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Optimizing of near infrared region reflectance of mix-waste tile aggregate as coating material for cool pavement with surface temperature measurement

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ABSTRACT

The heat generated from dark color asphalt, which is low in surface reflectance mainly contributes to the environmental problem called as urban heat island. Low reflectance at high energy wavelength of sunlight, such as visible light and infrared region will cause the pavement to have high surface temperature, due to high energy absorption from solar radiation. This paper presents the optimization result of cool pavement coating material based on selected tiles aggregate to achieve high near infrared region (NIR) reflectance. Three types of waste tiles were used in this study which are Full Body Porcelain (FBP), Monoporosa (MP) and Porcelain Glaze (PG). All the tiles were prepared in the form of aggregates. A linear model was formed as a function of mix tiles fraction and the analysis of ANOVA suggest that the linear term used for this model is significant. Diagnostics of the model was evaluated using box-cox plot, normal plot of residuals and optimized to predict the mix of the different type of tiles to produce the highest surface NIR reflectance value. The first solution suggests that 100% of MP tile can provide NIR reflectance of 0.53, whereas the second solution suggest that the combination of 50% FBP and 50% of MP tile aggregates could give NIR reflectance value of about 0.51. Experimental work on measuring surface temperature found that optimized samples, M1 and M2 with high NIR reflectance could significantly reduce surface temperature of asphalt pavement at range of 4.1 °C–9.6 °C. In conclusion, the results of optimization is reliable and this method able to provide significant information on optimizing mix of tiles material as to achieve high NIR reflectance value for coating materials of cool-pavement.

1. Introduction

Rapid development in modern cities creates significant impact to our environment, directly or indirectly. Modernization involves with the alteration of natural environment, from green natural surface to concrete jungle. Improper planning and design of the cities, e.g. (a) materials selection; and (b) building layout, directly affects the thermal condition in the cities, which is known as urban heat island (UHI) phenomena, a term used to describe the heating phenomenon in the urban areas. UHI is an environmental problem that is identified as a heating process in urban areas, that causing overall temperature at urban area higher compared to its surrounding rural areas [1–3]. A study in countries with four seasons all over the world shows that the daytime average air temperature in urban area is 5.6 °C higher than its surrounding areas [4]. Thermal discomfort, high energy consumption for increasing in cooling demand, and air pollution have been listed as several direct effects of UHI [5–8].

The surface reflectance or albedo of construction material plays important roles that significantly affects the existence of UHI [9]. Usually, the albedo of materials is correlated with the colour of surface materials. Most of the light colour materials have high

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Table 1
16 sets of run condition by the mix design model.

Run	Materials Composition (%)		
	Full Body Porcelain	Monoporosa	Porcelain Glaze
1	0.00	100.00	0.00
2	16.67	16.67	66.67
3	0.00	100.00	0.00
4	66.67	33.33	0.00
5	16.67	66.67	16.67
6	50.00	0.00	50.00
7	100.00	0.00	0.00
8	50.00	50.00	0.00
9	100.00	0.00	0.00
10	0.00	50.00	50.00
11	0.00	50.00	50.00
12	0.00	0.00	100.00
13	66.67	16.67	16.67
14	33.33	33.33	33.33
15	0.00	0.00	100.00
16	50.00	0.00	50.00

Component	Name	Units	Low actual	High actual	Low coded	High coded
A	Full Body Porcelain	%	0.00	100.00	0.00	1.00
B	Monoporosa	%	0.00	100.00	0.00	1.00
C	Porcelain Glaze	%	0.00	100.00	0.00	1.00

Response	Name	Units	Analysis	Minimum	Maximum	Ratio
Y1	NIR Reflectance	None	Polynomial	0.35	0.55	1.57143

Study type: Mixture.
Design type: D-Optimal.
Design model: Quadratic.
Runs: 16.

surface reflectance value. In developed urban cities, most of the construction materials are made from low albedo surface materials, thus creating low albedo canopy areas compared to the rural area that is mostly covered with light and green colour surfaces [10]. In addition, downtown urban areas could absorb and store twice the amount of heat when compared to its surrounding areas during daytime [11,12]. A study conducted in [13] reported that the changes of outdoor air temperatures both for daytime and nocturnal is albedo. Thus, the improvement of outdoor air temperature could be done by increasing the albedo of buildings and others construction materials such as road, external infrastructures, etc [7,14].

Asphalt pavements are usually dark in colour and cover significant percentage of urban surfaces and their thermal characteristic plays dominant role in UHI formation [15–17]. During daytime, source of sunlight energy, heated the pavement surface that contributed to the heating phenomenon of the air near to the surface. Furthermore, the incoming solar radiation is absorbed and stored as heat energy by the subsurface of the pavement and it is re-released at night [18–20]. Many studies shows that this urban structures caused surface temperature and overall air temperature to increase, both during daytime and at night [21,22]. Normally, conventional pavements are made of impervious asphalt materials, which has solar reflectance values ranging from 4%–45% [23] and peak surface temperature range from 48 °C–67 °C during summer [24]. Cool-pavement is one of a promising alternative technology that can potentially minimizing the effects of UHI. One important feature of cool-pavement is it has low surface temperature, which is due to its ability to reflect high amount of incoming solar energy. This mechanism significantly reduce the amount of heat released by the pavement into the atmosphere [25]. Thus, many research that are related with application of high reflectivity materials as coating for cool-pavement technology has gained lot of interest [26–30]. Some study shows that by increasing surface reflectance of asphalt pavement using heat reflective coating, could reduce its surface temperature up to 9 °C in a hot season [31–33]. Potential material that could be used for cool-pavement coating material should consist of high solar heat reflectance compound. As mentioned by [34], the presence of crystalline minerals, such as quartz could significantly increase solar reflectance of any flat surface. Study in [35] reported that pure SiO_2 has contribute to 89.4% of NIR reflectance of material surface.

This study focuses in the determination of optimal mix composition of cool-pavement materials that derived from three types of wasted tiles, which are Full Body Porcelain (FBP), Monoporosa (MP) and Porcelain Glaze (PG). Study in [34] shows the presence of NIR reflective compound in thus selected tiles, such as silica dioxide (SiO_2), titanium dioxide (TiO_2) and aluminium trioxide (Al_2O_3). Thus, the optimization is performed based on near infrared region reflectance value as the respond factor. The outcome of this study is to obtain the optimal amount each of the types of wasted tile, by percentage, that could achieve the maximum NIR reflectance value. Final part of this study is to evaluate the tested samples with optimal performance of high NIR reflectance based on its surface temperature. This is to confirm that by increasing NIR reflectance of asphalt surface will reduce its surface temperature, thus make it applicable for cool pavement material.

2. Methodology

2.1. Materials preparation

The materials used for making coating materials consisted of three types of wasted tiles (to be mixed together) with epoxy, as binder. The three types of wasted tiles that have been selected as the main material used in the study for the newly developed cool-pavement materials, were (a) Full body Porcelain; (b) Monoporosa; and (c) Porcelain glaze. The wasted tile materials were supplied by Malaysian Mosaic Berhad (MMB), Malaysia and the Coalcut epoxy resin that was provided by Nichireki Co. Ltd., Malaysia was selected

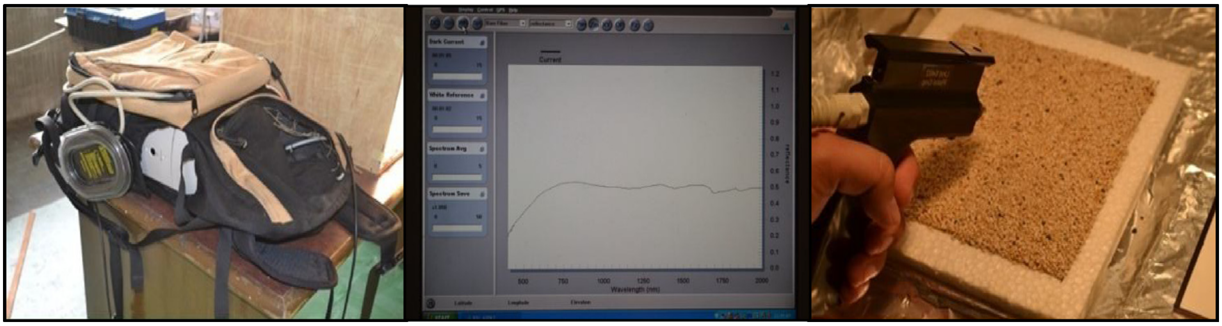

Fig. 1. Measurement of solar reflectance of tested samples.

as binder to adhere the tile aggregates at the given surface. The amount of epoxy used was at a constant rate of 1.2 kg/m^2, which is defined by Malaysian Public Work Department [36].

At first, the tiles obtained from MMB were crushed separately using a crushing machine to make it in the form of fine aggregates. Then, each of the wasted tiles were sieved separately to obtain the size in the range of 0.5 mm–2.0 mm. After that, the tile aggregates were washed thoroughly with water to remove dust and impurities, which will help to improve the bonding strength between the tile aggregates and epoxy. Then, the materials were dried using oven at 110 ± 5 °C for 24 h and now the material was considered ready to be used in the experiment.

2.2. Samples preparation

Sixteen mix design model of tile combinations have been prepared according to the model assigned by Stat-Ease Ver. 7.0. In our study, we choose D-optimal, which is the most suitable method of optimization for mixture of materials. The proportion of each type of the tiles and design summary assigned by Design Expert software is shown in Table 1. The design summary of the model is based on the range set for each components, which the D-optimal algorithm picked the points that minimized the integral of the prediction variance across the design space.

The size of each sample is 150 mm × 150 mm of area and thickness ranging from 2.0 mm–3.0 mm. Based on Table 1, each of the tile aggregates were weighed according to the volume-based percentage, then it was put together into a beaker, and mixed evenly using mechanical stirrer for 2 min. Then, the samples were labelled as M1 to M16 and the platform made from polystyrene, were used as surface foundation for the developed cool-pavement coating materials. The epoxy, mixed of resin to hardener at ratio of 1:1 by weight, was poured and spread evenly onto the sample polystyrene platform, size of 150 mm × 150 mm at the rate of 1.2 kg/m^2 or equal to 0.0027 kg. Then, prepared mix-tile aggregates in the beaker was spread evenly on the top of epoxy layer, accordingly, and labelled as M1 until M16. The roller compactor with weight of 20 kg was applied to make sure that the mix-tile aggregates stick strongly to the epoxy and polystyrene platform. Then, all samples were placed properly and left for hardened for two hours under sunlight. Finally, the residual materials were then removed and the measurement of surface reflectivity (albedo) was carried out 7 days later.

2.3. Experimental setup

Surface reflectance of the samples were measured using Field Spec-Spectrophotometer (Analytical Spectral Device), as shown in Fig. 1, which can capture the surface reflectivity of the samples within the wavelength of 350 nm to 2500 nm. However, for this study, the wavelength used was between 700–2000 nm, which is the wavelength for the near infrared region (NIR) of solar radiation.

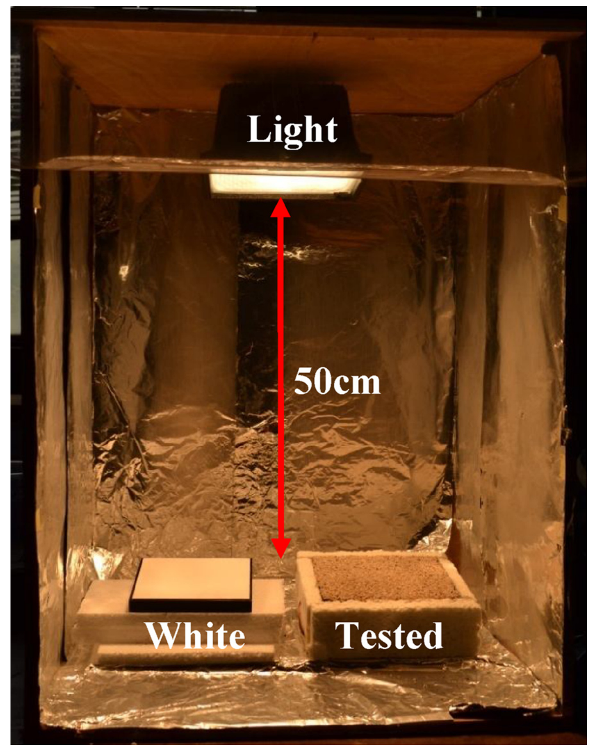

Fig. 2. Setting-up samples for measurement of surface reflectance.

The source of light to simulate the sunlight was generated using iodine tungsten lamp of 500W, which was located 50 cm above the sample [31], as shown in Fig. 2. In order to obtain accurate result, the reflectance data were taken at five point on the surface of the tested materials, and 10 reflectance data were taken for each of the point. Final value of the NIR reflectance is the average value of the reflectance data obtained for all the five measured point.

Further experiment of surface temperature measurement was performed for optimized samples based on actual weather condition in tropical climate. Surface temperature of all optimized samples were measured on a 24-h period for at least 6 days continuously of hot and sunny day weather condition. The surface temperature was taken by using thermocouple type T (Model TT-T-24), which are connected and recorded by data logger (Graphtec 220). Surrounding ambient temperature was taken at 1.5 m above the ground using HOBO U12 data logger (Model U12-011). The solar radiation intensity was measured simultaneously using pyranometer (MS-602), which is important parameter as to confirm that condition of weather during experiment are hot and sunny throughout the day.

Table 2
NIR reflectance value for tested samples.

Sample	Materials Composition (%)			Response
	Full Body Porcelain	Monoporosa	Porcelain Glaze	NIR Reflectance value
M1	0.00	100.00	0.00	0.51
M2	16.67	16.67	16.67	0.42
M3	0.00	100.00	0.00	0.55
M4	66.67	33.33	66.67	0.50
M5	16.67	66.67	16.67	0.47
M6	50.00	0.00	50.00	0.42
M7	100.00	0.00	100.00	0.49
M8	50.00	50.00	50.00	0.52
M9	100.00	0.00	100.00	0.49
M10	0.00	50.00	0.00	0.43
M11	0.00	50.00	0.00	0.46
M12	0.00	0.00	0.00	0.36
M13	66.67	16.67	66.67	0.49
M14	33.33	33.33	33.33	0.44
M15	0.00	0.00	0.00	0.35
M16	50.00	0.00	50.00	0.43

3. Results and discussion

3.1. Respond value of NIR reflectance

The three types of design expert software used in the experiment for optimizing the design are D-Optimal, A-Optimal, and IV-Optimal. Among which, D-optimal proved to be the most effective method to obtain the optimal composition of mix-tiles aggregate to achieved one respond, which is NIR reflectance value. The value of responds that obtained from experiment is shown in Table 2. Initial observation through the data found that all duplicated samples gives values that close to each other, which mean that experimental work has been done properly. However, these results will be discussed further for statistical analysis.

3.2. Analysis of NIR reflectance of tested samples

The NIR solar reflectance, as one of the response that was considered for the optimum design of the experiment and a linear model has been selected and fitted to the experimental results using Stat-Ease Ver. 7.0. The transformation was not required in order to provide the best fit for the result. The equation obtained to predict NIR reflectance of the given model is expressed as below:

$$\text{NIRReflectance} = (0.49 \times \text{A}) + (0.53 \times \text{B}) + (0.36 \times \text{C}) \quad (1)$$

where A, B and C represent the composition of FBP, MP tiles, and PG tiles, respectively.

From the diagnostic section, predicted NIR reflectance versus actual NIR reflectance was plotted as shown in Fig. 3. It was found that the model was successful in capturing the correlation between the mixture components with R-squared value of 0.9478. Adequate precision is the term used for measuring the signal-to-ratio and the value greater than 4 is desirable. The adequate precision for this model is 28.937, which is high and indicates adequate signal and implies the adequacy of the model used to navigate the design space.

The contour and 3D surface of the standard error of the design is shown in Fig. 4, which denotes that standard error of design, which is the root mean square error, is relatively small, ranging between 0.004 and 0.007. Furthermore, the almost uniform precision design has been achieved, which means that the error within the region is almost uniform and in addition, the data prediction in this region is good.

3.3. Analysis of variance (ANOVA)

The model fitness and significance can be performed with ANOVA test, using Stat-Ease Ver. 7.0 and the result is presented in Table 3. The F-value was use to compare the variation of the differences in the average responses at the design points, and the corresponding estimated responses using linear model, with the expected experimental variation as estimated from replicated design points. The model used for NIR reflectance showed F-value as 118.00, which means the model is significant.

The *p*-value (Prob> F) implies the probability of achieving the F-value. When the obtained value is less than 0.05, it means that there is a statistically significant difference between the means, while no difference between the means when the value is greater than 0.10, which is supported by [37]. The results in Table 3 summarize that the overall model *p*-value is less than 0.0001, which means the model is very significant.

3.4. Diagnostic test of the samples

The diagnostic test is use to analyse the model graphically and one of the diagnostic tools used in the experiment is normal plot of the residuals, as shown in Fig. 5. The point in the graph followed a straight line which means that the residual followed a normal distribution and the change in transformation would not improve the analysis.

The second diagnostic tool used was Box-Cox Plot to confirm this criterion as seen in Fig. 6. None transformation is suggested for this model since the ratio of maximum to minimum for the response shown in Table 1 is 1.57143, which is less than 10. Usually, transformation is required when the ratio of max to min is greater than 10 and thus no transformation is needed even the Box-Cox Plot is showing the best lambda value suggested to be as 0.48.

3.5. Effect of tile composition on NIR reflectance value

The results shown in ANOVA test for the linear model as in Table 3, indicate that all the parameters of the equation are significant and affects the NIR reflectance value, which is supported by the higher F-value for linear model. The linear equation of the model as suggested in Eq. (1) for linear term of A, B, and C represent the types of tile in having positive effects on increasing the NIR reflectance value and the coefficient for each of the materials are shown to be positive. Thus, it is clearly seen that the increase

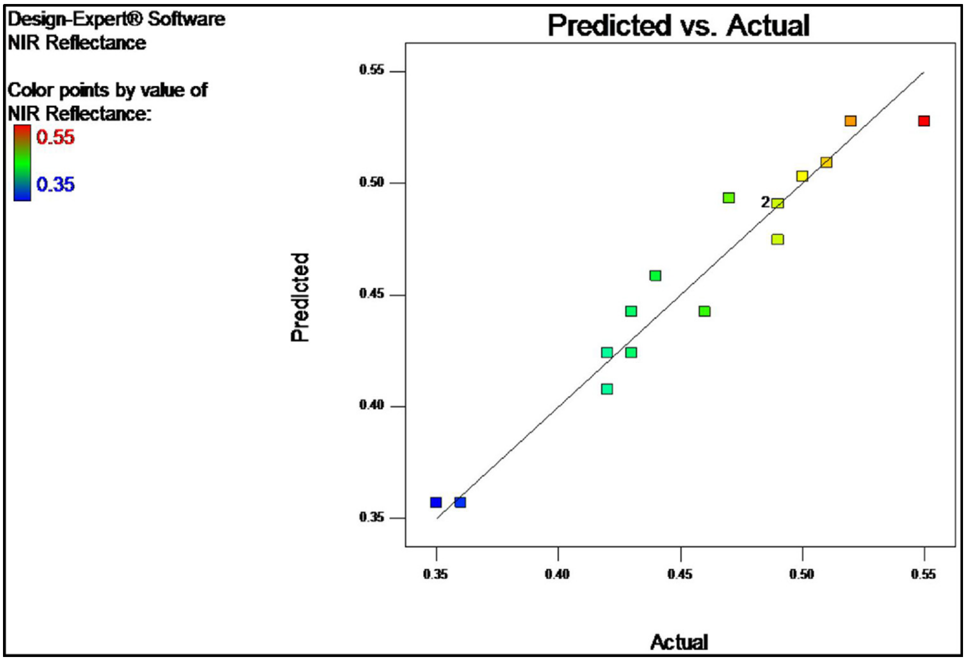

Fig. 3. Predicted NIR reflectance versus actual NIR reflectance.

Table 3
The ANOVA table.

Sorce	Sum of Squares	df	Mean square	F value	p-value Prob >F	Remarks
Model	0.044	2	0.022	118.00	<0.0001	Significant
Linear mixture	0.044	2	0.022	118.00	<0.0001	Significant
Residual	0.002404	13	0.0001849			
Lack of fit	0.002404	8	0.0001755	0.88	0.5870	Not significant
Pure error	0.0010	5	0.0002			

of each parameter would certainly affect the NIR reflective value (Fig. 7).

The effects caused by the simultaneously change of the parameters is presented using three-dimensional surface plot of the model, as shown in Fig. 8. When the percentage of MP increased from 0 to 100% with the fixed amount of FBP and PG, the NIR reflectance value increased constantly to 50% and it was also observed that by increasing the percentage of FBP the NIR reflectance value increased up to 50%. However, PG with the increasing proportion of material composition showed decrease in NIR reflectance of 0.35.

3.6. Optimization of mix composition of tile aggregate as coating materials with high NIR reflectance value

The outcome of this study was to determine the optimum amount of each tile to be used as coating material for cool-pavement that contains higher albedo or surface reflectivity. The optimization of these mix materials is presented in Table 4. All the factors goal, in this case proportion of tiles were set as "within the range" and the response as "maximize", together along with their higher and lower limits, which were required for the optimization of process as shown in Table 4. The model provided two solutions for mixing in order to achieve highest reflectance value, with solution 1, suggesting that in order to achieve maximum reflectance value, which is 0.53, the amount of full body porcelain, MP and PG to be used are 0%, 100% and 0%, respectively, with the desirability of 0.888. As per solution 2 in order to achieve the reflectance value of 0.51, the material composition required is 50% of full body porcelain tile aggregate, 50% of MP tile aggregate and 0.0% of PG tile aggregate as per the desirability value of 0.796.

Table 4
Summary of numerical optimization results.

Parameter	Goal	Experimental Range		Optimized Condition
		Lower	Upper	
Solution 1				
% of Full Body Porcelain	In range	0.0	100.0	0.0
% of Monoporosa	In range	0.0	100.0	100.0
% of Porcelain Glaze	In range	0.0	100.0	0.0
NIR Reflectance, %	Maximize	0.35	0.55	0.53
Solution 2				
% of Full Body Porcelain	In range	0.0	100.0	50.0
% of Monoporosa	In range	0.0	100.0	50.0
% of Porcelain Glaze	In range	0.0	100.0	0.0
NIR Reflectance value	Maximize	0.35	0.55	0.51

3.7. Surface temperature measurement of optimized samples

Surface temperature of asphalt samples with optimized surface coating material (as proposed Solution 1 and Solution 2 in Table 4), together with control asphalt sample (without coating) were measured to confirm effect of NIR reflectance toward reduction of surface temperature. The composition of mix tile for tested samples, together with control sample are summarized in Table 5.

Further analysis of the thermal behaviour of the developed materials then focused by considering the continuous six selected days for a totally hot and sunny day. In this study, 6 days of temperature data, starting from 17 Oct 2013 until 22 Oct 2013, was selected to since during measurement, weather are recorded as hot and sunny day condition. The results from 17 Oct 2013 until

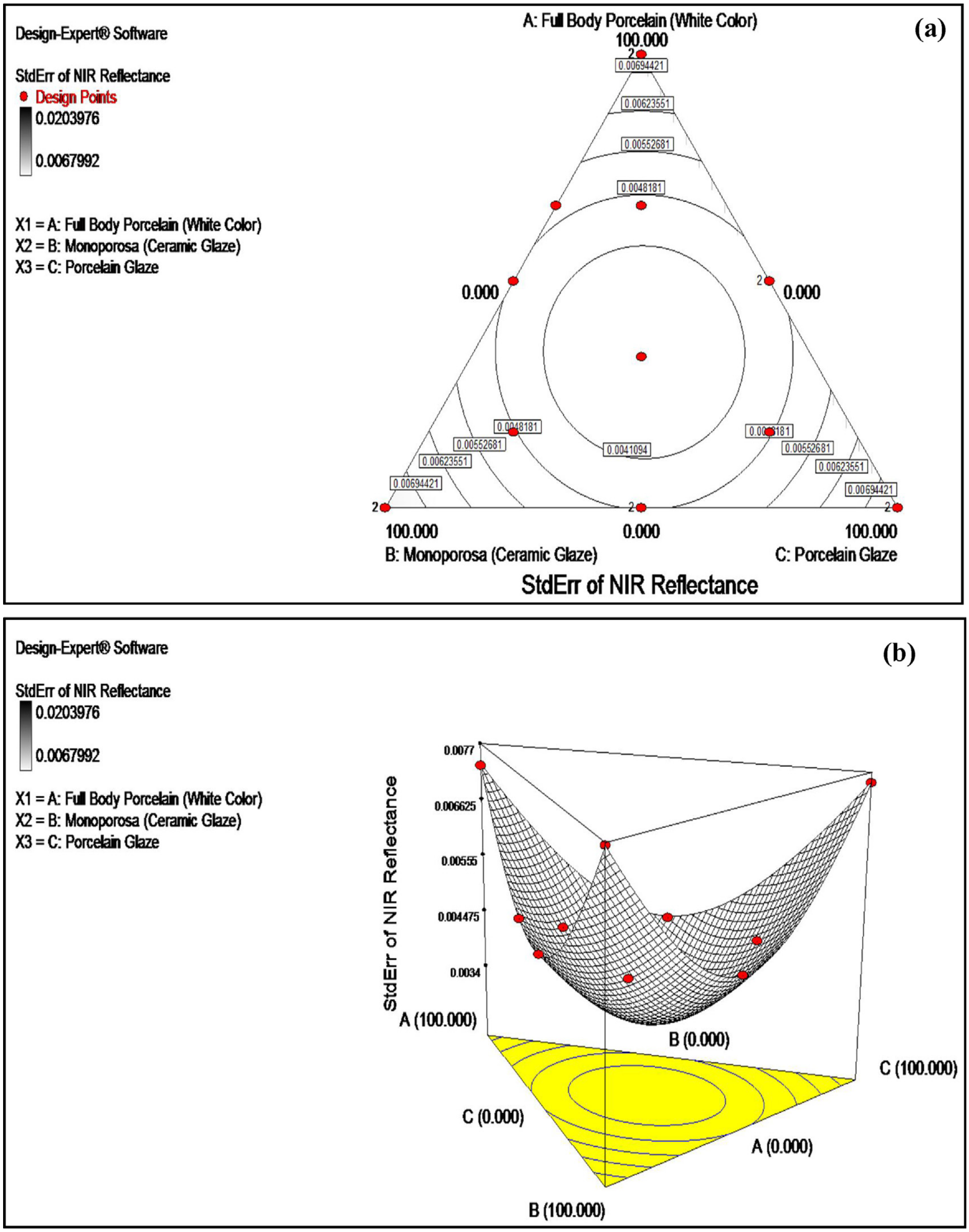

Fig. 4. (a) Contour plot for standard error. (b) 3D surface contour of standard error.

Table 5
Summary of mix tile proportion for tested samples.

Model	Mix Tile Composition (%)		
	Full Body Porcelain	Monoporosa	Porcelain Glaze
M1	50.00	50.00	0.00
M2	0.00	100.00	0.00
M3		Control asphalt sample	

22 Oct 2013 is plotted in Fig. 8. Early in the morning, the surface temperature for all the models shows to be very close to each other, including the uncoated surface asphalt sample, M3 as control. When the sunrise started, at 07:00 h. the intensity of the solar radiation increased over time and heating of the model surface caused the surface temperature of the models to increase.

The surface temperature of each model started to show difference among each other. It is clearly shown by the control sample, at faster rate of increasing surface temperature, it can achieve much higher temperature than other coated models. From Fig. 8, all the optimized samples with coated surface shows that the maximum surface temperature achieved were less compared with uncoated control sample, which showed maximum surface temperature above the threshold of 58 °C during the period of peak solar intensity, between 12:00 h. to 15:00 h. The intensity of solar radiation started to reduce at 15:00 h., which caused the surface temperature of the models to decline. The gradient of declination

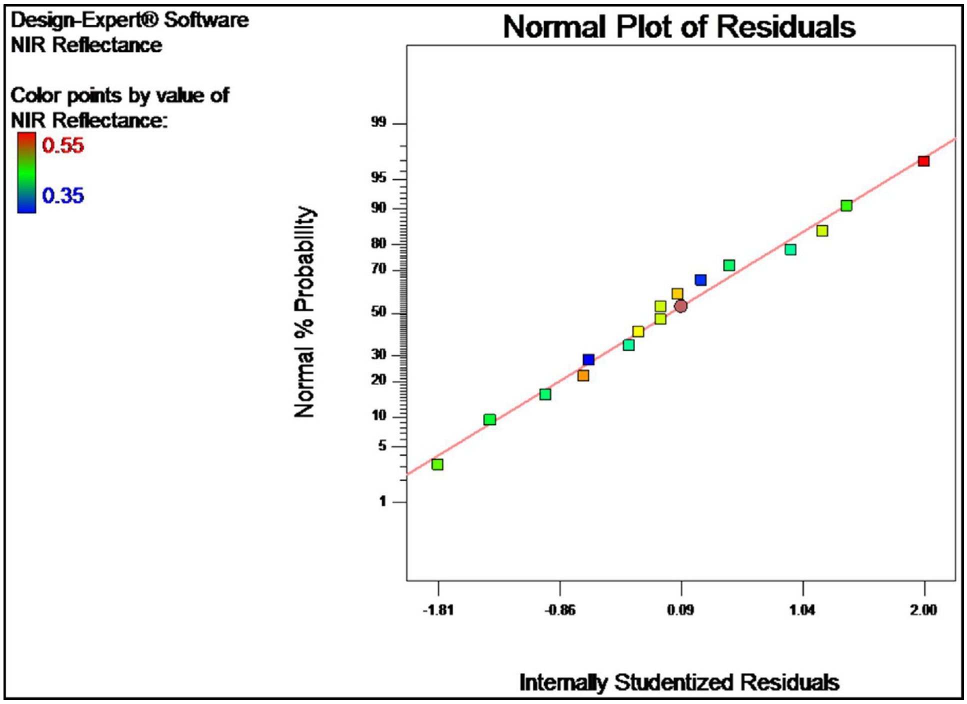

Fig. 5. Normal plot of residual for respond value.

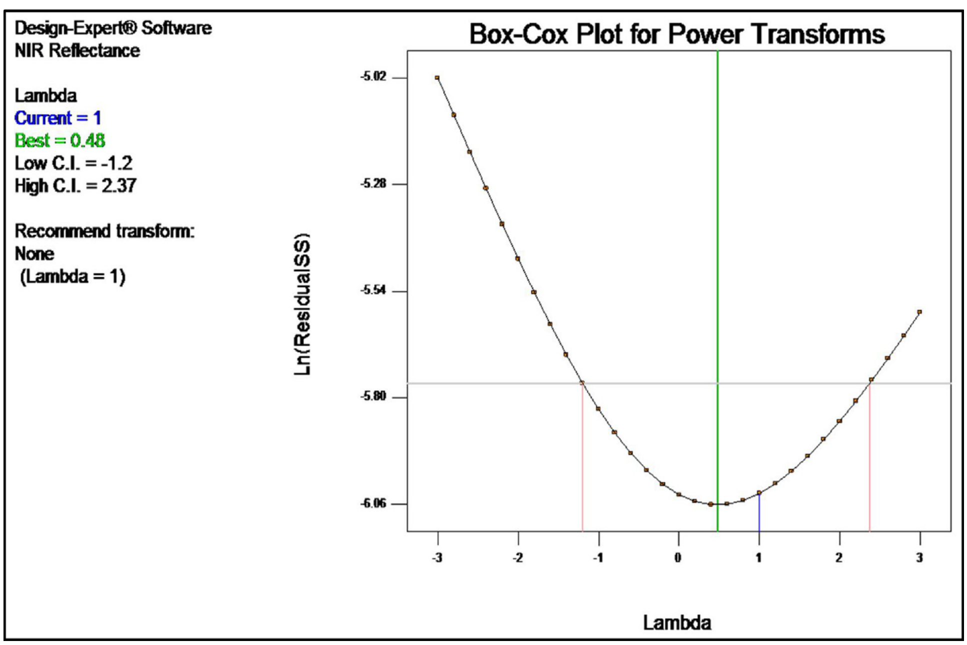

Fig. 6. Box-Cox plot diagnostic for power transformation.

of the surface temperature were found to be constant until the sunset, around 18:00 h. It is observed from the graph that the surface temperature of the models could drop and can become cooler than the ambient temperature after the sunset and this pattern occurred until the next morning of sunrise, which is also known as the nocturnal condition, where no source of energy is being supplied by the sunlight. Another clear information from the graph that differentiate the thermal behaviour between daily and nocturnal is the gradient of the temperature profile for each of the parameters, including surface temperature and ambient temperature.

Summary of mean maximum surface temperature of tested samples during peak solar intensity period (12:00 h–15:00 h) is shown in Table 6. From Table 6, it clearly shows all coated samples (M1-M2) have lower surface temperature compared with uncoated control sample M3.

Mean surface temperature for each of coated samples (M1 and M2) were compared with control sample, M3 and difference of surface temperature were calculated by using Eq. (2).

$$\Delta T = T_{mean\ \ \max(control\ \ sample)} - T_{mean\ \ \max(coated\ \ sample)} \quad (2)$$

The highest reduction of the surface temperature is recorded by model M1, which is combination of 50% FBP and 50% MP, with the reduction value range between 4.3 °C to 9.6 °C. Then it was followed by the 100% of MP tile aggregate, which is denoted as M2

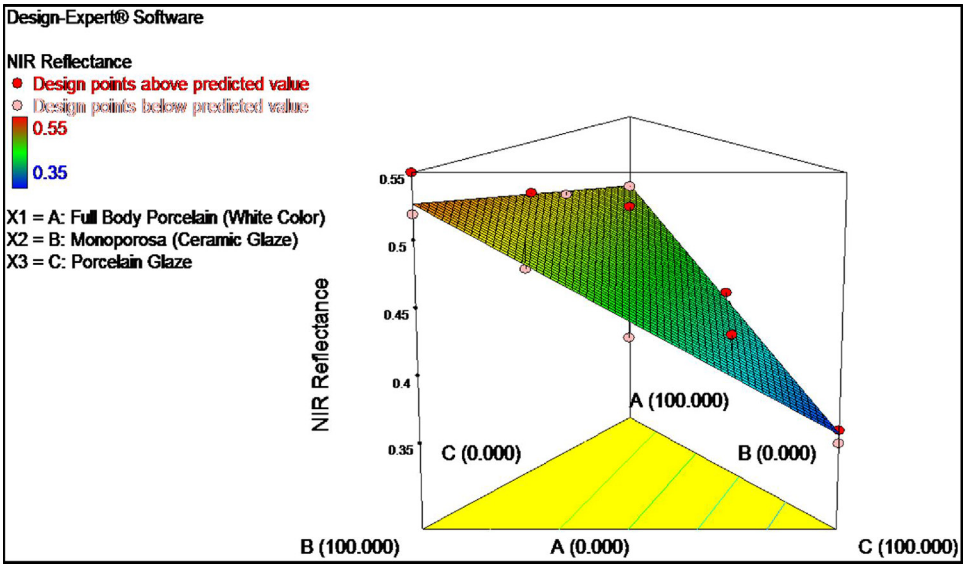

Fig. 7. 3D surface of the predicted NIR reflectance.

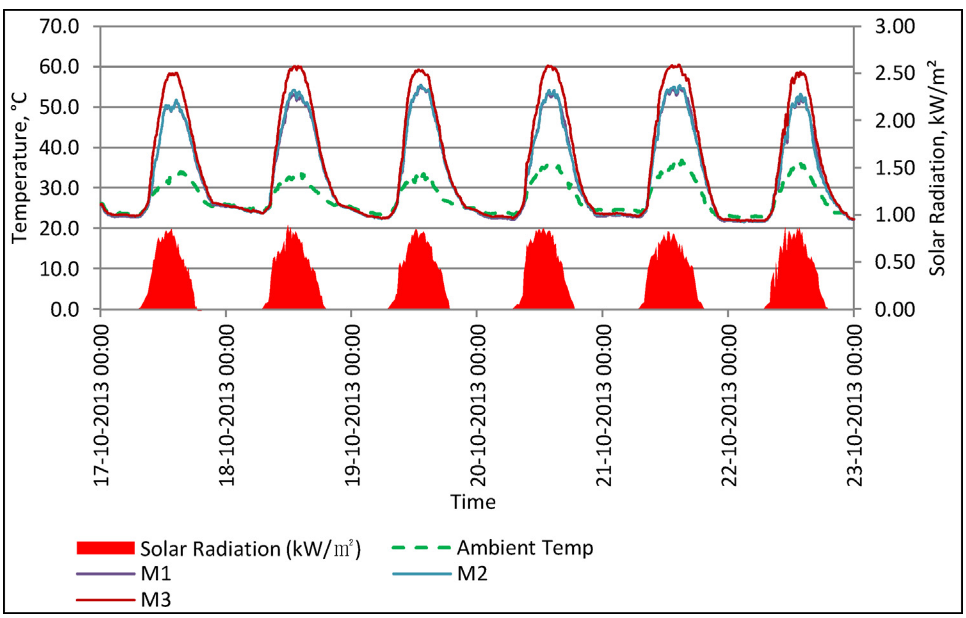

Fig. 8. Surface temperature profile of tested samples for continuous hot and sunny day condition.

Table 6
Summary of mean surface temperature of tested samples at peak solar intensity period.

Date	Mean Maximum Surface Temperature (°C)		
	M1	M2	M3 (Control)
17/10/2013	49.9	50.1	57.3
18/10/2013	52.2	52.9	59.4
19/10/2013	54.0	54.2	58.3
20/10/2013	51.9	52.3	58.7
21/10/2013	53.9	54.4	59.7
22/10/2013	51.0	51.3	57.5

with the reduction of surface temperature between 4.1° to 9.2 °C. Through these obtained results, it clearly shows that the optimum mix design as proposed by statistical model, sample M1 and M2 can reduce the surface temperature of the ordinary asphalt pavement. The results of temperature reduction provide positive correlation with NIR reflectance that achieved by optimized samples. Coating material with high NIR reflectance has good ability to reflect high amount of incoming heat energy from sunlight radiation at near infrared region, thus significantly reduce surface temperature of asphalt pavement. Surface that has high reflectivity in NIR region could provide good thermal comfort as near-infrared rays does not raise skin temperature in human body [38,33].

4. Conclusion

The component of developed coating material included three different types of tiles that were optimized by optimal mixture DOE using Stat-Ease 7.0, where 16 runs have been suggested by the software. The model was verified statistically and the ANOVA test concludes that the proportion of each type of tiles have significant effect on the NIR reflectance value. No transformation was required for the model and even the Box-Cox Plot suggest that the lambda value should be 0.48 as to improve the model, since the ratio of max to min for the response is less than 10. The optimum proportion of each type of wasted tiles that provided highest NIR reflectance was determined. The model suggested two solutions for achieving highest reflectance value which was by using 100.0% MP provided 0.53 NIR reflectance and with the combination of 50% of FBP, 50% of MP as the reflectance value achieved was 0.51%. The addition of PG type of tile reduced the NIR reflectance value according to the model. Measurement of surface temperatures of optimized samples shows that increasing NIR reflectance of asphalt surface could significantly reduce its surface temperature at range between 4.1 °C–9.6 °C. This values of surface temperature reduction could improve thermal comfort of surrounding area. Therefore, as a conclusion, the optimization by DOE can be considered as significant tool that provide reliable results and outputs for optimizing different types of mix-tile aggregate to achieved maximum NIR reflectance in application of cool pavement coating material.

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