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Field and laboratory measurement of albedo and heat transfer for pavement materials

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HIGHLIGHTS

- Investigated factors affecting field measurement of pavement albedo.
- Developed a new albedometer for laboratory measurement of albedo.
- Measured albedo and internal temperature of pavement materials exposed to solar radiation.
- Evaluated cooling effect of reflective coating for asphalt mixture.

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ABSTRACT

Albedo is an important indicator of the radiation reflectance of pavement surface and commonly measured using the field albedometer. In this study, factors affecting the field measurement of albedo including solar radiation intensity, incident angle and surrounding conditions were investigated. A new albedometer for laboratory testing of albedo and internal temperature at different depths in compacted asphalt mixture/Portland cement concrete (PCC) slabs was developed to overcome the negative effects of field measurements. Laboratory measurements of albedo were performed on three types of asphalt mixture (e.g. AC-13, SMA-13 and OGFC-13) and PCC with different surface textures using the developed albedometer. Three types of coating materials were prepared by mixing base material of transparent epoxy glue and the filler of Nano-TiO_2, Micro-TiO_2 and Nano-ZnO, respectively. The albedo and internal temperature of asphalt mixtures with coating materials were also measured and compared to those without coating materials. Results show that the developed laboratory albedometer can synchronously measure the accurate albedo and internal temperature of pavement materials. The albedo of three types of asphalt mixtures have a range of 5.46%–6.11%, while the albedo of PCC with different surface textures ranges from 22.8% to 26.4%. The gradation of asphalt mixture has little impact on the albedo. Rougher PCC surface reflect less solar radiation and produce a higher internal temperature. The filler of Micro-TiO_2 in pavement coating has the better reflectance than Nano-TiO_2 and Nano-ZnO.

1. Introduction

A large percentage of urban areas is covered with a high density of pavement including streets, parking areas, sidewalks, squares and playgrounds, and this proportion is expected to further increase [1,2]. When the pavement is exposed to the solar energy emitted by the sun, some of total solar radiation on pavement surface is reflected back into the air, and some is absorbed by the pavement, which will lead to temperature rise in the urban pavement and higher temperatures of urban area than that of rural area [3]. The temperature difference between the rural and urban area are a phenomenon known as the Urban Heat Island (UHI). Although the UHI can be affected by many factors, such as the population and population density of the urban area, spacing and height of buildings, heat generated by vehicles, vegetative cover and geographic location, the albedo of pavement surface is considered to be the main factor that can significantly influence the UHI. Albedo is the ratio of reflected solar radiation to the total solar on a surface and is considered as an indicator of the reflecting power of pavement surface [4]. An albedo of 0 means no reflecting power of a perfectly black surface (none reflected, all absorbed), an albedo

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of 100% means perfect reflection off a perfectly white surface. The relatively lower albedo and subsequent more thermal energy storage in pavement tend to generate more severe UHI effect [5–7]. In addition, the higher temperature due to the lower albedo is also considered as an important reason for the permanent deformation (rutting, pushing and shoving) of asphalt pavement in summer. Studies have shown that the viscosity and complex modulus of asphalt binder, and the dynamic stability of asphalt mixture decrease significantly with the increase of temperature due to the low albedo [8–11].

There are two methods reported in literatures to measure albedo of pavement materials: laboratory testing and field testing. Laboratory testing is conducted using a spectrophotometer, to obtain the spectral reflectance which is an approximate estimate of albedo as per ASTM E903 [12]. While field testing is performed using an albedometer (also called a double pyranometer) as per ASTM E1918 [13], which gives an accurate value for the location but is strongly dependent on weather conditions. Pomerantz et al. (2003) compared laboratory and field measured albedo of Portland cement concrete (PCC). The laboratory measured albedo of concrete with different mix proportions ranges from 0.33 to 0.45. While, field measurements of albedos show a range from 0.18 to 0.35, with an average of 0.26, which is lower than the average value of laboratory results. The reason for the difference between laboratory and field measured albedo may be the surface texture of the specimen cutting section in laboratory testing is quite different from those of pavement surface [14].

Considering that field measurements using the albedometer give a more accurate albedo of pavement, Pomerantz et al. (1997 & 2000) used the albedometer to measure the albedo of PCC and chip seals using light colored aggregates [15,16]. Wong et al. (2009) measured the albedo of three types of coatings materials under different wavelengths and compared the temperature at pavement surface with different coatings in Singapore [17]. In addition, Del Carpio et al. (2016) investigated the albedo and temperature of 20 types of pavements in Brazil. [18]. Sen and Roesler (2016) conducted field measurements on a series of asphalt and concrete pavement test sections of varying ages in Rantoul, Illinois, USA and developed a non-linear aging albedo model for asphalt pavement [19]. However, Li et al. (2013) pointed that the field measured albedo changes over time under weathering and trafficking. Cloud cover negatively affects the value of albedo measured. The measured albedo is higher in the early morning and in the late afternoon than that measured in the mid-day [20].

Over the years, besides the comparison of albedo among different types of pavements, the reflective surfaces known as 'cool' pavement surfaces were proposed for the mitigation of UHI, which mainly include thermochromic pavement with doped reflective pigments and reflective pavements with seal treatments. As for thermochromic pavement, Anak Guntor et al. (2014) prepared a type of cool asphalt mixture by replacing aggregate with some light-colored aggregates [21]. Compared with the traditional asphalt mixture, the cool asphalt mixture can be 4 °C lower at noon of a hot summer time. When incorporating thermochromic pigments to asphalt binder, it was found this binder stayed 6 °C cooler in summer time and about 3 °C warmer at cold weather, in comparison to normal asphalt binder [22]. Similarly, adding thermochromic pigments to cement paste can keep 4–6 °C cooler at hot weather and keep 2–3 °C warmer at low temperature environment, compared to normal concrete paste [23]. However, impregnating thermochromic material in concrete may decrease the strength of the concrete [23,24]. In addition, although thermochromic materials have been marketed [25], their prices are still very high, which significantly limits the use of these materials especially in pavement engineering.

As for reflective concrete pavements, Santamouris et al. (2012) reported an application of 4500 square meters of concrete blocks of light yellow color in an urban park in the greater Athens area. It is found that the extensive application of reflective pavements may reduce the peak daily ambient temperature up to 1.9 °C and surface temperatures are reduced up to 12 °C during a typical summer day [26]. According to Boriboonsomsin and Reza (2007) and Marceau and Vangeem (2008), the pozzolanic additive slag increases the albedo of concrete while fly ash decreases albedo [27,28]. As for reflective asphalt pavement, the albedo of chip seal pavement is found decrease with age but remain higher than that of standard asphalt concrete for about five years [29]. Painting with light-colored paint or microsurfacing with light-colored materials also increase the reflectance of asphalt pavement substantially [30].

Besides the chip seal and light-colored coating, nonwhite pigments with high reflectance of near-infrared light are recently developed to coat pavement to reflect more near-infrared light than white pavement. Kinouchi et al. (2004) developed a new pavement to satisfy both high albedo and low brightness with the innovative paint coating [31]. The average reflectivity was 83% for the near infrared (750–2100 nm wavelength) and 20% for the visible (350–750 nm). The maximum reduction of surface temperature from the conventional asphalt pavement was about 15 °C in Tsukuba and more than 17 °C in Okinawa. Nishioka et al. (2006) compared the temperature of pavement surface using materials including Blue Impala polished granite (BIPG), Rosa Tanggo polished granite (RTPG), Fontana concrete (FC), and asphalt (AS) in three different environments namely open space (OS), near water (NW), and under shade (US). BIPG was 15.5 °C cooler than AS during 12:00 $\sim$ 15:00 in OS locations. However, BIPG and RTPG surface temperatures increased in NW locations as compared to OS and US locations from 12:00 to 18:00 [32]. Wang et al. (2013) developed an overlay composed of acrylic or epoxy resin filled with nano TiO_2 or nano $TiNO_2$. The surface temperature of asphalt pavements deceases by about 10 °C when the pavement temperature is about 60 °C [33]. According to Cao et al. (2015 & 2016), asphalt pavement sprayed by the emulsion composed by TiO_2 with the particle size of 200 $\sim$ 1000 nm has an excellent cooling effect and aging of the emulsion coating has an obvious reduction on the cooling effect [34,35].

It was concluded from the literature review that: (1) although the field measurement using the double pyranometer gives a more accurate albedo of pavement than the spectrophotometer testing in laboratory, the field conditions including the intensity of solar radiation, the incident angle and cloud cover have potential impacts on the value of albedo. It is essential to investigate the influence of field conditions on the measured albedo and develop a new laboratory testing system of albedo on the basis of the double pyranometer to avoid the negative effect of field conditions; (2) although many types of coating materials were proposed recently, the measurement of albedo have mainly focused on the pavement without coating. Comparison of the albedo among different coating materials is needed to pave reflective coating for the typical asphalt pavement surface; (3) the temperature measurement of pavement surface is separated from the albedo testing recently. Combining the albedo testing with the temperature measurement of different depth in pavement is extremely useful for better understanding the thermal properties of pavement materials.

2. Objective and scope

The objectives of this study are to: (1) obtain the effect of the solar radiation intensity, the height of double pyranometer, incident angle of solar radiation and surrounding environment of testing sites on the field measurement of albedo; (2) develop a new synchronous system for laboratory testing of albedo and temperatures at different depths in pavement slabs to overcome the defects of field measurement; (3) perform laboratory measurement of albedo and temperature on PCC and asphalt mixture slabs with different coating materials; and (4) compare the albedo and internal temperature for different materials to obtain the optimal coating materials (filler type and usage of coating).

3. Factors affecting the field measurement of albedo

3.1. Experimental equipment and plan

A double pyranometer was utilized to examine the factors affecting the field measurement of albedo, as shown in Fig. 1. The double pyranometer is composed of two pyranometers, in which one pyranometer faces upward and the other faces downward. The incident solar radiation within wavelength of 0.3 μm–3 μm is measured by the upward facing pyranometer and the radiation reflected from pavement surface is measured by the downward facing pyranometer. Separate outputs are provided for each pyranometer, which can be read separately from an indicator and recorded together using a computer.

According to Li et al. (2013), no impact of wind speed or air temperature on albedo is observed [20]. In this section, solar radiation intensity, height of pyranometer, incident angle of solar radiation, and surrounding conditions of the testing sites were chosen as the potential affecting factors of field measurement, as shown in Fig. 1. The incident and reflected radiation measurement was performed on pavement surface paved by asphalt mixture with the nominal maximum aggregate size (NMAS) of 13.2 mm (AC-13). A summary of the experimental plan is shown in Table 1. It should be noted that the incident angle in albedo testing is controlled by the testing time. In Table 1, the testing time (t_a) for incident angle of 25°, 70°, 110° and 155° is 7:20 am, 10:40 am, 1:42 pm and 4:48 pm on August 15th, 2018, respectively, which is calculated by the Eq. (1).

$$t_a = t_1 + \frac{12 - t_1 + t_2}{180} \cdot \alpha \tag{1}$$

where α is the incident angle of solar radiation (°), t_1 and t_2 is the time of sunrise and sunset on the test day respectively, which is 5:29 am and 6:49 pm on August 15th, 2018.

3.2. Effect of solar radiation intensity on albedo

The incident and reflected radiation of the asphalt pavement surface was measured respectively at mid-day (from 12:00 pm to 12:10 pm) on August 14th, 2018 (sunny) and August 15th, 2018 (cloudy) with the height of pyranometer of 80 cm. The results of radiation at every one minute were shown in Fig. 2. It can be clearly seen that the incident solar radiation intensity fluctuated violently even within ten minutes on both sunny and cloudy day. According to Liou (2002), the latitude, altitude and cloudiness are the main factors affecting the solar radiation reaching the ground or pavement [36]. In this study, the latitude and altitude of testing site are constant. Only cloudiness can be considered as the reason for the fluctuation of measured solar radiation. In addition, the low reflected radiation occurs with the low incident solar radiation and

Table 1
Experimental plan for field albedo measurement.

Solar radiation intensity	Height of pyranometer (cm)	Incident angle of solar radiation (°)	Surrounding environment
Change with clouds in air	20, 40, 60, 80	25, 70, 110, 155	Grass, soil

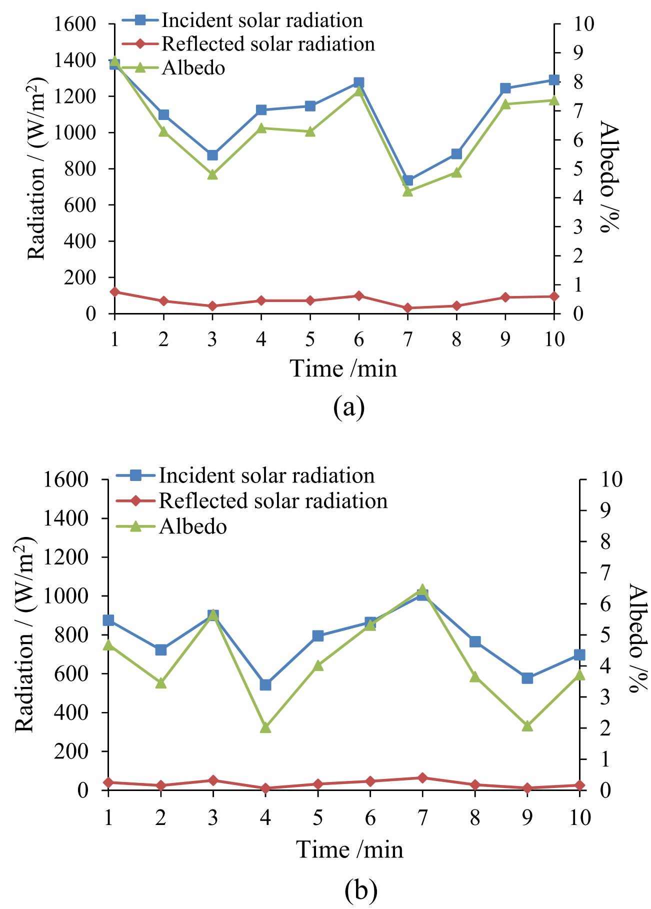


Fig. 2. Solar reflectivity within ten minutes on (a) sunny and (b) cloudy day.

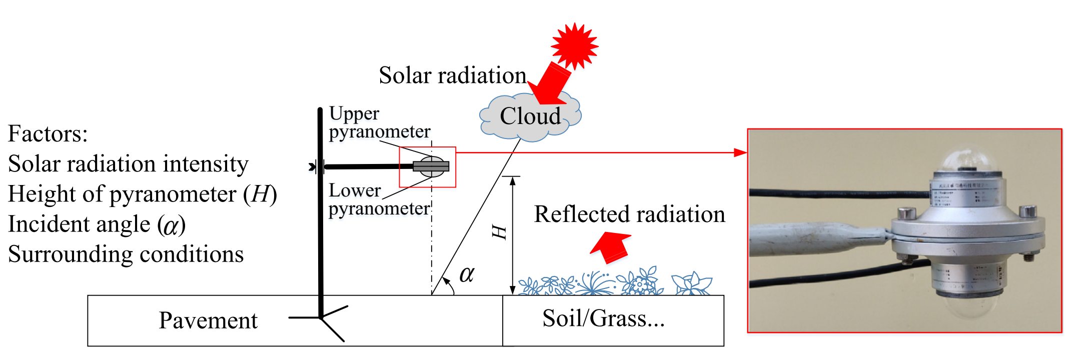


Fig. 1. Potential factors affecting field measured albedo of pavement.

the high reflected radiation occurs with the high incident radiation. On sunny day, the measured albedo decreased from 9% to 4% as the decrease of incident radiation from 1376 W/m^2 to 735 W/m^2 within ten minutes, while on cloudy day the albedo decreased from 6.5% to 2% as the decrease of incident radiation from 1005 W/m^2 to 543 W/m^2. This implies that the weather condition (cloudiness) has a remarkable effect on the value of measured albedo even on sunny days. A lower albedo will be given with the effect of cloud.

3.3. Effect of incident angle on albedo

The field measurement of incident and reflected radiation were performed at 7:20 am, 10:40 am, 1:42 pm and 4:48 pm respectively on August 15th, 2018 to examine the influence of incident angle on measured albedo within ten minutes. As shown in Fig. 3(a), as expected, the incident solar radiation at angle of 25° and 155° (measured at 7:20 am and 4:48 pm) ranging from 142 W/m^2 to 438 W/m^2 is much lower than that at the angle of 70° and 110° ranging from 450 W/m^2 to 1490 W/m^2. However, the reflected radiation measured at the angle of 25° and 155° are in the range of 19 W/m^2–83 W/m^2, which is close to the reflected radiation measured at the angle of 70° and 110° ranging from 15 W/m^2 to 110 W/m^2. A possible reason that cause this phenomenon is that the measured incident radiation was undervalued owing to the pyranometer not facing the sun with the small incident angle. This is proved by the Fig. 3(b), in which smaller incident radiation was observed under lower incident angle. This implies that the incident angle has effect on the measured albedo. A higher albedo will be given on the early morning or late afternoon.

3.4. Effect of pyranometer height on albedo

The solar reflectivity was measured on one testing site at four heights of pyranometer (e.g. 20 cm, 40 cm, 60 cm and 80 cm) respectively. For each height, the incident and reflected radiation were monitored over time within ten minutes, as presented in Fig. 4. As mentioned previously, the reflected radiation and albedo fluctuated over time with the fluctuation of incident solar radiation. Therefore, the average value within ten minutes was calculated and presected in Fig. 4. It can be seen that the average value of albedo measured with pyranometer height of 80 cm, 60 cm, 40 cm and 20 cm is 6.38%, 5.97%, 5.82% and 6.19%, respectively. There is no obvious relationship between the solar reflectivity and the height of pyranometer. This indicates that the pyranometer heights selected in this study have no effect on the measured value of reflected radiation and albedo.

3.5. Effect of surrounding conditions on albedo

It is expected that the surrounding people, grass and/or soil with different albedo will affect the measured value of pavement albedo. The influence of grass and soil nearby the testing sites on measured albedo was studied in this section. Fig. 5 gives the measured albedo of pavement sites with the distances of 20 cm, 30 cm and 40 cm from grassland and soil. The albedo of grass and soil was measured to be 22.0% and 30.1% at the incident radiation intensity

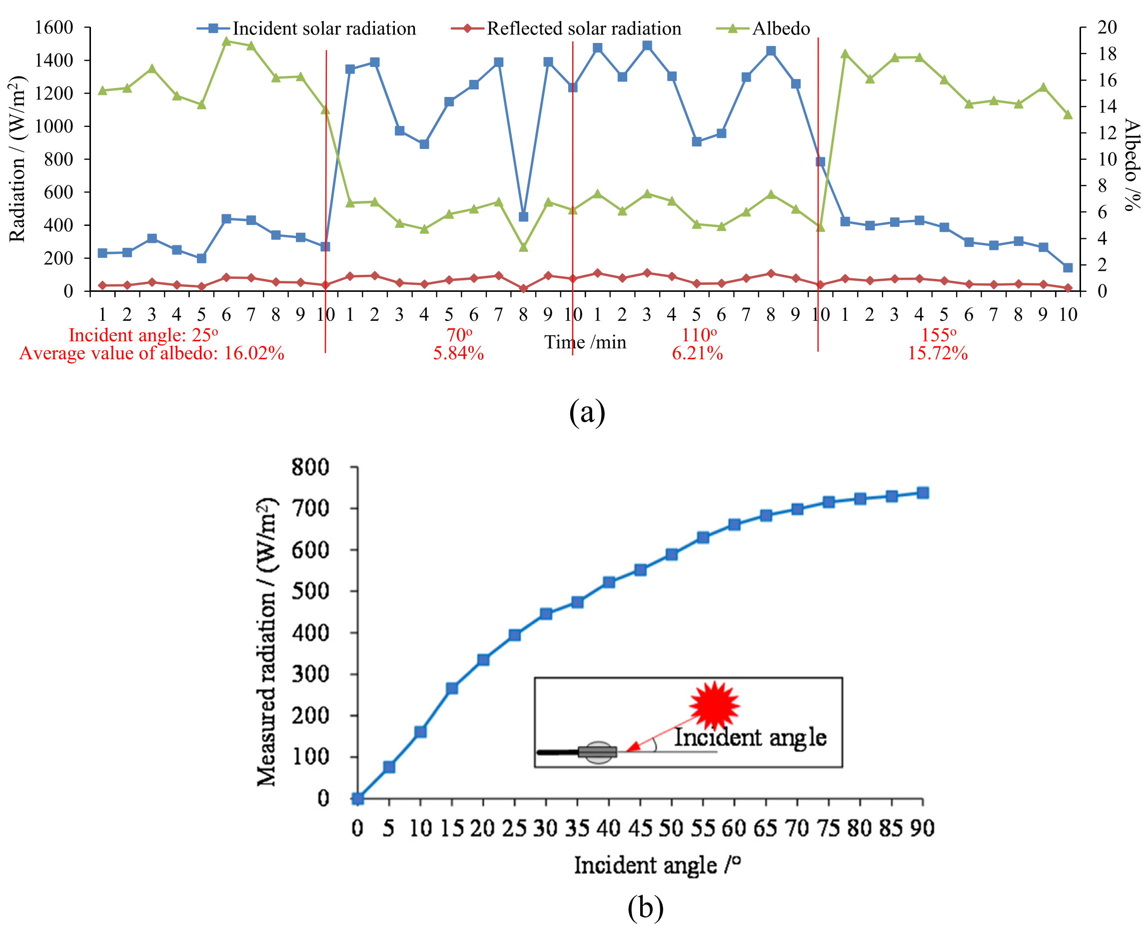


Fig. 3. Illustration of (a) measured solar reflectivity at different incident angles and (b) measured incident radiations under different incident angles.

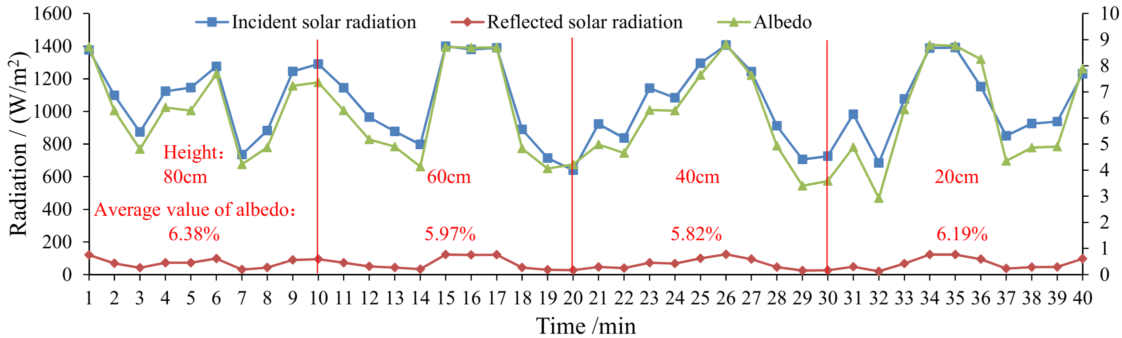


Fig. 4. Measured solar reflectivity at different heights of pyranometer.

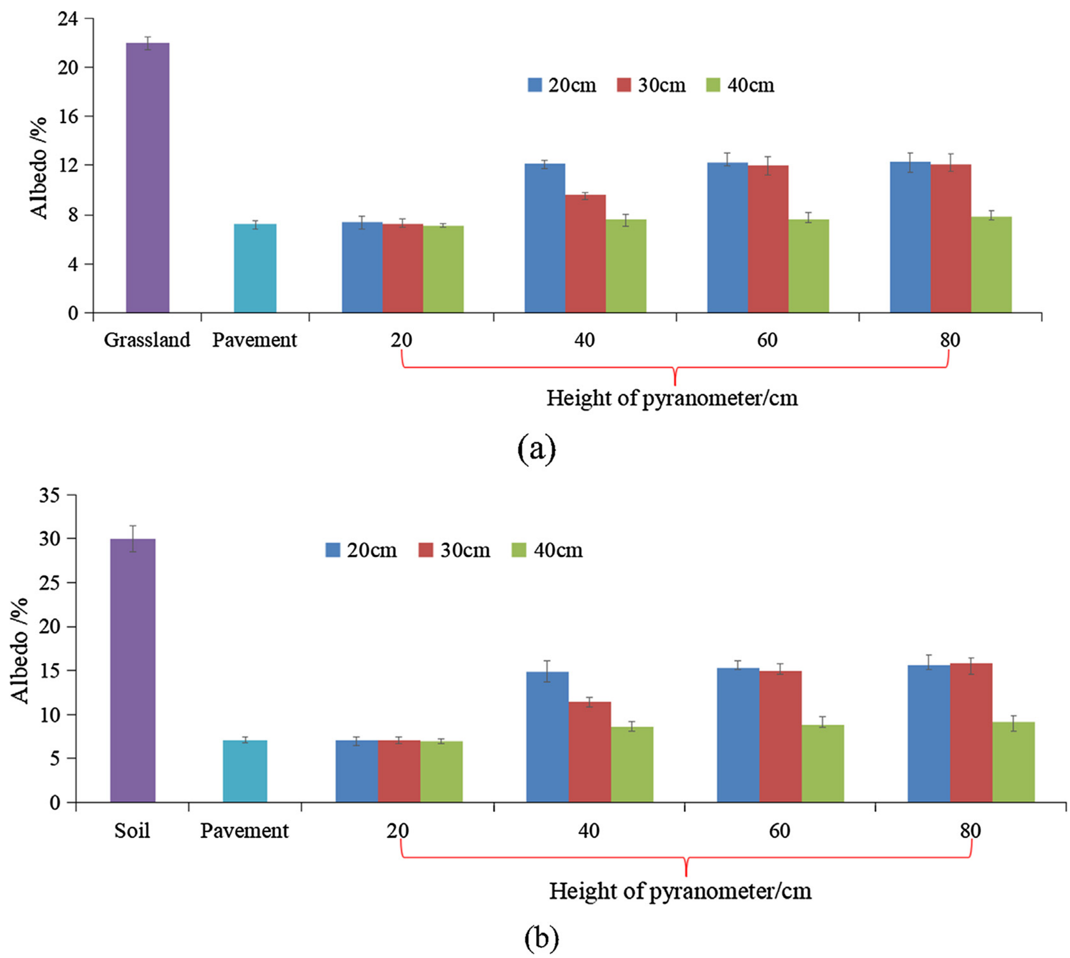


Fig. 5. Measured albedo of pavement with different distances from (a) grass and (b) soil.

of 1200 W/m^2–1250 W/m^2, respectively (also shown in Fig. 5). At the same height of pyranometer, the measured albedo of pavement increased as the decrease of the distance between testing site and the grass and soil. This proved that the surrounding grass and soil with different albedo affects the measured value of pavement albedo. Moreover, the measured albedo at the distance of 40 cm varies from 6% to 7%, which is close to the albedo of pavement measured without the effecting of surrounding grassland and soil. This implies that to avoid the effect of surrounding environment on accuracy measurement of albedo, the distance from the testing site to surrounding soil and grass must be longer than 40 cm.

4. Laboratory testing equipment, methods and materials

4.1. Laboratory measurement equipment of albedo and temperature

As mentioned above, solar radiation intensity, incident angle and surrounding conditions have effect on the accuracy of albedo in field measurement. In order to avoid the field factors affecting the measurement of albedo, a new albedometer was developed using the double pyranometer, as shown in Fig. 6. The developed albedometer includes three parts: radiation collector, slab specimen box and temperature measurement. Considering that most of the sun solar energy comes from the near infrared wave with

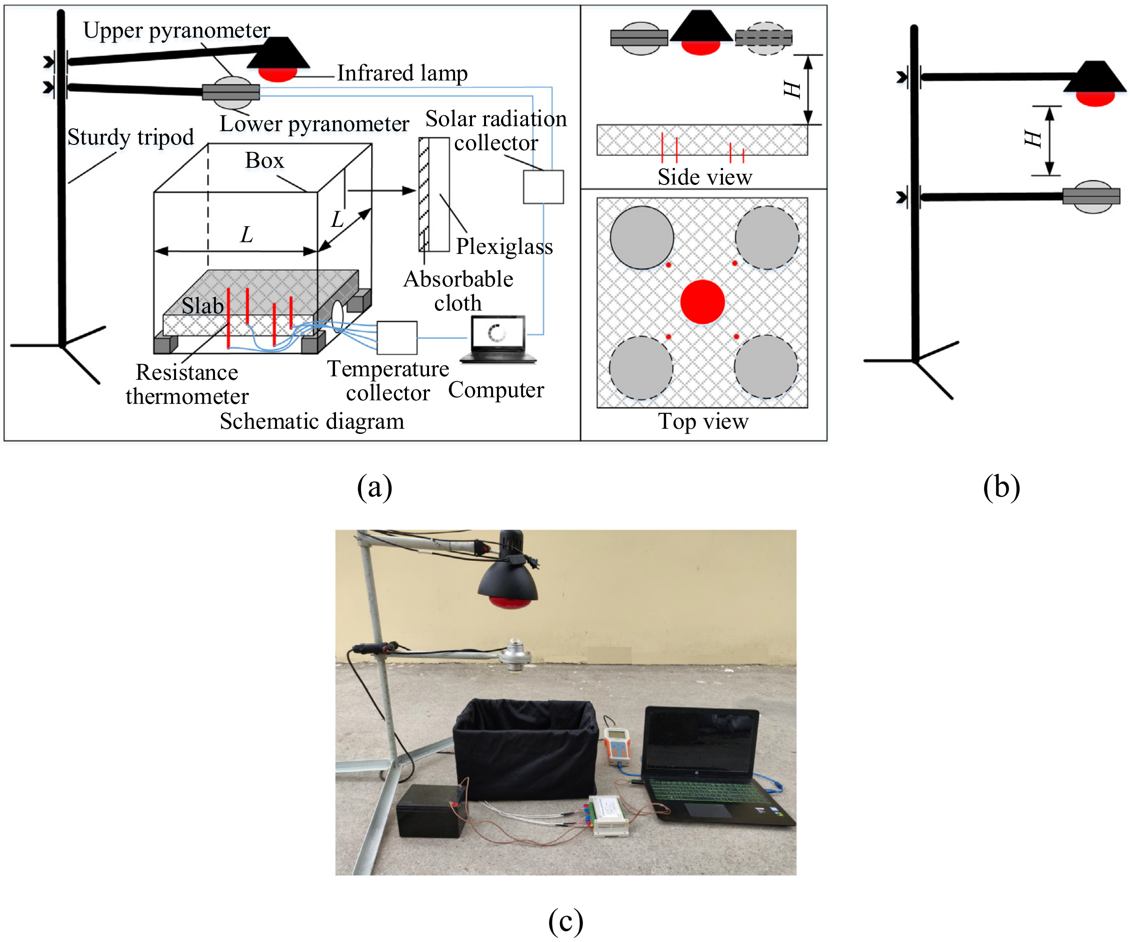


Fig. 6. Illustration of (a) measurement of reflected radiation, (b) measurement of incident radiation, and (c) customized equipment.

the length ranging from 0.75 μm to 3 μm, the infrared lamp with the wavelength of 0.3 μm– 3 μm was used to simulate the solar radiation. The double pyranometer composed of two pyranometers was also used to absorb the incident and reflected infrared radiation. The heights of both the infrared lamp and the double pyranometer and the horizontal distance between them can be adjusted in the sturdy tripod.

The specimen box is made of two-layer materials, in which the black cloth with high solar absorption is the inside material and the plexiglass is the outside material. With the developed albedometer, the albedo can be laboratory measured without the effect of solar radiation intensity, incident angle and surrounding conditions.

Another distinct advantage of the albedometer is that the internal temperature of specimen exposed to infrared radiation can be measured. For each slab specimen, four temperature sensors was embedded at the depths of 1 cm, 2 cm, 3 cm and 4 cm, as shown in the side view of Fig. 6(a), which will be introduced in the following section. The internal temperatures at four depths of the slab exposed to infrared radiation were read and recorded in the computer. To avoid the effect of floor on the temperature measurement, four heat insulating pads were placed at the corners inside the box.

Using the developed measurement equipment, the testing procedure includes the following steps:

(1) Placing the slab specimen embedded with four resistance temperature sensors on the four corner pads in the box. Adjusting the infrared lamp height to assure that the vertical distance between the infrared lamp and the slab surface is 20 cm. The double pyranometer with the same height of infrared lamp was held above one corner of the slab, as shown in Fig. 6(a).
(2) Reading the initial internal temperature at four depths of the slab. Turn on the infrared lamp and then the internal temperature was monitored every one minute.
(3) Reading the reflected radiation from the lower pyranometer every 30 s. After three minutes, the double pyranometer was moved to the position above another corner of the slab, as shown in top view in Fig. 6(a).
(4) Repeating step (3) for each corner of the slab. The reflected radiation of the slab is the average value of the monitored radiations.
(5) Removing the specimen box and then moving the infrared lamp and double pyranometer to assure that the vertical distance between them is 20 cm, as shown in Fig. 6(b). The incident radiation from the infrared lamp is measured by the upper pyranometer. The albedo (A) of the slab is calculated by the Eq. (2).

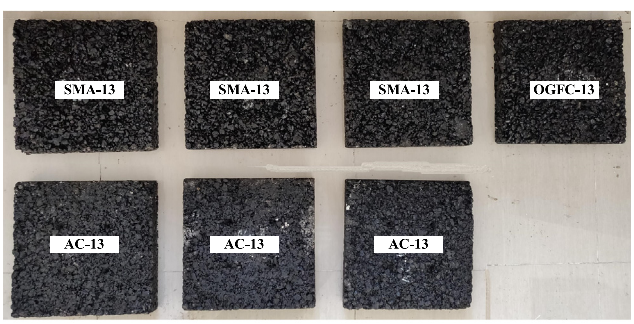
$$A = \frac{R}{I} \times 100\% \quad (2)$$

where R is the reflected radiation of the slab (W/m^2), and I is the incident radiation (W/m^2).

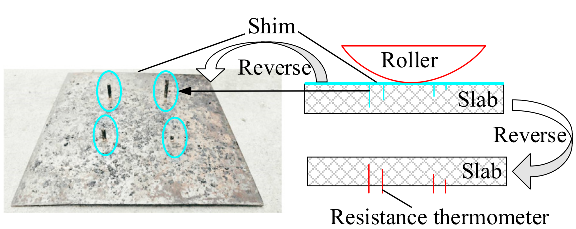
4.2. Preparation of pavement slabs embedded with thermometer

Seven asphalt mixture slabs, each with the side of 30 cm and thickness of 5 cm were prepared for the albedo and internal temperature laboratory measurements. In total, three slabs for asphalt concrete (AC) with the NMAS of 13.2 mm (AC-13), three slabs for stone matrix asphalt (SMA) with the NMAS of 13.2 mm (SMA-13), and one slab for open graded friction course (OGFC) with the NMAS of 13.2 mm (OGFC-13) were fabricated by using crushed basalt aggregate, limestone filler, and modified asphalt, as shown in Fig. 7(a). The aggregate gradation used in the three types of asphalt mixtures were shown in Table 2. The modified asphalt was prepared by mixing 90# base asphalt and 5.4% styrene-butadienestyrene (SBS), and its basic rheological properties were tested and listed in Table 3. The slabs of AC-13, SMA-13 and OGFC-13 were compacted using the roller compactor. During the compaction of each slab, a self-made shim (shown in Fig. 7(b)) was used under the roller to produce four holes with depths of 1 cm, 2 cm, 3 cm and 4 cm in the slab. The holes were reserved for the resistance thermometers to measure the internal temperature in the slab exposed to near-infrared radiation.

Three PCC slabs were also prepared for comparing the albedo and heat transfer with asphalt mixture. The sand ratio, water-cement (W/C) ratio and mix proportion of PCC were listed in Table 4. The self-made shim was pressed on the unhardened concrete slab to produce four holes with a depth of 1 cm, 2 cm, 3 cm and 4 cm, and the resistance thermometers were inserted into the holes immediately, as shown in Fig. 8. To investigate the effect of the surface texture on the albedo of PCC, one PCC slab was prepared without surface treatment to produce smooth surface, the other two slabs were surface-brushed using the steel brush twice and four times before the hardening of cement concrete to produce rough and very rough surface.



(a)



(b)

Fig. 7. Illustration of (a) AC-13, SMA-13 and OGFC-13 mixture slabs, and (b) preparation of asphalt mixture slabs.

4.3. Reflective coating materials

Reflective coating can be divided into two categories: solvent-based coating and water-based coating. Compared with solvent-based coating, the drying time of water-based coating is longer and its anti-abrasion performance is lower, which results in a relatively shorter life [2,16,21,33]. In this study, a type of solvent-based coating consists of epoxy glue and filler was used. The transparent epoxy glue is the two-component material (A and B) with the function of holding the filler particles together and providing the bond to substrate. Based on recommendations from the supplier of the epoxy glue, the mass ratio of A and B component was 3:1. The basic properties of A and B component, and the epoxy glue after curing were listed in Table 5.

Three types of fillers (Nano-TiO_2, Micro-TiO_2, and Nano-ZnO as shown in Fig. 9) with high infrared radiation reflectivity were employed and mixed with the transparent epoxy glue respectively to produce three types of coating materials. The mean particle

Table 4
Mix proportion of PCC.

W/C	Sand ratio	Mass percentage/%			
		Cement	Aggregate	Sand	Water
0.4	0.31	19.2	50.5	22.5	7.8

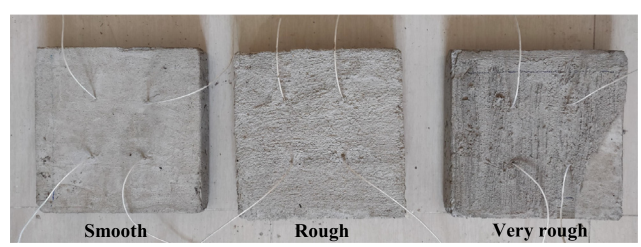


Fig. 8. PCC slabs with different surface texture.

Table 2
Gradation and asphalt binder content (ABC) of AC-13, SMA-13 and OGFC-13.

Type	Mass percentage/% passing the sieve size/mm										ABC/%
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
AC-13	100	96.7	76.1	48.3	34.2	22.5	15.6	10.0	6.0	4.6	5.2
SMA-13	100	94.6	61.3	26.8	20.9	18.5	16.4	12.8	11.5	8.8	5.7
OGFC-13	100	93.3	64.6	28.0	19.4	13.7	10.6	8.1	6.2	5.2	5.4

Table 3
Properties of modified asphalt.

Softening point (°C)	25 °C penetration (0.1 mm)	5 °C ductility (cm)	60 °C viscosity/(Pa·s)	After RTFO Aging		
				Mass loss (%)	25 °C penetration ratio	5 °C ductility (cm)
90.5	63	34	145,008	0.001	53	28

Table 5
Basic properties of base material.

		Before mixing	
Component	Chroma	Viscosity (mPa.s)	Density (g/cm^3)
A	<1	2000–4000	1.05
B	<1	80	0.98
		After mixing (A:B = 3:1)	
Viscosity (mPa.s)	Allowable operation time (min)	Initial curing time (h)	Final curing time (h)
500–600	25	5	12
		After curing	
Hardness (Shore D)	Applicable temperature (°C)	Compressive strength (kg/mm^2)	Bending strength (kg/mm^2)
90	−40 ~ 110	30	22

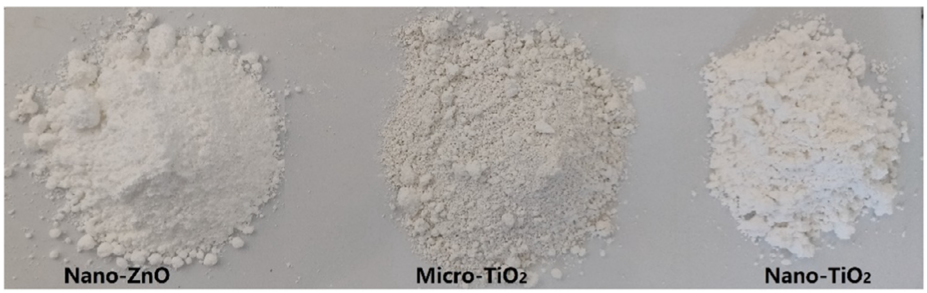


Fig. 9. Three types of filler used in coating materials.

Table 6
Mean size of filler particles.

Filler materials	Nano-TiO_2	Micro-TiO_2	Nano-ZnO
Size (nm)	405	1020	100

diameter of Nano-TiO_2, Micro-TiO_2 and Nano-ZnO were shown in Table 6. The optimum ratio of filler to transparent epoxy glue is determined in the following section. It should be noted that the prepared coating pastes must be painted on compacted asphalt mixture quickly due to the limitation of curing time of 20 min at the air temperature of 32 °C.

5. Laboratory measured albedo and heat transfer of pavement materials

5.1. Albedo of asphalt mixture and Portland cement concrete without coating

The albedo laboratory measurements were performed on AC-13, SMA-13, OGFC-13 and PCC slabs without coating materials at air temperature of 25 °C and the pyranometer height of 20 cm using the developed albedometer. Fig. 10 shows the results of measured albedo. The albedo test was conducted on four corners of each mixture, so the standard deviation values were shown as the error bar from the averages in the figure.

As shown in Fig. 10, the measured albedo of three types of asphalt mixture varies within a narrow range from 5.46% to 6.11%. This implies that the albedo of asphalt mixture mainly depends on its black color and the gradation has little impact on the albedo. Different from the low albedo of asphalt mixture, PCC with grey surface has larger albedo ranging from 22.8% to 26.4%. This clearly indicates that PCC pavement surface reflects more solar radiation and produces a lower pavement temperature than asphalt pavement. Moreover, as shown in Fig. 10, PCC with the roughest surface is found with the lowest albedo of 22.8%. The smooth PCC surface is beneficial to reflect solar radiation and decrease internal temperature of pavement.

5.2. Albedo of asphalt mixture with different coating materials

Three types of coating pastes (with filler of Nano-TiO_2, Micro-TiO_2, and Nano-ZnO) were painted on asphalt mixture, and their albedo were measured and compared with asphalt mixture without coating. To determine the optimum content of filler in coating material, the albedo of AC-13 coated with different mass contents of filler were measured firstly. According to Zhen et al. [37], the maximum usage of coating materials in this study was 0.9 kg/m^2, which was painted by three layers (each with the usage of 0.3 kg/m^2). It should be noted that the coating materials with more than 60% filler content is too viscous to paint. The albedo of AC-13 with the coating usage of 0.9 kg/m^2 using filler content of 0, 10%, 20%, 30%, 40%, 50% and 60% was measured respectively and presented in Fig. 11. It can be seen that the albedo increases rapidly as the increasing of filler content from 0 to 30%. As the content of filler further increased from 30% to 60%, the albedo only appeared slight improvement. Therefore, the value of 30% was used as the optimum mass content of filler. From Fig. 11, the rank of reflectance of three types of filler at the same content is Micro-TiO_2 > Nano-ZnO > Nano-TiO_2. This indicates that Micro-TiO_2 has

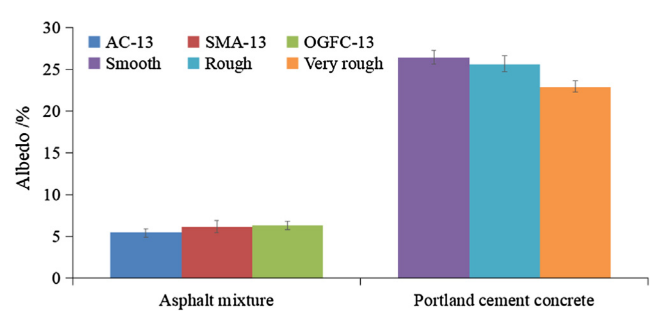


Fig. 10. Albedo of asphalt mixture and Portland cement concrete without coating materials.

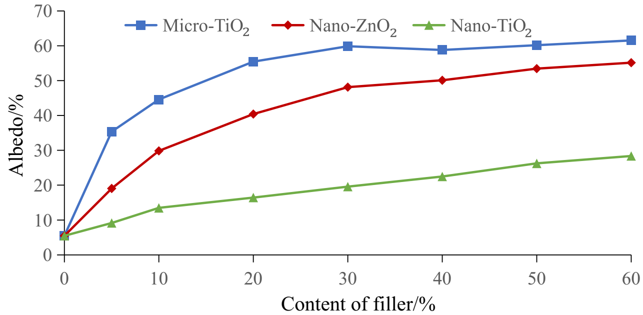


Fig. 11. Measured albedo of AC-13 coated with different contents of reflective filler.

the best reflectance for asphalt pavement. The comparison of three types of filler particles as the reflective coating materials will be further discussed in the following sections.

Using the optimum filler content of 30%, three types of coating pastes were prepared and coated on the asphalt mixture slabs by three layers, each with a usage of 0.3 kg/m^2. The albedo was measured on the slab with each layer's coating, as shown in Fig. 12(a). Fig. 12(b) shows the pictures of coated AC-13, SMA-13 and OGFC-13 slabs. It can be observed that asphalt mixture with coating materials has larger albedo than that without coating materials regardless of the type of filler. The measured albedo increased as the increasing of usage of coating materials. This indicates that the near-infrared radiation can be reflected by fine particles of Nano-TiO$_2$, Micro-TiO$_2$ and Nano-ZnO. In addition, Micro-TiO$_2$ has the best reflectance among these three types of fillers, whose albedo is 32.8%, 31.2% and 34.2% of AC-13, SMA-13 and OGFC-13 even with 0.3 kg/m^2 coating. The albedo of asphalt mixture with Nano-TiO$_2$ coating is the lowest, which only reached 18.8% and 19.9% for AC-13 and SMA-13 with the coating usage of 0.9 kg/m^2. Compared with Fig. 10, the albedo of three types of asphalt mixture coated with Micro-TiO$_2$ is much larger than that of PCC. This implies that Micro-TiO$_2$ is an effective reflective filler for asphalt mixture. Black asphalt pavements can obtain the larger albedo than grey Portland cement pavements by using the reflective coating.

It should be noted that when the Micro-TiO$_2$ coating was painted on the surface of OGFC-13 slab, a proportion of coating material penetrated into the slab owing to the large amount of open and connected voids in porous mixture [38,39], which caused clogging and reduction of the permeability and noise reduction. Therefore, OGFC-13 is not recommended to be painted with coating materials.

5.3. Internal temperature transfer of mixture slab exposed to near-infrared radiation

During the measurement of albedo, the slab of asphalt mixture/PCC was exposed to the near-infrared radiation and the temperature at four depths (1 cm, 2 cm, 3 cm and 4 cm) inside the slab were measured every one minute using the resistance thermome-

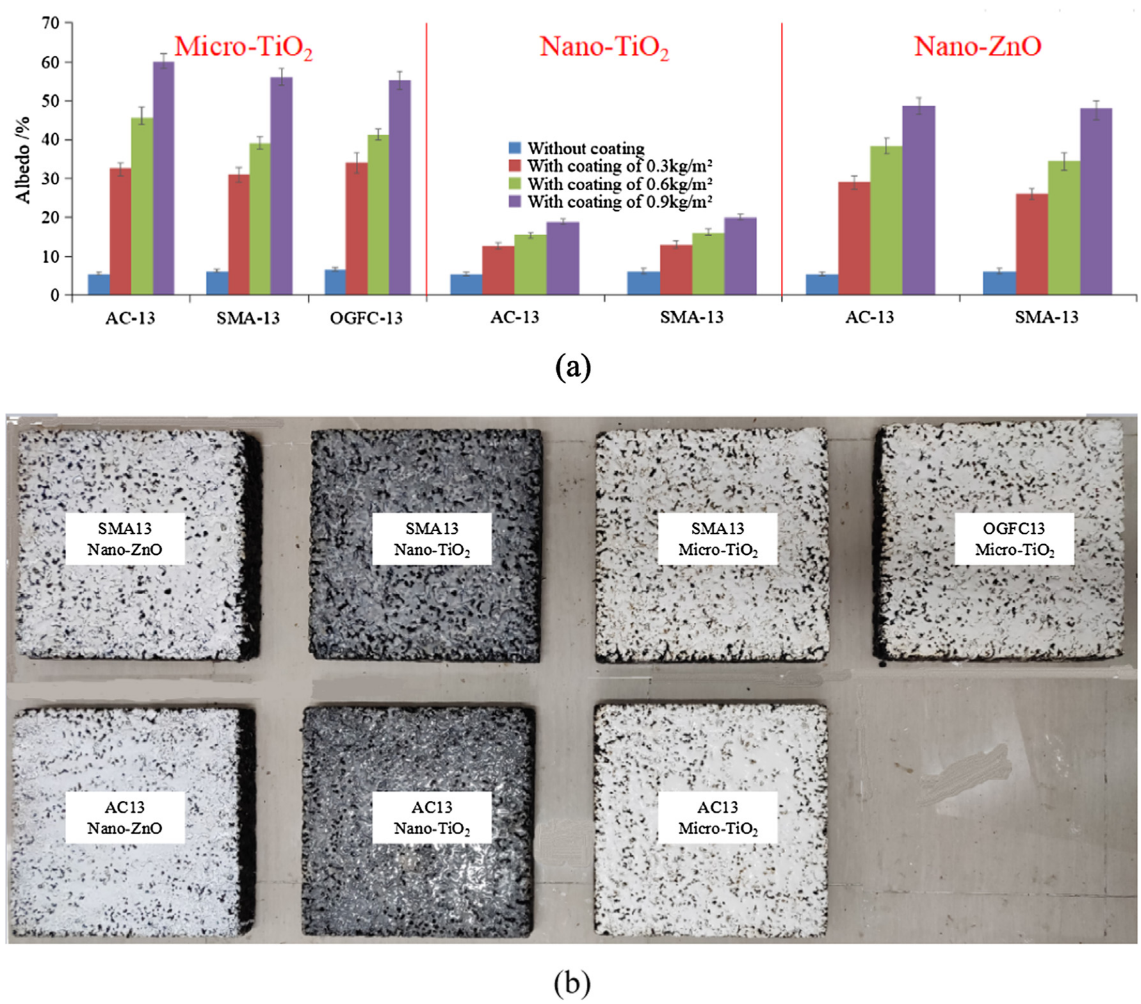


Fig. 12. Illustration of (a) measured albedo of asphalt mixture slabs; and (b) asphalt mixture slabs coated by three types of coating materials with usage of 0.9 kg/m^2.

ter (as shown in Figs. 6(a) and 8). Fig. 13 shows the internal temperature at four depths of slab (with the initial temperature of 25 °C) exposed to the near-infrared radiation for 60 min. It can be seen that the temperature rises slowly within the beginning three minutes and then grows linearly as the increase of exposure time regardless of depth. Moreover, the rate of temperature increasing varies significantly at different depths. Specifically, the temperature at 1 cm depth of AC-13 increased from 25 °C to 38 °C within 60 min, while the internal temperature only increased by 10 °C, 7 °C and 6 °C at the depths of 2 cm, 3 cm and 4 cm, respectively. The temperature at 1 cm depth of PCC increased by 8 °C–10 °C, which is less than the increase of 12–15 °C for three types of asphalt mixture. In addition, the difference of internal temperature at four depths of PCC is less than that in asphalt mixture. The reason may be that PCC has higher thermal conductivity than asphalt mixture [40]. PCC slab can transfer the surface heat faster than asphalt mixture, which yields lower temperature difference along depths [41]. This indicates that PCC has not only lower temperature due to higher albedo but also the higher heat transfer efficiency.

Fig. 13(c) gives the increasing extent (T) of internal temperature at four depths of AC-13, SMA-13 and OGFC-13 without coating materials after being exposed to radiation for 60 min. As shown, the increasing temperature at 1 cm depth in OGFC-13 was 2 °C and 1.5 °C lower than that in AC-13 and SMA-13. There is no obvious difference of temperature at the depth of 3 cm and 4 cm among three types of asphalt mixture. This indicates that the difference of temperature among four depths decreased as the increasing of the depth and the porous asphalt mixture is useful for the reduction of temperature at pavement surface or near-surface. In addition, PCC with rougher surface is observed to have more increasing extent of internal temperature. The reason is that rougher PCC pavement surface reflect less incident solar radiation (as shown in Fig. 10) and produce a higher pavement temperature. This clearly implies that PCC surface texture affects not only the skid resistance of pavement but also the internal temperature and the resultant thermal stress.

5.4. Cooling effect of asphalt mixture slab due to reflective coating

As mentioned above, the internal temperature of asphalt mixture without coating increased significantly when it was exposed to near-infrared radiation. In this section, the internal temperature of AC-13 and SMA-13 with three types of reflective coating of 0.3 kg/m^2, 0.6 kg/m^2 and 0.9 kg/m^2 were measured, respectively. The increasing extent of internal temperature (T_{rc}) after 60 min exposure were calculated. The difference between T_{rc} and T (D_T) were used to evaluate the cooling effect of reflective coating. Fig. 14 shows the D_T of four depths of AC-13 and SMA-13 with three types of coating materials.

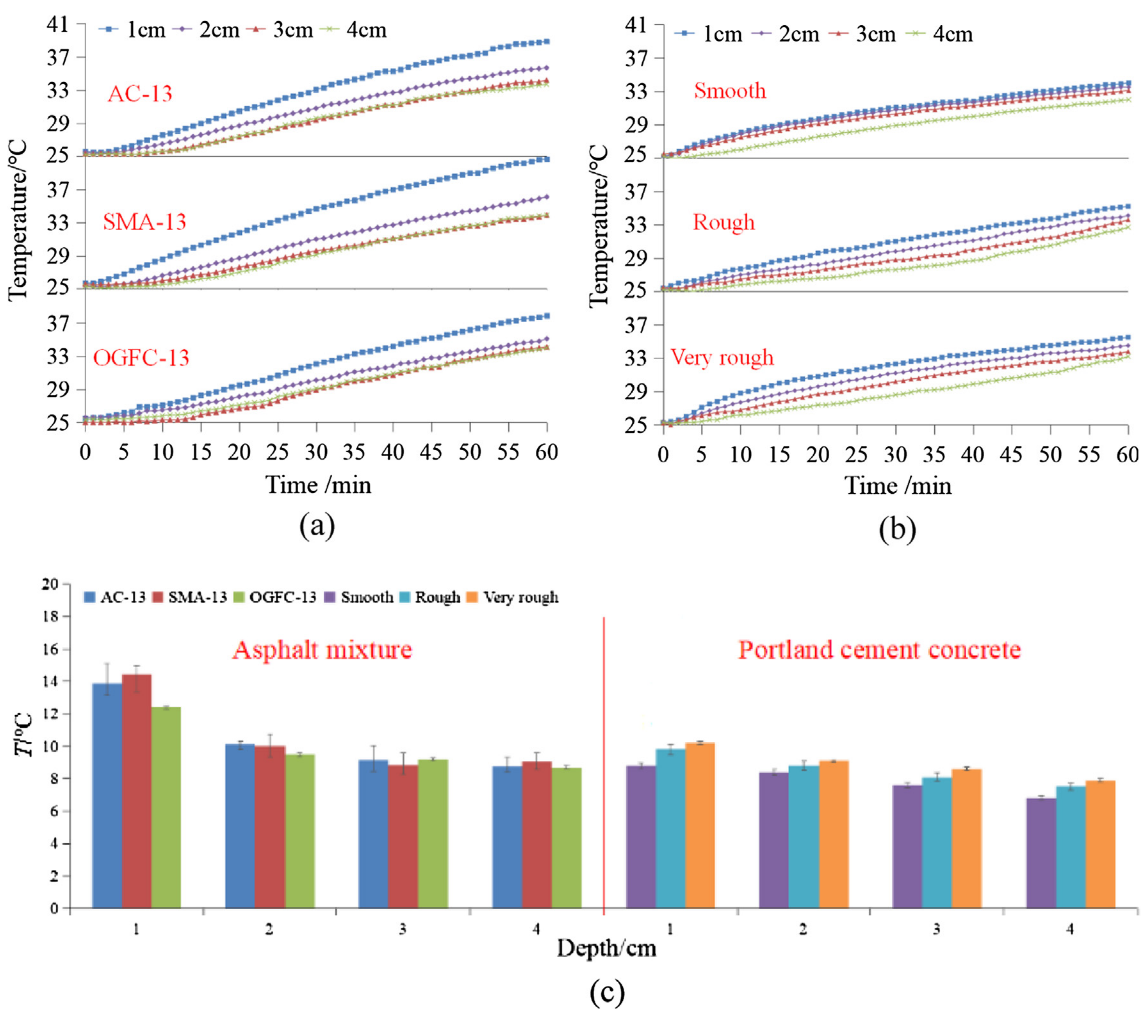
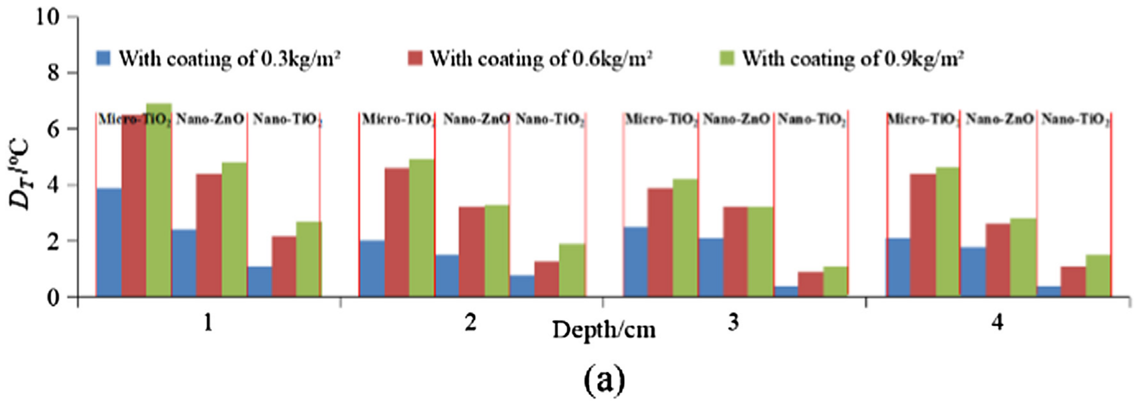


Fig. 13. Illustration of (a) temperature of four depths in asphalt mixture; (b) temperature of four depths in PCC; and (c) increasing extent of internal temperature after 60 min exposure to infrared radiation.



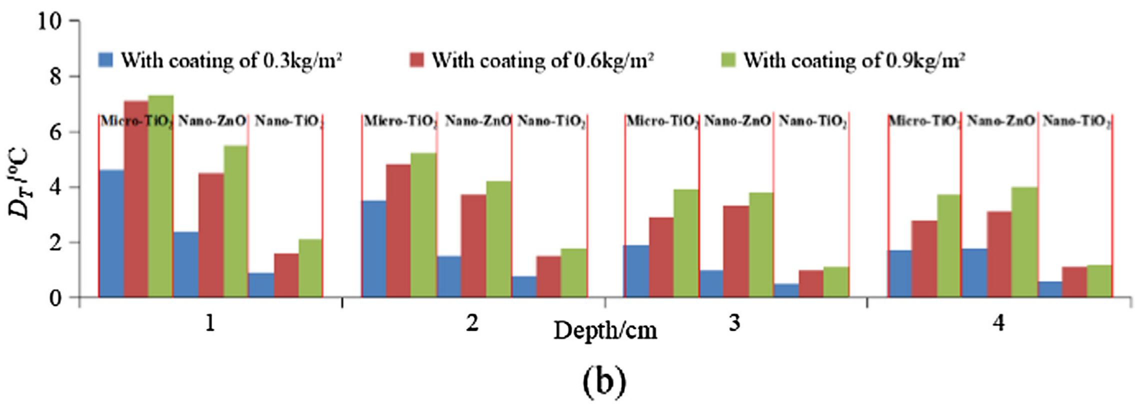


Fig. 14. Cooing effect of three types of coating materials coated on (a) AC-13 and (b) SMA-13.

As shown in Fig. 14, compared with AC-13 without coating, the temperature at 1 cm, 2 cm, 3 cm and 4 cm depth in AC-13 with Micro-TiO_2 coating of 0.3 kg/m^2 decreased by 3.9 °C, 2 °C, 2.5 °C and 2.1 °C, respectively. The cooling temperature at 1 cm depth is larger than that at other three depths for the same type of asphalt mixture and coating material. There is no obvious difference of cooling effect between 3 cm and 4 cm depth. This indicates that the coating has significant and effective cooling effect mainly for pavement surface. In addition, for any depth of asphalt mixture, the rank of cooling effect of three types coating materials is Micro-TiO_2 > Nano-ZnO > Nano- TiO_2. This further proved that Micro-TiO_2 is the most effective coating filler for cooling pavement exposed to solar radiation.

6. Conclusions

This study investigated the factors affecting the field measurement of pavement albedo and developed a new albedometer for laboratory measurement. Using the developed albedometer, the albedo and internal temperature of asphalt mixture with coating materials and Portland cement concrete (PCC) were measured. The major conclusions of this study are summarized as follows:

(1) Solar radiation intensity, incident angle and surrounding environment have remarkable effect on the field measured value of albedo, which makes it difficult to measure pavement albedo accurately.
(2) The developed laboratory albedometer can accurately measure the albedo and the internal temperature of pavement materials at the same time without the negative effect of solar radiation intensity, incident angle and surrounding environment.
(3) The albedos of asphalt mixtures are lower than those of PCC. The gradation of asphalt mixture has little impact on the albedo. Rougher PCC surface reflect less incident solar radiation and produce a higher pavement temperature.
(4) The reflective coating using Nano-TiO_2, Micro-TiO_2, and Nano-ZnO can significantly increase the albedo and decrease the temperature of asphalt mixture, especially for mixture surface. Micro-TiO_2 has the better reflectance than Nano-TiO_2 and Nano-ZnO.

The findings obtained from this study indicate the potential of using the developed laboratory albedometer to evaluate the albedo of pavement materials and using Micro-TiO_2 coating to provide functional benefits in mitigation of UHI. The bond to substrate and skid resistance of coating materials need to be further studied. The investigation of durability of coating materials and development of aging albedo model are also needed to evaluate their long-term cooling effects.

Conflict of interest

None.

Acknowledgments

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References

[1] J.S. Golden, The Built environment induced urban heat island effect in rapidly urbanizing arid regions-a sustainable urban engineering complexity, Environ. Sci. 1 (4) (2004) 321–349.

[2] H. Akbari, L. Rose, H. Taha, Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California, Lawrence Berkeley National Laboratory, Berkeley, CA, 1999.
[3] L.Q. Hu, Y.Y. Li, X.L. Zou, S.W. Du, Z.Z. Liu, H. Huang, Temperature characteristics of porous Portland cement concrete during the hot summer session, Adv. Mater. Sci. Eng. (2017) 10. Article ID 2058034.
[4] E. Carnielo, M. Zinzi, Optical and thermal characterisation of cool asphalts to mitigate urban temperatures and building cooling demand, Build. Environ. 60 (2013) 56–65.
[5] H. Akbari, H.D. Matthews, Global cooling updates: reflective roofs and pavements, Energy Build. 55 (2012) 2–6.
[6] H. Li, J. Harvey, T.J. Holland, M. Kayhanian, The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater, Manage. Environ. Res. Lett. 8 (1) (2013) 015023.
[7] B. Yu, Q. Lu, Estimation of albedo effect in pavement life cycle assessment, J. Clean. Prod. 64 (2014) 306–309.
[8] S. Ghasan, A. Majeed, M. Ratnasamy, The effect of binder type and temperature differential on the rutting performance of hot mix asphalt, Int. J. Appl. Eng. Res. 12 (17) (2017) 6841–6852.
[9] J. Harvey, L. Popescu, Rutting of Caltrans Asphalt Concrete and Asphalt-Rubber Hot Mix under Different Wheels, Tires and Temperatures-Accelerated Pavement Testing Evaluation (Report), University of California, Berkeley, 2000.
[10] Q.S. Zhang, Y.L. Chen, X.L. Li, Rutting in asphalt pavement under heavy load and high temperature, GeoHunan Int. Conf. (2009) 39–48.
[11] H.Q. Shi, T. Xu, R.L. Jiang, Combustion mechanism of four components separated from asphalt binder, Fuel 192 (2017) 18–26.
[12] ASTM International, ASTM Standard E1918: Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field, Standard, West Conshohocken, PA, 2006.
[13] ASTM International, ASTM Standard E903: Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres, Standard, West Conshohocken, PA, 2012.
[14] M. Pomerantz, H. Akbari, S.C. Chang, R. Levinson, B. Pon, Examples of Cooler Reflective Streets for Urban Heat-Island Mitigation: Portland Cement Concrete and Chip Seals, Lawrence Berkeley National Laboratory, Berkeley, CA, 2003, p. 24.
[15] M. Pomerantz, H. Akbari, A. Chen, H. Taha, A. Rosenfeld, Paving Materials for Heat Island Mitigation, Lawrence Berkeley National Laboratory, Berkeley, CA, 1997.
[16] M. Pomerantz, H. Akbari, J. Harvey, Cooler Reflective Pavements Give Benefits Beyond Energy Savings: Durability and Illumination, Lawrence Berkeley National Laboratory, Berkeley, CA, 2000.
[17] C.W. Wong, N.H. Wong, T.P. Ping, A.Z.W. Aloysius, A study on the effectiveness of heat mitigating pavement coatings in Singapore Berkeley, California, U.S., The Second International Conference on Countermeasures to Urban Heat Islands, 2009.
[18] J.A.V. Del Carpio, D.L. Marinoski, G. Trichês, R. Lamberts, J.V.S. De Melo, Urban pavements used in Brazil: characterization of solar reflectance and temperature verification in the field, Sol. Energy 134 (2016) 72–81.
[19] S. Sen, Roesler. Aging albedo model for asphalt pavement surfaces, J. Clean. Prod. 117 (2016) 169–175.
[20] H. Li, J. Harvey, A. Kendall, Field measurement of albedo for different land cover materials and effects on thermal performance, Build. Environ. 59 (2013) 536–546.
[21] N. Anak Guntor, M. Md Din, M. Ponraj, K. Iwao, Thermal performance of developed coating material as cool pavement material for tropical regions, J. Mater. Civ. Eng. 26 (2014) 755–760.
[22] J. Hu, X. Yu, Experimental study of sustainable asphalt binder-influence of thermochromic materials, Transp. Res. Rec. 2372 (2013) 108–115.
[23] Y. Ma, B. Zhu, Research on the preparation of reversibly thermochromic cement based materials at normal temperature, Cem. Concr. Res. 39 (2009) 90–94.
[24] D.P. Bentz, R. Turpin, Potential applications of phase change materials in concrete technology, Cem. Concr. Compos. 29 (2007) 527–532.
[25] M.A. White, M. Le Blanc, Thermochromismin commercial products, J. Chem. Educ. 76 (1999) 1201.
[26] J.T. Kevern, L. Haselbach, V.R. Schaefer, Hot weather comparative heat balances in pervious concrete and impervious concrete pavement systems, J. Heat Island Inst. Int. 7 (2) (2012) 231–237.
[27] K. Boriboonsomsin, F. Reza, Mix design and benefit evaluation of high solar reflectance concrete for pavements, Transp. Res. Rec. 2011 (2007) 11–20.
[28] N.L. Marceau, M.G. Vangeem, Solar reflectance values for concrete: intrinsic material properties can minimize the heat island effect, Concrete International, 2008, pp. 52–58.
[29] M. Pomerantz, H. Akbari, S.C. Chang, R. Levinson, B. Pon, Examples of Cooler Reflective Streets for Urban Heat- island Mitigation: Portland Cement Concrete and Chip Seals, LBNL, Berkeley, CA, 2003, pp. 1–24. Paper LBNL-49283.
[30] N. Tran, B. Powell, H. Marks, R. West, A. Kvasnak, Strategies for design and construction of high-reflectance asphalt pavements, Transp. Res. Rec. 2098 (2009) 124–130.
[31] T. Kinouchi, T. Yoshinaka, N. Fukae, M. Kanda, Development of cool pavement with dark colared high albedo coating Vancouver, Canada, in: Proceedings of the 5th Conference for the Urban Environment, 2004, pp. 1–4.
[32] M. Nishioka, M. Nabeshima, S. Wakama, J. Ueda, Effects of surface temperature reduction and thermal environment on high albedo coating asphalt pavement, J. Heat Island Int. Inst. 1 (2006) 46–52.
[33] H. Wang, J. Zhong, D.C. Feng, J. Meng, Xie N. Nanoparticles-modified, Polymer-based solar-reflective coating as a cooling overlay for asphalt pavement, Int. J. Smart Nano Mater. 4 (2) (2013) 102–111.
[34] X.J. Cao, B.M. Tang, X.L. Zou, L.H. He, Analysis on the cooling effect of a heat-reflective coating for asphalt pavement, Road Mater. Pavement Des. 16 (3) (2015) 716–726.
[35] X.J. Cao, B.M. Tang, Y. Yuan, X.L. Zou, Indoor and outdoor aging behaviors of a heat-reflective coating for pavement in the chongqing area, J. Mater. Civ. Eng. 28 (1) (2016) 01565496.
[36] K.N. Liou, An Introduction to Atmospheric Radiation, second ed., Academic Press, Waltham, MA, 2002.
[37] M.L. Zhen, L.T. He, X. Gao, Analysis of heat-reflective coating property for asphalt pavement based on cooling function, J. Traffic Transp. Eng. 13 (5) (2013) 10–16.
[38] J.H. Zhang, J. Li, Y.S. Yao, J.L. Zheng, F. Gu, Geometric anisotropy modeling and shear behavior evaluation of graded crushed rocks, Constr. Build. Mater. 183 (2018) 346–355.
[39] J. Chen, X. Yin, H. Wang, X. Ma, Y. Ding, G. Liao, Directional distribution of three-dimensional connected voids in porous asphalt mixture and flow simulation of permeability anisotropy, Int. J. Pavement Eng. (2018), https://doi.org/10.1080/10298436.2018.1555330.
[40] J. Gui, P.E. Phelan, K.E. Kaloush, J.S. Golden, Impact of pavement thermophysical properties on surface temperatures, J. Mater. Civ. Eng. 19 (8) (2007) 683–690.
[41] X. Shi, Y. Rew, E. Ivers, C.S. Shon, E.M. Stenger, P. Park, Effects of thermally modified asphalt concrete on pavement temperature, Int. J. Pavement Eng. (2007), https://doi.org/10.1080/10298436.2017.1326234.