

Mitigating Thermal/Solar Heat Gains on Pavements and Its Influence on the Environment

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Abstract
With the vast quantity of natural vegetation being replaced by heat absorption materials due to urbanization, incident solar radiation is seen to be one of the most prominent heat sources. This increases the storage of sensible heat on these materials which accumulates heat impinged on the surrounding surfaces and is entrapped within the urban canyon. A large percent of the urban fabric is seen to be covered by pavements. It is therefore likely that the outdoor thermal environment is most influenced by the surface temperature of pavements increase the overall air temperature as well as the surface temperatures of the wall – hence temperature transfers to the interior, contributing to the operational indoor temperatures. This paper presents a review on paved surfaces aimed at studying the process of thermal heat gains of pavement materials with respect to their surface temperature under continual exposure to solar radiation. An experiment was carried out on three pavement materials to determine its surface temperature during the whole period of the day. Findings show excessive heat on paved surfaces especially during the day. Cool pavements (Porous/ high solar reflectance) however were significantly lower in surface temperature than the conventional impermeable pavements for all paved materials sampled because of its high reflectance and porous nature. This review analysis shows that an improvement on the thermal properties of outdoor spaces can be expected if the solar reflectance of paved surfaces is increased by retrofitting and the porosity be a key feature on the surface of pavements.
Keywords: Pavements, Heat gain, Surface Temperature, Solar Radiation.

INTRODUCTION

Paved surfaces are seen to be one of the main elements controlling outdoor thermal environment (Doll and Ching, 1985: Asaeda and Ca, 2000: Lin *et al* 2007). They cover a significant portion of urban and suburban surfaces (EPA 2008; Santamouris *et al* 2011) and store up energy absorbed from solar radiation within the pavement subsurface, thereafter released as latent heat back to the atmosphere during the evening and night (Doll and Ching 1985; Asaeda *et al* 1996). Studies have shown, that the distinct high temperature of the ground surface and successive harsh thermal conditions within the urban scale is a consequence of the heating process of impermeable pavements surfaces. During the day time an impermeable paved surface absorbs large amount of solar radiation and in the absence of evaporation, this makes the surface temperature of pavement to rise higher than the temperature of the overlying atmosphere (Asaeda and Ca 2000). Further studies also reveal that most of the infrared radiation from the ground was absorbed within 200m of the lower atmosphere, This affects the ambient temperature near the ground and is entrapped within the urban canyon contributing to the formation of urban heat island (Voogt and Oke, 2003; Pomerantz *et al*., 2000a, b; Asaeda *et al*., 1996; Asaeda and Ca 1993). Santamouris *et al* (2011) also reveal that the heating process on pavement surfaces depends mainly on its thermal properties, radiative properties, surface emission, reflectivity and evaporation from the surface (Esuf and Asaeda 1996).

On the other hand several technological advances have been proposed to change urban surfaces through the use of materials known as cool pavements. Cool pavements have the ability to increase the solar reflectance of pavements which reduce the solar radiation absorbed by pavements and induce evaporation through permeable pavements. They allow water drain through to the subsurface layer thereby promoting evaporation. During this process, a part of the net downward radiation is converted to latent heat similar to that which occurs on natural surfaces (Asaeda and Ca 2000). The surface temperature of permeable pavements therefore does not elevate as high as impermeable pavements which may be a feasible method of mitigating the impact of heated pavements on its environment. With the purpose of understanding the heating process on the surfaces of various pavements, the aim of this paper is to qualitatively review and study experimentally the thermal performance of three pavement materials as well as possible means of reducing the heat gains that cause the urban heat Island phenomenon.

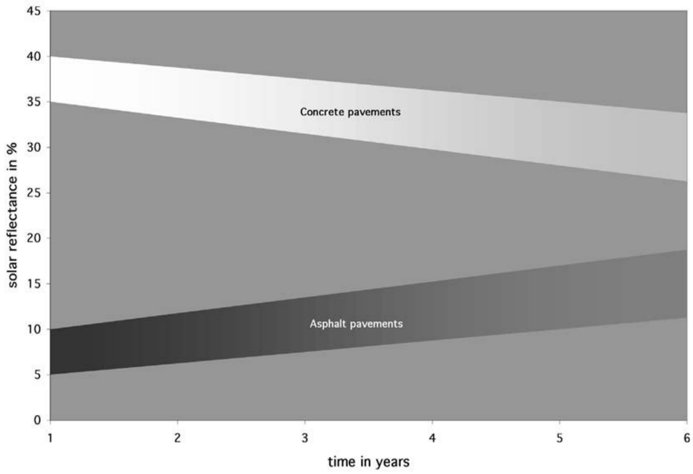
CATEGORY/TYPES OF PAVEMENTS AND ITS THERMAL IMPACT ON THE ENVIRONMENT.

Materials used on hard surfaces of urban structures play an important role in the thermal comfort of the environment. They absorb and accumulate solar and infrared radiation, thereby releasing through convective and radiative processes to the overlying atmosphere and increasing its ambient temperature. The technical characteristics of the materials used determine to a high extent the energy consumption and comfort condition of individual buildings as well as open spaces. Various studies therefore have been carried out to understand better the optical and thermal characteristics of the materials used for pavements as well as their impact on the city climate. (Yap, 1975; Berg and Quinn, 1978; Gustavsson and Bogren, 1991; Taha *et al*., 1992; Asaeda *et al*., 1996; Doulos *et al*., 2004; Niachou *et al*., 2008; Santamouris *et al*., 1999; Chen *et al*., 2009; White *et al*., 2010). Pavements have been technically categorized as conventional sealed and cool pavements.

Conventional Sealed Pavements:
They are usually impervious and made of concrete and asphalt, which can attain surface temperatures of 48^0C-67^0C (EPA, 2009b; Santamouris, 2001; Doulos *et al*., 2001; Pomerantz *et al*., 2000a). Other non popular materials in use for impervious surfaces include stone, marble, granite and pebbles.

Asphalt pavement: is a heavy black or grey in colour with mineral substances; one of which is a hydrocarbon called bitumen. It is a strong versatile, weather and chemical resistant binding material used on roads, streets, and airport runway. Studies by Gartland 2008 show that asphalt has solar reflectance values of 5-10 percent when new and tend to lighten and become more reflective as it ages as shown in Figure 2 below. Their relatively dark color however, tends to keep asphalt pavements at 65^0C (150^0F) or higher during summer. Studies carried by Gartland (2008) on the surface temperature and heat flow in and out of the pavement, It was observed that the pavement surface had a solar reflectance of 10 per cent and a surface temperature on a 34^0C (93^0F) day reached 57^0C (135^0F).

Concrete pavements: is the second most prevalent type of pavement in use today also known as PCC (Portland cement concrete). Concrete pavements are light grey with 30-40 percent solar reflectance. With time, it gets darker and its solar reflectance lowers to 23-35 per cent. Studies by Gartland 2008 show concrete pavements are much cooler than asphalt often 50^0C (120^0F) in the sunniest conditions. Figure 1 below shows how solar reflectance of asphalt and concrete vary overtime as a result of a lighter shade of concrete even when it gets darker overtime time due to dirt attraction, it tends to stay cooler on a sunny day than asphalt (Asaeda *et al* 1996). Further studies show that on a 34^0C (93^0F) day the concrete heats up to38^0C (100^0F) mainly because the surface reflects more of the sun's radiation away reducing its net radiation to a peak of 350Wm^2 versus 520Wm^2 for asphalt.



Source: Gartland 2008

Figure 1: Variation of the solar reflectance of asphalt and concrete pavements over time

Cool Pavements
Refer to materials that tend to store less heat and experience lower surface temperatures as compared to conventional pavements (Santomourus *et al*., 2010). Cool paving reduces pavement temperatures by 19.5^0C (30^0F) or more (Asaeda *et al,* 1996; Pomerantz et al,2000; Gartland 2011). The most heated pavements tend to be impermeable and dark in color. According to Cambridge systematic Inc (2005), various studies have shown to date possible mechanisms for creating a cool pavement can be listed as:
a. Increased solar reflectance which reduces the solar radiation absorbed by the pavements.
b. Increased permeability which cools the pavement through evaporation of moisture (Golden *et al* 2007).

Increase Solar Reflectance
In increasing the solar reflectance of pavements, several methods have been employed on asphalt pavements. One technique is by using white colored aggregates (gravel, white stone) or pigment in the asphalt. This can

increase the solar reflectance of the asphalt surface to about 0.3. Others are the white topping technique which involves laying a thin layer of concrete over an existing pavement. This has the capacity of increasing the solar reflectance of asphalt pavement to that of concrete by (0.3-0.45). The chip seals is a maintenance technique that consists of pressing rock chips over an asphalt binder so that the solar reflectance of the road is determined by the reflectance of the light colored aggregate. Concrete pavements on the other hand are considered cool pavements; however it can become cooler if lighter colored binders, aggregates and sands are mixed with it (Brez et al., 1997; Tinget al., 2001; Gartland 2008).

Levinson and Akbari (2002) conducted an experiment on the composition and environmental exposure of the albedo of (PCC) and developed concrete samples with albedo as high a 0.77. Further studies show there are many other forms of cool pavements which have not been explored. In order to conduct a self check on pavement samples to determine their solar reflectance, the solar reflectance is being used as a variable to compare the coolness of various pavement materials. It has been accepted by the US Green Building Council (USGBC) in its leadership in energy and environmental design (LEED^{TM}) to adopt Green building rating system as a methodology to determine if a pavement design aids in mitigating the UHI effect (Haselbach 2008, Marceau and Van Geem 2007). Allan Robinson (2010) developed an equation to calculate the solar reflectance within a controlled environment. The gonioreflectometer was used to record the amount of radiation with the desired wavelength that was reflected by the controlled surface. To first calculate the solar reflectivity this was given as

$$P(y) = R(y)/I(y)$$

Where p(y) is the reflectivity of solar radiation with a wavelength of y.
R(y) is the reflected radiation of wavelength y and
I(y) is the incident radiation of wavelength y
To determine the solar reflectance from the solar reflectivity. The solar reflectance is the square of the solar reflectivity,

So $q(y) = (R(y)/I(y))$ ^2 where q is the solar reflectance

To interpret the solar reflectance, it is simply the square of the percentage of radiation that an object reflects for a given wavelength of light. The reflectance will therefore be a value between 0 and 1. A reflectance of 0 indicates that the object does not reflect any light of the given wavelength and 1 indicates that the object reflects all the light of the given wavelength it can also be expressed as a percentage.

Increased permeability

Another way to cool an asphalt or concrete pavement is to make it porous or permeable. This allows rainwater drain through the pavement and store in the layers and soil below, water can then evaporate and cool the pavement under high temperatures. Asphalt and concrete pavements are made porous by leaving the smaller particles, or fines of sand and rocks out of the pavement mix. These ‘open-graded’ pavements then have a void space between the larger rocks that allow water drain through the pavement. These void spaces must be carefully sized to avoid getting clogged by dirt and other materials. Both asphalt and concrete versions of porous pavements have been used on roads and parking lots (Smith, 1999; Maes and Youngs, 2002).

The conventional state of pavements are impermeable, retrofitting to permeable may not be feasible. However a new approach towards storm water management instead of runoff is a good advantage of permeable pavements. The use of light colour shades on pavement surfaces should be encouraged before applying coatings on any site/zone, a thorough study should be carried out in order to estimate the impact of such reflective surfaces on the surrounding microclimate, avoiding increased glare or unwanted solar gains through other means.

HEATING PROCESS OF PAVEMENTS

Esuf *et al* (1997) studies have revealed pavements to be one of the main factors altering the thermal balance of urban environment. It is thereby necessary to understand the heating process of pavements. In the case of permeable pavements, it follows the similar mechanism of radiation transport in which 52 per cent of the solar energy felt as heat (EPA 2008) is incident and absorbed by the pavement surface and subsurface layer. It is thereafter converted to latent heat and released back to the atmosphere by evaporation. This makes the surface temperature of the permeable paved surfaces lower as compared to the impermeable surfaces (Santoumouris *et al* 2011: Asaeda and Ca 2000). This phenomenon however is completely different in the case of impermeable or non porous paved surfaces, during the day nonporous pavement surfaces due to their low reflectivity and high thermal conductivity absorbs large amount of infrared solar radiation. It is stored on the subsurface and released immediately during the day and night in the form of sensible heat and upward long wave radiation (Esuf and Asaeda 1996). According to Asaeda and Ca (1993) the underground heat storage and sensible heat exchange between the ground surface and atmosphere are diminutive during the heating process. The lower- atmospheric upward infrared radiation emitted by the ground surface is nearly balanced by downward infrared radiation from the atmosphere when the difference between the temperature of the air in the lower atmosphere and that of the ground surface is very little (Figure 1).

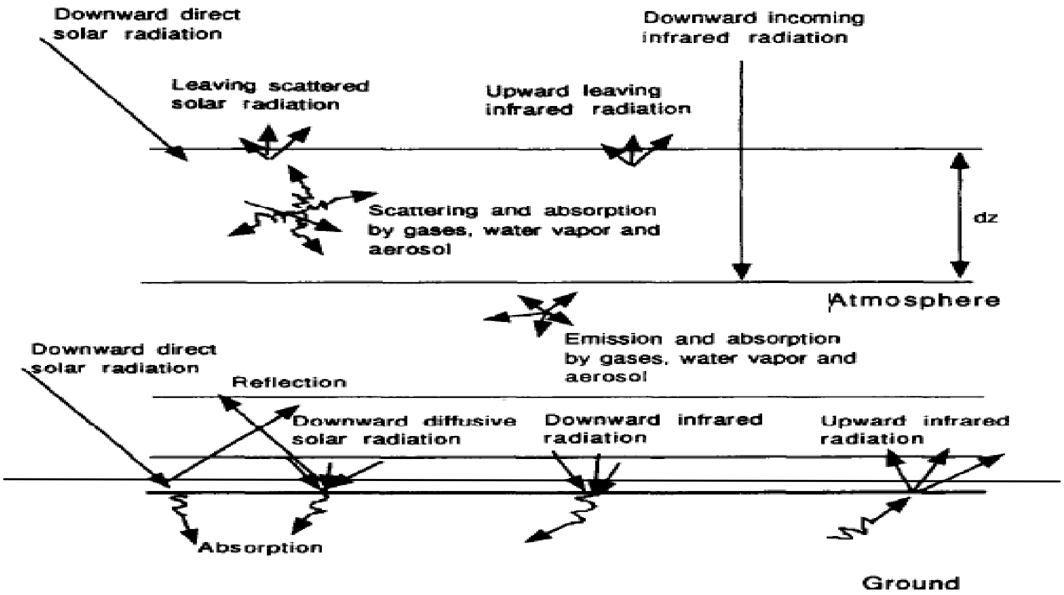


Figure 1: Sketch of the Parallel atmospheric layers model Source: Asaeda *et al* (1993).

However, when the temperature of the ground surface far exceeds that of the overlying air as in the case of a heated pavement during the day, the upward infrared radiation emitted from the ground surface is significantly higher than the downward infrared radiation from the sun to the atmosphere. The absorption of this upward infrared radiation by the overlying atmosphere may become a significant component of atmospheric overall heat budgeting (Asaeda and Ca, 1993). Studies conducted in the US by Kevern *et al* (2010) compared the overall heating of Portland cement concrete (PCC) and Portland cement pervious concrete (PCPC) during several diurnal cycles in summer based on the bulk mass of the various layer depths of the systems. Asaeda *et al.* (1996) however reported the experimental results of a study where the impact of various pavement materials used commonly in urban environments were tested during the summer period.

Findings show the surface temperature, heat storage and subsequent emission to the atmosphere were significantly higher for asphalt than for concrete and bare soil. This shows that it may be necessary to coat asphalt with lighter colors to improve its reflectance in regions with high solar radiation.

MODES OF HEAT TRANSFER ON PAVEMENTS

According to Yavuzturk and Ksaibati (2002) the primary modes of heat transfer are incident solar radiation, thermal long-wave radiation; which occurs between the pavement surface and the sky and convection due to heat from the surface to the subsurface. Figure (2a) shows findings on how heat is stored and released in an asphalt pavement over a whole day through the three practical periods of the day (Asaeda et al 1996). The surface temperature and heat flow in and out of the pavement was observed to have experienced a solar reflectance of 10 per cent and the surface temperature on a 34^0C (93^0F) day reached 57^0C (135^0F). The curve shows that the temperature was most prominent during the day due to the high intensity of solar radiation and low reflectance of asphalt; being a dark colored material which has higher heat absorption capacities.

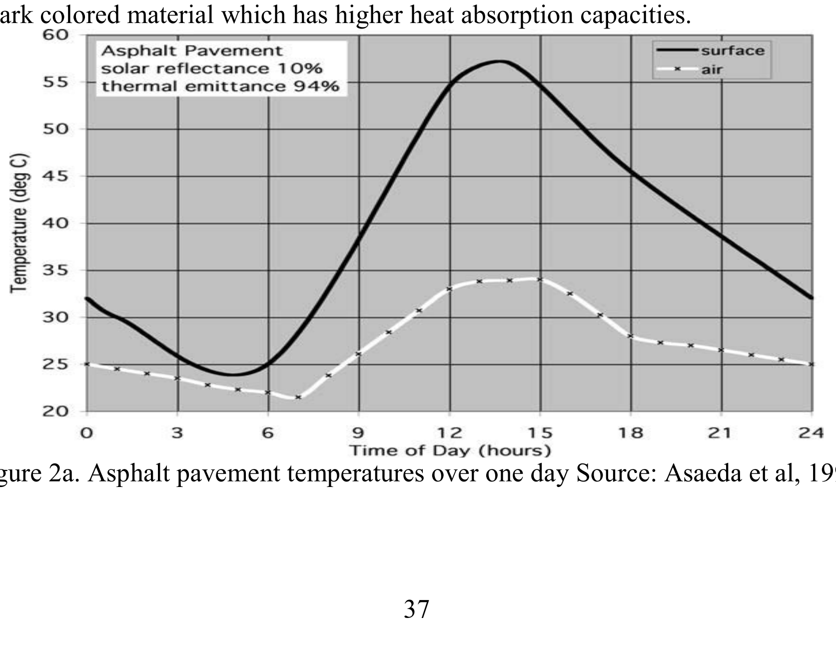


Figure 2a. Asphalt pavement temperatures over one day Source: Asaeda et al, 1996

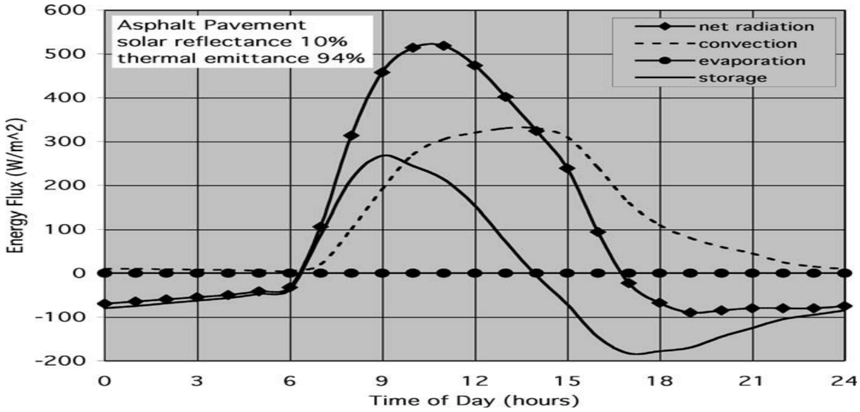


Figure 2b. Asphalt pavement heat flow over one day Source: Asaeda et al, 1996

Figure (2b) shows that as net radiation; radiation from the sun and the sky minus the reflected solar radiation and radiation emitted from the pavement surface to the pavements climbs, heat is released to the air through convection. Convection during the morning and early afternoon is not enough to keep the pavement cool and therefore heat is stored in the pavement from mid day till the solar energy decreases. The asphalt was able to release stored heat and stay cool in the absence of evaporation. Figure 3 shows the temperature and heat flow of a porous pavement with solar reflectance of 25 per cent which reached a maximum temperature of 43ºC (109ºF) on a 35ºC (95ºF) day. The net radiation into the porous pavement reached 550Wm^2 even higher than the 520Wm^2 of the asphalt pavement. But the porous pavement stays cool by using the sun's heat to evaporate water stored in the pavement and the soil below; this means that pervious pavements have a tendency to heat up higher than impervious pavements when dry, but after a rainy day due to evaporation, the pervious surface tends to be cooler than the impervious surface.

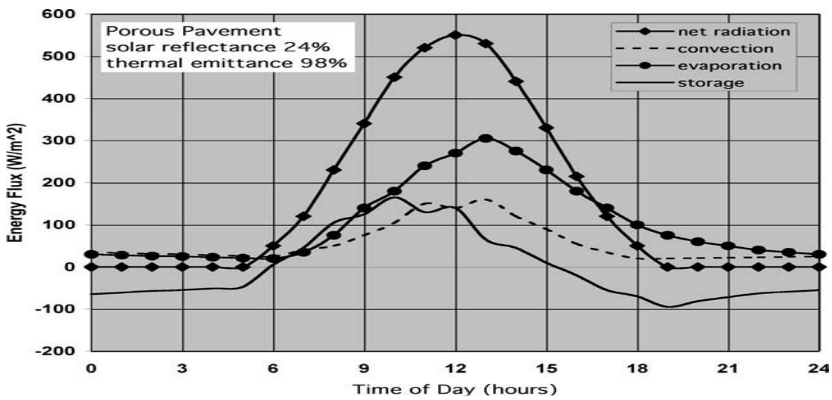


Figure 3; Porous pavement heat flow over one day Source: Asaeda and Ca, 2000.

FIELD EXPERIMENT

Materials and Methods

Field experiments were conducted from October 2010- November 2010 at Universiti Teknologi Malaysia, located 20km north of Johor Bahru (1^{0}29'N - 103^{0}44'E) of the equator. The experiment involved three samples of pavement materials used within the premises; Asphalt, Interlocking concrete tiles and terracotta clay bricks. It aimed at evaluating the thermal performance of the various materials (Surface temperature). The samples where at different locations within the study area and the layouts of the samples are depicted in figure 1. The surface temperatures were measured physically using the infrared thermometer and the kestrel weather tracker.

A. Interlocking tiles B. Terracotta clay tiles C. Asphalt

Figure 1. Layout of the surface samples

Surface temperature variation on the three pavement samples

During the experiment it was observed that the heat budget on pavements depends mainly on the intensity of solar radiation. Incident *solar radiation* has *significant* effects on the *thermal performance of paved surfaces (Byerley and Christian 1994).* The exposed pavement was seen as the most sensitive variable to the solar radiation incidence on it; escalating the temperature of the surface. According to Lin *et al* (2007) the surface temperature of paved surface is nearly 10^{0}C higher than the bare soil and green areas. The surface temperature of pavements gets as high as 42.7^{0}C in summer. Figure 2 illustrates the surface temperature distribution of asphalt, interlocking concrete tiles and clay bricks. It shows the surface temperature of each of the samples for a whole day; the variation of surface temperature for each pavement was minimal during the morning and evening and significantly higher during the day especially on the asphalt pavements were a very steep slope was observed during the day.

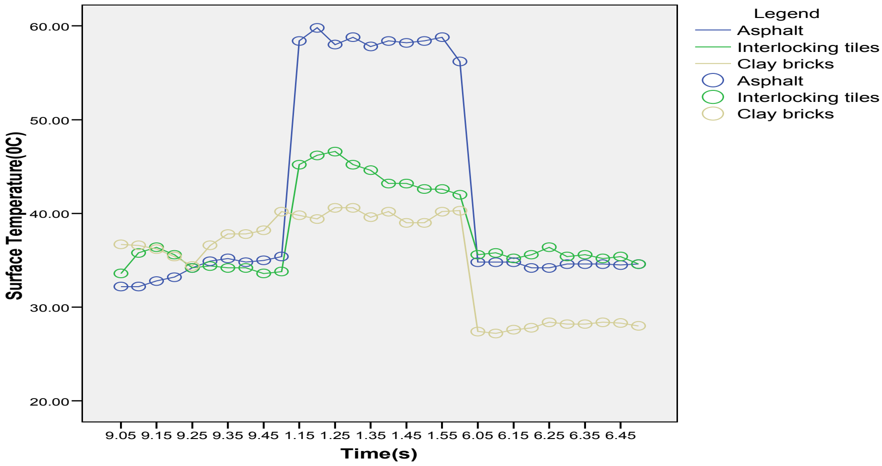


Figure 2. Surface temperature variations for three pavements

Figure 3 shows the average surface temperature of each pavement during the three practical periods of a typical day. The average surface temperature evaluated for all samples shows that the temperatures were most elevated during the day. Asphalt was seen to be significantly higher with a temperature of 58.28^{0}C. This was mainly due to its low reflectivity and consequently high absorption rate of solar radiation as being documented by Brez *et al* (1997); a material with low solar reflectance when exposed to solar radiation will experience higher surface temperature than materials with high solar reflectance. The interlocking concrete tiles had a higher reflectance capacity; as it was lighter in color, it had an average surface temperature of 44.14^{0}C. According to NAASRA (1980) clay bricks have good insulating properties; which explain why it computed the lowest average surface temperature of 39.87^{0}C as compared to other materials sampled. The values of the surface temperature agree with other experiments carried out by Tan and Fwa (1992) which also displayed Asphalt as the hottest with 60^{0}C while other materials were 10^{0}C lower than asphalt. The above findings reveal that the average surface temperatures of the pavements were most pronounced during the day and had less heat output during the morning and evening observations. The albedo of the materials determined to a large extent the level of reflectivity of the various materials and its thermal performance.

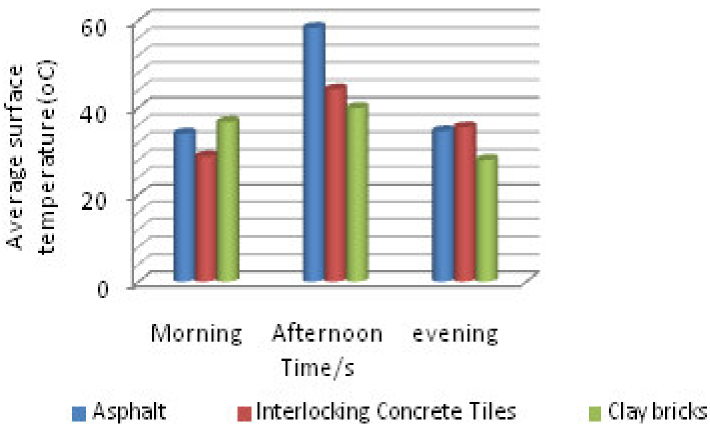


Figure 3: Average surface temperature of three pavement samples.

Through the Primary modes of heat transfer, Incident solar radiation, thermal long wave radiation. It was observed that Surface temperature followed closely behind the air temperature variations and temperature fluctuated less with depth.

DISCUSSION

Pavements cover a large percentage of the land cover in most part of the world and mainly in urban centers where most urban activities take place. Pavements are no doubt a main source of heat to its ambience which is translated as Urban Heat Island (UHI). UHI is a condition of elevated temperatures in the surrounding caused by properties of the urban fabric and human activities. They are conventionally made of Asphalt and concrete materials, both materials have a tendency to absorb solar radiation and reach extremely high temperatures. Dark colours such as Asphalt has a solar reflectance value of 5-10 percent when new and tend to lighten and become more reflective as it ages. Their relatively dark color however, tends to keep asphalt pavements at 65^{0}C (150^{0}F) or higher during summer.). Concrete pavements are light grey with 30-40 percent solar reflectance. With time, it gets darker and its solar reflectance lowers to 23-35 per cent. This review has shown concrete pavements are much cooler than asphalt often 50^{0}C (120^{0}F) in the sunniest conditions. The field experiment carried out on the three pavement samples show the average surface temperature of each pavement during the three practical periods of a typical day. The average surface temperature evaluated for all samples shows that the temperatures were most elevated during the day. Asphalt was seen to be significantly higher with a temperature of 58.28^{0}C. This was mainly due to its low reflectivity and consequently high absorption rate of solar radiation, a material with low solar reflectance when exposed to solar radiation will experience higher surface temperature than materials with high solar reflectance. The interlocking concrete tiles had a higher reflectance capacity; as it was lighter in color, it had an average surface temperature of 44.14^{0}C. clay bricks with its good insulating properties; explained why it computed the lowest average surface temperature of 39.87^{0}C as compared to other materials sampled.

CONCLUSION

The global climate change due to one of many other environmental factors known as urban heat island. Pavements were seen to be one of the main elements giving rise to this effect. A review on the thermal performance of pavements previously studied showed the primary modes of heat transfer are incident solar radiation, thermal and long-wave radiation between the pavement surface and the sky, convection due to heat transfer between the pavement surface and the fluid; air or water that is in contact with the surface, and conduction inside the pavement. It was observed that conventional pavements experience surface temperatures as high as 57^{0}C (135^{0}F) during the day and a solar reflectance ranging from 0.04-0.45 however, advances in technology have brought about cool pavements which through increasing the solar reflectance and porosity of the surface can reduce pavement temperature by 19.5^{0}C (30^{0}F) or more. Porous pavements also served as a means of utilizing storm water instead of runoff.

The experiment carried out on the three pavement materials examined shows that the albedo of paved surfaces determines to a great extent the solar heat absorption rate. Dark materials such as asphalt attract and absorb more heat than light colored materials such as concrete. Among the materials tested asphalt was observed to have experienced a surface temperature of 58.20^{0}C during the day were terracotta was the lowest with 39^{0}C.

The rises in pavement temperature were suppressed via the combined effect of water evaporation and reflection of solar radiation which will aid in easing the elevated temperature of pavements and subsequently the environment.

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