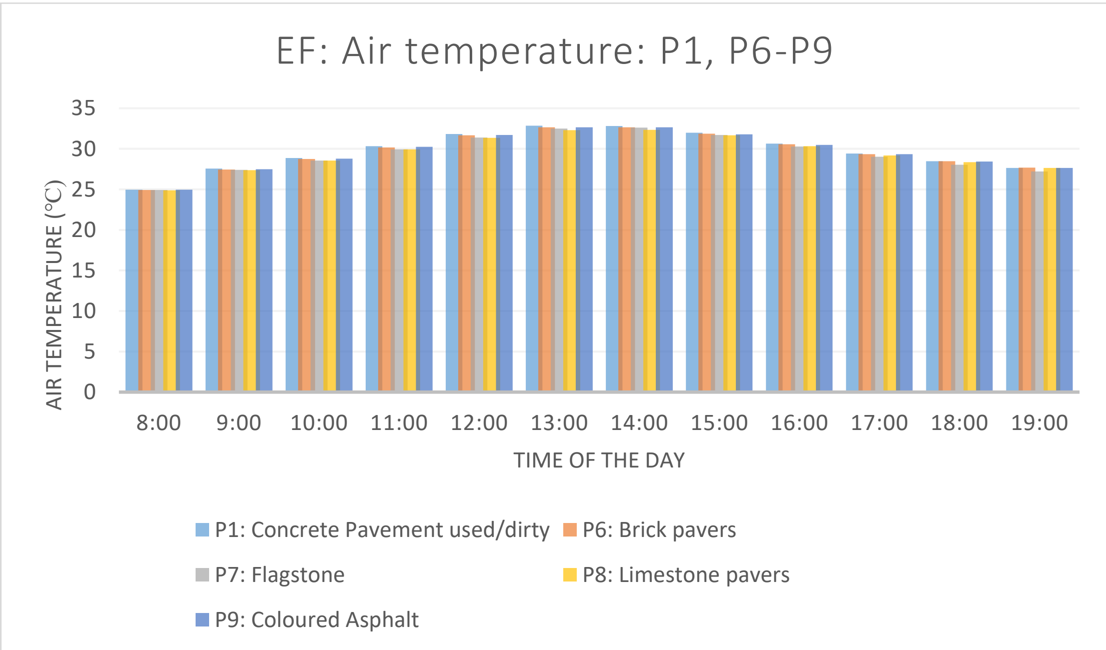


Figure 5-95 Comparison of Potential air temperature by changing pavements (brick pavers, flagstone, limestone pavers, colored Asphalt) in East facing Sidewalk.

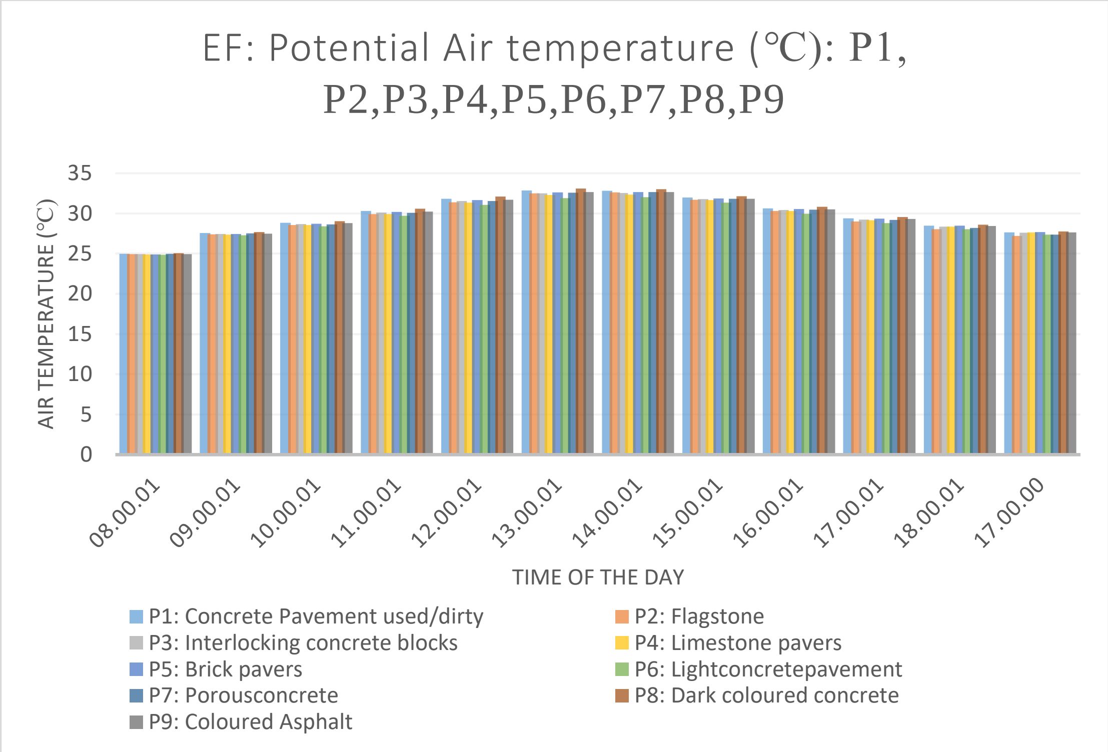


Figure 5-96 Comparison of Potential air temperature by changing pavements in East facing Sidewalk

For East facing Sidewalk, Changing the regular Asphalt to colored Asphalt decreases the air temperature slightly (only up to 0.09℃). Changing the concrete pavement to dark color increases the air temperature by 0.173 ℃. Changing the concrete pavement to light color decreases the air temperature by 0.548 ℃.Changing the pavement to flagstone decreases the air temperature by 0.3 ℃. Changing the pavement material to brick pavers decreases the air temperature by 0.1℃. Changing the pavement material to porous concrete decreases the air temperature by 0.19℃. Changing the pavement material to interlocking concrete blocks decreases the air temperature by 0.18℃.

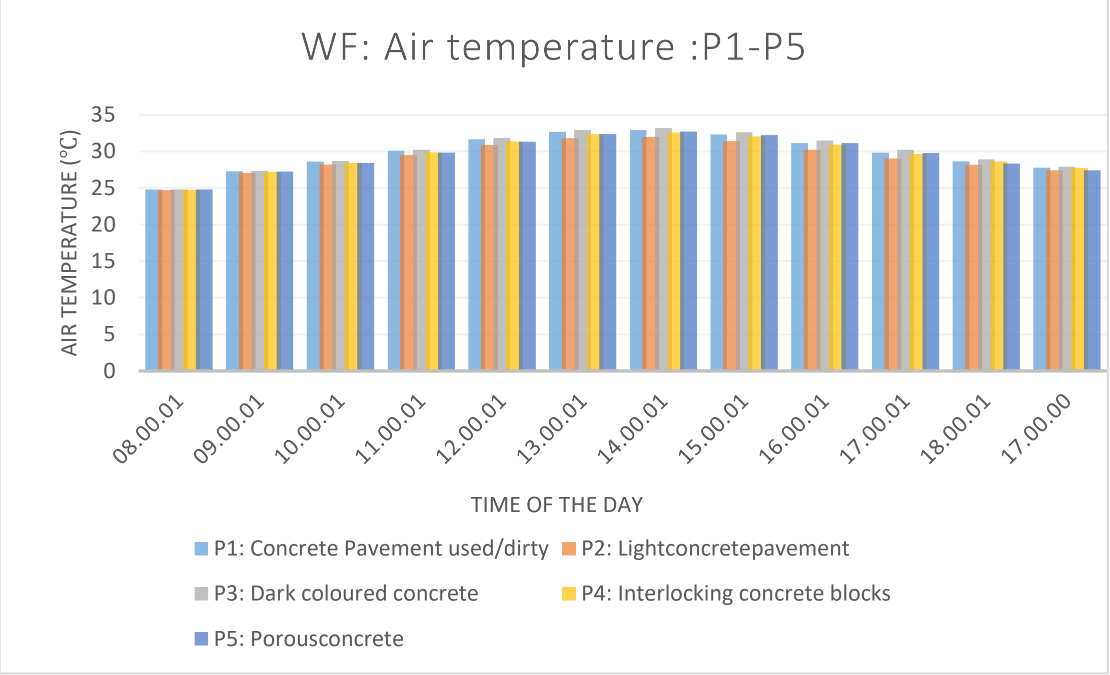


Figure 5-97 Comparison of Potential air temperature by changing pavements (Light color , dark color concrete, interlocking concrete blocks, porous concrete) in West facing Sidewalk.

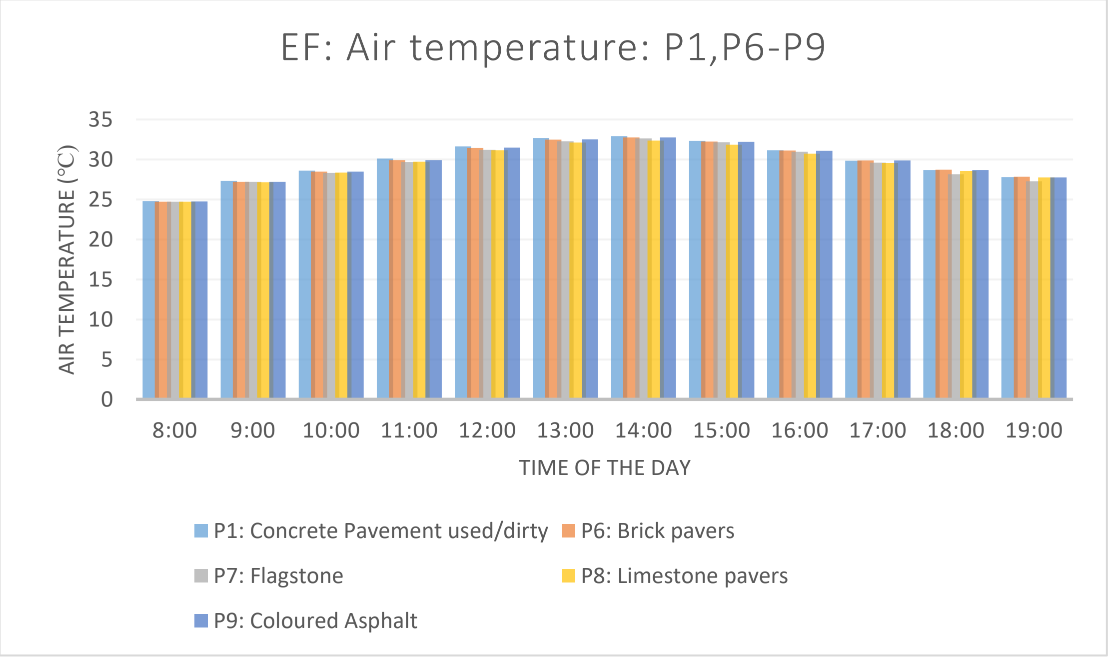


Figure 5-98 Comparison of Potential air temperature by changing pavements (brick pavers, flagstone, limestone pavers, colored Asphalt) in West facing Sidewalk.

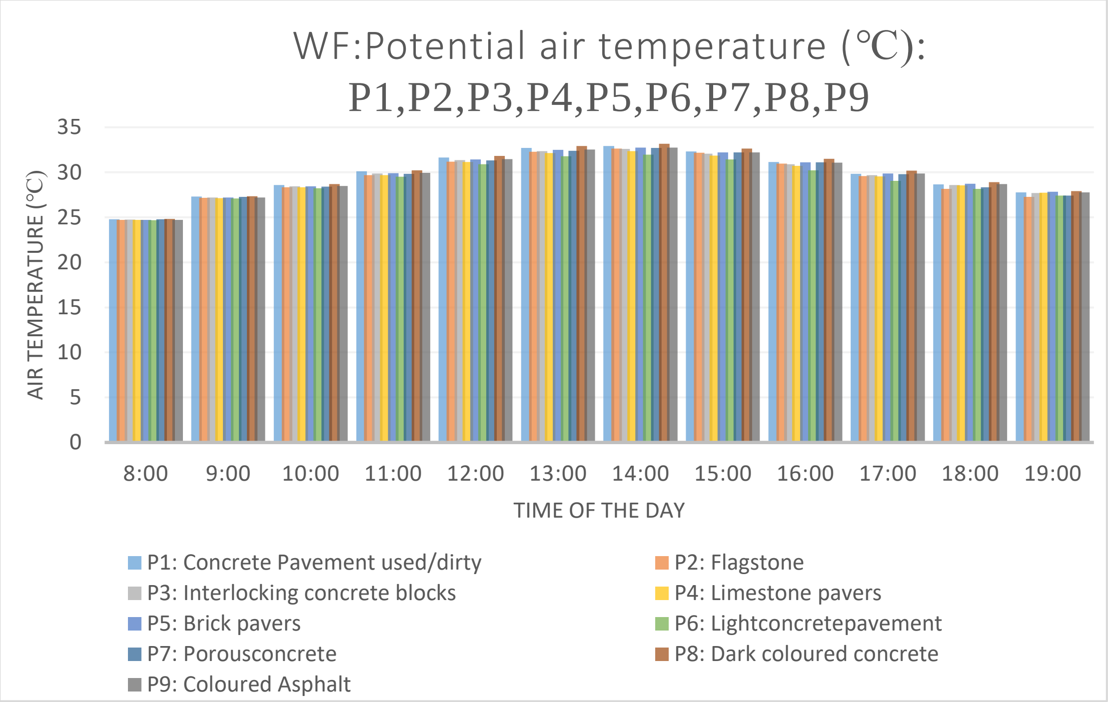


Figure 5-99 Comparison of Potential air temperature by changing pavements in West facing Sidewalk

For West facing Sidewalk, Changing the regular Asphalt to colored Asphalt decreases the air temperature slightly (only up to 0.09℃). Changing the concrete pavement to dark color increases the air temperature by 0.2 ℃. Changing the concrete pavement to light color decreases the air temperature by 0.61 ℃.Changing the pavement to flagstone decreases the air temperature by 0.29 ℃. Changing the pavement material to brick pavers decreases the air temperature by 0.08℃. Changing the pavement material to porous concrete decreases the air temperature by 0.18℃. Changing the pavement material to interlocking concrete blocks decreases the air temperature by 0.19℃.

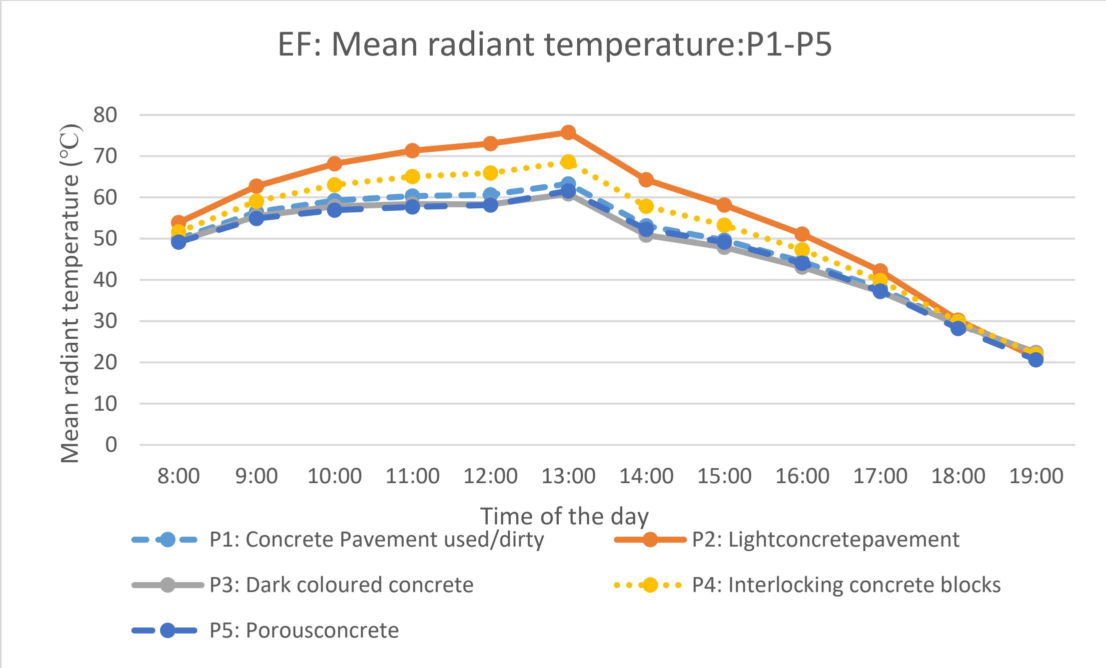


Figure 5-100 Comparison of Mean radiant temperature by changing pavements (Light color , dark color concrete, interlocking concrete blocks, porous concrete) in East facing Sidewalk.

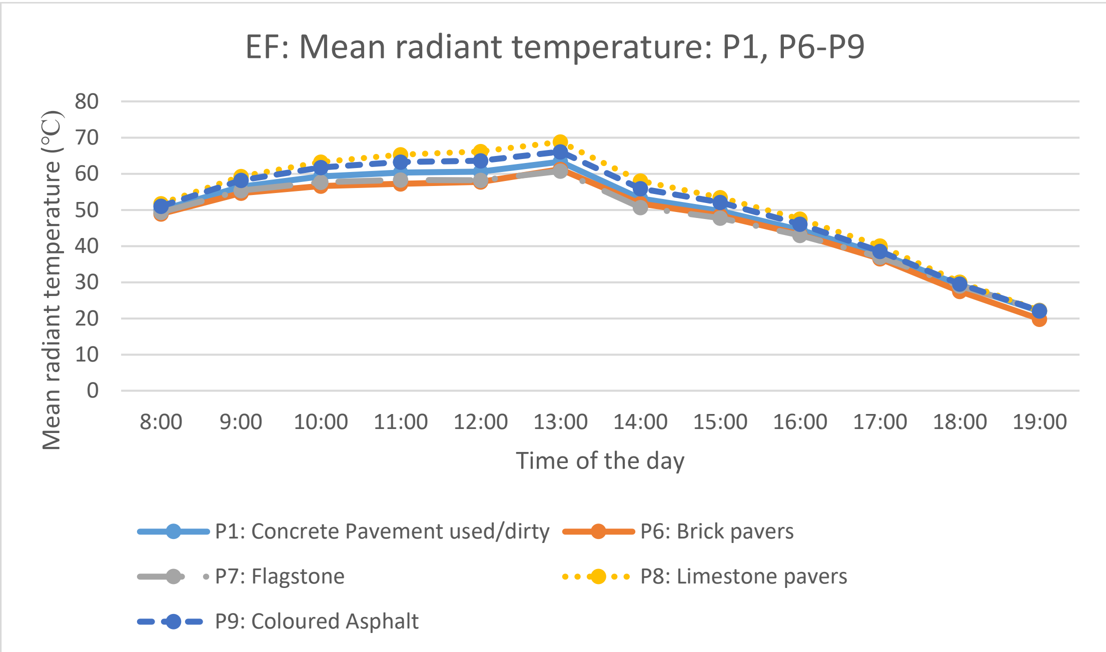


Figure 5-101 Comparison of Mean radiant temperature by changing pavements (brick pavers, flagstone, limestone pavers, colored Asphalt) in East facing Sidewalk.

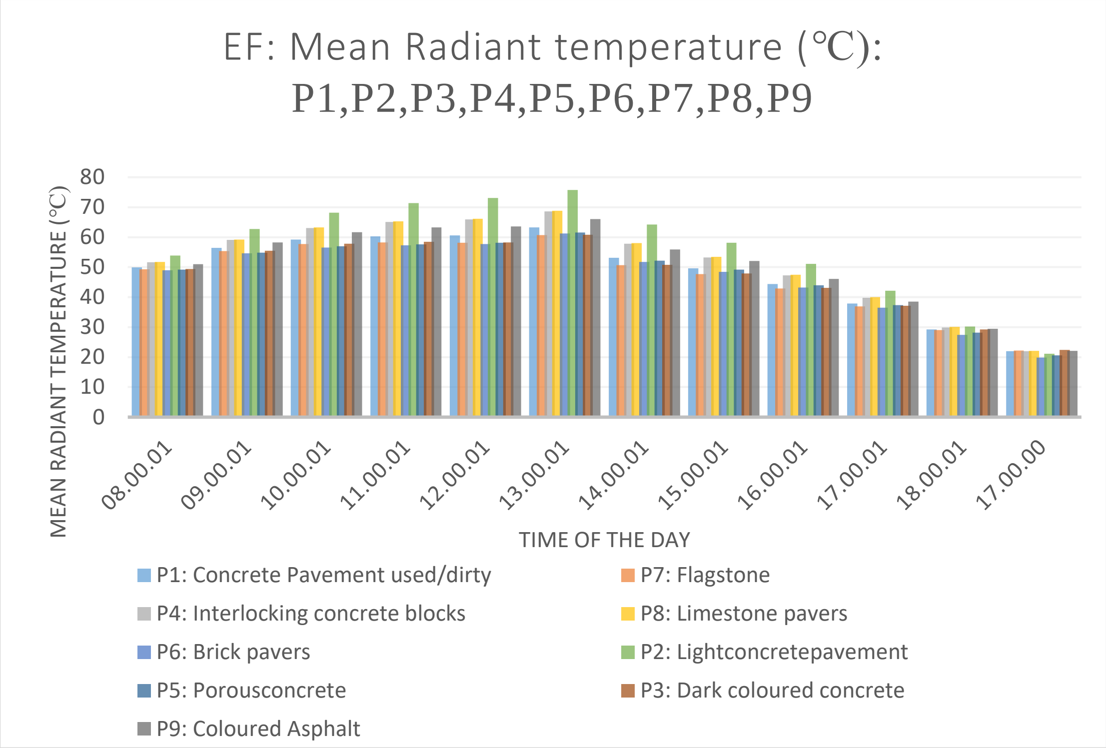


Figure 5-102 Comparison of Mean radiant temperature by changing pavements in east facing sidewalk

The figures show the Mean radiant temperature by changing the pavement materials in east and west facing sidewalk. The pavement materials replaced in base case scenario are interlocking concrete blocks. Brick pavers, porous concrete, flagstone, limestone, light concrete pavement, dark colored concrete and changing the asphalt to colored Asphalt.

For East facing Sidewalk, Changing the regular Asphalt to colored Asphalt increases mean radiant temperature by 1.8℃. Changing the concrete pavement to dark color decreases the mean radiant temperature by 1.29 ℃. Changing the concrete pavement to light color increases the mean radiant temperature by 7.14 ℃.Changing the pavement to flagstone decreases the mean radiant temperature by 1.89 ℃. Changing the pavement material to brick pavers decreases mean radiant temperature by 1.44℃. Changing the pavement material to porous concrete decreases the mean radiant temperature by 1.36℃. Changing the pavement material to interlocking concrete blocks increases the mean radiant temperature by 3.1℃.

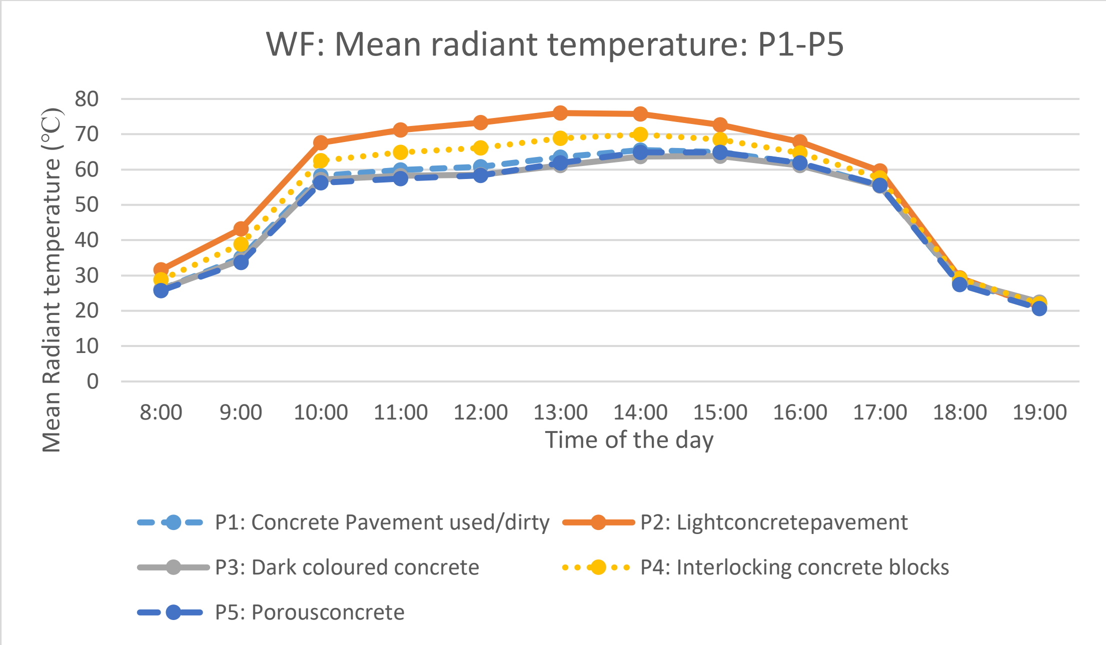


Figure 5-103 Comparison of Mean radiant temperature by changing pavements (Light color, dark color concrete, interlocking concrete blocks, porous concrete) in West facing Sidewalk.

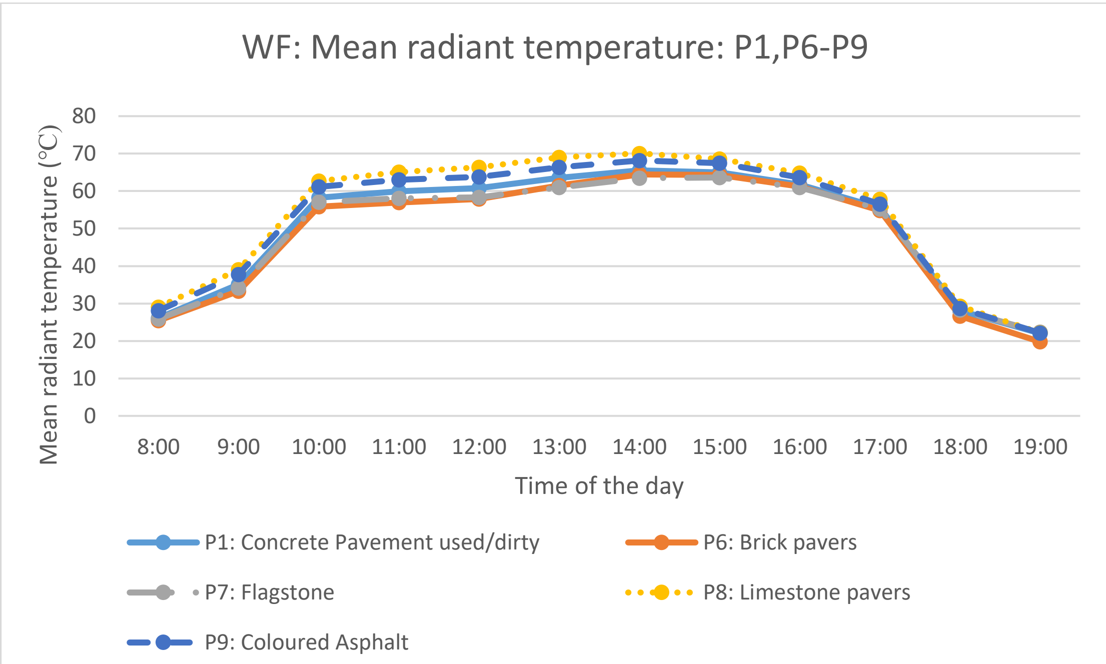


Figure 5-104 Comparison of Mean radiant temperature by changing pavements (brick pavers, flagstone, limestone pavers, colored Asphalt) in West facing Sidewalk.

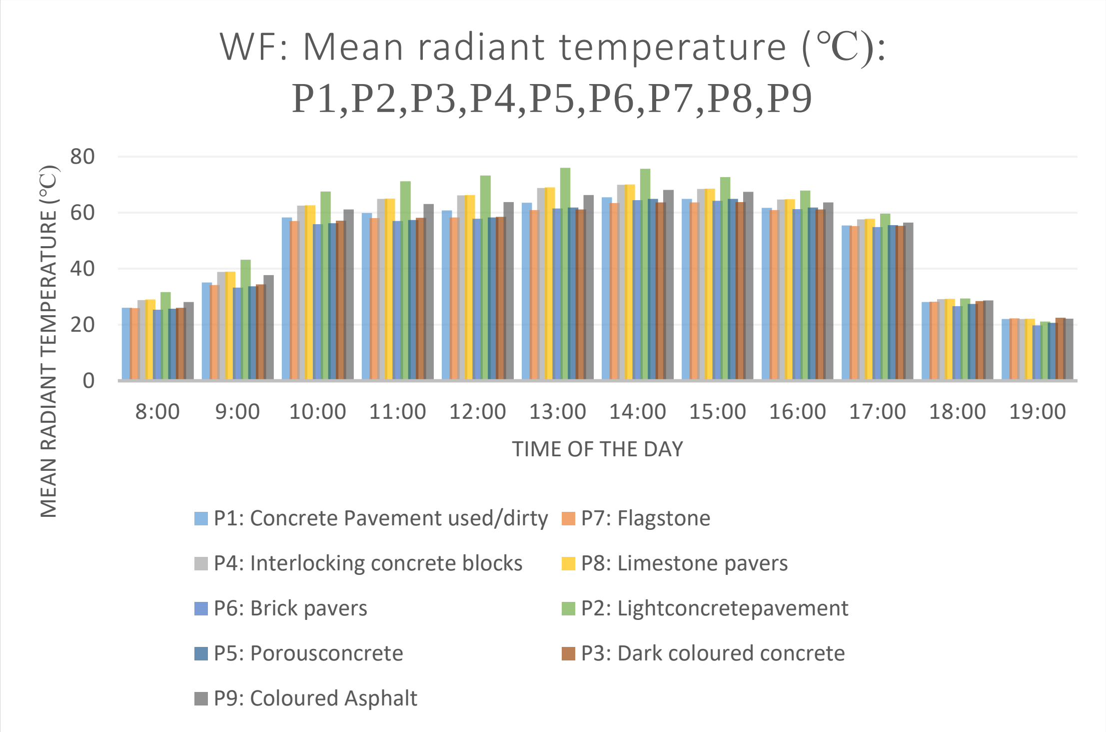


Figure 5-105 Comparison of Mean radiant temperature by changing pavements in west facing sidewalk

For West facing Sidewalk, Changing the regular Asphalt to colored Asphalt increases mean radiant temperature by 2.21℃. Changing the concrete pavement to dark color decreases the mean radiant temperature by 1.08 ℃. Changing the concrete pavement to light color increases the mean radiant temperature by 7.3 ℃.Changing the pavement to flagstone decreases the mean radiant temperature by 1.61 ℃. Changing the pavement material to brick pavers decreases mean radiant temperature by 1℃. Changing the pavement material to porous concrete decreases the mean radiant temperature by 1.08℃. Changing the pavement material to interlocking concrete blocks increases the mean radiant temperature by 3.37℃.

5.1.4 Comparison of Scenarios V1P1, V1P2, V1P5, V1P7

The figures show the potential air temperature by changing the pavement materials in east and west facing sidewalk. The pavement materials replaced in base case scenario are interlocking concrete blocks. Brick pavers, porous concrete, flagstone, limestone, light concrete pavement, dark colored concrete and changing the asphalt to colored Asphalt.

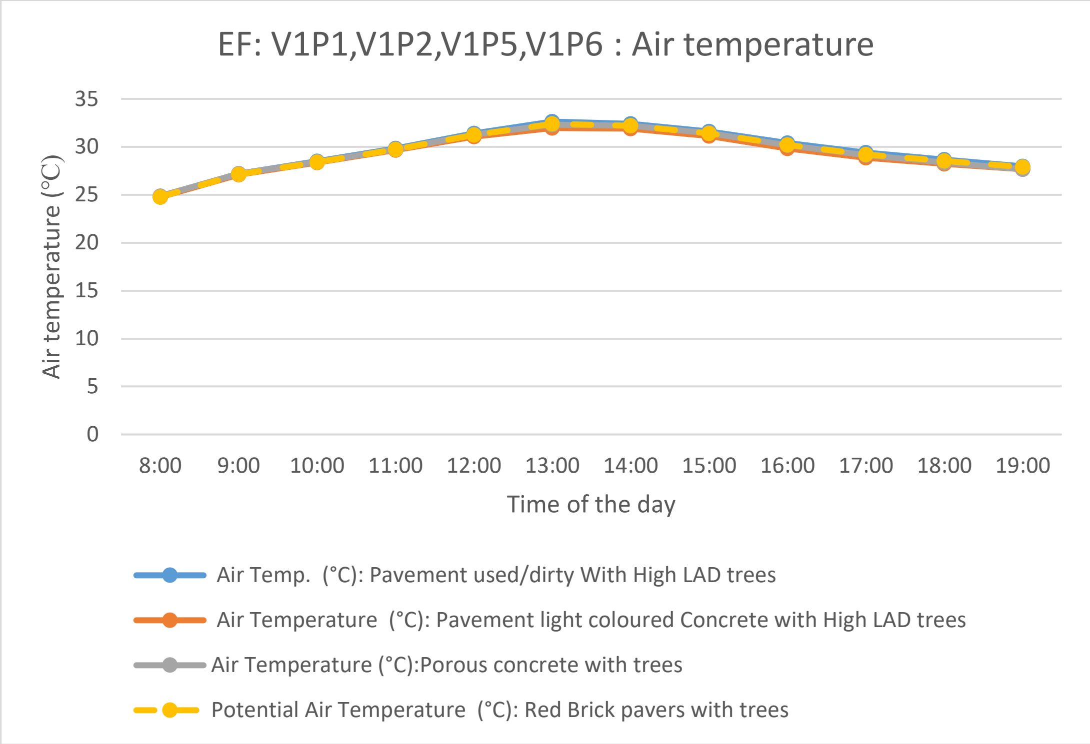


Figure 5-106 Comparison of Potential air temperature by changing pavements (light colored concrete, porous concrete, red brick pavers) and adding high LAD trees (9m X10m) in East facing Sidewalk.

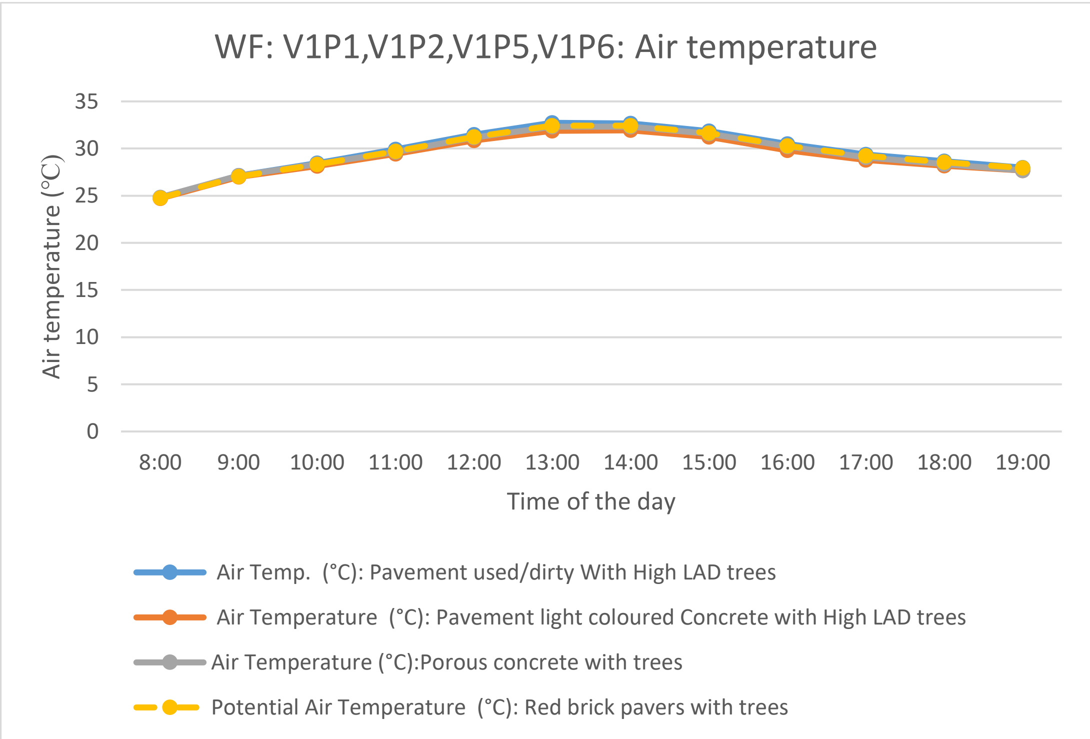


Figure 5-107 Comparison of Potential air temperature by changing pavements (light colored concrete, porous concrete, red brick pavers) and adding high LAD trees (9m X10m) in West facing Sidewalk.

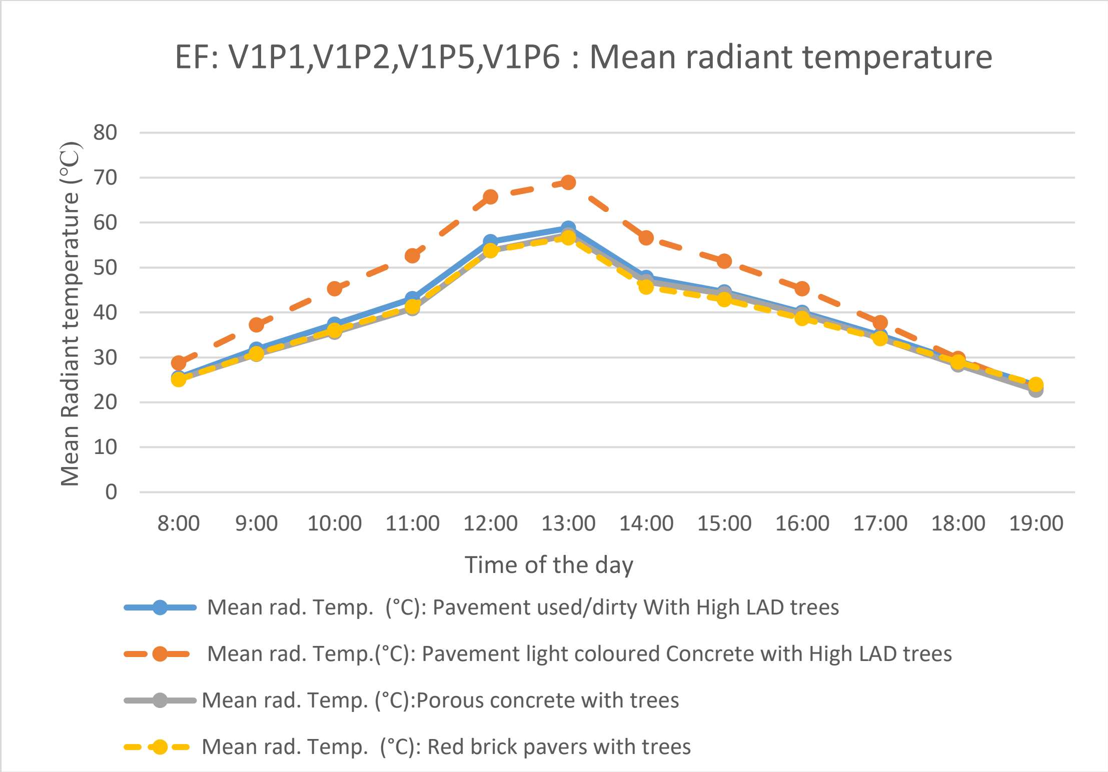


Figure 5-108 Comparison of Mean radiant temperature by changing pavements (light colored concrete, porous concrete, red brick pavers) and adding high LAD trees (9m X10m) in East facing Sidewalk.

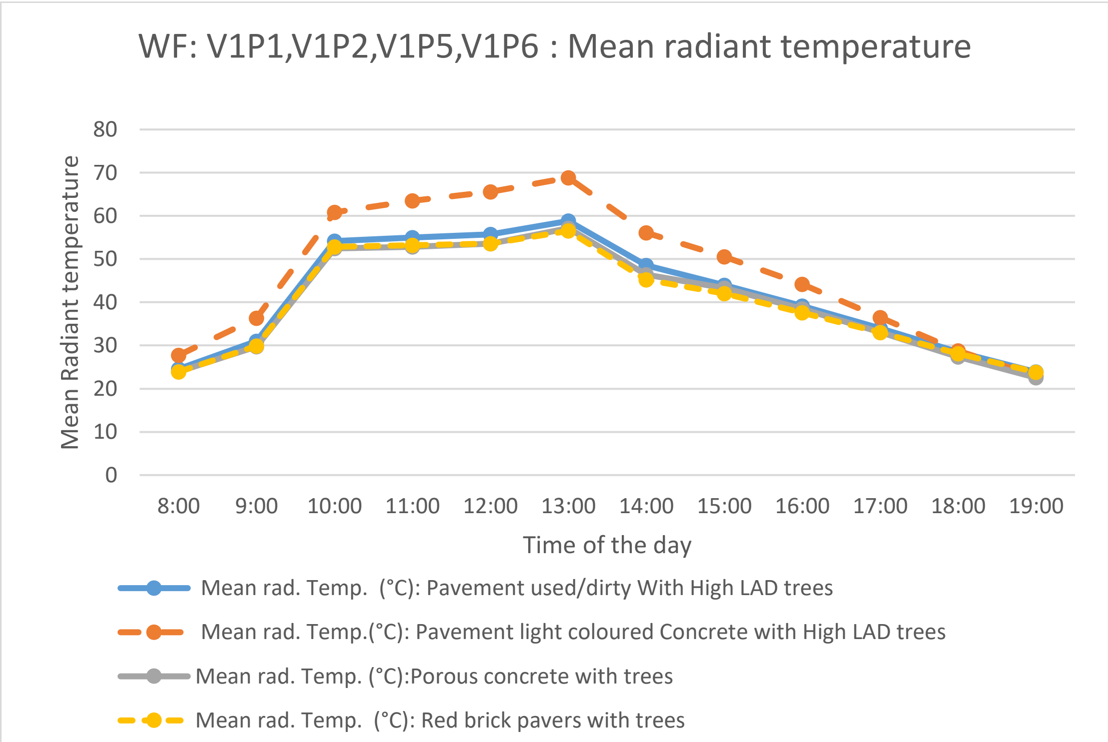


Figure 5-109 Comparison of Mean radiant temperature by changing pavements (light colored concrete, porous concrete, red brick pavers) and adding high LAD trees (9m X10m) in West facing Sidewalk.

For east facing Sidewalk, when changing from scenario V1P1 (High LAD trees with pavement concrete dirty/used, to V1P2 (High LAD trees with pavement light color concrete), the potential air temperature decreases by 0.42℃ and mean radiant temperature increases by 5.61℃. When changing from Scenario V1P1 to V1P5 (High LAD trees with pavement Porous Concrete), the potential air temperature decreases by 0.2 and mean radiant temperature decreases by 1.23℃. When changing from Scenario V1P1 to V1P6 (High LAD trees with pavement brick pavers) the potential air temperature decreases by 0.15 °C and mean radiant temperature increases by 1.33℃.

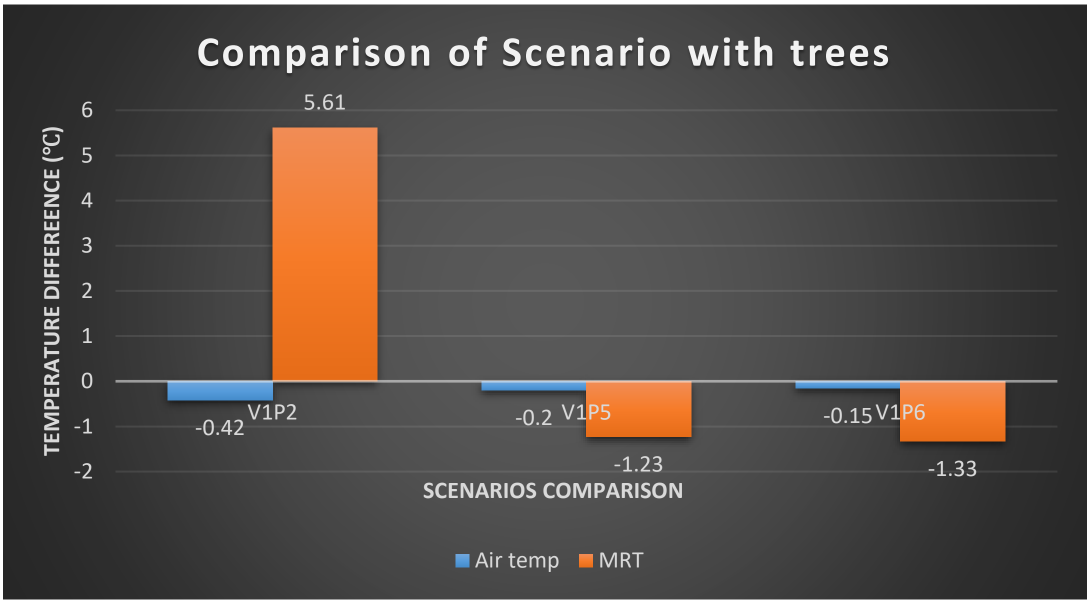


Figure 5-110 Potential air temperature difference between scenarios V1P2 (High LAD trees with pavement light color concrete), V1P5 (High LAD trees with pavement porous concrete), V1P6 (High LAD trees with pavement red brick) with respect to V1P1

The figure shows the potential air temperature difference among the scenarios V1P2 (High LAD trees with pavement light color concrete), V1P5 (High LAD trees with pavement Porous Concrete) and V1P6 (High LAD trees with pavement brick pavers) with respect to V1P1 (High LAD trees with pavement concrete used/dirty).

6 CHAPTER SIX FINDINGS AND DISCUSSION

The purpose of the study was to evaluate the effectiveness of various landscape elements in improving the thermal comfort of pedestrians on sidewalks. The study used measurements, questionnaire surveys, and simulations as methodological tools to achieve its objectives.

The first objective of this study was to determine the outdoor comfort parameters and evaluate the thermal environment of selected street segments. As mentioned in various literature, the study of outdoor thermal comfort is more complex than indoor thermal comfort.The research on outdoor thermal comfort dates back to the last decades of the twentieth century and is continued till today. One of the first studies of microclimate on outdoor activities were conducted in 1971 led to the conclusion that the physical conditions of a place affect people's thermal comfort. As per the literature studies, the outdoor comfort parameters can be broadly classified into subjective and objective aspects. The subjective aspect is the behavioral and the psychological aspect of human beings. The objective aspect deals with the air temperature, radiation, metabolic heat, wind, and humidity and clothing insulation. They can be further categorized as the personal and environmental factors. Mean radiant temperature is important parameter in assessing the human comfort outdoors. It is considered as the key variable in evaluation of thermal sensation in outdoor environment (Toudert, 2005; Middel et al. 2016). Several physical parameters determine the thermal environment for the pedestrians in the sidewalks: the pavement materials, presence/absence of vegetation, street aspect ratio, no. of the people and vehicles passing by the street. So, if a person feels "hot," in street, it may be from the solar radiation or from the materials used in the surrounding environment, such as asphalt/concrete used as pathway.

The thermal environment of the stretch was evaluated by the Questionnaire survey. To, summarise the findings from the Questionnaire Survey, most of the people surveyed (around 52%) were there for the work and mostly visited during the time of 10am to the 2 pm. The 12 days of measurement in the site shows the highest temperature during the period of 10 am to 2 pm as shown in the figure 6-1. Hence the temperature might not be one of the influencing factors for visiting the street especially people who are committed to work. However, the people who are there for entertainment of fun have a choice of visiting the street during the time when they feel comfortable in terms of thermal aspect.

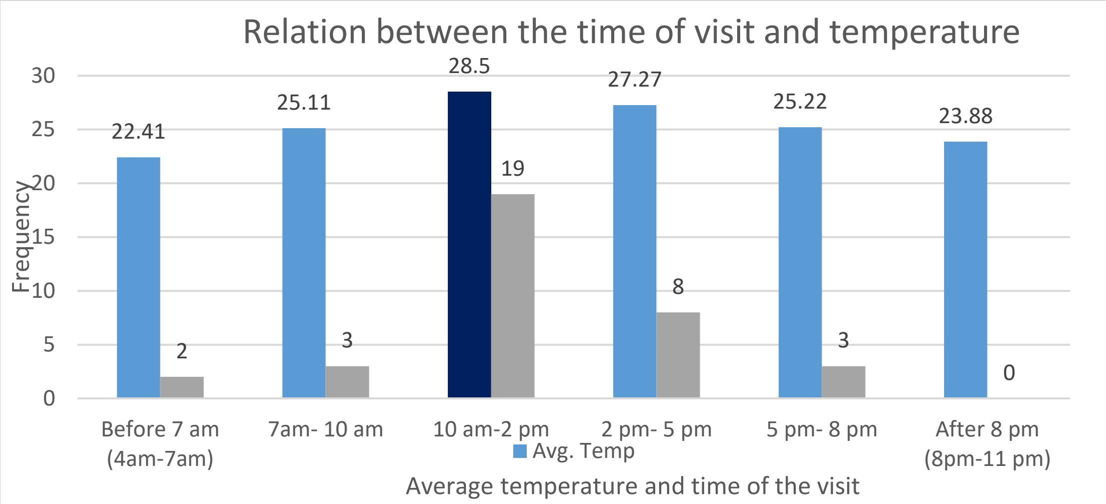
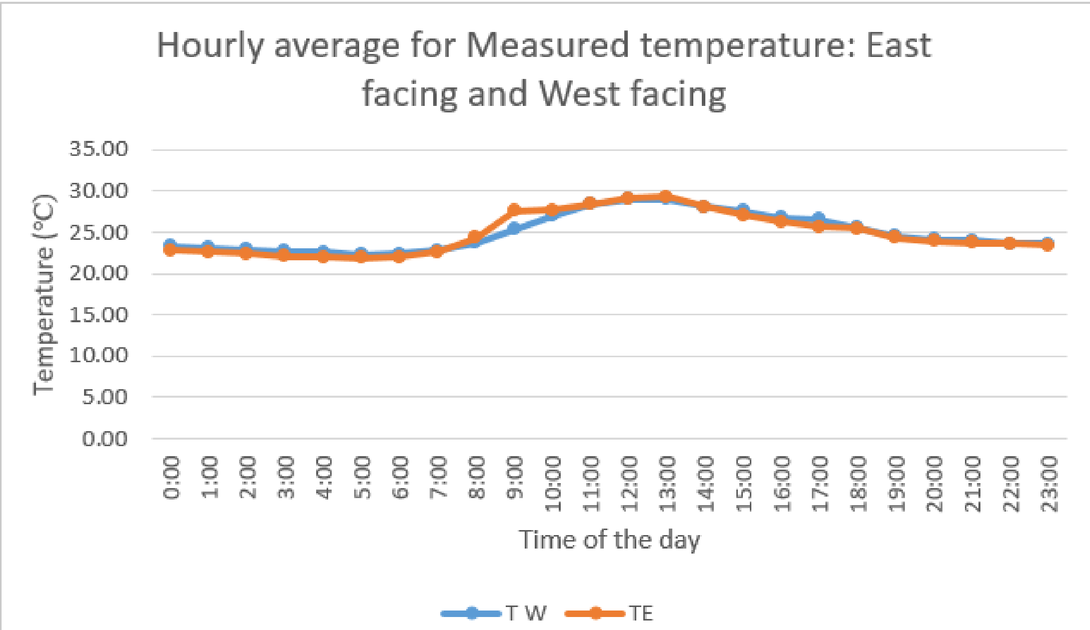


Figure 6-1 Relation between the time of the visit and average temperature during the period of the day.

As mentioned earlier most of the people prefer east facing street or both. Though there is not much of difference in temperature in both street. (See figure 6-2) The reason people prefer East Facing Street might be because of the presence of street furniture and also Restaurants, shops available there compared to the other side of the street. Otherwise people have tendency to walk through the shade during the summer.



v

Figure 6-2 Hourly average temperature for east and west facing sidewalk for 12 days of measurement

Most of the people preferred to walk/sit/stand in particular place due to the tree shade and the majority of the people feel heat from the pavement. A majority of the people surveyed felt hot (36.11%) or warm sensation (27.78%) and preferred for the weaker sun (58.33%) and cooler air temperature (69.44%). Hence we can say that the street is not comfortable in terms of thermal aspect as per the questionnaire survey results and hence some changes are to be made in the street to improve pedestrian comfort.

The second objective of this research was to evaluate and compare the impact by altering soft (tree) and hard landscaping elements (pavement) on sidewalks for thermal-comfort improvement for pedestrians.Various parameters considered were orientation, leaf Area Density, Tree canopy size height and spacing, adding trees in median and pavement materials.

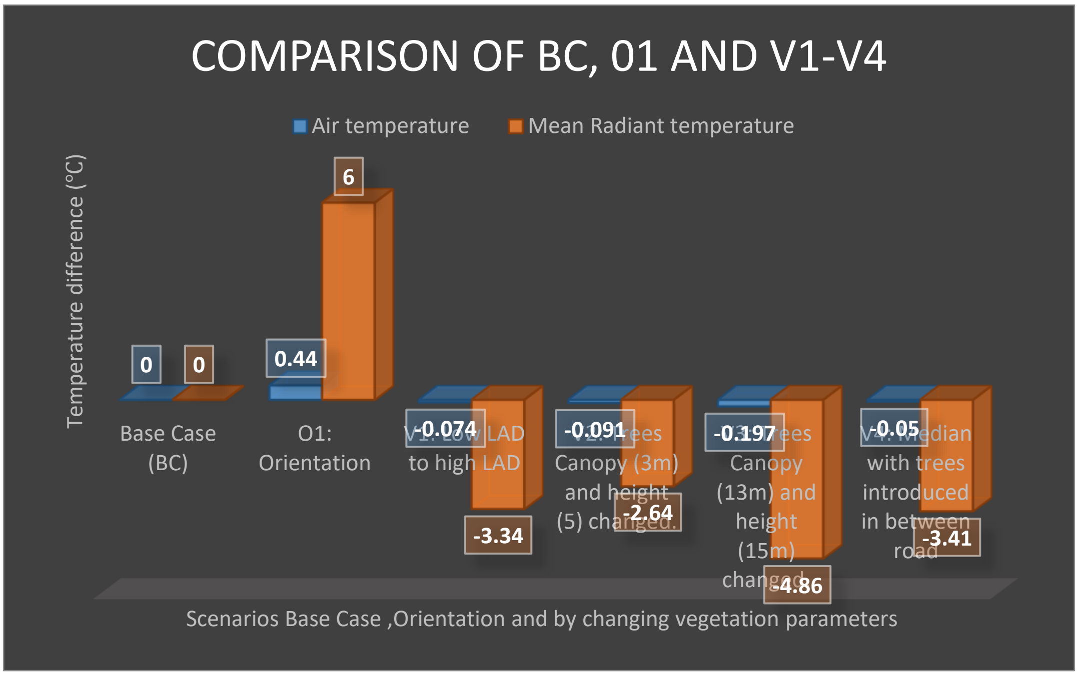


Figure 6-3 Comparison of Scenarios: BC, O1 (Changing orientation) and (V1-V5)

The figure 6-3 shows the air temperature and mean radiant temperature difference among considering the orientation and vegetation parameters. When the orientation was changed to EW orientation, potential air temperature increased by average of 0.44 °C and mean radiant temperature increased by average of 6 °C. The potential air temperature decreased by average 0.074 °C when the low LAD trees were changed to high LAD trees. The potential air temperature decreased by average of 0.197 when the tree canopy size was increased to 13 m and height was increased to 15m. The mean radiant temperature decreased by almost 4.86°C in the same case.

The figure 6-4 shows the air temperature and mean radiant temperature difference by changing the pavement materials. Among the various pavement materials in various scenarios for the simulation, the light concrete pavement showed the highest decrease in terms of the air temperature (0.579 °C) however the mean radiant temperature was highest (7.22°C) for the same material. This is due to the fact that it has more albedo

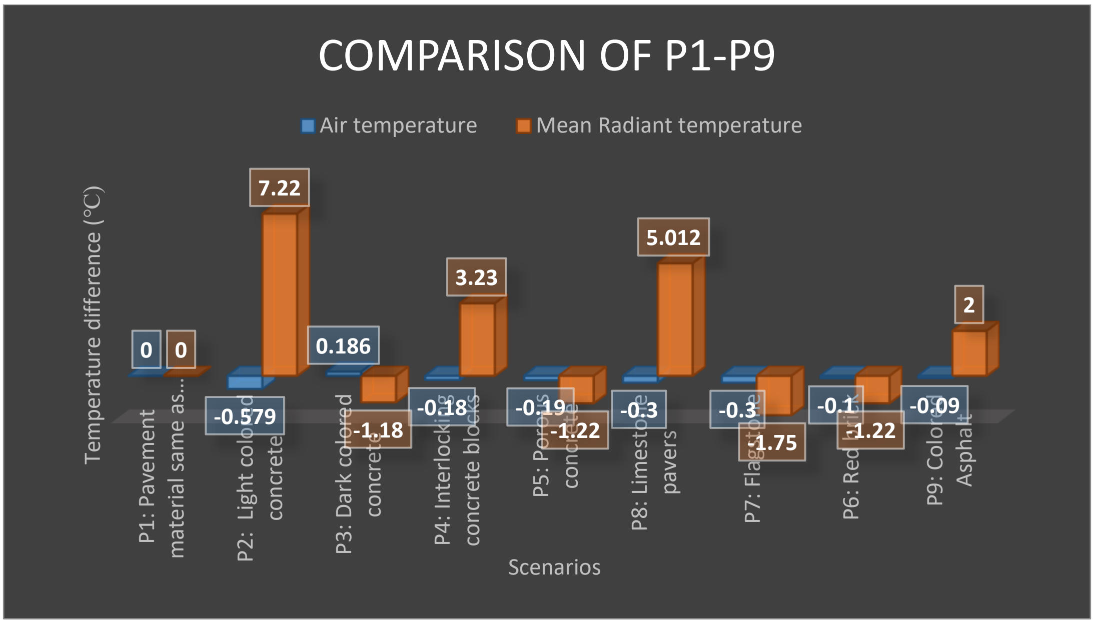


Figure 6-4 Comparison of Scenarios: By changing pavement material

Than the other pavement materials used in the simulation. Hence the material which decreases the air temperature might also not improve or worsen the thermal comfort for the pedestrians. The materials which showed the decrease in both air temperature and mean radiant temperature were porous concrete, flagstone and brick pavers.

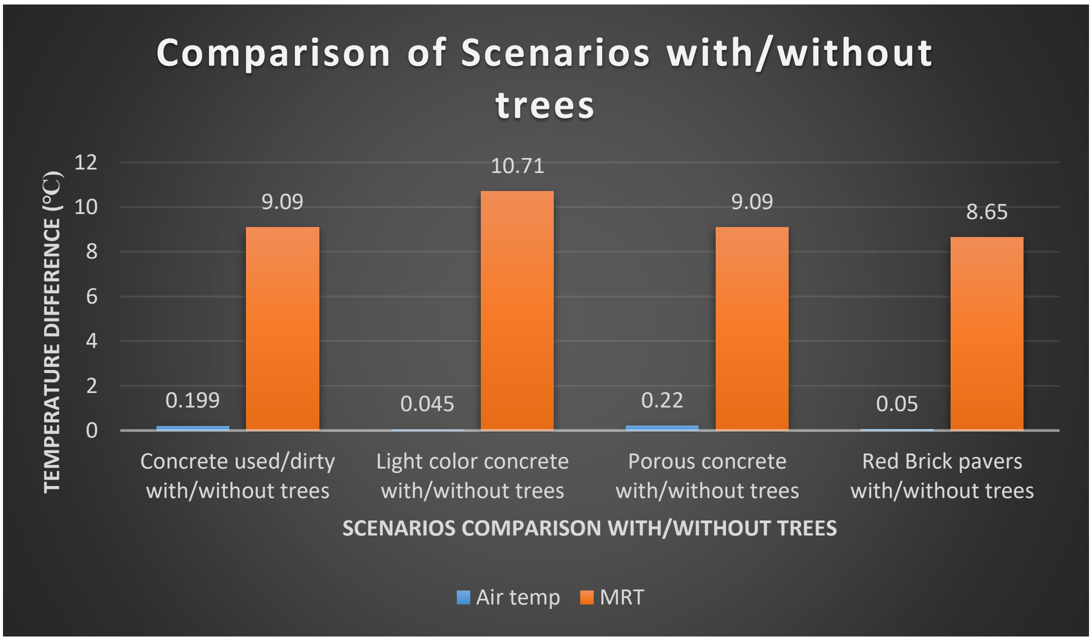


Figure 6-5 Comparison of Scenarios V1P1, V1P2 (High LAD trees with pavement light color concrete), V1P5 (High LAD trees with pavement porous concrete), V1P6 (High LAD trees with pavement red bricks).

When the scenarios with and without trees (V1P1 and P1, V1P2 and P2, V1P5 and V1P6) were compared, the potential air difference was found maximum in porous concrete (0.22℃) and the mean radiant temperature difference was found maximum in light color concrete. The potential air temperature difference with and without ranges from 0.045℃ to 0.22℃ and Mean radiant temperature difference with and without trees ranges from 8.65℃ to 10.71℃.

7 CHAPTER SEVEN CONCLUSION

7.1 Conclusion

In this research, the effectiveness of various landscape elements (mainly trees and pavements) was evaluated in improving the thermal comfort of pedestrians on sidewalks by taking one of the busy streets in Kathmandu: Durbarmarg. The study used measurements, questionnaire surveys, and simulations as methodological tools to achieve its objectives.

The study concludes that the physical characteristics of the sidewalks such as the shade of buildings, the presence of vegetation (trees), and the surfacing materials affect the thermal environment of the sidewalks. Among the various vegetation parameters considered, leaf area density is of utmost importance to maintain the thermal comfort. Among the various pavement materials considered, the pervious concrete, brick pavers enhances the thermal comfort for pedestrians. For the high reflective surfaces, the surface /air temperature is reduced but it increases the mean radiant temperature and hence might not be appropriate for the thermal comfort of the pedestrians. This also comply with the findings of other studies **(**Taleghani & Berardi, 2017**;** Li, et al., 2012).

The results of questionnaire survey show that the sidewalks were not comfortable in terms of thermal comfort. However, the sample size of the survey should be increased to get more accuracy.

7.2 Recommendations and Further Research

It can be concluded that certain interventions in sidewalk landscape (trees and pavements) can make significant difference in the microclimate of the street. Hence, the street design guidelines in Kathmandu should also consider the thermal environment of the street/sidewalks while considering the landscape design of the street. Brick pavers, flagstone and porous concrete (evaporative cooling effect) can be used instead of traditional impervious concrete. Trees with high leaf area density can be used to provide the cooling effect in hot climate. Similar studies can be done to enhance pedestrian thermal comfort in Terai region of Nepal. These kind of study

/research should be done and will be useful in also creating the public pocket parks within the city to get the maximum thermal benefit.

Further research is needed as the study was conducted in a typical street section and only during the few summer days. In temperate climatic regions like Kathmandu, the study is also important in winter. However, the study was conducted only during summer. Various parameters like the street aspect ratio, tree species and other landscape feature like water bodies can be considered for the further studies.

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APPENDIX A

Survey Location

☐ East facing Sidewalk ☐ West facing sidewalk

GPS location Date of survey

Time of Survey Sky condition

Activity while surveying

☐ Standing ☐ Walking ☐ Sitting ☐ Others______________

Respondent type:

☐ Vendor ☐ Pedestrian ☐ Shopkeeper ☐ Others______________

Clothing ________________________

Temperature_______________________ Relative Humidity_______________________

……………………….(Above details to be filled by surveyor)…………………………………….

Demographic

Gender

☐ Male ☐ Female ☐ Others

Age

☐ 20-30

☐ 30-40

☐ 40-60

☐ 60+

Weight

☐ < 40 ☐ 60-70

☐ 40-50 ☐ 70-80

☐ 50-60 ☐ 80+

Purpose of visit

1. What is your reason for visiting in this street?
   ☐ Strolling ☐ For work ☐ Entertainment/Fun ☐ Shopping

   ☐ Others ________________

2. How often do you walk in this street? (Frequency of travel)
   ☐ Daily ☐ Few times a week ☐ Weekly ☐ Monthly ☐ Rarely

3. At what time of the day do you visit this street?

☐ Before 7 am ☐ 7am-10 am ☐ 10am-2 pm ☐ 2pm-5pm ☐ 5pm-8 pm ☐ After 8 pm

4. Which side of street do you prefer to walk?

☐ Sidewalk facing East ☐ Sidewalk facing West ☐ Both ☐ None

5. Why do you choose to sit/stand/walk at this particular place? (can choose more than one item)

☐ Due to shade ☐ Tree-cover ☐ Fresh air

☐ Under Sunshine ☐ Going somewhere ☐ Close to home/school/office

☐ No particular reason ☐ Entertainment ☐ Others_____________

6. Do you feel the heat from the pavement?

☐ Yes ☐ No

Past thermal experience

1) Have you been staying in Kathmandu in the past 6 months?

☐ Yes ☐ No

2) In the past 15 min prior to the survey, have you been to (or stayed in) air-conditioned indoor spaces (cooled or heated spaces including cafe, office etc.)?

☐ Yes ☐ No

3) What were you doing in the past 15 min prior to the survey?

☐ Standing ☐ Walking ☐ Sitting ☐ Exercise

☐ Working ☐ Driving (4-wheelers) ☐ Driving (2-wheelers) ☐ Others______________

Thermal sensation

1) How do you feel right now?

☐ Very hot +3 ☐ Hot +2 ☐ Warm +1 ☐ Neutral a0 ☐ Cool -1 ☐ Cold -2 ☐ Very cold -3

2) How is your Skin in terms of wetness?

☐ Sweaty ☐ moist ☐ Just right ☐ Dry ☐ Very dry

Preference for microclimate

a) How do you wish for the air temperature to be?

☐ Cooler (-1) ☐ No change (0) ☐ Warmer (+1)

b) How do you wish for the Sun to be?

☐ Weaker sun (-1) ☐ No change (0) ☐ Stronger Sun (+1)

c) How do you wish for the Wind to be?

☐ Weaker wind (-1) ☐ No change (0) ☐ Stronger Wind (+1)

APPENDIX B

S.N	Date-Time	Parameters	Hobo MX 2304	Hygrometer HTC-2	DHM	Diff. (hobo Hygro)	Diff.(Hygro DHM) T	RH	Diff. (Hobo DHM)
1	06/23/2022 15:15:00	T (°C)	28.87	29.2	28.72	0.33	0.48		0.15
		RH		42	38.46			3.54	
2	06/23/2022 15:20:00	T	28.87	29	28.84	0.13	0.16		0.03
		RH		42	38.07			3.93	
3	06/23/2022 15:25:00	T	29.00	28.7	28.93	0.30	0.23		0.07
		RH		41	37.72			3.28	
4	06/23/2022 15:30:00	T	29.13	29	28.99	0.13	0.01		0.14
		RH		41	37.26			3.74	
5	06/23/2022 15:35:00	T	29.13	29	29.13	0.13	0.13		0.00
		RH		40	37.05			2.95	
6	06/23/2022 15:40:00	T	29.30	29	29.19	0.30	0.19		0.11
		RH		40	36.94			3.06	
7	06/23/2022 15:45:00	T	29.34	28.7	29.06	0.64	0.36		0.28
		RH		40	37.28			2.72	
8	06/23/2022 15:50:00	T	29.21	29.1	28.87	0.11	0.23		0.34
		RH		39	37.4			1.6	
9	06/23/2022 15:55:00	T	29.08	29.1	28.87	0.02	0.23		0.21
		RH		40	37.7			2.3	
10	06/23/2022 16:00:00	T	29.17	28.8	28.97	0.37	0.17		0.20
		RH		39	37.08			1.92	
11	06/23/2022 16:05:00	T	29.34	29	29.08	0.34	0.08		0.26
		RH		39	36.58			2.42	
12	06/23/2022 16:10:00	T	29.56	29	28.99	0.56	0.01		0.57
		RH		38	36.95			1.05	
	Average difference					**0.28**	**0.19**	**2.71**	**0.20**

APPENDIX C

IOE Graduate Conference
[Placeholder for Publication Information]

Assessment of Pedestrian thermal comfort on Sidewalks

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Abstract

With the growing problem of urban densification and the urban heat island effect, the thermal comfort of pedestrians in the outdoor spaces of urban areas has deteriorated. Since the street is the most important outdoor space that can promote physical activity, and especially with the emerging concept of walkable cities, thermal comfort in streets should be given utmost importance. Thermal comfort for pedestrians is the absence of any sense of discomfort when interacting with the outdoor thermal environment. Considering that a thermally comfortable street promotes walkability, this study aims to identify the comfort parameters in the sidewalks of the street and evaluate the thermal environment through a questionnaire survey. The study adopted a quantitative approach and chose the questionnaire survey as a research method to achieve its objective. The survey was conducted on both sidewalks of Durbarmarg, one of the dense and busy streets of Kathmandu, with a random sample of 18 people. The results of the study showed that the physical characteristics of the street, such as building shade, the presence of vegetation, and the paving material, are the most important factors for pedestrian comfort. The survey also found that the selected street section was not thermally comfortable in summer, as the majority of people felt hot, warm, or very hot sensation and preferred cooler air temperature, weaker sunlight, and stronger wind. The study concludes that subjective assessment of the thermal environment through a comfort survey is important and probably the first step before taking measures to improve thermal comfort, especially under the climatic conditions in Kathmandu.

Keywords

Pedestrian, Thermal Comfort, Sidewalks

1. Introduction

Rapid population growth has resulted in dense urban areas that are changing urban morphology. The change in the proportion of vegetation and the type of land cover led to the phenomenon of urban heat island effect [1] . This has and worsens urban comfort conditions. The outdoor environment in cities includes the variety of activities for pedestrians. The comfort level of pedestrians is one of the determining factor for the number of the people outside. The rough definition of the pedestrian comfort is the pleasant feeling that people get when interacting in the environment. The concept of pedestrian thermal comfort falls under the umbrella concept of pedestrian comfort.

ASHRAE (American Society of Heating and Refrigeration and Air conditioning Engineers) defines human thermal comfort as condition of the mind that expresses satisfaction with the thermal environment which is determined by environmental and individual variables. The thermal comfort of streets is particularly important because they have a high potential to promote physical activity. This is evidenced by the fact that they are frequently used for walking and other outdoor activities. Sidewalks are pedestrian paths that run along a street. Sidewalks provide pedestrian mobility and access to the buildings, parks and other amenities.

Street has its own microclimate. The amount of solar radiation absorbed by street surfaces, as well as their orientation and geometry, create their own microclimate. The microclimate of streets affects the comfort of pedestrians walking. Walking is the most natural and most common way of transportation in cities including Kathmandu. Walking for short distances could be one of the promising strategies to reduce Vehicle Miles Traveled (VMT), transport-related energy consumption, and associated environmental impacts [2]. Walkability, or the ease with which pedestrians can move around a city, is cited by many urban planners as the factor that makes a city livable. Thermal comfort is one of the most important factors influencing pedestrian health, and increasing thermal comfort improves walkability [3].

The Kathmandu Valley, with an estimated population of 2.54 million, is growing at an annual rate of 6.5 percent, making it one of the fastest growing metropolitan areas in South Asia[4]. Mishra, et al, [5] study of the urban heat island in Kathmandu found an average temperature difference of 5°C between forested and urban areas in the Kathmandu Valley. Moreover, an annual increase of 0-2°C was found over the last 18 years. This means that Kathmandu is getting hotter day by day. The current urbanization and motorization in Kathmandu does not provide a safe and pleasant environment for walking. Most streets do not even have sidewalks, and those that do exist are either poorly maintained or occupied by parked vehicles and street vendors. Electricity and telecommunication poles were placed indiscriminately throughout the city, often in the middle of sidewalks[6]. Many street improvement projects carried out under the Municipal Infrastructure Improvement Project (MIIP), Kathmandu Sustainable Urban Transport Project (KSUTP) have focused on vehicular movement and drivers' convenience rather than pedestrian comfort, convenience and safety [7].

In such an environment, thermal comfort for pedestrians on sidewalks is a distant prospect. Therefore, the study aims to assess the comfort level of pedestrians and determine the comfort parameters on sidewalks in one of the street sections of Kathmandu.

2. Literature Review

The study of outdoor thermal comfort is the growing field of interest among researchers. The beginning of studies on outdoor thermal comfort dates back to the last few decades of the 20th century [3] . Majority of the researches were based on simulations or were experimental without subjective results. In 2001, one of the first studies in the field of outdoor thermal comfort was conducted based on human behavior. In this study Nikolopoulou et al. [8] investigated thermal comfort conditions in open spaces in Cambridge, United Kingdom. They rated the sensory perception of each individual on a scale of 1-5. In this study, only 35 percent of the participants experienced the desired thermal comfort. In last decades, over 500 studies were done with subjective results [9].

Outdoor thermal comfort is mainly related to thermo-physiology, i.e. physiology and heat balance of the human body [10] that is directly affected by meteorological conditions. There are various parameters for outdoor thermal comfort. They can be categorized into subjective and objective. The subjective parameter consists of behavioral and psychological aspect whereas the objective parameter consists of air temperature, mean radiant temperature, metabolic heat, wind, and humidity and clothing insulation. They can be further categorized as the personal and environmental factors. There are three approaches to defining thermal comfort. To begin, the psychological aspect refers to the mental expression of satisfaction with the outdoor thermal condition. Second, the thermo-physiological aspect influences biological reactions and thermal receptors on the skin in response to the external environment. Third, the energetic aspect is concerned with the flow of heat from and to the human body.

Sidewalks run parallel to street and Sidewalks and streets not only facilitate easy movement for pedestrians, but are also considered the most important public spaces in a city. Sidewalks mainly consists of 3 zones: Frontage zone, pedestrian through zone and street furniture/curb zone. The frontage zone is a section of the sidewalk that serves as an extension of the building. The pedestrian through zone is the main accessible pathway for pedestrians and the street furniture/curb zone consists of street furniture and amenities such as lighting, benches and bicycle parking. As per Urban Road Standard 2076, for comfortable movement of people with disabilities, the minimum clear width of a footpath should be 2.0 m, but 2.4 m is desirable, at least along arterial and secondary roads.

Several physical parameters determine the thermal environment for the pedestrians in the street: the pavement materials, presence/absence of vegetation, street aspect ratio, no. of the people and vehicles passing by the street. If a person feels "hot," it may be from the sun or from the materials used in the environment, such as asphalt used as pathway [11].

Sidewalks consist of trees and grass as soft landscaping elements and paving materials and street furniture as hard landscaping elements. Trees and Vegetation contributes to the modification of street micro-climate in primarily providing shading, evapotranspiration and directing wind [12].Paving materials have a strong effect on the street micro-climate and represent one of the main contributors to the increase of urban heat island [1]. The different characteristics of vegetation like the foliage shape and dimensions, height of trunk, leaf area density has impact on outdoor thermal comfort. Similarly, the thermal properties of the pavement materials can be modified to enhance the thermal comfort in streets. Cool pavements have been identified as solution worldwide which are basically pavements with modified thermal properties than traditional pavements. They have different properties than regular ones in order to lower their surface temperature.

3. Research Setting

For this research, the street with proper sidewalks and immense flow of pedestrians was selected for case study. The selected case study area, Durbarmarg (informally known as Kings's way), is located in the metropolis of Kathmandu and is a very dense and lively street in Kathmandu. It leads to the royal palace of Narayanhiti. Durbar Marg, built in 1961 by the then Crown Prince Birendra Bir Bikram Shah Dev, was known as a center for travel business with airlines, travel agencies, restaurants and tourist shopping. Slowly, it has evolved into a business district that serves people as a shopping and entertainment destination. The pedestrian flow on the street is immense. The number of pedestrians passing the street at a certain point was recorded at different times of the day and on both sidewalks. It was found that pedestrian flow was greater on east facing Sidewalk than west facing sidewalk. On June 27 at 4:30 p.m., approximately 36 people passed in one minute.

The selected stretch is about 300 metres long and oriented in the N-S direction. The street consists of commercial buildings that vary from 2 to 5 floors. A variety of stores, restaurants and bars, shopping centres and offices can be found in the selected area.

The street consists of the vehicular zone and pedestrian zone. Vehicular zone consists of the 4 lanes. The sidewalks are on both sides. For convenience: they are named East facing sidewalk and West facing Sidewalk.

The frontage zone of the sidewalks varies between 2 and 3 m, the pedestrian passage zone is 2.8 m, and the curb zone is 1.3 m. There is little street furniture on the east-facing sidewalk. The tree species planted in the

Figure 1: Location map of the selected street section

Figure 2: Plan of Selected street section

street is Jacaranda Mimosifolia, and on the sidewalks there are different paving materials that vary in the building frontage and pedestrian zone.

4. Methodology

The methodology adopted for the study of the outdoor thermal comfort so far includes the use of simulation software, questionnaire survey and measurement and combination of simulation software and questionnaire survey.However, the study adopted a quantitative approach and chose the questionnaire survey as a research method to achieve its objective. It is the method used to collect data from the target group of respondents in order to gain knowledge about the topic of interest.

The questionnaire was prepared and first tested among the few pedestrians, and the necessary changes were made. The questionnaire was divided into demographic information, purpose of visit, thermal sensitivity, and micro-climate preference. Demographic information included gender, age group, weight, etc. Reason for visit included purpose, frequency, and time of visit. The heat sensation survey is a standard parameter in most thermal experiments. It is a 7 point scale ranging from -3 (cold), neutral (0) to +3 (hot).The survey was done for 7 days from 27th of June to 6th of July on favorable climatic conditions on the both sidewalks. Random sampling was done for the survey. Most of the pedestrians did not want to take part in the survey due to various reasons and hence and the total number of respondents were limited to 18.

5. Data Set, Analysis and Discussion

The following figures show the results of the questionnaire survey. Data analysis was performed using the Kobotool box and the software IBM SPSS.

5.1 Demographic details

Though the target group for this survey were pedestrians, few security guards and street vendors were also surveyed. Among the no. of respondents, 61 percent of them were male and 67 percent of them were from the age group 20-30 and the weight of the respondents ranged from 60-80. Figure 5 shows the

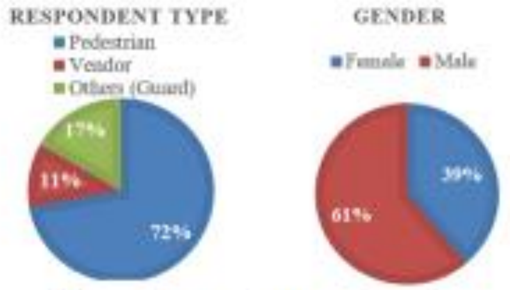

Figure 3: Respondent type and gender

Figure 4: Weight and age group of Respondents

sky conditions during the survey. 33 percent of the survey time the sky was mostly sunny, 28 percent partly sunny and the rest of the time the sky was mostly cloudy or overcast. The survey was carried out

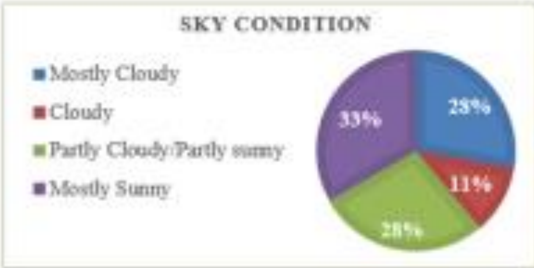

Figure 5: Sky condition during Survey

in both sidewalks and the percentage of no. of respondents in the sidewalks in shown in the figure 8. Most of people either preferred east facing sidewalk (45 percent) or both sidewalks (33 percent). As mentioned earlier the pedestrian movement is more in east facing sidewalk, the reason might be because of the presence of the street furniture, restaurants and shops. Since the people have tendency to walk in the shade during summer, the thermal comfort might be also one of the reasons.

Figure 6: Survey Location

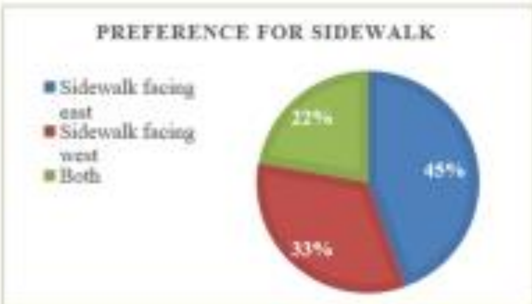

Figure 7: Preference for Sidewalks

5.2 Activity mapping during Survey

Figure 8: Activity mapping during Survey

Activity mapping was also done during the survey with its GPS location. The figure 8 shows the location of the survey within the site and the activity of the individuals during the survey. 39 percent of the individuals were sitting, 33 percent were standing, and 28 percent were walking during the survey. Most of the people surveyed were sitting on the benches along the roadside in east facing sidewalk and around Sherpa mall in west facing Sidewalk. Most respondents (30.4 percent) chose the particular place to sit/stand/walk mostly because of tree cover and 26.1 percent of them chose the place due to shade. As mentioned earlier, vegetation and the physical attributes of a place also influences the thermal environment of the place.

Figure 9: Choosing the particular place

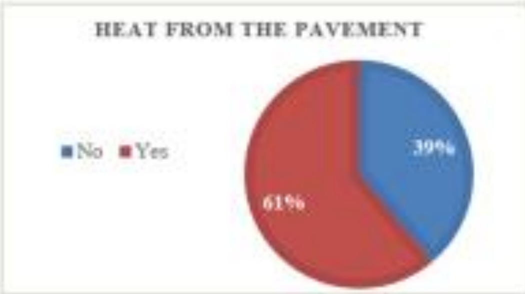

Figure 10: Heat from the pavement

From the literature studies, the paver materials also affected the thermal environment of the sidewalks, hence the question was included. Majority of the respondents (61 percent) felt the heat from the pavement.

5.3 Reason and time of visit

The figures 11 and 12 show that the reason for visiting the street was work and that 50 percent of the respondents visits the street in the period from 10 am to 2 pm. The temperature is generally highest in the period from 10 am to 2 pm, but since the majority of respondents were there because of work, it can be assumed that thermal comfort has the least influence on visiting the street in this period.

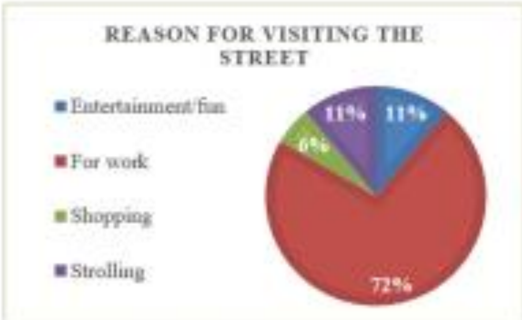

Figure 11: Reason for visiting the street

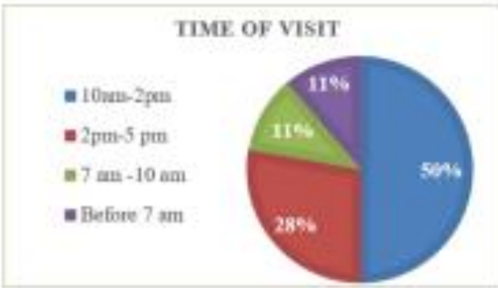

Figure 12: Time of visit to the street

5.4 Thermal Sensation

7 point scale was used to assess the thermal sensation of the respondents. Around 33.33 percent felt neutral thermal whereas the rest of them felt either warm, hot or very hot sensation during the survey. The table 1 shows the relation between Sky condition and thermal sensation. Since the solar radiation has major role to play for the thermal comfort, it is expected that the pedestrians feel most uncomfortably warm or hot during the sunny bright day in summer. As seen from the table 1 , out of the 33.33 percent of sunny sky condition same percentage of people (16.7percent) felt hot and neutral despite of the sky condition, it might be because of the clothing level, activity level of respondents and also the location of the pedestrians within the street. Other climatic factors such as wind, relative humidity can also affect the comfort level of pedestrians.

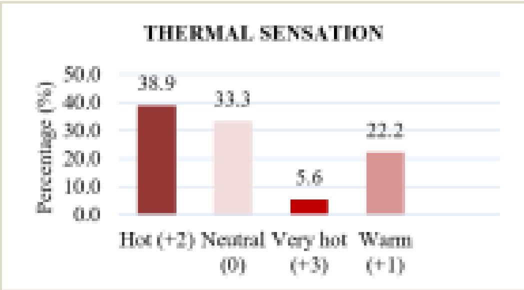

Figure 13: Thermal Sensation

Table 1: Relation between Thermal Sensation and Sky Condition

Sky condition	Thermal Sensation Hot (+2)	Neutral (0)	Very hot (+3)	Warm (+1)	Total
Mostly Cloudy	11.1%	5.6%		11.1%	27.8%
Cloudy		5.6%		5.6%	11.1%
Partly Sunny	11.1%	5.6%	5.6%	5.6%	27.8%
Mostly Sunny	16.7%	16.7%			33.3%
	38.9%	33.3%	5.6%	22.2%	100.0%

5.5 Preference for microclimate

The last part of the survey dealt with the preference for microclimate. 66.7 percent of respondents wanted a cooler air temperature, while the remaining 33.3 percent of respondents wanted no change in air temperature. Similarly, 61.1 percent of respondents preferred weaker solar radiation, while the remaining 38.9 percent of respondents wanted no change in solar radiation. For wind, 55.6 percent of respondents preferred stronger wind, while the remaining 44.4 percent of respondents wanted no change in wind.

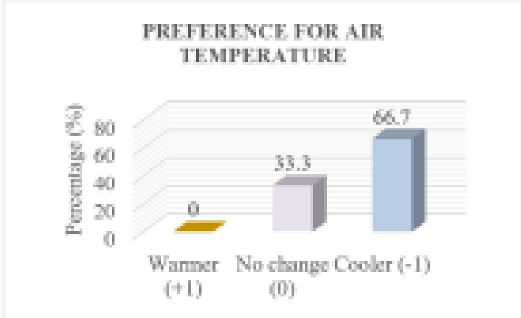

Figure 14: Preference for air temperature

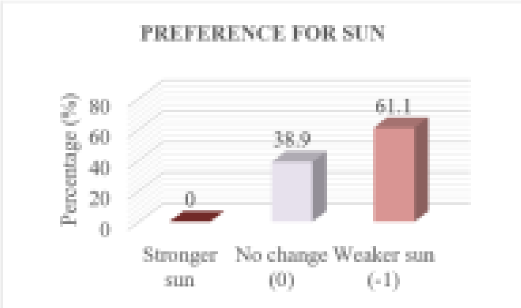

Figure 15: Preference for Sun

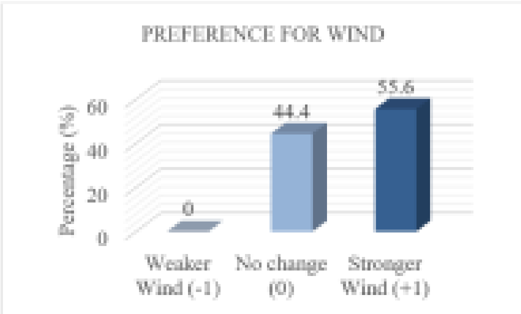

Figure 16: Preference for Wind

6. Conclusion and Recommendation

In this study, the thermal comfort of pedestrians was investigated using one of Kathmandu's busiest streets as an example. Durbarmarg. The results of the study are consistent with the literature review. The physical characteristics of the sidewalks such as the shade of buildings, the presence of vegetation (trees), and the pavement materials affect the thermal environment of the sidewalks. Since a majority of the people (66.7 percent) felt either the hot ,warm or very hot sensation and most of the people preferred the cooler temperature (66.7percent), weaker sun (61.1 percent) and stronger wind (55.6 percent), it can be concluded that the sidewalks of Durbarmarg was not thermally comfortable for pedestrians during summer.

The study concludes that activity mapping and thermal sensation study are of utmost importance especially in the climatic conditions of Kathmandu. In temperate climatic regions like Kathmandu, the study is also important in winter. However, the study was conducted only in summer. Therefore, further research is needed as the study was conducted in a typical street section and only during the few summer days. A random sample was drawn for the questionnaire survey and the sample size was small (total number of respondents: 18), so the results of the survey cannot be generalized to a larger population. Similar studies can be conducted in different street segments and in summer and winter if the sample is large enough. The study also shows that further studies can be conducted considering parameters such as the aspect ratio of the street, vegetation, and paving materials using the simulation research method.

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