Thermal Behaviour of Cool-Pavement Materials Development using Palm Oil Shell Aggregate

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ABSTRACT

Cool-pavement technology has emerged as a potential solution to environmental issues posed by the urban heat island phenomenon, with surface temperature acting as a vital parameter in the evaluation of its thermal performance. This study focuses on the thermal performance results of modified asphalt concrete mix, wherein palm oil shell (POS) serves as a replacement for fine aggregate. Modified asphalt samples prepared using the Marshall Mix Design, with varying degrees of fine aggregate substitution (0%, 10%, 20%, 30%, 40%, and 50%), underwent a 24-hour continuous surface temperature measurement over a span of 20 days, under real-world tropical climate conditions. The findings demonstrated that sample P5, comprising 50% fine aggregate substitution, exhibited the highest reduction in surface temperature when compared to control sample P0, registering a significant decrease of up to 3.29°C during the period of peak solar intensity. ANOVA test-based statistical analyses confirmed significantly lower temperatures for all test samples, barring sample P1 (10% aggregate replacement), relative to the control sample. The results highlight the efficacy of POS as a fine aggregate substitute in asphalt concrete, significantly lowering asphalt pavement surface temperature, thereby endorsing the potential use of POS-modified asphalt in cool-pavement applications.

1. Introduction

Urbanization is one of the processes that have been experienced by most of developing and developed countries in the world, parallel to the economic and population growth in megacities. Without proper planning at early stage, it can significantly affect environmental condition, thus reducing quality of life for human being. Urban heat island (UHI) has been listed as one of major environmental problem that been experienced by most of megacities in 21st century\textsuperscript{[1-3]}. UHI is defined as phenomena where average air temperature in the urban area is much higher compared with its surrounding rural areas.
area. As reported in some research, cities that have been affected by UHI having overall ambient temperature range from 2.0 – 5.6°C higher than its surrounding rural area and found to be increased from year by year [4-6]. There are various factors that cause the formation of UHI in the city, such as a) improper city planning; b) lack of vegetation to promote evaporation; and c) most of city build-up covered with material with low albedo surface. Phenomenal of UHI cause serious impacts on economy and societies, such as increasing energy consumption, thermal discomfort, degradation of human health quality, and increase intensity of air pollution in the cities [7-9]. Since then, there are much research have been conducted to study on the potential mitigation measures and solution of minimizing the effects of UHI. There are various aspect has been explore and proposing innovative mitigation technologies, such as cool-pavement, green roof, modification of building envelope and reservation of green park [10-15].

Pavement has covers significant percentage of urban surface, which is up to 45% of the total land in cities area. Most of researchers found that the heating mechanism by low albedo or surface reflectance of asphalt material for pavement has contribute significant role in formation of UHI [16,17]. Conventional asphalt pavement usually dark in colour and has low albedo value, range from 0.04 – 0.45. This will cause the asphalt pavement absorbs huge amount of energy from solar radiation, which then turn into heat that resulting to high surface temperature of the pavement. During hot clear sunny day, surface temperature of asphalt pavement can achieve very high temperature, range from 48°C to 67°C [16,18].

Cool-pavement has been identified as part of mitigation technology for combating urban heat island, and numerous of research have reported convincing result that applying this technology could significantly reduce the asphalt surface temperature, thus helping to reduce amount of heat emitted by the pavement into atmosphere. Theoretically, there are two main important parameters that contribute of the cooling mechanism by cool-pavement; a) increase pavement surface’s albedo; and b) increase pavement’s permeability which promote cooling effect through evaporation process [16,19,20]. An experimental finding reported by Qin et al., (2018) found that a water-retaining paver block that has low albedo, range of 0.10 – 0.15, have surface temperature that significantly lower than conventional pavement, in the range of 2°C - 10°C on hot summer day due to evaporation process [21]. Meanwhile, increasing albedo or surface reflectance of the pavement will reduce amount of heat to be absorbed, thus reducing its surface temperature and quantity of heat to be re-radiated into the ambient. Albedo of the asphalt pavement can be increased by a) applying surface coating material; and b) inclusion of high near infrared region (NIR) into the mix material [12,22-24]. Crystalline mineral pigment such as quartz or silica dioxide (SiO₂), titanium dioxide (TiO₂), aluminium trioxide (Al₂O₃) and iron trioxide (Fe₂O₃) are mix of compound that could increase the NIR reflectance of material’s surface. Pure SiO₂ could reflecting up to 89.4% of heat from solar radiation [22]. There are more advance formulation of cool-pigment that derived from those listed mineral pigment, which currently apply for roof [25,26].

Therefore, this study was conducted to explore the potential of applying palm oil shell (POS) to be recycled and reused as fine aggregate in asphaltic concrete mixture. POS is a hard protective layer of the palm kernel. Previous study on the investigation of chemical composition have found that NIR reflective pigment, such as SiO₂, Al₂O₃ and Fe₂O₃ has presence in the POS material [11,27]. The tested sample of asphaltic concretes were mixed with varies composition of POS as fine aggregate replacement. Series of experimental work of measuring surface temperature of tested samples at actual weather condition were performed to evaluate their thermal performance. Further statistical analysis was conducted to determine the level of significant of obtained data from the experiment. Thus, the findings reported in this study could provide significant information to apply palm oil shell
as fine aggregate replacement in asphaltic concrete that able to reduce the surface temperature of the pavement, which potentially be part of mitigation technology of urban heat island phenomenon.

2. Experimental Methodology

2.1 Sample Preparation

The palm oil shell (abbreviated as POS) for this research was obtained from Malaysian’s local company, that is located at Johor, Malaysia. Initially, the POS material, in the bulk form was washed repeatedly for several time to remove dirt, dust or any impurities and free from deleterious material. After that, the POS material was air-dried naturally under the sunlight for 24-hours, and then, the material was crushed into fine grain size in between 0.05mm to 2mm. The crushed POS material was oven dry for approximately 24-hours at temperature of 110°C±5°C. After drying process, then crushed POS material was sieved to obtain POS fine aggregate with the size between 0.075mm to 1.18mm. Finally, once again, the prepared POS fine aggregate was washed using clean water to remove dust, which then enhance the bonding strength of its surface with the asphalt binder.

The procedure for Marshall mix design is in accordance to Public Work Department of Malaysia [28] employed to design hot mix asphalt (HMA). A total of 18 HMA samples were prepared, with 3 samples for each mix design were prepared for the purpose of testing and experiments. Table 1 shows the samples for percentage of POS replacement and denoted as samples P0 to P5. The POS percentage are varies to investigate its effects towards temperature reduction in asphalt. Meanwhile, Figure 1 shows the laboratory work to prepare the asphalt samples.

<table>
<thead>
<tr>
<th>Samples</th>
<th>% of POS replacement by weight of aggregate</th>
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<tbody>
<tr>
<td>P0</td>
<td>0%</td>
</tr>
<tr>
<td>P1</td>
<td>10%</td>
</tr>
<tr>
<td>P2</td>
<td>20%</td>
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<td>P3</td>
<td>30%</td>
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<td>P4</td>
<td>40%</td>
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<td>P5</td>
<td>50%</td>
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Figure 1 shows the laboratory work to prepare the asphalt samples.
2.2 Experimental Work

All the tested samples, together with control sample, with an average size of 110mm diameter and 68.9mm height, each, were further prepared before measuring its surface temperature. The sides surface of the tested samples was cover with polystyrene to ensure that the heat only flow in one direction and enter through opening surface on top of the sample. The experiment was conducted on the rooftop of Advance Highway Engineering Laboratory, Universiti Tun Hussein Onn Malaysia (Batu Pahat, Johor, Malaysia). The location of samples is positioned away from any shades and the samples were exposed directly to sunlight in the open space. Setting up of the experiment is shown in Figure 2.
Thermocouple sensors will be installed in each mix sample for measured the pavement surface temperature. The experiment was conducted for 24 hours period for 20 consecutive days starting from 12 Jan 2017 – 1 Feb 2017, under actual surrounding ambient of tropical climate by considering rain falls several times during the experimental period. Surface temperature of the pavement samples were recorded every 5 minutes using Graphtec 220 data logger that connected with thermocouple type T. Meanwhile, the solar intensity and ambient temperature was measured using Radio Globale Pyranometer that connected to the Babuc data logger.

3. Analysis and Discussion

3.1 Surface Temperature Behaviour of Tested Samples

Surface temperature measurement was carried out to investigate the thermal performance of the control and modified asphaltic concrete samples. The surface temperature profile for 24 hours period of each tested pavement mixture is shown in Figure 3. The surface temperature data of the pavement samples were measured continuously for 20 days. The collected data reflecting both sunny and rainy days, where it is presenting the weather condition in tropical climate. Three asphalt pavement samples were used for each mixture to measure the surface temperature to obtain an average. The experimental period for 24-hour measurement is divided into four sub-periods which is daily, nocturnal, diurnal, and peak started from 08:00 to 19:00; 22:00 to 05:00; 00:00 to 00:00, and 12:00 to 15:00 [16,19,30]. In this study, the data of surface temperature from each pavement were collected during daily and peak period.
At the peak period of 12.00 to 15.00 or during afternoon, the graph in Figure 3 shows that the surface temperature of control sample is higher compared with modified samples. However, surface temperature of the control sample recorded could have achieved up to 50.0°C in this period during a sunny day. During daytime in between 08.00 to 19.00, all tested pavement samples indicate higher surface temperature compared with ambient temperature.

The natural event of rainfall and turbid seem significantly affect the surface temperature of tested pavement samples. As demonstrated from the graph, data of solar intensity shows the presence of cloud is noticed on 12th January 2017 until 15th January 2017, 22nd January 2017 and 1st February 2017. The most adverse weather condition was recorded from 23rd January 2017 until 25th January 2017 directly affecting the maximum surface temperature achieved by the tested samples. The maximum surface temperature of the samples instantly dropped into 24°C at the peak hour period.

As shown from the graph Figure 3, due to cloud and rain on 24th Jan 2017 the maximum surface temperature recorded by controlled sample was found significantly lower at 24°C as compared to the hot and sunny day on 17th Jan 2017 where the temperature can rise to 50°C. Based on the previous study, the researchers stated the conventional pavement surface temperature measurement can be in the range between 48°C to 67°C [31,32]. The asphaltic concrete will remain low in temperature when there is less amount of heat generated by the pavement surface due to the presence of cloud which block the solar radiation, therefore less radiation energy would be received by the pavement surface [16]. Table 2. depicted the mean surface temperature and difference mean surface temperature of control and modified samples.

As tabulated in Table 2, the difference of mean surface temperature between controlled and modified pavement mixture are high during peak hour. The presence of 50% POS as cool material in asphaltic concrete by replacing fine aggregate could reduce the mean surface temperature of asphaltic concrete sample by 3.29°C during peak period instead of 1.95°C for daily period. The result shows that POS as cool material could reduce the surface temperature of conventional surface pavement because of NIR reflectivity, due to the presence of Al₂O₃ [11,22].
In Table 3, it summarises that the highest mean surface temperature recorded for peak period is 37.0°C were obtained from control sample. Furthermore, the lowest mean surface temperature recorded for peak period are from 50% of POS sample where the temperature was 33.0°C. The mean temperature difference between pavement samples 50% and 0% is almost 90%. The mean temperature between modified samples was reduced by 1°C when the content of POS is increased in the mixture. As shown, the samples for 30% and 40% have small difference for mean surface temperature which is 0.4°C.

3.2 Thermal Performance of the POS as Aggregate Replacement in Asphalt Pavement

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4. Conclusions

Palm oil shell aggregate were used as fine aggregate replacement in asphaltic concrete, and it was found that this cool material can significantly reduce the surface temperature by offering reflectivity to the asphalt pavement. Thermal performance of the modified pavement with POS replacement was found to be more efficient than the control sample (conventional asphaltic concrete). The best outcome in term of thermal performance is by replacing fine aggregate with 50% of POS. It is because 50% replacement can obtain the most eminent surface temperature reduction which is at temperature 3.3°C rather than other amount of percentage replacement (10%, 20%, 30% and 40%).

Introducing the POS as aggregate replacement materials into the asphalt mix increase amount of void, which then increase the porosity of the modified asphaltic samples. Presence of void significantly reduce the asphalt surface temperature when it filled with water. The cooling effect is promoted by the evapotranspiration process - the movement of liquid water from asphalt void to the atmosphere. It is proved by the experimental work that modified asphalt with POS delayed the surface temperature achieved highest peak temperature after rainfall event.

Statistical analysis by using ANOVA test for surface temperature has been conducted. Based on the analysis, mean surface temperature for peak period are significant where p<0.05, given this point indicates the null hypothesis (H0) is rejected. The results show a significant difference on pavement surface temperature in each type 0%, 10%, 20%, 30%, 40% and 50% of POS sample results at daily period and peak period. It can be concluded, the proportion of each control and modified sample of POS replacement has a significant effect on the surface temperature difference.

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