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Case study

Field measurements of road surface temperature of several asphalt pavements with temperature rise reducing function

Hiroshi Higashiyama[a,*], Masanori Sano[b], Futoshi Nakanishi[c], Osamu Takahashi[d], Shigeru Tsukuma[d]

[a] Department of Civil and Environmental Engineering, Kinki University, 3-4-1, Kowakae, Higashiosaka, Osaka 577-8502, Japan
[b] Research Institute for Science and Technology, Kinki University, 3-4-1, Kowakae, Higashiosaka, Osaka 577-8502, Japan
[c] Technical Department, Kansai Branch, Toa Road Corporation, 1-4-17, Motomachi, Naniwa-ku, Osaka 556-0016, Japan
[d] Operations Department, The Kanden L&A Co., Ltd., 4-8-17, Nishitenma, Kita-ku, Osaka 530-0047, Japan

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ABSTRACT

In the urban area, the heat island phenomenon and hot nights when the temperature does not fall below 25 °C outdoors are becoming environmental problems. Pavements cover a high percentage of the urban area and largely affect the development of the urban heat island phenomenon. The authors have developed water retaining pavements with several cement-based grouting materials poured into voids of open graded asphalt pavements (porous asphalt pavements) to reduce the surface temperature in the hot summer climate. The cement-based grouting materials consist of cement, ceramic waste powder, and fly ash or natural zeolite. In field measurements conducted in the summer season, all of the water retaining pavements reduced the surface temperature by 10 °C and more, when the porous asphalt pavement reached over 60 °C. Especially, one of the water retaining pavements, which uses ultra-rapid hardening cement, ceramic waste powder, and natural zeolite, reduced the surface temperature by about 20 °C. In this paper, the details of the cement-based grouting materials used in the field tests are described. Also, the field test results on the thermal performance of the water retaining pavements are reported.

1. Introduction

In the urban area, the heat island phenomenon and hot nights when the temperature does not fall below 25 °C outdoors are becoming environmental problems. Pavements cover a high percentage of the urban area and largely affect the development of the urban heat island phenomenon. There are many reports on cooling pavements to improve the thermal conditions in the urban environment and to reduce the energy consumption (Santamouris, 2013; Kinouchi et al., 2004; Synnefa et al., 2011; Hendel et al., 2014). As countermeasures in the field of road engineering, water retaining pavements and solar radiation reflective pavements with the surface temperature rise reducing function (STRRF) have been developed. Especially, a water retaining pavement consists of open graded asphalt pavement (porous asphalt pavement: PoAs) and a cement-based material grouted into voids in the PoAs. In general, the cement-based grouting material (CBGM) has a high water absorption of, for example, 40–80% by mass, and the water retaining pavements reduce the surface temperature by 10 °C and more, as compared with a conventional asphalt pavement, which reaches over 60 °C in the hot summer climate.

* Corresponding author. Fax: +81 72 995 5192.
E-mail address: h-hirosi@civileng.kindai.ac.jp (H. Higashiyama).

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Kinouchi et al. (2004) have developed an asphalt pavement with high albedo (reflection coefficient) and low brightness using an innovative paint coating. Their field measurements show that the maximum surface temperature of the paint-coated asphalt pavement is lower than that of the conventional asphalt pavement. Synnefa et al. (2011) have developed colored thin lay asphalt pavements with higher solar reflectance. The results of their field measurements show that an off-white asphalt sample having the highest solar reflectance has the greatest difference from the conventional asphalt sample.

On the other hand, the infinite use of resources to meet consumer demand in the growing economic will cause continual increase in the industrial waste. Material recycling is an attractive solution in industrial wastes disposal, because the availability of landfill is limited. Ceramic porcelain insulators discarded from electric power industries can also be industrial wastes. The ceramic porcelain insulators are chemically stable and have high quality. Their particles after the crushing process have sharp and knife-like edges, which can be dangerous to use as constructional aggregates. Sano et al. (2009) have proposed a recycling method for producing safe and round ceramic waste aggregates through crushing and grinding processes. Subsequently, the authors have investigated the utilization of ceramic waste aggregates for construction materials (Higashiyama et al., 2012a,b, 2013). In the above processes, ceramic waste powder, which is collected by a dust chamber, also constitutes about 20% of the total mass of the ceramic waste.

In this study, the utilization of ceramic waste powder as a part of components in water retaining pavements is investigated and the STRRF of several CBGMs developed is evaluated to measure the surface temperature of pavements through field measurements conducted in the summer season. The CBGMs, which each consist of cement, ceramic waste powder, and fly ash or natural zeolite, are developed to apply for roadways, sidewalks, and parking lots considering the economic efficiency of the materials. In this paper, the thermal performance of the water retaining pavements in fields is reported.

2. Cement-based grouting materials

2.1. Materials and mixtures

The CBGMs developed for the PoAs with the STRRF fundamentally consist of cement (C), ceramic waste powder (CWP) (supplied from The Kanden L&A Co., Ltd., Japan), and fly ash (FA) (supplied from Nippon Steel & Sumikin Slag Products Co., Ltd., Japan) or natural zeolite (NZ) (produced in Izumo, Shimane, Japan). For the CWP, improvement of fluidity and strength gain is expected, and the FA and the NZ are selected as supplementary cementitious materials. The physical and chemical properties of these powder materials are shown in Table 1. Two types of cement (produced by Sumitomo Osaka Cement Co., Ltd., Japan), i.e., normal Portland cement (NPC) and ultra-rapid hardening cement (URHC), were used in this study. The specific gravity and the specific surface area in Blaine of the FA were 2.10 and 3494 cm^2/g. The particle size of the NZ used was less than 200 μm. The specific gravity and the specific surface area in Blaine were 2.30 and 6770 cm^2/g. The URHC and the NZ have creamy color. Each CBGM and the combination of those powder materials are shown in Table 2.

For a water retaining pavement, the required abilities of the CBGM poured into the PoAs are principally fluidity and water absorption. From the previous study (Higashiyama et al., 2016). the mixture proportion using the URHC and the FA was determined as C:CWP:FA = 0.5:0.35:0.15 by mass. In the case of using the NZ instead of the FA, the mixture proportion was

Table 1
Physical and chemical properties.

Properties	NPC	URHC	CWP	FA	NZ
Chemical compositions (wt.%)					
SiO_2	20.68	NA	70.90	50.50	70.15
Al_2O_3	5.28	NA	21.10	26.10	12.28
Fe_2O_3	2.91	NA	0.81	–	1.16
CaO	64.25	NA	0.76	2.90	1.98
MgO	1.40	NA	0.24	1.13	0.53
SO_3	2.10	NA	–	–	–
Na_2O	0.28	NA	1.47	–	1.93
K_2O	0.40	NA	3.57	–	2.38
TiO_2	0.28	NA	0.33	–	0.17
P_2O_5	0.25	NA	–	–	–
MnO	0.09	NA	–	–	0.06
SrO	0.06	NA	–	–	–
Fe	–	NA	–	3.57	–
S	–	NA	–	0.18	–
Cl	0.015	NA	–	–	–
Physical properties					
Loss on ignition (%)	1.80	0.80	NA	NA	9.25
Specific gravity	3.15	3.05	2.43	2.10	2.30
Specific surface area in Blaine (cm^2/g)	3360	5230	1810	3494	6770

Table 2
Combinations of powder materials and their names.

Name	Combination
NCZ	NPC + CWP + NZ
NCF	NPC + CWP + FA
UCZ	URHC + CWP + NZ
UCF	URHC + CWP + FA

the same as that. The water-to-cement ratio (W/C) was kept constant at 1.3 by mass. Furthermore, when the URHC was used, an air entraining and high-range water reducing agent (supplied from BASF Japan Ltd., Japan) and a setting retarder were added to constitute 3% and 0.4% of the URHC by mass, respectively. The CBGMs were prepared in a Hobart mixer of 5 L capacity with a mixing time of 2–3 min.

2.2. Test methods

2.2.1. Fluidity test

A fluidity test for the CBGMs was carried out in a room at 20 ± 2 °C and 60 ± 10% RH. After each CBGM was mixed, the fluidity, which is indicated by the falling flow time of the CBGM, was immediately measured by a method using a P-type funnel with a volume of 1725 ml according to JSCE-F 521 (Japan Society of Civil Engineers, 2005a) as shown in Fig. 1.

2.2.2. Water absorption test

A water absorption test was carried out on ø50 mm × 100 mm cylindrical specimens at the age of 1 day for specimens using the URHC and 3 days for specimens using the NPC (three specimens at a time). After the specimens were submerged in water for 1 h, they were dried in an oven under 60 °C for 24 h. Then, the water absorption ratio was calculated by using the mass difference before and after the oven dry.

2.2.3. Compression test

A compression test was carried out on ø50 mm × 100 mm cylindrical specimens at the age of 1 day and 7 days for specimens using the URHC, and 3 days and 7 days for specimens using the NPC (three specimens at a time). The specimens were cured in a room at 20 ± 2 °C and 60 ± 10% RH until each test was conducted. A compressive load was applied by using a 500 kN capacity universal testing machine under a constant loading speed of 0.1 N/mm^2/s according to JSCE-G 505 (Japan Society of Civil Engineers, 2005b).

2.3. Physical and mechanical properties

The physical and mechanical properties of the CBGMs are shown in Table 3. The flow time of each CBGM was within 9–13 s, which is a range of the flow time recommended by road constructors in Japan. For the flow time, these CBGMs satisfy the recommended range and can be easily grouted into voids in a PoAs. The water absorption ratio of each CBGM tested on each curing day was at the same level and was 48%. The compressive strengths of the CBGMs using the NPC were overall less than those using the URHC. To enable opening for traffic, even if the URHC is used for the CBGM, the curing time of at least

Fig. 1. P-type funnel used for a fluidity test.

Table 3
Physical and mechanical properties of CBGMs.

Properties	NCZ	NCF	UCZ	UCF
Flow time (s)	9.33	9.62	11.38	10.33
Water absorption ratio (%)	48.9	48.3	48.1	48.9
Compressive strength (N/mm^2)				
1 day curing	–	–	3.26	4.69
3 days curing	2.01	1.52	–	–
7 days curing	3.88	2.91	8.28	8.45

one day is needed. Although the compressive strength gain of the CBGMs using the NPC came late, these CBGMs would be suitable in economic terms for sidewalk or parking lot constructions when the curing time can be secured without any severe constructional constraints.

3. Field measurements

3.1. Construction procedures

The field measurements were conducted at two construction sites owned by The Kanden L&A Co., Ltd.: first, the UCZ and UCF pavements (Higashiyama et al., 2016) were constructed at the site of Shikama-ku, Himeji, Hyogo, Japan as shown in Fig. 2; and second, the NCZ and NCF pavements were constructed at the site of Yasutomi, Himeji, Hyogo, Japan as shown in Fig. 3. At the first construction site, the PoAs using straight asphalt binder (ST60/80) with a thickness of 50 mm and a void ratio of 23% was paved before grouting of the CBGMs of the UCZ and the UCF. The surface temperature of each pavement was measured by a T-type thermocouple embedded at a depth of 5 mm from the top surface. The same T-type thermocouple was also fixed at a height of 1.5 m from the surface of the pavement to measure the atmospheric temperature (AT) simultaneously. The CBGMs using the UCZ and the UCF were poured into the PoAs and vibrated as shown in Fig. 4. Finally, the surface was treated with a rubber rake. The surface temperature of those pavements including the PoAs was monitored from Aug. 1 to 30 in 2014.

At the second construction site, the PoAs using straight asphalt binder (ST60/80) with a thickness of 50 mm and a void ratio of 15% was paved before grouting of the CBGMs of the NCZ and the NCF. Similarly to the above procedure, the surface temperature of each pavement was measured by a T-type thermocouple embedded at a depth of 5 mm from the top surface. The same T-type thermocouple was also fixed at a height of 1.5 m from the surface of pavement to measure the AT simultaneously. The surface temperature of those pavements including the PoAs was monitored from July 23 to Aug. 26 in 2015.

3.2. Surface temperature distributions

The surface temperature of each pavement was recorded at 1 h intervals during the field measurements at the two construction sites. The surface temperature distributions of the UCZ and UCF pavements and the PoAs for three days from Aug. 19 to 21 in 2014, when the surface temperature of the PoAs over 60 °C was observed during the field measurement and without rain, are presented in Fig. 5. The surface temperature of the PoAs over 60 °C was observed only for these three days

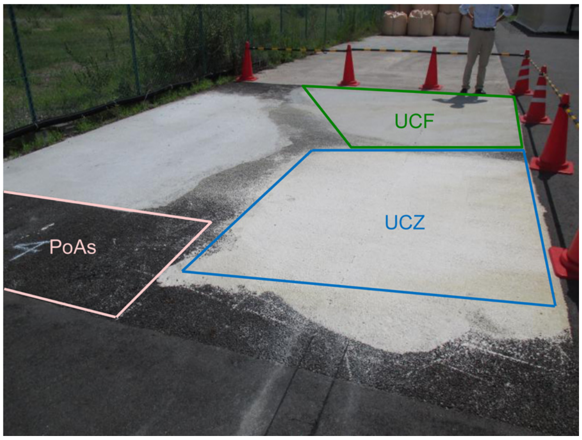

Fig. 2. UCF and UCZ pavements (Higashiyama et al., 2016) tested at the first construction site (Shikama-ku, Himeji, Hyogo, Japan).

Fig. 3. NCF and NCZ pavements tested at the second construction site (Yasutomi, Himeji, Hyogo, Japan).

Fig. 4. Construction of the CBGMs.

during the field measurement. These results have been reported in (Higashiyama et al., 2016). Furthermore, the surface temperature distributions of the NCZ and NCF pavements and the PoAs for three days from Aug. 1 to 3 in 2015 without rain are shown in Fig. 6. The surface temperature of the PoAs over 60 °C was observed in twelve days during the field measurement.

From the results shown in Fig. 5, the UCZ pavement reduced the surface temperature more than the UCF pavement. The surface temperature difference (average value for three days), when the surface temperature of the PoAs was over 60 °C, was 20.6 °C for the UCZ pavement and 12.8 °C for the UCF pavement. This can be due to the fact that the UCZ pavement using the URHC and the NZ was creamy colored, while the UCF pavement containing the FA was some gray colored. Moreover, from the results of the NCZ and NCF pavements as shown in Fig. 6, the NCZ pavement reduced the surface temperature more than the NCF pavement. The surface temperature difference (average value for twelve days) was 16.4 °C for the NCZ pavement and 10.0 °C for the NCF pavement. The surface temperature of the NCZ pavement was lower than that of the UCF pavement. The reason for this phenomenon is the same as the above mentioned, or the surface color of the NCZ pavement using the NZ was more creamy than the UCF and NCF pavements containing the FA. The CBGMs using the NPC, however, reduced the surface temperature less than that using the URHC. It depends on the color of the cement itself.

The surface temperature reduction of a pavement grouting a CBGM results from the higher solar reflectance (Synnefa et al., 2011). In general, a water retaining pavement is required to reduce the surface temperature by 10 °C and more, when a conventional asphalt pavement reaches 60 °C in the hot summer climate. From the field measurements, all of the CBGMs developed in this study satisfy the required surface temperature reduction, and the efficiency of their surface temperature reduction can last without rain water or additional water sprinkling. Furthermore, the NZ with creamy color used in this study is effective for the STRRF, compared with the FA.

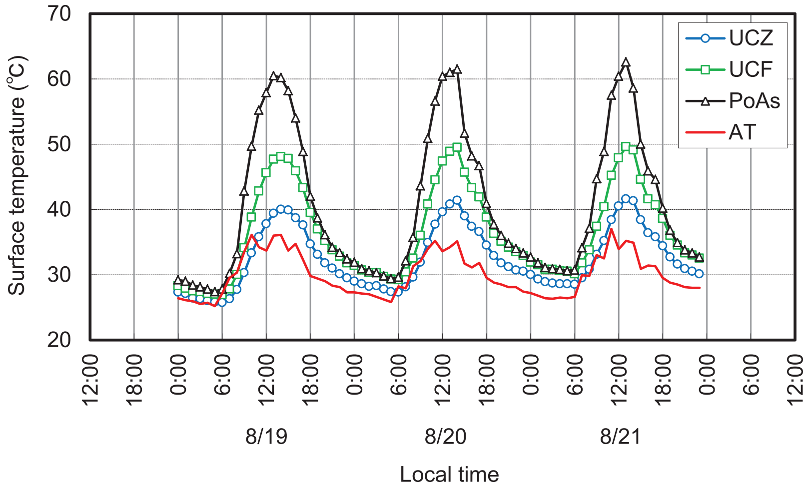

Fig. 5. Surface temperature distributions of UCZ and UCF pavements and the porous asphalt pavement (PoAs) with the atmospheric temperature (AT) for three days from Aug. 19 to 21 in 2014 (Higashiyama et al., 2016).

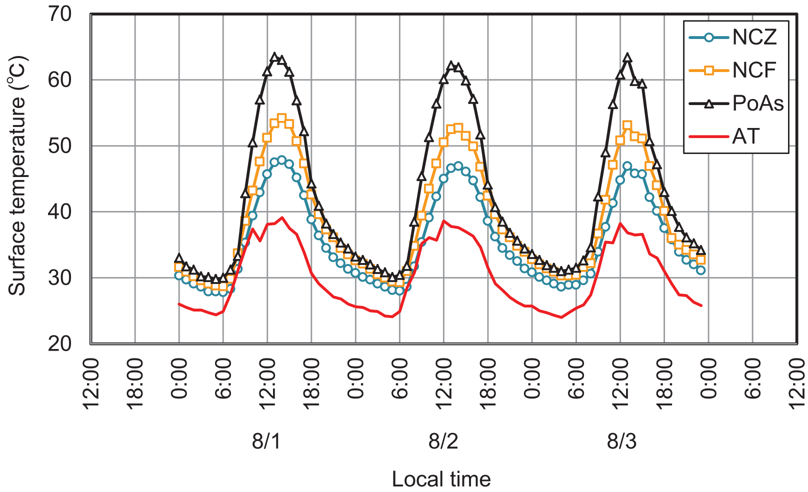

Fig. 6. Surface temperature distributions of NCZ and NCF pavements and the porous asphalt pavement (PoAs) with the atmospheric temperature (AT) for three days from Aug. 1 to 3 in 2015.

3.3. Surface temperature properties

From the surface temperature distribution of each pavement during the field measurement, the surface temperature difference between each pavement and the PoAs was calculated. The relationships between the surface temperature difference of each pavement and the surface temperature of the PoAs in the daytime (from 6:00AM to 6:00PM) are shown in Fig. 7a to d. It can be seen that the surface temperature difference and the surface temperature of the PoAs have a linear relationship for each pavement. From these relations, the surface temperature of the pavement with the CBGM can be estimated from the surface temperature of the PoAs under the same environmental conditions. The surface temperature deference of each pavement, when the surface temperature of the PoAs is 60 °C, is 20.3 °C for the UCZ pavement, 12.5 °C for the UCF pavement, 14.8 °C for the NCZ pavement, and 8.9 °C for the NCF pavement.

These pavements contribute to the mitigation of the urban heat island phenomenon and to utilization of the ceramic waste powder. The UCZ pavement shows superior thermal performance, and the surface temperature reduces by up to about 20 °C. The thermal performance of these pavements developed in this study will be continuously investigated through further field tests and fundamental tests in the laboratory.

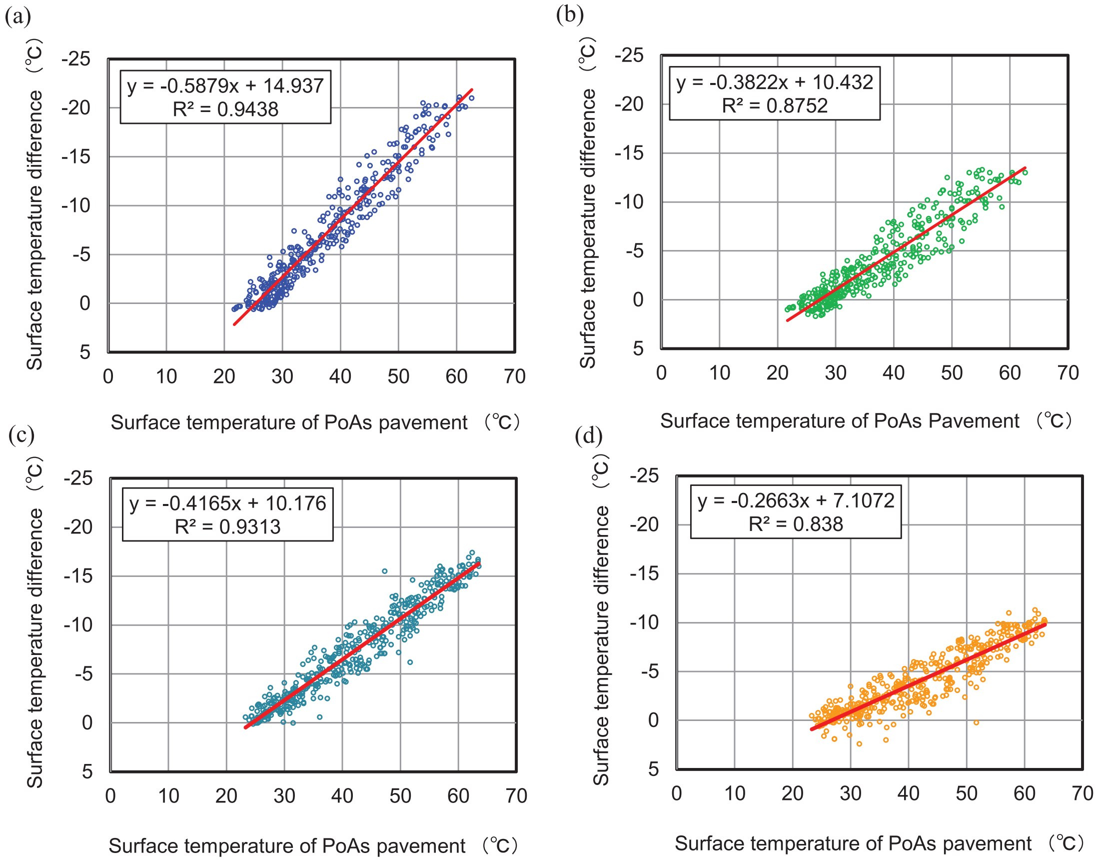

Fig. 7. Relationships between the surface temperature difference and the surface temperature of the porous asphalt pavement in the daytime (from 6:00AM to 6:00PM) for (a) UCZ pavement; (b) UCF pavement; (c) NCZ pavement; and (d) NCF pavement.

4. Conclusions

Asphalt pavements cover a high percentage of the urban area and largely affect the development of the urban heat island phenomenon. This study has two purposes: to utilize the ceramic waste powder and to improve the thermal conditions in the urban environment. In this study, the cement-based grouting materials used for the water retaining pavements were developed and the surface temperature of those water retaining pavements was measured in the field tests. All of the cement-based grouting materials were confirmed to effectively reduce the surface temperature of the asphalt pavement. The combinations of cement-based grouting materials can be selected from a viewpoint of economical and thermal performance. Especially, the ultra-rapid hardening cement and the natural zeolite having creamy color as the cement-based grouting material for the water retaining pavement more effectively reduce the surface temperature of the asphalt pavement. Their application to the urban area can have great potential in reducing the surface temperature and contribute to the mitigation of the urban heat island phenomenon. Moreover, the ceramic waste powder is utilized.

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