COOL PAVEMENT SYSTEMS AS A MITIGATION STRATEGY OF URBAN HEAT ISLAND EFFECT: A LITERATURE REVIEW

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ABSTRACT

The urban heat island effect is the rise of ambient temperature in urban areas due to the progressive replacement of natural surfaces. Buildings and paved surfaces are contributing most to this phenomenon as per the properties of their material. Conversely, urban heat islands have a direct influence on building occupants' comfort levels, building cooling loads and energy costs as well. Although there are existing researches on green buildings, there is a significant lack of literature on cooler paved surfaces; particularly in tropical countries.

To bridge this research gap, and to explore the applicability of cooler pavement systems in search of mitigating urban heat island effect in the micro and meso level, this study was executed as a desk study based on a literature survey of environmental implications of unsustainable rapid urban development, their mitigation strategies, and where existing pavement systems stood in all this. The literature synthesis of existing work by authors from around the globe led to the discussion and analysis of the paper, and resultant further study areas.

This paper compares alternative "cool" pavement systems, which are defined as pavements with improved solar reflectivity and permeability characteristics. The paper suggests how these can be used effectively in a sustainability conscious building facility, and by infrastructure developments which has a wider role of reducing local heat islands, increasing pedestrian comfort and reducing runoff water. The scope of this paper was limited to pedestrian pavements and gives reference to construction professionals who are engaged with sustainable building and infrastructure projects on their usability.

Keywords: *Green Building Materials; Pedestrian Pavements; Sustainability; Urban Heat Island Effect.*

1. INTRODUCTION

Since the end of the civil war in mid-2009, Sri Lanka's economy has been on a strong growth trajectory led by determined property and infrastructure development (Jones Lang LaSalle (JLL), 2011). However, such developments comes with a certain downside as identified by Sarat and Eusuf (2011) that with urbanization, buildings and paved surfaces have gradually replaced pre-existing natural landscape. As a result, solar energy is absorbed into paved materials, causing the surface temperature of urban areas to become 10-21^{0}C higher than the ambient air temperatures. This phenomenon is identified as the Urban Heat Island Effect (UHIE) and paved surfaces contribute considerably to this in cities because they cover a remarkably large fraction of urban surfaces (Levinson *et al.*, 2010; Pomerantz *et al.*, 2003). Hence, a pavement system of a building is directly linked with its environmental performance evidenced in the work of Lin *et al.* (as cited in Sarat and Eusuf, 2011) where it is reasoned that outdoor thermal environment is impacted by the built environment. The potential for research and development under sustainable construction and building materials into this area is still not fully harnessed in the Sri Lankan context although in the global context it is found that pavement construction materials have been historically used as a countermeasure for urban heat islands (Santamouris *et al.*, 2001). The aim of this research is to bridge this research gap exploring the environmental implications imposed by pedestrian pavement systems and how alternate cooler pavers can assist a city to achieve a level of sustainability. Methodology

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adopted for the research was gathering literature under the subject purview and synthesizing the existing work to identify prospective alternative pavement systems which have improved thermal and permeability characteristics over the existing systems. The study is limited to a desk study concerning sustainability in construction, urban heat islands and pedestrian pavement systems which are elaborated in latter parts of the paper arriving at a discussion of the topic and future study areas that needs to be undertaken.

2. METHOD: LITERATURE REVIEW

2.1. URBAN HEAT ISLANDS: A GLOBAL ISSUE

Grimmond *et al*. (2010) in their publication, "Climate and More Sustainable Cities: Climate Information for Improved Planning and Management of Cities" expresses that cities and their inhabitants are key drivers of global climatic change and they use a disproportionate share of resources and produces climate-altering atmospheric pollutants. Moreover, cities are the main source of anthropogenic carbon dioxide emissions due to the burning of fossil fuel for heating and cooling, industrial processing, transport of people and goods and so forth.

With more people being vulnerable to urbanization problems around the globe as urban population is ever increasing, which was estimated as 48% or three billion, is expected to be 6.3 billion by 2050 (Department of Economic and Social Affairs (DESA), 2012).The adverse effects of urbanization ranges from a global scale to regional levels, where it is more serious and obvious as industrial activities and heavy use of synthetic construction material are commonly observed (Rizwan *et al*., 2008).

Furthermore, Rizwan *et al*. (2008) states that as a result, the natural environment and ecology are tremendously affected and have lost necessary balance. This has led to a phenomenon of higher ambient temperature, observed in cities as compared to its surroundings; called Urban Heat Islands (UHI).

This has been formally defined as the rise in temperature of any man-made area and is known to be caused by the progressive replacement of natural surfaces by built surfaces through urbanization (Pena, 2009;Wong *et al*., 2007).The urban heat island phenomenon is recognized to be a consequence of increased urbanization and abrupt changes in the outdoor environment. The temperature rises in urban environments are caused by the changes of street surface materials and reduction of green areas (Wong *et al*., 2007).

The causes of urban heat island effect are identified and listed by Santamouris (2001) as follows;

1. Absorption of short-wave radiation from the sun in low albedo (reflection) materials and trapping by multiple reflections between buildings and street surface
2. Air pollution in the urban atmosphere absorbs and re-emits long wave radiation to the urban environment
3. Obstruction of the sky by buildings results in a decreased long-wave radiative heat loss from street canyons. The heat is intercepted by the obstructing surfaces, and absorbed or radiated back to the urban tissue
4. Anthropogenic heat is released by combustion processes, such as traffic, space heating and industries
5. Increased heat storage by building materials with large thermal admittance. Furthermore, cities have a larger surface area compared to rural areas and therefore more heat can be stored
6. The evaporation from urban areas is decreased because of 'waterproofed surfaces' – less permeable materials, and less vegetation compared to rural areas. As a consequence, more energy is put into sensible heat and less into latent heat

7. The turbulent heat transport from within streets is decreased by a reduction of wind speed

Rizwan *et al.* (2008) cites several significant adverse effects of UHI;such as, the deterioration of living environment, increase in energy consumption (Konopacki and Akbari, 2002),an increase in mortality rates (Changnon *et al.*, 1996), andan elevation in ground-level ozone (Rosenfeld *et al.*, 1998). In their work Mirzaei and Haghighat (2010) further elaborates that UHI also intensifies pollutant concentration over urban areas. Furthermore, Taha (1997) explains how it impacts the local meteorology by altering local wind patterns, forming cloud and fog, increasing humidity, and changing the precipitation rate.

The field of UHI has become highly interesting for scientists and engineers due to its adverse environmental and economic impacts on the society (Rizwan *et al.*, 2008). Different strategies have been developed by researchers to mitigate UHI and the most common strategies carried out by different municipalities are based mainly on the change of street pavement and roofs, commonly known as cool pavements and cool roofs (Kleerekopera *et al.*, 2012). Several cities such as Houston have introduced cool pavement strategies in their plans to mitigate the UHI effect (Hitchcock, 2004).

According to He and Hoyano (2010) the reason for high contribution for UHIof buildings and infrastructure is that most types of pavement and building exteriors are fabricated from materials with low albedo and high thermal retention capacities, such as asphalt and concrete.

Conventional asphalt has an albedo of approximately 0.1; concrete has a higher average albedo of 0.45 (Asaeda *et al.*, 1996). Moreover, Gui *et al.* (2007) points out thatasphalt covers as much as 29-45% of total urban surface area. Accordingly, Forkes (2010) in her study on Mitigating Urban Heat in Canada infers that cooler pavements help reduce UHIs.

2.2. NEED FOR PEDESTRIAN PAVEMENTS WITH PASSIVE FEATURES

Pedestrian pavements found in building and infrastructure developments are designed to be technically, economically and aesthetically suitable for users and developers (Mendoza *et al.*, 2012). As discussed earlier, the most common types of pedestrian pavements are concrete (considered consistent, durable and economic) and asphalt: chosen for their initial low cost, but they have a shorter service life than concrete and more susceptible to damage from weather and normally require more maintenance, increasing their economic cost over time (Federation of Canadian Municipalities and National Research Council, 2004).

However, Mendoza *et al.* (2012) identifies that these designs fails to apply comprehensive life cycle environmental data to identify suitable construction solutions and urban management strategies that contribute to minimizing their environmental impacts.

In their work on relationship between pavement systems and building energy usage, Yaghoobian and Kleissl (2012) noted that radiative, conductive and convective properties of construction materials and the urban form can be engineered or selected to achieve different urban climate objectives which are used in UHI mitigation measures such as increases in albedo and urban greeneries.

This effort to mitigate urban heat islands are further reflected by Cambridge Systematics (2005) in their report which avers that cool pavement strategies seek to control the temperature of the pavement by controlling one or more of the material properties, i.e. albedo, permeability, conductivity, emissivity, thickness and convective airflow; as a direct action to control the heat island effect (US Environmental Protection Agency (EPA), 2008).

Therefore, permeable pavements are used as a sustainable building material for alternative designs. Forkes (2010) defines permeable pavements as paving methods for roads, parking lots and walkways that allow the movement of water and air around the paving material. This may be interlocking brick, gravel or open grid concrete or plastic cells. The permeability of the pavement makes it possible for water to infiltrate thoroughly to the soil.

However, as Lin *et al.* (as cited in Citraningrum, 2012) argues this infiltration may increase soil moisture and making it become softer, making it only suitable for light duty and infrequent usage area such as parking area or pedestrian access. Accordingly Citraningrum (2012) lists three such permeable pavements that are commonly used on the field: permeable asphalt concrete pavement, pervious concrete pavement, and permeable interlocking concrete pavers. He suggests that these permeable pavements when wet; can lower air temperature through evaporative cooling. Similarly, EPA (2008) explains that moisture within the pavement structure evaporates as the surface heats, thus drawing heat out of pavement.

In his studies Citraningrum (2012) agrees with other researchers that permeable interlocking concrete pavers (more commonly known as interlocking concrete pavement blocks) has a higher air temperature reduction and building energy consumption reduction compared to other type of pavements.

As discussed earlier, through urbanization cities replace most of the bare ground and vegetation with impermeable surfaces such as buildings and pavements which reduce the cooling caused by evaporation of water. Pomerantz *et al*.(2003) points out these effects of urbanization are difficult to reverse; according to Forkes (2010) measures are implemented to add vegetation in cities, and progressive replacement with permeable surfaces.

In the meanwhile, researchers like Pomerantz and Akbari (1998), Li (2012) and Yaghoobian and Kleissl (2012) focus on the colour of existing impermeable surfaces which affects the temperatures within the city; believing that the most practical means of mitigating urban heat islands is to make city surfaces more reflective of the sunlight, both visible and invisible (mostly infrared). The quantitative measure of the total solar reflectivity is called “albedo” (Pomerantz *et al*., 2003).

Therefore, pavement systems with high albedo (i.e. solar reflectivity) are used more frequently to mitigate urban heat islands. As Marceau and VanGeem (2007) points out, the widely acclaimed US based green building rating system LEED serves up to 2 points for reducing the heat island effect. These points can be obtained for using paving material with a solar reflectance index (SRI) of at least 29 for a minimum of 50% of the site hardscape (including roads, sidewalks, courtyards, and parking lots). The Sri Lankan green rating system Green^{SL} has a similar interest in heat island mitigation by means of paving material (Green Building Council Sri Lanka (GBCSL), 2010).

Essentially, high albedo and high emissivity paving material can be defined as cool pavements that help lower surface temperatures and reduce the amount of heat absorbed into the pavement (Forkes, 2010). Even so, permeable and porous pavement is sometimes also referred to as a cool pavement due to its ability to remain cool through using evaporation. A number of cool pavement alternatives are currently available as products, and these are either light in colour to reflect solar energy or may also be porous to allow evaporation (EPA, 2008). Table 1 gives a comparison made between such pavement systems;

Table 1 Comparison of Existing Pavement Systems in Relation to their Cool Features

Technology	Initial solar reflectance	Solar reflectance over time	Permeability[4]	Service life (Years)	Impact on Urban Heat Islands
Conventional asphalt	5-10%[1]	10-15%	Low	20-30	Low
Rubberized asphalt	5-10%[2]	20-15%	Low	20-30	Low
Porous asphalt	5-10%[2]	10-15%	High	15-20	Medium
Conventional concrete	35-40%[1]	20-30%	Low	15-20	Medium
Pervious concrete	35-40%[2]	35-40%	High	15-25	Medium
White cement concrete	70-80%[1]	40-60%	Low	20-35	High
Concrete pavers	10-80%[2]	10-80%	High	15-20	Medium
Titanium Dioxide cement	35-40%[2]	35-40%	Low	20-35	High

Technology	Initial solar reflectance	Solar reflectance over time	Permeability[4]	Service life (Years)	Impact on Urban Heat Islands
Colour pigments and seals	10-80%[3]	10-80%	Low	3-7	Medium
Chip seals	20%[3]	Declines	Low	5-10	Medium
Scrub/ Slurry/ Cape seals	5-10%[2]	10-15%	Low	3-7	Low
White topping	40%[3]	25%	Low	10-15	Medium
Resin based products	33-55%[2]	Declines	Low	Unknown	Medium
Grasspave and Gravelpaveproducts	26-60%[2]	26-60%	High	10-15	Medium

[1] Levine (2011)
[2]Nichols Consulting Engineers (2012)
[3] EPA (2008)
[4]Citraningrum (2012)

As evident in the above Table 1, there is no one best way of paving that would mitigate UHI as well as provide runoff reduction, provided that cool pavement technologies are still under development (Synnefa *et al*., 2011), unlike cool roof strategies. On the other hand, pavement systemsare highly reliant on site specific conditions regarding their cool performance (Kevern *et al*., 2009), and the subbase and subgrade conditions of the pavement system, as well as the soil properties of the installation.

3. URBAN HEAT ISLAND EFFECT IN COLOMBO, SRI LANKA

Colombo, Sri Lanka, is a metropolis located near equator, generally having tropical climatic conditions where temperatures remain relatively high with humid conditions (i.e. warm humid) (Halwatura, 2008). Colombo is blessed with 2,623.5 hours of mean annual sunshine and 2,523.7mm of annual mean precipitation with over 145 average annual precipitation days (World Meteorological Organization (WMO), 2013). Colombo and its suburbs are on a steady development course resulting in increased changes to the land cover, which has its toll on the urban micro climate.

Even so, the Colombo still holds shades of green as opposing to its sister cities like Shanghai or Saint Petersburg. In the heat waves preceding monsoon seasons Colombo faces high outdoor temperatures which is intensified by the city to create urban heat islands. Nonetheless, Colombo city has not fully undergone an irreversible transformation into a concrete forest like many business cities around the globe. However, in the work of Silva (2004) who held, with reference to Sri Lankan urban climatic data, that Colombo has provoked deep changes in thermal energy balance, which indicates a growing UHI problem that create unpleasant microclimatic conditions at the pedestrian level.

Other regional tropical cities like Kuala Lumpur, Bangkok, and Jakarta have documented the micro climatic changes due to rapid urbanization, which bringing about increased urban heat, atmospheric pollution (with dust and pollutants) and reduced humidity as indicated by Sham and Jamaluddin (as cited in Sarat and Eusuf, 2011). Cities like Houston (Hitchcock, 2004) or Chicago (Chicago Department of Transportation, 2007) are facing the full wrath of the UHIE, which is literally costing the cities millions of dollars annually, in related expenses of enduring and mitigating UHI. These cities are reacting upon repercussions of what they have done to their environment and are desperately trying to amend for their deeds, whereas in the case of Colombo still the city of Colombo has time to act proactively to incorporate sustainability features to the town planning and development master plans. This may ensure that future of Colombo will be sustainable with minimal environmental detriments and related socio-economic implications.

UHI in Colombo has been studied by several authors, each focusing on different mitigation strategies such as; urban physical elements (Bandara, 2003), green roofs (Wijerathne and Halwatura, 2012) and tree shades and urban canopy Silva (2004). However, pavements structures with passive cooling effects in mitigating UHI are a potential research area that has still not yet been explored.

4. DISCUSSION

It is established that the pavement design and materials selection can be exploited to significantly reduce the environmental impact of urban development, and that it can greatly reduce substantial cost impacts in the maintenance phase in the life cycle of pavement systems (Muga *et al*., 2009).

A cooler pavement inherently reduces its surface temperatures and the heat stress on the pavement itself. Laboratory tests have found that cooler pavements may be considerably more durable against rutting and embrittlement (Pomerantz *et al*., 2000) ensuring increased lifetime of the pavement, which in turn is a potential cost saving. In addition to the environmental benefits, cooler roads and pavements can be cheaper to construct, and may also last considerably longer (Pomerantz and Akbari, 1998). On the ultimate end, the lifecycle costs of maintenance, rework and disposal of pavements will be reduced.

It was established that highly reflective pavement surfaces are a basic approach of cool pavements (Li, Harvey and Kendall, 2013). Highly reflective pavements offer an additional benefit of enhancing night illumination from light reflected off the pavement, amounting to less energy demand on night time roadside illumination. Pomerantz *et al*. (2000) suggests that enhanced visibility due to reflective pavements will help avoid accidents and reduce the costs of automobile insurance, whilst probably reducing auto theft and other street crimes. On the other hand, cool pavements directly affect the energy demand of a building by affecting the outside temperature as argued earlier in this paper. Altogether, more reflective, cooler pavements are capable of presenting a significant reduction in the huge expenditures on the nation's roads and cities.

Brattebo and Booth (2003) claim that permeable pavement compares extremely well in surface durability, infiltration capacity and water quality performance against classic asphalt. Therefore, as a strategy for storm water management and to control urban runoff water, permeable pavements have a wider role other than their assistance in mitigating UHIE. However, Brattebo and Booth (2003) claims although due to windblown dust or particulate matter washed off from storm water, permeability of pavements may reduce over time; the infiltration capacity does not fall drastically, suggesting the long-term permeability performance may not be problematic. Similarly, Gilberta and Clausen (2006) notes that even with decreased infiltration, the use of concrete pavers is preferable over traditional asphalt for control of nonpoint source pollution. However, it is noteworthy that a generalization of good performance cannot be guaranteed in every instance as permeability relies on many factors which are unique to each installation.

Obla (2007) agrees that permeable pavements assist sustainable development. He points out that it acts as a filter for pollutants, where the pavements capture the first flush of rainfall which will lead to the runoff of most pollutants, allowing pollutants to be percolated into the ground where soil chemistry and biology treats the polluted water. Obla suggests that pervious pavers function like a storm water retention basin and allowing the storm water to infiltrate the soil over a large area, facilitating local groundwater recharge. These benefits lead to more effective land use.

An important fact to consider while considering cool pavement strategies is the essential "trade-off" between pavements' thermal, permeability and structural characteristics. With reference to Table 1 it can be seen that high permeability does not necessarily mean high impact on UHIE. Even so, it has its merits as high storm water infiltration and as a pollution inhibitor. Meanwhile, increased perviousness has an adverse impact on the structural integrity; thus, limiting its strength. Conversely, alternatives with high albedo and low permeability maybe more efficient in mitigating UHIE and may withstand large compressive forces. However, environmental performance of such a system may not be sufficient for a sustainable built environment which demands a more holistic approach. Therefore, while suggesting for the incorporation of cool pavements as a driver for sustainability in the rapidly urbanizing Colombo and its suburbs this trade-off has to be found and compromises be made according to site-specific conditions.

The implementation of urban heat island mitigation strategies such as cooler pavement initiatives is primarily conditioned on receiving the necessary governmental and local community support. The difficulty in implementing cooler pavements is in taking a holistic view at the situation where most often without regard for the shortened lifetime of hot pavements or the heat-island effect; decisions are made on the basis of initial cost (Akbari, 2008). If these are taken into account, as studied by Ting *et al*. (2001) the life-time costs of cooler pavements may be lower for many kinds of pavements. Strategies for effective implementation may include: Green Building standards or rating systems, incentive schemes for voluntary actions and most effectively through inculcating these strategies into zoning, building and energy codes of the country.

5. FURTHER RESEARCH

The adverse social, environmental and economic issues of urbanization are manifesting in many forms from which urban heat island effect carries heavy significance. This paper discussed an overview of the issue and proposed a mitigation strategy based on existing literature. However, city-wide implementation of such strategies is still far from reality for Colombo due to various reasons.

The approach to overcome these constraints is through extended research and development, which will be the overall key to a sustainable city. Therefore, new alternative pavement systems with possible composite materials as greener building materials should be explored. Further studies needs to be carried out focusing on the thermal characteristics of pavement systems in local tropical climatic conditions. These studies should be extended to include permeability characteristics of pavement systems as well. In that sense research should also be focused on short term and long term effects of contaminants and clogging or pervious pavements in the local context.

However, extensive studies must be carried out on the costs and benefits of cool pavements as well as their durability, longevity and life cycle costs and life cycle environmental aspects. These studies shall be the base for studies on the self-sustainability of new cool pavement systems.

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