Effect of Street Canyon Materials on the Urban Heat Island Phenomenon in Colombo

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Abstract

An Urban heat island (UHI) is best visualized as a dome of stagnant warm air, over the heavily built-up areas of the city. These have been observed practically all over the world and Colombo, Sri Lanka is no exception. It is known that the replacement of natural surfaces and radiation trapped in 'street form' urban canyons is one of the primary drivers of this phenomenon.

This study quantifies and compares the local warming effects caused by materials used in street canyons in the warm, humid climate of Colombo.

A process of ascertaining street canyon materials by survey and simulation using a simple force restore model, the Surface Heat Island Model (SHIM) generate data for specific urban canyons and the respective local warming effects they cause.

Aluminium cladding in buildings, showed the highest and the lowest intensity. The highest UHI intensity of 2.87^{o}C was recorded In LCZ2-commercial. While, the lowest UHI intensity of 1.78 ^{o}C can be seen at LCZ3-sea front zone.

Analyses highlight the predominant material occurrence and discuss implications for nocturnal UHI amelioration, in warm, humid, Colombo, Sri Lanka.

Keywords: Urban Heat Island, Warm Humid Tropics, Street Canyon Materials, Local Climate Zone, Surface Heat Island Model, Colombo, Sri Lanka

Introduction

Almost 90% of the global urbanization between now and 2025 will occur in countries of the developing world located mostly in tropical/ subtropical regions. Such statistics underscores the urgency of studying the human consequences of tropical urbanization.

There is evidence that researchers are increasingly turning their attention to tropical urban climate issues. (Emmanuel, 2005) Yet, urban design and planning policy instruments for mitigation of the negative impacts of

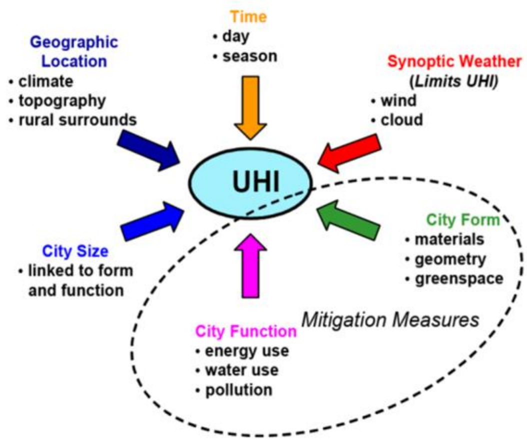

Fig 1: Factors that affect the UHI phenomenon: A focus on mitigation measures
Source: Voogt, 2011

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tropical urban climate remains largely unexplored.

The Urban Heat Island (UHI) phenomenon is a key reason for the microclimatic change in cities. Many important factors influence the UHI intensity (Fig 1). With a focus on mitigation of these effects, emphasis is placed on the City Form. The research is further limited to street canyon materials, within a fabric of specific geometry.

Background

Apart from the adverse global impacts, urbanization and industrialization affect regional urban areas more seriously and perceptibly, where more urbanized and heavy use of synthetic construction materials is commonly observed.

Higher urban heat is mainly caused due to the anthropogenic heat released from vehicles, power plants, air conditioners and other heat sources and due to the heat stored and re-radiated by massive and complex urban structures. Similarly, huge quantities of solar radiation is stored and re-radiated in urban areas due to construction material and enhanced due to decreased sky view factor.

The manmade structures such as walls, roofs, gardens, paved areas etc., and natural structures continuously absorb and store this radiation in the form of heat energy from sunrise until late afternoon. (Rizwan, et al., 2007).

Urban heat island is known to occur on two distinct scales; Urban Canopy Layer and Urban Boundary Layer. Canopy level layer characterized by air less mixed, air temperature with more influenced by local surface heat island effects (Oke, 1982). The focus here is on the UCL heat island.

Urban heat island intensity (UHII)

UHII is determined as the spatially averaged temperature difference between an urban and its surrounding rural area (Kim and Baik, 2005). UHIIs have been based on the difference between air and surface temperatures (Rizwan et al., 2007). Many studies have reported that the UHIIs were high during nighttime or early morning and low in daytime.

Urban Heat Island Mitigation

Heat Island mitigation is a growing need for human thermal comfort in the urban outdoors. The mitigation measures could be categorised relative to reducing anthropogenic heat release, related to better roof design, other design factors. (Humidification, increased albedo, photovoltaic canopies etc.) Some of them could only be implemented during the design and planning stage such as building material, sky view factor etc. These following facts are the basis of most mitigation methods. (Kannamma 2012).

The provision of:

- shade & shelter (trees, awnings, narrow spaces)
- high reflection or emission of radiation surfaces (light surfaces, surface films)
- surface moisture (water, vegetation, permeable covers)
- good or poor heat storage (massive walls, roof insulation)

Material properties on Urban Heat Island

Akbari (1997) reported that the UHI measured at the canopy layer may exhibit high spatial and temporal variation as a result of the variable thermal properties of the urban construction materials that in combination with the three-dimensional geometry of built-up surfaces modifies neighbouring air temperatures. The formation of urban heat islands relates to the thermal properties of the urban fabric. The heat capacity and consequently the thermal inertia, of urban construction materials, such as concrete and asphalt are greater than that of natural materials found in rural environments.

The complex geometry of urban surfaces influences air temperature. There will be increased friction created by a rough urban surface as compared to a smooth rural surface reduces horizontal airflow in the city. The urban surface also can change the urban radiation budget. During the day, vertical canyon walls trap (reflect & absorb) short-wave radiation. Nighttime losses of infrared energy are also retarded due to the decreased sky view below roof level. Rural surfaces have comparatively smooth and greater nocturnal radiative flux divergence than complex urban surfaces.

The adding natural ventilation, vegetation covers and high albedo and high emissivity materials in urban areas can reduce UHI effects and balance energy consumption. The surface temperature of the material is lower than that of a material with low albedo. Because the urban ambient temperature is associated with the surface temperatures of the building façade, lower surface temperature can obviously decrease the ambient air temperature and eventually contribute to better urban thermal environment (Shahmohomadi et al., 2010). As researched by Bretz and Akbari (1997), while the term “white” and “light coloured” is used to mean high-albedo and “dark coloured” defines low- albedo.

Material with high albedo can reduce the solar heat gain during daytime. Because the urban ambient temperature is associated with the surface temperatures of the building façade, lower surface temperature can obviously decrease the ambient air temperature and eventually contribute to better urban thermal environment (Shahmohomadi et al., 2010).

Method

The objective of the method is to ascertain the local warming effects caused by materials used in the urban canyons, in Colombo, Sri Lanka. A numerical scheme to simulate the cooling of rural and urban canyon surfaces on calm, cloudless nights is the main methodological tool for the study.

To limit the scope of the study and therefore focus on the critical aspects of Colombo’s microclimate, a step-by-step process of extracting salient patterns is adopted. Here, the data generated from the preceding action becomes the input values for the next.

These steps are defined as;

- Site selection and representative focus areas based on local climate zone classification, predominant land use and proximity to natural areas
- Survey and establishment predominant material typology in the selected representative urban fabric of Colombo
- On-site measurements of surface temperature

- Simulations using SHIM to establish nocturnal cooling patterns within distinct urban canyons of identified materiality

Site selection

Colombo, Sri Lanka is located at 6^0 54’ N, 79^0 52’E on Sri Lanka’s West coast. With the rapid and haphazard urban development and warm humid climatic context, it typifies a microclimate of a city affected by UHI in the region.

Colombo is a lowland region with a typically hot humid climate that is affected by the seasonal wind reversal of the Asian monsoon. The monsoon blows from the SW from late May to late September and the NE from late November to mid February. Air temperature and humidity are high throughout the year. Wind speeds are low, especially during the inter-monsoon periods of March to April and October to November. The annual rainfall is 2300mm with two seasonal peaks. Solar radiation is intense under clear sky conditions. However, there is a high probability of cloud development, especially during the afternoon. The main daily sunshine duration varies between 5 hours in June and 9 hours in February (http://www.meteo.gov.lk/)

Local Climate Zones

A significant problem in heat island methodology, is that the term urban has no single, objective meaning, and thus no climatological relevance. What is described as urban in one city or region differs from that of another city. The term urban is therefore impossible to define universally for its physical structure, its surface properties or its thermal climate. (Stewart and Oke, 2012)

In response to the above statement, the study adopts the LCZ classification system developed by Stewart (2011) to simplify the urban context. The LCZ classification uses observational data to define zones based on characteristic geometry and land cover that generate a unique near-surface climate under calm, clear skies.

The name, LCZ, is derived because the classes are local in scale, climatic in nature and zonal in representation. The physical properties are measurable and nonspecific as to place or time. (Stewart and Oke, 2009).

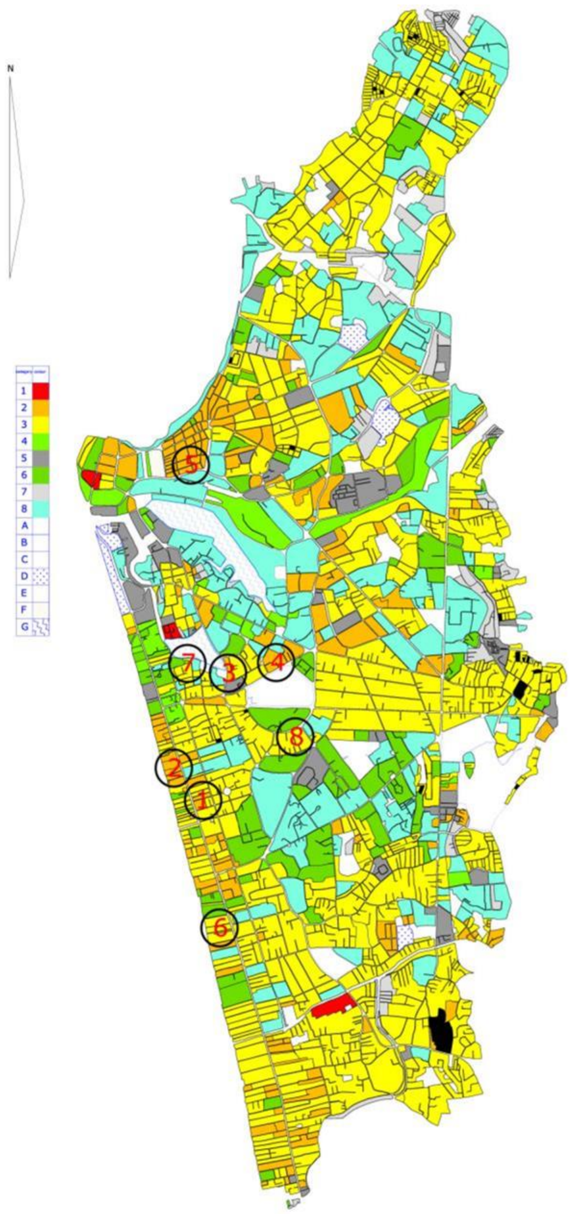

Fig 2: Local Climate Zone Map, Colombo Showing selected sites. (Source: Perera et al, 2012)

The LCZ and representative site selection utilises the LCZ map of Colombo (Fig 2) developed by Perera et al., (2012) (Perera, Emmanuel, & Mahanama, 2012) as the primary resource. A detailed account of the process of classification is included in the same, therefore not repeated herein.

A survey of LCZ typologies relevant for Colombo showed that much like many developing cities Colombo is dominated by residential and mixed-use zones (more than 55% of the total land use). Much of these zones fall under LCZ3 – Compact Low-rise, LCZ2 – Compact Midrise and LCZ8 – Large Low-rise categories. (Perera, Emmanuel, & Mahanama, 2012)

In consideration of the above sites encompassing LCZ2 and LCZ3, of four distinct land use and proximity sites are selected as representative sites for which a 'typical' street canyon is analysed. Each of these defined street canyons will have a specific form and materiality.

Table 1 : Typical characteristics of selected sites (as shown in Fig 2)

Site	LCZ	Proximity / land-use	Description	Representative image
Site 1	LCZ2	commercial	Dense mix of midrise buildings 4-9 storeys. Flat. Compact skyline. Vary in height and construction. More lightweight construction materials. Land cover & street paved. High traffic flow. Commercial buildings. No green cover. East front	
Site 2	LCZ2	Sea front	Dense mix of midrise buildings 4-6 storeys. Small buildings. Pitched and flat roofs. Uniform in height and construction. More heavy construction materials. Land cover & street paved. Less green cover. Low traffic flow. Opposite to sea.	
Site 3	LCZ2	Lake front	Compact set buildings 4-9 storeys. Natural surroundings. Some green cover. Pitched roofs. Uniform in construction. Commercial & residential buildings. Land cover & street paved. Low traffic density. Lakefront.	
Site 4	LCZ2	residential	Dense mix of low-rise buildings 4-9 storeys. Large buildings. Flat. Apartment buildings. More heavy construction materials. Land cover & street paved. Facing to an open park area. Less green cover. Moderate traffic flow.	
Site 5	LCZ3	commercial	Dense mix of low-rise buildings 2-3 storeys. Flat. Compact skyline. Uniform in height and construction. Heavy and light mix construction materials. Land cover & street paved. High traffic flow. No green cover. Commercial buildings. South-facing.	
Site 6	LCZ3	Sea front	Mix of low-rise buildings 1-3 storeys. Small buildings. Pitched and flat roofs. Uniform in height and construction. Heavy construction materials. Land cover & street paved. Less green cover. Low traffic flow. Opposite to Sea.	
Site 7	LCZ3	Lake front	Compact set buildings 1-3 storeys. Natural surroundings. Some green cover. Pitched roofs. Uniform in construction. Commercial & residential buildings. Land cover & street paved. Low traffic density. Lakefront.	

Site 8	LCZ3	residential	Dense mix of low-rise buildings 1-3 storeys. Small buildings. Pitched roofs. Residential. Heavy construction materials. Land cover & street paved. Facing to an open park area. Less green cover. Low traffic density.		

Survey and establishment predominant material typology

The survey of materials adopts the building envelope as the primary element influencing the urban canyon. Therefore, the data collected encompasses building façades and categorised as per LCZ and proximity. Fig 3 shows the summary of the survey, where material and frequency of occurrence within a typical sample of 20 buildings is signified. Glass and Aluminium are predominant in LCZ2 while LCZ3 shows more of a mix with Glass, Aluminium and Rough plastered facades.

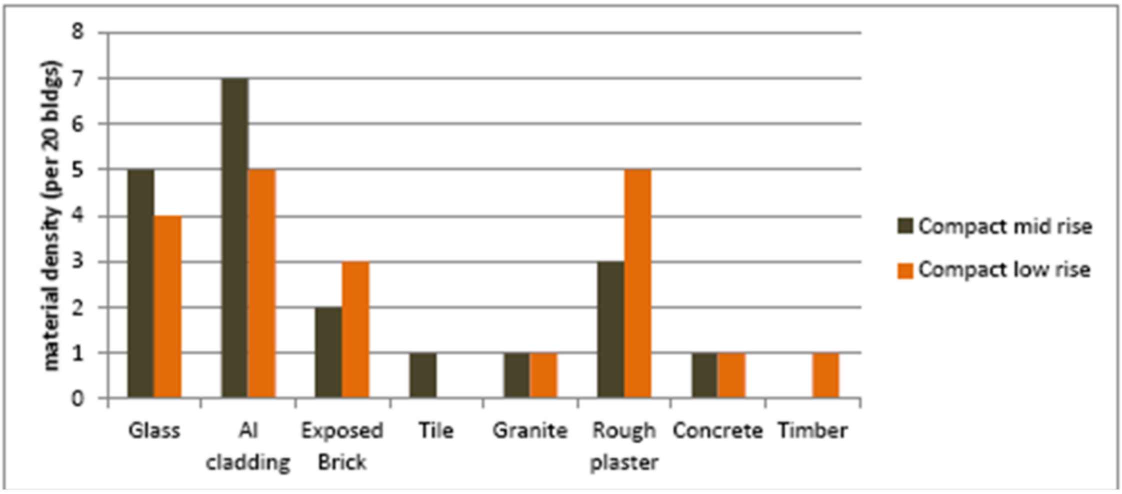

Fig 3: Survey summery of materials & frequency of occurrence
Source: Author

On-site measurements of surface temperature

Infrared thermal images of surface temperature were captured with a FLIR ThermaCAM S60 (Fig 4) at key locations of selected buildings. Captured images were obtained by mobile sampling measurements at peak time. The temperatures were observed in a calm clear in March when the incoming long wave radiation is high.

Two measurements for each façade materials were obtained, one in the morning one in the evening. Further, the surface temperature probe (Technoterm 9400 Surface Temperature Probe) (Fig 5) was utilised to ensure the accuracy of the thermal camera. This probe was specially used to measure floor surface temperatures.

Fig 4: FLIR ThermaCAM S60
Source: Author

SHIM Simulations

The SHIM is a simple force-restore model that simulates the nocturnal cooling of an urban canyon (walls and street) (Fig 6) under 'ideal' conditions of calm winds and clear skies, therefore, all cooling is assumed to take place via radiative heat loss. No account of evaporative heat transfer is possible. However, the SHIM is an excellent tool to isolate the effects of urban geometries (density, height: width ratio and the sky view factor) as well as surface thermal properties. It thus enables us to explore the urban warming potential of rapid changes in urban growth epitomised by densely arranged buildings with excessive thermal capacities. (Emmanuel et al, 2011)

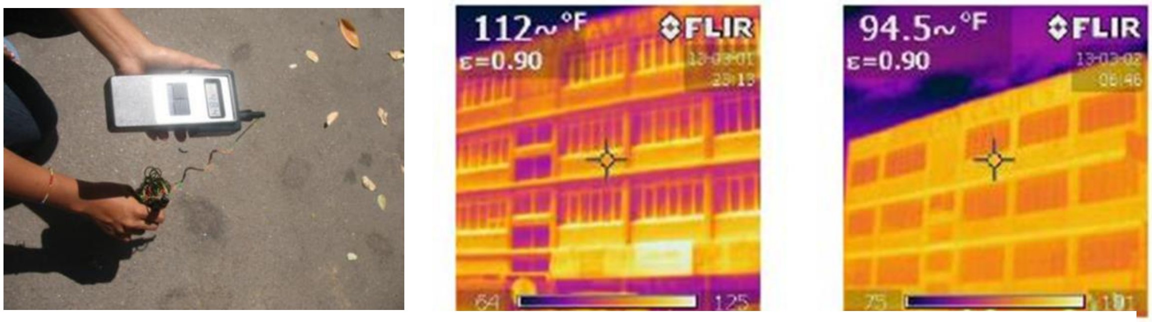

Fig 5: Technoterm 9400 Surface Temperature Probe & Thermal images in morning – evening
Source: Author

SHIM is initiated at the time of sunset and requires several inputs to run the model.

The governing force-restore equation used by SHIM for the nocturnal cooling of a homogeneous substrate with layer thickness D is given as:

$$\frac{dT(D_i,t)}{dt} = L^*\frac{\sqrt{2\Omega}}{\mu_i} - \Omega\left(T(D_i,t) - T_D\right)$$

Where T (Di, t) is the temperature of a layer i at time t, TD represents a "deep temperature" that is constant, μ is the thermal admittance of the soil, Ω is the angular frequency of the heating wave and L* is the net long-wave radiation.

SHIM requires initial values of the surface temperature (T), deep soil and/or building temperature (T_G or T_B), surface thermal admittance (μ), sky view-factor (ψ_S) and surface emissivity (ε) for all of the surfaces to be simulated in addition to the incoming long-wave radiation to the total system ($L_\downarrow$). (Johnson et al., 1991)

Values for each were determined by various means as outlined below together with the values defined by the individual LCZs.

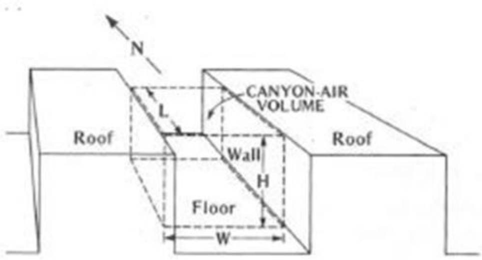

Fig 6: Typical Urban Canyon
Source: Oke, 1987

(source : Oke, 1987)

T Measured directly or a measured near-surface air temperature was used as a surrogate, (using FLIR ThermaCAM S60 and Technoterm 9400 Surface Temperature Probe)
T_g Estimated using the 3-day average air temperature as suggested by Deardorff (1978)
T_B Estimated from building interior set point temperature (assumed to be 27^{O}C)
μ Estimated from published values (e.g. Oke, 1987)
Ψ_s Calculated from fisheye lens photographs
ε Estimated from published values (especially Arnfield, 1982 and Oke, 1987)
$L_{\downarrow}$ Calculated using the empirical formulae of Idso and Jackson (1969) with measured humidity and air temperature.

The surface heat island model is available in simple computer spreadsheet form to simulate the cooling effects over variable urban/rural context as a function of the built features and rural aspects of any environment. The model acts as a mechanism to understand the highly complex nature of urban effects during night-time commencing at 6pm (Brazel & Crewe, 2002)

The SHIM model simulation results are compared with the rate of cooling at a ‘rural’ station (using data from the synoptic weather station at the Colombo International Airport (Lat: 7° 10'N; Lon: 79° 52'E; Elevation: 8m asl; WMO Station ID: 434500) and an ‘urban’ weather station at the Colombo City Airport (Lat: 6° 49'N; Lon: 79° 52'E; Elevation: 5m asl; WMO Station ID: 434670).

Limitations

The main limitation to the method is seen in both the LCZ classification and SHIM simulation, where 'ideal' conditions of calm winds and clear skies were assumed. It is known that the UHI is most intensive under these conditions. The morphological and materiality simplification as a representative sample of the city has limitations, such that in a real world scenario, the urban fabric is much more heterogeneous.

Results and Discussion

Relationship between UHI intensity and materials in different LCZs and Proximity

UHI intensity discussed in the following analyses signifies the temperature difference between the rural site and the urban. It is essentially the disparity between the nocturnal cooling potential between contexts. Fig 7 shows the variation of UHI intensity by different materials under selected climatic contexts. Significant temperature difference/ highest UHI intensity is recorded in LCZ2-commercial for all selected materials. Where the zones are influenced by vegetation, wind and water bodies (sea front and lake front zones), it is evident that the intensity is lower than that of the land locked LCZs.
Aluminium cladding in LCZ2-commercial, recorded the highest UHI intensity of 2.87^{o}C. While, the lowest UHI intensity of 1.78 ^{o}C can be seen at LCZ3-sea front zone, also for Aluminium cladding.

Considering materials within a particular LCZ only, overall, brick and aluminium cladding have the greatest intensity in LCZ2. A distinct change in the behaviour of Aluminium cladding in the LCZ2 and LCZ3-sea front zones is highlighted, where it cools faster than in other zones and materials.

Reflective Glass shows the lowest intensities across all LCZs and proximities. An exception is seen only in the sea front proximity, where Aluminium cladding is cooler.

Overall, materials with the ability to store incoming radiation, like brick and Aluminium cladding (which usually includes a brick inner structural layer) tend to cool slower. Yet, in contexts that

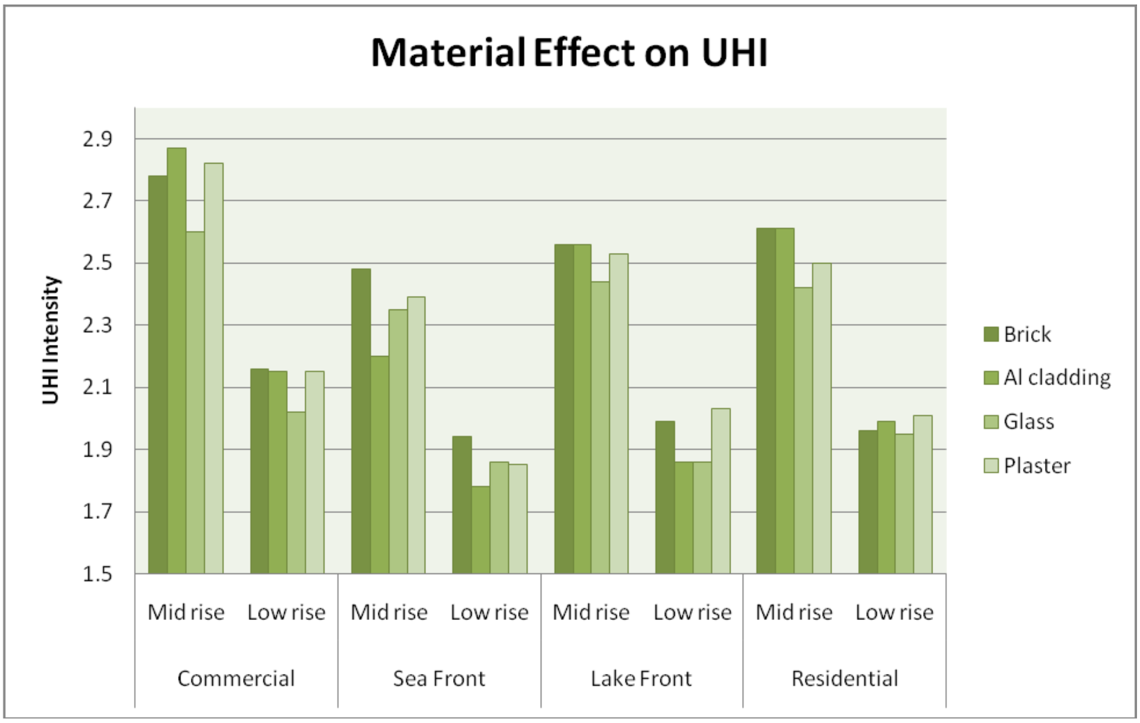

Fig 7: Material Effect on UHI
Source: Author

have enhanced ventilation and therefore disperse radiation more efficiently, perform markedly better. Plastered brick walls with usually painted façades cool faster than exposed brick. The increase in the ability to cool is deemed due to the increase in albedo of plastered, painted brick.

Façades that utilise Glass, with its ability to reflect most of the incoming radiation, cools faster, than all materials compared.

The design implications of the study are clear and in line with established thinking, that high-albedo materials are more effective in ameliorating nighttime UHI. Yet, Errel et al. (2012) highlights that the reduced surface temperature due to reflected radiation and thus reduced long-wave emission can have a negative effect on the pedestrians using the street.

“Increasing the albedo of urban surfaces may thus be a small increase in the thermal stress to which pedestrians are exposed – rather than the expected improvement in thermal comfort”. (Erell, Pearlmutter, & Boneh, 2012)

Although, outdoor thermal comfort cannot be ignored, it is well established according heat transfer theories, that indoor temperature significantly depends on outdoor temperature. Therefore, the exploration of the link between the urban microclimate and indoor thermal comfort is key, to provide for buildings that adopt passive strategies for thermal comfort and thus, reduced energy use. (Perera, Emmanuel, & Arooz, 2012) In this context it is crucial to consider all aspects relative to material use and its repercussions, albeit in the urban outdoors, indoors, diurnally and in terms of thermal comfort.

Urban design strategies to ameliorate night time UHI should encompass:

- Use high albedo materials like reflective glass, yet adopt strategies to shield pedestrians from the reflected radiation. Use both horizontal, vertical shading and double skin façades to shade.
- Restrict use of materials like aluminium cladding. Shade façades from solar radiation, thereby avoid excessive storage and release at nighttime.
- Encourage urban level ventilation to encourage rapid radiation loss in general and from canyon surfaces in particular.

Relationship between UHI intensity and canyon façade material combinations

In real-world situations, building façades in urban canyons is rarely comprised of a single material, but a combination of two or more materials. The preceding analyses adopt canyon façades of predominantly one material. Here, a series of combinations are explored for greater applicability. The method adopts walls of differing materiality on either side of the street canyon and therefore surface temperature used as input values for SHIM, is specific to the façade material on either side of the canyon. The comparison is made for the warmer LCZ2-commercial, as the worst-case scenario among LCZs and proximity, discussed in the preceding section (Fig.8).

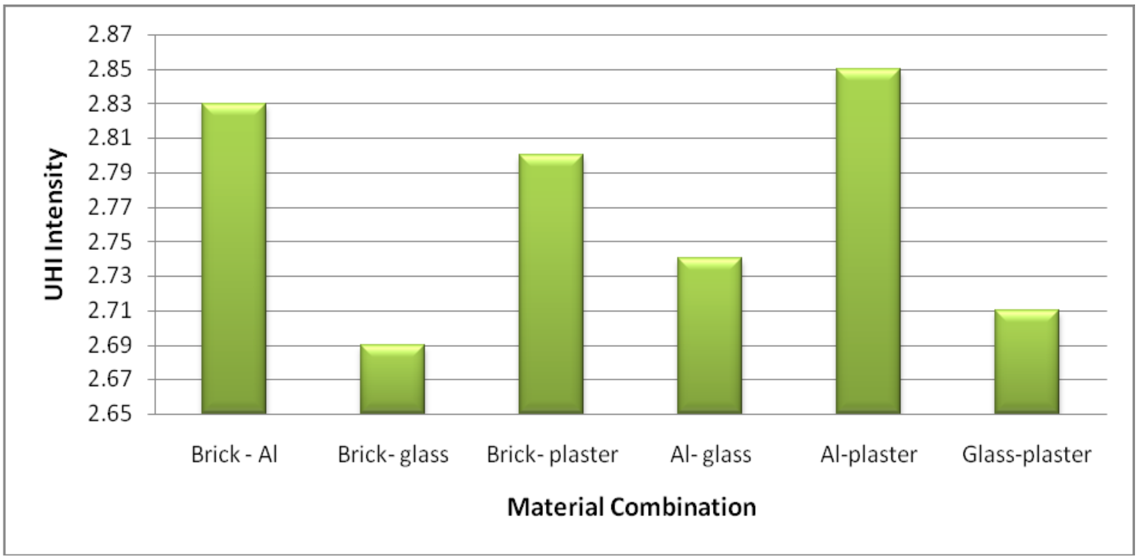

Fig 8: Effect of material combinations on UHI intensity (LCZ2-commercial proximity case)
Source: Author

The warmer street canyons include Aluminium cladding, while, the coolest are the combinations that include reflective glass. Even though glass was seen as the material in which nocturnal cooling was most rapid, here, a combination with Aluminium cladding diminishes this ability, thus showing significant UHI intensity. This is true for combinations with other materials as well, all showing higher intensity than the base, glass only canyon.
The results show that conscious mixing of the street canyon façades can help mitigate the ill effects of nocturnal warming and excessive radiation emitted by high albedo materials in the daytime.

Implications are explored within the framework discussed in the previous section;

- Adopt material combinations to decrease the negative impact of a particular type of material, whilst reaping the benefits of its positive aspects.
    - Materials could be controlled to get the best of them, depending on the function, period and time of use. Thus, the materiality of the fabric could correspond to the zoning of functions in a public outdoor space.
    - Define maximum façade material ratios and window to wall ratios
        - Explore control of material in a particular context to avoid over use.
        - Define ideal window to wall ratios for indoor visual and thermal comfort, energy use and effect on the urban outdoors
    - Explore best-case scenario materials for particular contexts and orientations of street canyons within urban fabric.

Conclusion

The main objective of the research was to quantify and compare the local warming effects of street canyon materials in the warm, humid climate of Colombo, Sri Lanka.

A survey of LCZs based on the LCZ map of Colombo developed by Perera et.al, (2012) showed that LCZ2 and LCZ3 are predominant. They were also seen as critical in terms of local level warming. The simplified interpretation of the urban fabric by the use of the LCZ system allowed a better focus on the envisioned material aspects.

Data collection of materials within selected LCZs showed that Aluminium cladding, Brick, Plastered walls and reflective glass were predominant.

Analysis of data generated using SHIM for street canyons of specific materiality showed that; Aluminium cladding in LCZ2-commercial, recorded the highest UHI intensity of 2.87^{o}C. While, the lowest UHI intensity of 1.78 ^{o}C can be seen at LCZ3-sea front zone also for Aluminium cladding.

Similarly, simulations that explored material combinations in street canyons showed that the inclusion of Aluminium cladding adversely affected the UHI intensity than those of other combinations. Street canyons that included Reflective Glass showed a higher rate of nocturnal cooling, thus, of lower UHI intensity.

In this context, it can be concluded that the materiality of the existing fabric of Colombo has a negative effect on the UHI intensity. The use of materials like Aluminium cladding is rapidly growing. It has generated a building typology of blank façades with no possibility for passive light or ventilation. These buildings generate large amount of anthropogenic heat by its use of mechanical ventilation and artificial lighting, also resulting in extensive energy use. The research clearly demonstrates that trend is not healthy for the city.

Similarly, the 'glass box' commercial building was the predecessor to the aluminium-clad façade, in Colombo. Although, the high internal heat gain and cooling load resulting energy hungry usage of such buildings is evident, a possibility for natural lighting and better nocturnal cooling of façade materials, places it on a better footing.

Strategies for UHI amelioration in warm humid Colombo, needs to adopt conscious material usage patterns, according to applicability, rather than for mere adherence to a trend. Trends, which are deemed irrelevant and ill advised in terms of urban design, architecture and climate sensitive design.

Further research should encompass the complete range of LCZs and with it a wider material exploration. Methodological limitations of analysing nighttime UHI could be broadened to ascertain the effects of materials on the urban outdoors for the total day, thereby include not only UHI amelioration, but thermal comfort as well.

The challenge of future research and design is to ascertain and establish the appropriate materiality for the city. These efforts should encompass aspects of not only UHI mitigation, but also avenues for achieving outdoor thermal comfort.

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