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APPRAISING THE INFLUENCE OF PAVING MATERIALS ON PEDESTRIAN THERMAL STRESS IN TROPICS: *Evaluating the effects of tree shading on surface thermal performance*

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Abstract
Escalating trend in the formation of urban heat island (UHI) in the cities of tropical Asia contributes to warming microclimates and imposes a greater challenge on human health and well-being. Rapid urbanization and declining green plot ratio has contributed to the formation of an UHI in the city of Colombo. Consequences of UHI on urban green spaces exaggerate with the increasing use of paved surfaces. As surface heat inflation causes thermal discomfort for dwellers, it is vital to understand the thermal performance of different artificial and natural paving materials with a particular focus on tree shade variation.

This study experimentally investigated parks of Independence Square and the Water's edge in Colombo. Onsite field investigation was performed on a typical hot season identifying most users perceive settings inside the park. The Mean Paving Surface Temperature (MPST) and predicted Physiological Equivalent Temperature (PET) values were obtained in relation to Crown Volume Coverage (CVC) of trees. Results explicitly confirm PET values inside the parks correspond to high discomfort range. Exposed concrete paving is evident for high PET levels and the shaded surfaces are apparent for a reduction of 10°C of mean MPST. The Lowest PET of 30 °C was evident over the shaded grass paving with 31°C mean MPST. Reduction of the MPST significantly correlated ($p=0.00$) with increasing tree CVC. Thus, the findings of the study inform natural paving design implications with improved shading composition can promote less heated urban green spaces in developing cities of tropics.

Keywords: *Urban Heat Island, Surface Temperature, Thermal comfort, Tree canopy coverage.*

1. Introduction

Accelerating urbanization trend prioritize 66% of the population growth in urban areas by 2050. According to the UN projections the highest urbanization evident in Asia, which will respectively increase to 64% by 2050 (United Nations, 2004). Simultaneously rapid densification of structural mass in cities triggered the urban heat island effect (UHI) by generating heat trapped environments. Current urban settings are recording 4.0°C to 10°C temperature difference compared to the peri-urban surroundings (Gartland, 2008) leading to thermal discomfort in city dwellers inducing greater risk in terms of increased morbidity and mortality (Shahmohamadi et al., 2011).

UHI effect is not an exception for the megacities of Sri Lanka. Exaggeration of impervious ground surfaces is one of the major drivers of UHI effect in local context (Ranagalage et al.,2017). The development trends in past decade have imposed sever ground modifications by reduction of green plot ratio in cities. This intense application of heat-absorbing surfaces and paving materials contribute to generate Surface UHI (SUHI) intensity in microclimates of Urban Green Spaces (UGS) (Sharifi et al. 2015). Thus, it is paramount important to understand the thermal performance of different artificial and natural paving materials on human thermal comfort in green precincts.

1.1 THERMAL BEHAVIOR OF URBAN PAVED SURFACES

The thermal performance of paved surfaces directly integrated with SUHI phenomenon altogether with environmental aspects of heat stress and air pollution (Chudnovskym et al., 2004). In urbanized areas paving materials differentiated with various energy absorption rates and albedo indexes (Ghazanfari et al., 2009). However, urban paving materials of higher heat capacity tend to absorb and re-emit solar radiation increasing the microclimatic temperature profile. When UGS are replaced by high thermal admittance materials, it's a worst-case scenario triggering thermal dis-comfortability for park users.

1.2 HUMAN THERMAL COMFORT

Thermal comfort interpret as the physiological interval where the human can operate or tolerate the thermal environment with a state of satisfaction (ASHRAE Standard 55P, 2003). The comfortability of thermal environment of human are best determined with aid of the thermal indices based on energy balance of human body , interpreted as PMV (Predicted Mean Vote) (Fanger 1972), PET (Physiologically Equivalent Temperature) (Höppe 1999), SET (Standard Effective Temperature) (Gagge et al. 1986).

Exposed to high heat in micro settings contributes to heat exhaustion, heat cramps, heat-related rash and heat stroke (OSHA, 1999). Thus, it is crucial to identify mitigation measures to reduce the SUHI phenomenon in urban public spaces.

1.3 URBAN TREES ON SURFACE URBAN HEAT ISLAND (SUHI) EFFECT

Urban tree canopies can enhance the local radiation balance through shading effect, regulating both of the person's body itself and of the surrounding ground or built surfaces (Holst and Mayer 2011). These surfaces maintain a lower radiant temperature when shaded than when exposed by intercepting solar radiation and preventing the heating of the surface under their canopy (Brandani et al. 2016). Thus, the application of canopy interventions with maintaining a standard surface energy budget is a crucial scenario to mitigate SUHI.

1.4 CRITICAL CASE ON URBAN HEAT ISLAND IN TROPICS

Research on the thermal performance of paving applications in tropics is yet to be explored. The limited research explored, SUHI phenomena in Colombo Sri Lanka (Ranagalage et al. 2017); Land surface characteristics in Heat mitigation (Chowdhury et al. 2017) in India ; Urban morphology on thermal conditions of street canyons in Thailand (Takkanon et al.2018) and Cooling effect of tree canopies Malaysia (Tukiran et al. 2016).

Field studies on thermal comfort are less represented in Sri Lanka and no studies to address the synergies between paving SUHI and thermal comfort. Thus, this study explored the thermal performance of the differed paving materials in the UGS of Colombo, with special reference to tree canopy coverage to configure landscape interventions to establish outdoor thermal comfort indices for tropics.

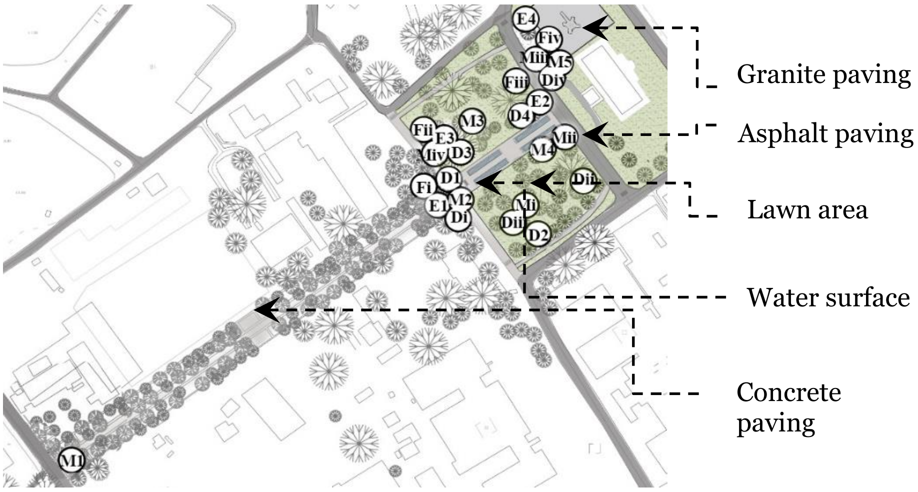
2. Experimented Urban Parks

This study was performed in two highly popular urban parks situated in the city of Colombo (6.9° N, 79.8° E) in Western province, Sri Lanka. The City of Colombo represents the highest population density of the country with 3438 persons/Km^2 and it is the most congested city due to rapid urban sprawl for economic and employment activities (Dept. census & Statistics, 2012).

According to World Health Organisation (WHO), 9.5 m^2 of green area per capita is the minimum requirement for healthy living. Urban development in Colombo precincts has altered the urban landscape by decreasing green areas, resulting in an uneven spatial green area distribution. Due to this scenario 34 out of 55 administrative divisions were not complying with the WHO standards for the city (Senanayake, 2013). Thus, its paramount importance to re-establish healthy green areas within the city limits.

Location of the urban parks and its landscape characteristics are shown in figure 1. Independence square (ISP) is a historical commemoration park positioned in a highly urbanized area of Colombo. The façade landscape design of this park spreads in 2 Hectares with dense vegetation.

a. ISP: Independent Square Park



b. WEP: Water's Edge Park

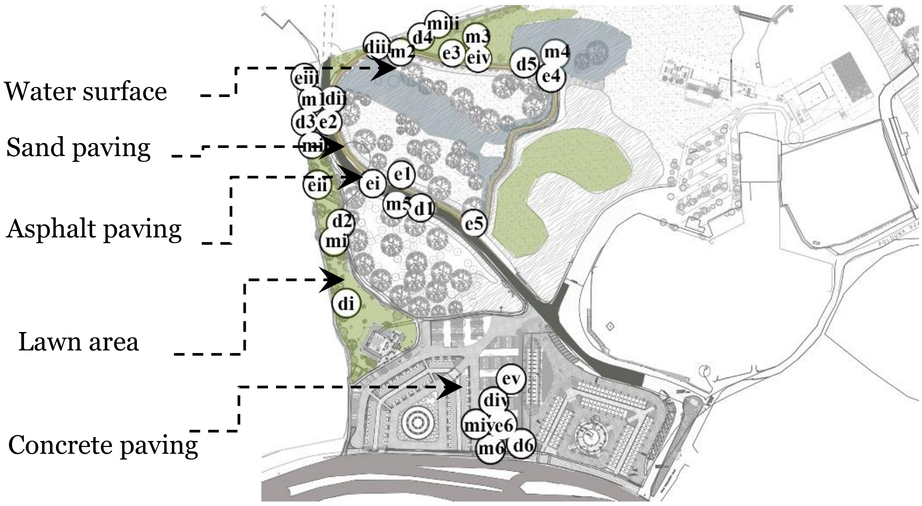


Figure 1, Landscape paving design including weekday and weekend peak usage profiles of experimental urban parks; (a) ISP *(microclimatic settings of M1 to E4 and Mi to Eiv and paving characteristics)* and (b) WEP *(microclimatic settings of m1 to e6 and mi to ev and paving characteristics)*

Water's Edge Park (WEP) is a suburban wetland in Sri Jayawardhanapura, Kotte. This park contains 12 Hectares of land amalgamated with watershed environment and averagely dense vegetation. Both parks provide facilities for active and passive modes of exercises such as relaxing, walking and jogging.

2.1 EXPERIMENTAL METHODOLOGY

The experimental methodology of this study is consists of a walk through survey, formulation of a tree inventory and onsite thermal recordings to quantify the park users' exposure to SUHI levels in the investigated parks.

2.1.1 Walkthrough survey: Mapping of the peak usage profiles

A walkthrough survey was performed on a typical weekday and weekend during three peak usage time slots such as Morning (M), Daytime (D) and Evening (E). Time periods for morning, daytime and evening are from 8 to 11 am, 12 to 3 pm and 4 to 6 pm respectively. These sampling locations represent 25 and 31 peak usage settings of ISP and WEP.

2.1.2 Recording of Landscaping characteristics

Landscaping characteristics of 56 places were recorded by developing tree inventories. This inventory is consists of four main variables of trees such as Species, quantity, height, and diameter of the crown (Nowak, 2008). A three-dimensional green quantity model was used as an indicator to characterize urban vegetation structure and which is represented as Crown Volume Coverage (CVC).

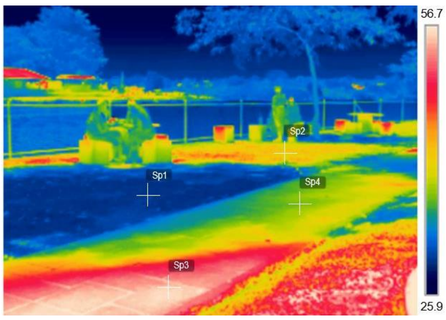
$$CVC = \text{Total Crown volume } (m^3) / \text{ Surface area } (m^2) \qquad (1)$$

This model considers the geometrical difference of the crown of tree species and combines the diameter (x), height (y) and coverage of the crown to calculate its CVC per unit area (Zhou, 2001). Crown volumes of all inventoried live trees were calculated using equation 1 and the common growth of each tree species were recorded by calculating the mean of diameter Xp and height Yp of the crown.

In addition, the normalized crown volume (Vn) and CVC of the tree species were calculated. Total crown volume coverage (CVC) of identified microclimatic settings represents tree species located within $100m^2$ coverage.

2.1.3 Onsite experimental Investigation: Measurements of Mean Paving Surface Temperature (MPST) of peak usage settings

MPST was measured by thermal imagery recorded in each micro climatic setting by FLIR T530 Thermal Imaging Camera. FLIR tools processed thermal imaging plus software to acquire the surface temperature measurements and parameters (emissivity and Reflective temperature) as shown in figure 2.



Surface Material		Spot	MPST °C
Lawn	Shade	Sp1	30.2
	Unshade	Sp2	42.9
Concrete paving	Shade	Sp3	55.1
	Unshade	Sp4	37.7
Emissivity		0.81	
Refl. temperature.		20 °C	

Figure 2, Spot measurements of the different paving surface temperatures in a selected microclimatic setting of WEP.

2.1.4 Measuring Human Thermal Comfort via PET

To measure the thermal comfort of the park user, microclimatic parameters such as air temperature (Ta), relative humidity (RH), and wind velocity (v) were measured in 56 places of investigated two parks. Sampling protocol was established to collect data for 10 minutes in each microclimatic setting with an acquisition time of 10 seconds. Adopting the measured data PET values were calculated using the RayMan1.2 for each microclimatic setting.

Table1, Ranges of the PET for different grades of thermal perception by human beings and physiological stress on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.5 clo (Matzarakis and Mayer 1996)

4°C 8°C 13°C 18°C 23°C 29°C 35°C 41°C	Very cold Extreme cold stress	PET Thermal perception (Grade of physiological stress)
	Cold Strong cold stress	
	Cool Moderate cold stress	
	Slightly cool Slight cold stress	
	Comfortable No thermal stress	
	Slightly warm Slight heat stress	
	Warm Moderate heat stress	
	Hot Strong heat stress	
	Very hot Extreme heat stress	

3. Results and Discussion

3.1 SURFACE HEAT ISLAND EFFECT AND THERMAL STRESS

Park user's thermal stress index was calculated for the microclimatic settings of ISP and WEP and was appraised based on hourly meteorological Ambient Temperature (AT) and microclimatic Air temperatures (MAT).

3.1.1 Independence Square Park (ISP) Surface Heat Island effect

Figure 3, shows the SUHI effect in peak usage profiles in ISP during typical two sampling days. Two sampling days consists of 25 places (M1 to Eiv). Results explicitly prove that the MAT (min, max, avg) of the particular microclimate is higher than the meteorological AT.

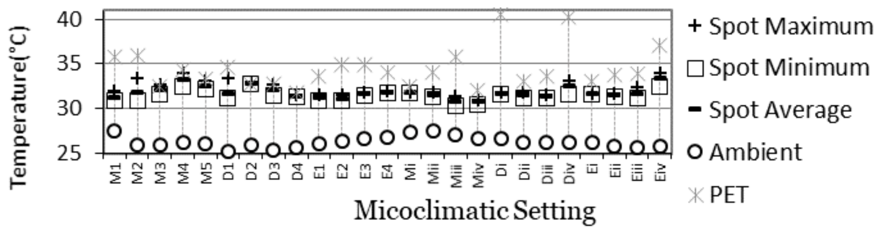


Figure 3, SUHI effect on ISP in selected microclimatic settings

In two sampling days of ISP evident a MAT ranges from 32.3°C to 31.4°C, whereas AT represents 26.3°C. Respectively the mean SUHI intensity (UHII) on the ISP evident 3.94 °C difference. Thermal Sensation profile of the park ranges from PET, 40.5°C - 31.7°C to average 34.4°C, which indicate warm moderate heat stress. The paving surface temperatures measured by thermal imaginary in ISP indicated by figure 4.

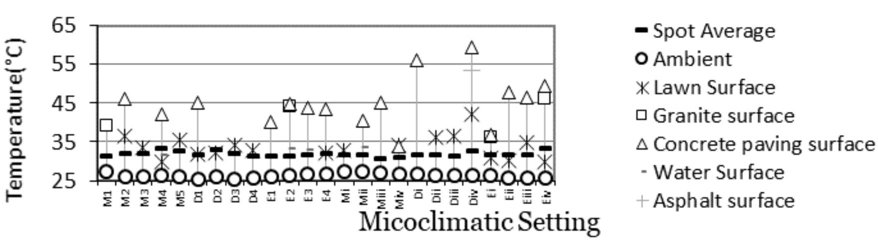


Figure 4, MPST of different natural and artificial paving types in ISP.

The SUHI has created in the specific settings due to ground MPST. PET and MPST evident p=0.00 significant strong positive relationship with R2=0.919. In ISP concrete pavings represent 68% from paved surfaces evident PET range 32.1°C - 40.5°C average PET of 35.2°C respectively. Lawn surfaces 32% PET ranges from 33.6°C - 31.7°C average PET of 32.8°C. Thus, the concrete paving dominated spaces create moderately "Hot Strong heat stress" while natural lawn paving evident spaces maintain "warm Moderate heat stress" for park users.

3.1.2 Waters Edge Park (WEP) Surface Heat Island effect

SUHI effect of the microclimatic settings of the peak usage profiles of WEP during a typical weekend and weekday is shown in figure 5. All the sampling areas are consists of 31 Places (mi to e6).

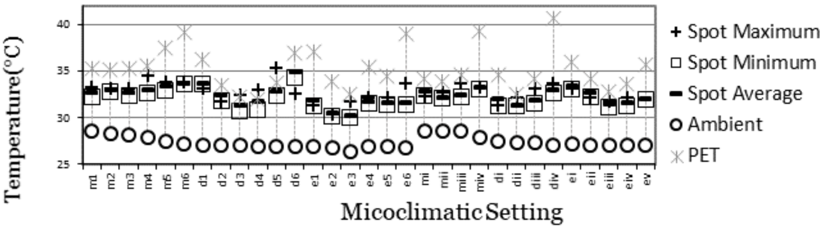


Figure 5, SUHI effect on WEP in selected microclimatic settings

WEP microclimatic settings prioritize MAT ranges from 32.8 °C to 31.9°C while mean ambient temperature represent 27.3°C. The SUHI effect indicates a mean temperature difference of 5 °C for WEP, which is high comparing the ISP. The mean PET values in WEP ranges from max 40.7 °C to min 32°C to average 35.1°C which indicates a "hot Strong heat stress" thermal sensation for the park users.

Figure 6 indicates the surface temperature in different sampling sites due to different paving heat storage capacities.

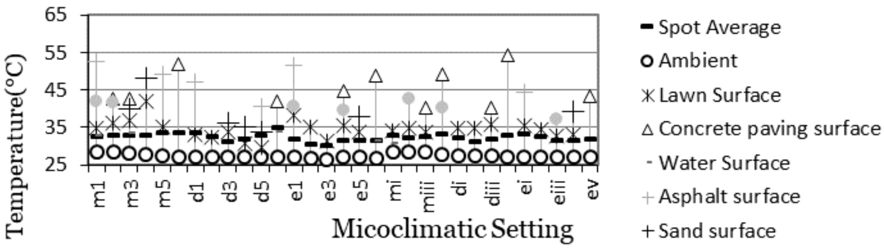


Figure 6, MPST of different natural and artificial paving types in WEP.

In WEP, high surface temperature is evident on concrete paving and asphalt paving. Dominates 55% from the chosen paving settings, concrete evident a PET range of 40.7°C - 34.2 °C to mean PET of 36.8. Whereas 16% Asphalt paving, represents PET range of 37.5°C-33.7°C average PET of 36.06°C. Both Asphalt and Concrete dominated spaces created "Hot Strong heat stress" sensation for the park users. 35% Natural Lawn prioritize PET ranges from 35.5°C-32°C to mean PET of 33.6°C perceiving "Warm Moderate heat stress".

Table 2, MPST acquired by thermal imaginary for different paving types in ISP and WEP

ISP	Maximum°C	Minimum°C	WEP	Maximum°C	Minimum°C
Lawn	42	29.8	Lawn	41.8	29.2
Concrete	63.8	33.9	Concrete	58.7	32.5
Water	34.7	31	Water	33.8	30.8
Asphalt	60.2	46.6	Asphalt	59.8	38.5
Granite	47	33.9	Sand	48	33.2

The heat storage capacity of the different ground materials according to the study is shown in table 2. The evident results for the MPST emphasis a very high temperature in Asphalt and Concrete Paving. Moderate surface temperature shown by the Granite and Sand. Very low surface temperature is evident by Lawn and Water surfaces.

3.2 INFLUENCE OF SHADE VARIATIONS ON SURFACE HEAT

Normalized crown volume (Vn) was measured by applying the three-dimensional green quantity model in respective to the tree composition of the identified 56 places of both parks. The values were accumulated by previous research (Rajapaksha et al., 2018) carried out on 17 common tree species of investigated parks.

Figure 7 shows the impact of CVCs on MPST levels in ISP and WEP respectively. Results demonstrate a negative relationship between MPST and CVC for both parks.

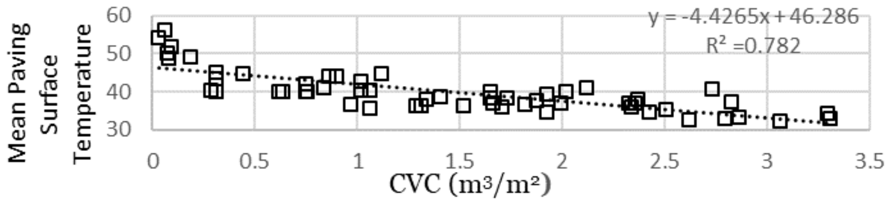


Figure 7, Relationship of CVC and MPST levels for ISP and WEP

Analysis informs the significant relationship between CVC and MPST. The person co-relation analysis reveals p=0.00 with negative regression of 0.782 (m^3/m^2). The CVC varied from 3.30(m^3/m^2) to 0.03(m^3/m^2) whereas, high CVC (<2.5(m^3/m^2)) evident low MPST (>35°C) and low CVC (>2.5(m^3/m^2)) resulted in high MPST (<35°C) correspondence with shading effect.

Moreover, the shading effect is an important criterion in regulating MPST. The calculated MSPT from shaded and non-shaded paving environments are shown in figure 8.

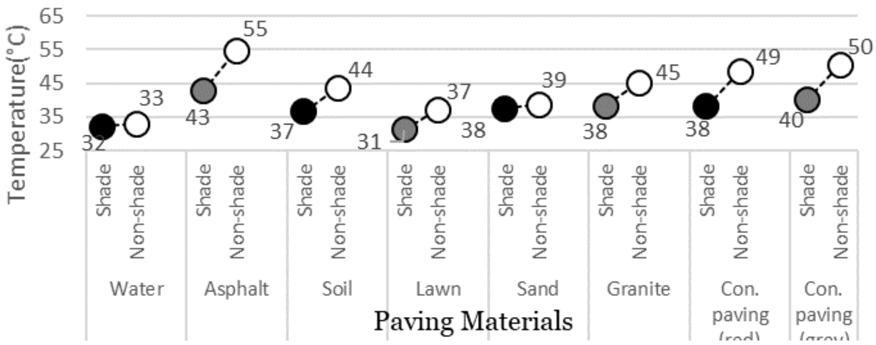


Figure 8, Measured MPST for shaded and non-shaded paving settings

Figure 8, indicate the effect of tree shade on the MPST to reduce SUHI in urban green spaces. The shaded Concrete and Asphalt paving evident 21% reduction of surface heat than non-shaded. The Natural paving typologies of Lawn, Soil, and Granite evident 16 - 15 % surface heat reduction in the shaded environment. The natural paving typologies such as water and sand prioritize the lowest gradient 2% of temperature reduction in shaded conditions.

4. Conclusion

Influence of paving surfaces on thermal stress of UGS of Independence Square (ISP) and Water's Edge (WEP) were explored in this study. As peak usage profiles, 56 microclimatic settings were identified for both parks. An onsite thermal imagery recording was conducted to measure different surface temperatures alone side with microclimatic measurements. Moreover, characteristics of vegetation were recorded to evaluate the effect of shading on the paving heat reduction. The conclusions derived from the detailed analyses and discussions are as follows;

- ISP mean air temperature (MAT) is 31.8°C whereas Ambient Temperature (AT) is 3.98°C, with a recorded SUHI intensity of 3.98°C.
- In WEP MAT recorded as 32.3°C while AT 27.3°C with SUHII of 5°C.
- Thus, the mean PET for most of the settings of ISP is 34.4°C, highlighting "warm moderate sensation" for users.
- In WEP, PET is comparatively high which stimulated as 35.1°C, scaled as "hot strong heat stress".
- PET and MPST significantly correlated (p=0.00) with each other emphasizing positive regression (R^2) of 0.919.
- The highest PET evident for concrete and asphalt paving ranged from 36°C to 36.6°C respectively. Likewise MPST of 44.95°C and 47.68°C
  for concrete and asphalt.
- The Lowest PET value measured paving material was lawn with 33.2°C PET and MPST of 34.1°C
- The CVC has a pronounced effect over the MPST with strong significant co-relationship (p=0.00).
- The shading effect of trees resulted in percentage surface temperature reduction. Concrete and Asphalt from 21%, and 16 to 15% from Lawn, Soil, and Granite. Shading effect has a very low impact on water and sand.

The study reveals that the local UGS are in an uncomfortable PET range of 40-30 °C due to SUHI effect. Thus, the finding of the study informs that the natural paving design implications with improved shading composition can promote comfortable thermal performing green spaces for the city dwellers.

5. Acknowledgment

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