Road Temperature Mitigation Effect of Water Retentive Material Using Blast Furnace Slag

K. Takahashi & K. Yabuta
Steel Research Laboratory, JFE Steel Corporation, Chiba, Japan

ABSTRACT: Water retentive pavements are used in urban area to mitigate heat island phenomenon recently. Surface temperature of these pavements is cooled by vaporization of water released from the pavement. We developed water retentive material using blast furnace slags for the pavement, and it can be handled in the same way as cement, but has a water retentive character of at least 65% of its volume. Its pore diameter is about 2 μm; therefore, the solidified material can absorb and desorb water depending on temperature and humidity. Durability of temperature reducing effect is also important property for its in-service period, and water absorbing properties of the material are maintained at a high level after the accelerated aging test. Mitigation effect of pavements' temperature of the third summer season is almost the same as initial. Both simulation and observation indicate that water retentive pavements using blast furnace slag with 10cm thickness keep its surface temperature low for almost a week after a single rain.

KEY WORDS: Heat island, water retentive pavement, blast furnace slag.

1 INTRODUCTION

The recent progress of urbanization has brought a host of urban environmental problems to the fore. “Heat island,” temperature in urban area is higher than nearby outlying suburbs, is a typical example and it has been recognized since the 19th century. But with the abrupt advance of urbanization in recent years, the effect of this phenomenon has been increasing at an accelerated pace (Hoyano, 2001). Based on definitions from the United Nations, populations in urban areas now account for about 50% of the world population overall (U.N., 2006). We should think of the heat island phenomenon not merely as an urban environmental problem, but as an environmental problem of global scale.

A host of causes behind the heat-island phenomenon have been enumerated, such as changes of the earth’s surface, the intensive consumption of energy, and the intensive exhaust of heat, together with the effects of air pollution and the like. One of the main factors behind the temperature increase in urban centers is the replacement of green areas and bare areas with asphalt pavement and concrete structures. This change remarkably decreases the capacity of the cityscape to retain water, and it promotes the accumulation of heat in materials with larger heat capacities. Countermeasures such as rooftop gardening have been attempted in various ways, and water-retentive pavements are being adopted for roads. Water-retentive pavement is produced by pouring a water-retentive material into the voids of open-graded asphalt. The pavement has the same advantage of all artificial pavements, but can be cooled by the evaporation of the water retained within it. The water-retentive pavement not only reduces temperature of the road surface, but also restores water circulation on a macro scale.

The following three points can be enumerated as properties required of a water-retentive material: (1) the ability to suppress a temperature rise in fine weather, (2) sustainability of the effect in suppressing temperature rises after a single rainfall, and (3) a minimal decrease in performance after extended use.

On the other hands, reluctant of CO_2 emission become an important challenge against global warming. Blast furnace slag is used for cement addition and some other solidification purpose and it helps to reduce CO_2 emission from cement production. We focus on several properties of blast furnace slag and developed a water-retentive material using it (Hasegawa and Takahashi, 2006).

This paper describes an investigation of changes in the water absorption behavior of the water-retentive material after accelerated curing, measurements of the temperature rise suppressing performance of an actual parking space surface paved with this water-retentive material for three years, and a simulation of the sustainability of the temperature rise suppressing effect after a single rainfall.

2 EXPERIMENT METHOD

2.1 Basic Properties of the Water-Retentive Material using Blast Furnace Slag

A fine blast-furnace powder generated by the blast-furnace process, an admixture used in cement and the like, is one of the main raw materials of the water-retentive material. Figure 1 shows an SEM image of the fine structure of the material after solidification and its pore diameter distribution. The presence of voids among fine particles was observed after solidification, and its pore diameter close to 2 μm. This material has volume absorption rates of at least 65% of water, which suggest that water is retained in the voids observed in the solidified material, and the sharp pore diameter distribution ensures stable water absorption and discharge and volume stability.

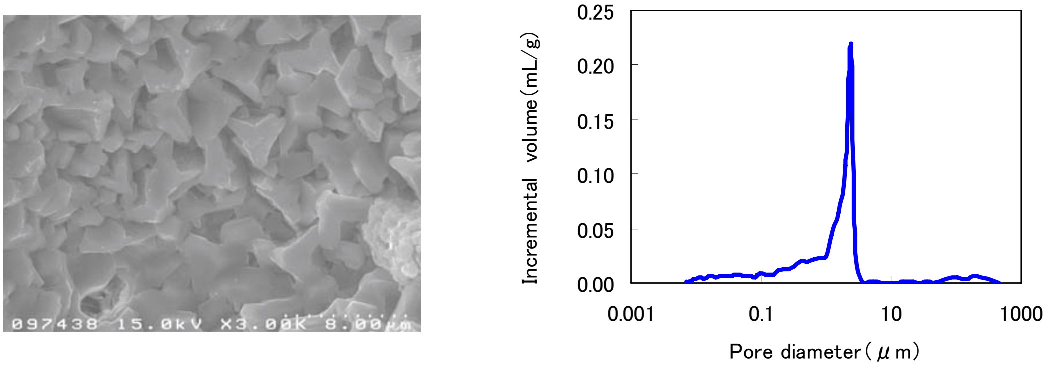

Figure1: SEM image of the fine structure of the material after solidification and its pore diameter distribution.

Table 1 shows the results of a leaching test conducted on Road Cool by the method described in Notification No. 46 of the Ministry of the Environment. A solidified water-retentive material was pulverized to 2 mm in diameter or less. The results confirmed that none of the leaching values for the elements exceeded their lower limits.

Table1: Results of a leaching test on the water-retentive material using blast furnace slag

Element	Leaching value(mg/l)	Element	Leaching value(mg/l)	Element	Leaching value(mg/l)
Cr (IV)	N.D.	Pb	N.D.	CN-	N.D.
Hg	N.D.	Se	N.D.	F	0.34
Cd	N.D.	As	N.D.	B	N.D.

2.2 Change in Water-Absorbing Properties of Water-Retentive Material by Accelerated Test

The accelerated curing test for the water-retentive material was conducted by immersing samples in water at 60°C (a temperature close to the maximum temperature of roads in actual use), accelerating the solidification reaction, and then conducting an absorbing test. The water-retentive material was mixed at a water-powder ratio of 100, molded into 10 cmφ × 20 cm cylindrical shape and cured for one week at 20°C in a sealed condition. The curing samples obtained were immersed for 1 to 7 days in warm water at 60°C, dried in air at 40°C, and tested by the water-absorbing test (proposed by Hosuisei-hosou-gijuts-kyokai, 2005). Two sample materials were used: 1) developed water-retentive material using blast furnace slag; 2) a test material with a comparable water-absorbing speed to that of 1) after room temperature curing and using higher binder material ratio.

2.3 Performance Change of Water-Retentive Pavement Used for a Long Period

A water-retentive pavement with the material using blast furnace slag was prepared in the parking area of JFE Steel R&D Laboratories. Figure 2 shows a schematic overview of the one of the test sites. The pavement temperature was measured with type K thermocouples buried at a depth of 15 mm from the pavement surface and curried out continuously for the next three years.

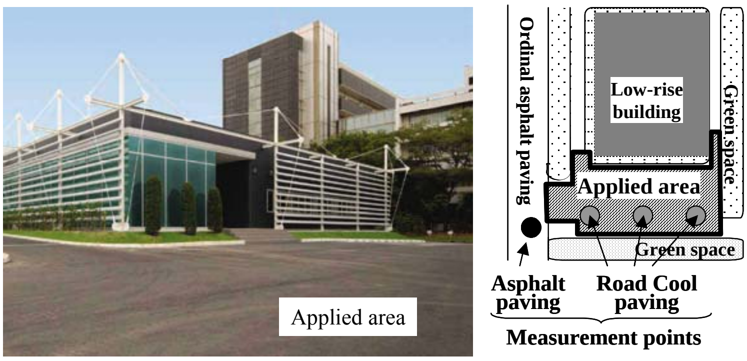

Figure2: Schematic overview of temperature measurement of water retentive pavement using blast furnace slag.

3 EXPERIMENTAL RESULTS

3.1 Water-Absorbing Properties of Water-Retentive Materials

Figure 3 shows (a) the water-absorption behavior of the water-retentive materials obtained when the curing conditions were changed (20°C and 60 °C) and (b) durability of these materials aged in 60 °C water indicated by the 24-hour water absorption when the curing time was changed. In the 20°C -aged material, a layer of water of 20 cm in height was completely suctioned in less than 4 hours in both cases. On the other hands, water absorption performance after aged in the 60°C water was quite different. In case of the material using blast furnace slag, the water was initially suctioned at the same speed as 20 °C case and the water suction performance, upto a height of 20 cm, was achieved about 2 more hour, which indicated sufficient water absorption performance was almost maintained. In contrast, the water-absorbing speed of the comparative material substantially decreased after curing at 60°C, while the water-absorbing speed of the sample cured at room temperature was almost the same as the material using blast furnace slag.

Water absorption level of 60°C cured materials were compared and in the material using blast furnace slag, the initial level of water absorption was maintained even after the material was cured for 1 week. In the comparative material with a higher binder content, the level of water absorption sharply decreased as the curing time with water was extended.

These results suggest that the water-absorbing properties change as the curing conditions change, and thus that the material performance should be investigated in actual use environments. The water-retaining capacity of the material using blast furnace slag appears to maintain in high level over time.

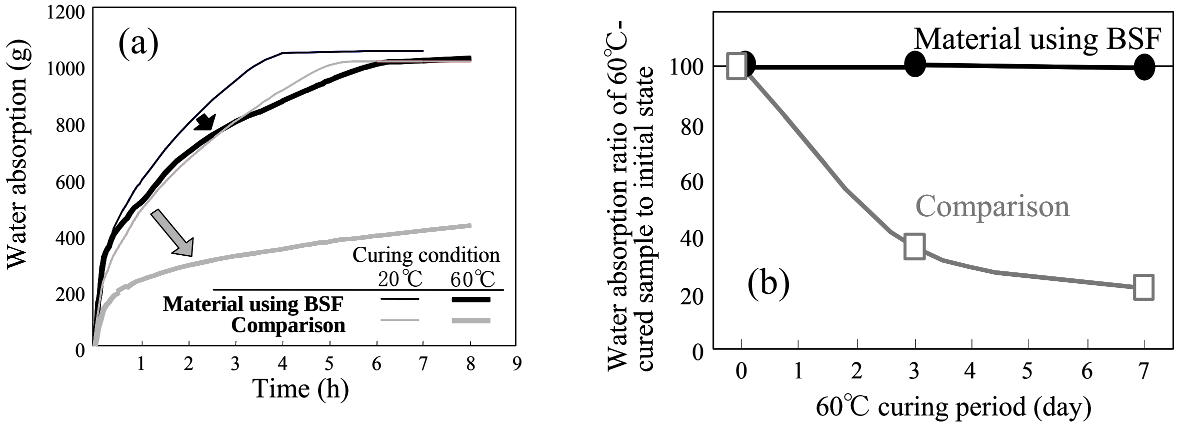

Figure3: Water absorption of water retentive materials after 20°C and 60°C aging (a) and 24-hour water absorption of the 60°C -cured materials after various curing period (b).

3.2 Performance Change of Water-Retentive Pavement Used for an Extended Period

The water-retentive pavement with blast furnace slag was used in an actual parking area for three summer seasons to investigate the effect of the material in suppressing temperature rises of the road surface. Figure 4 shows examples of a daytime temperature change of the water-retentive pavement and a dense-graded asphalt pavement in the third summer (a) and temperature difference distribution of cross section of both pavements in autumn season (b).

In the case shown in Fig. 4(a), the difference in the maximum temperature between the water-retentive pavement and the dense-graded asphalt pavement was about 14°C, that indicate water retentive pavement using blast furnace slag continued to confer a cooling effect even in the third summer. In autumn season, the temperature difference was observed in large area, but the highest temperature gap got smaller than that of summer season.

About the pavement surface condition, small amount of aggregate chipping were observed around the seams of asphalt pavement, but the substantial change, such as flow rut, had not been seen during the experimental period.

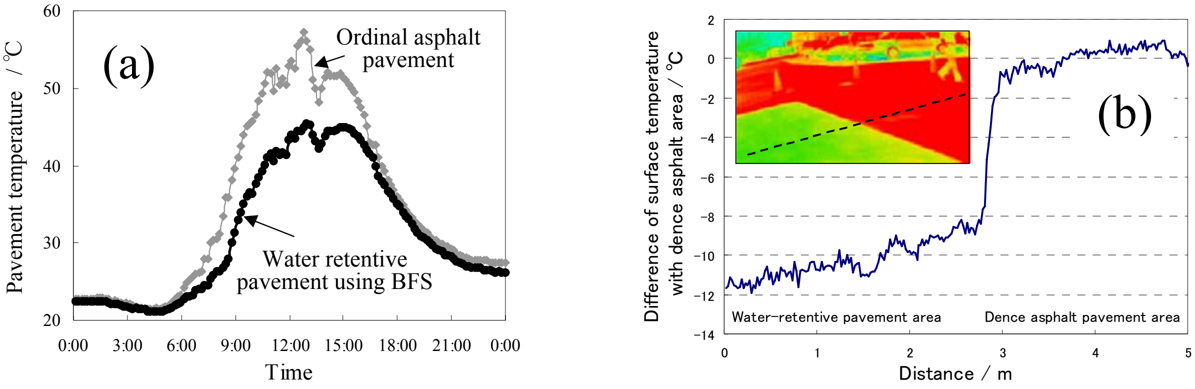

Figure4: Examples of a daytime temperature change of the water-retentive pavement and a dense-graded asphalt pavement in the third summer (a) and temperature difference distribution of cross section of both pavements in autumn season (b).

Figure 5 shows the relation of the temperature difference between the water-retentive pavement and the dense-graded asphalt pavement in the second day after a rainfall. The temperature difference became more apparent as the temperature of the dense-graded asphalt pavement rose, and the temperature difference trend was almost the same in the first year and third year. On this basis, the properties of the water-retentive pavement can be assumed to have scarcely deteriorated after the lapse of three summers.

Basically, temperature differences of more than 10°C were observed when the temperature of the dense-graded asphalt surface exceeded 50°C; however, variations in the temperature difference were observed at the same time. This was presumably caused by changes in the evaporation efficiency due to the precipitation and sunshine conditions on the day before, the moisture of the atmosphere, and other factors.

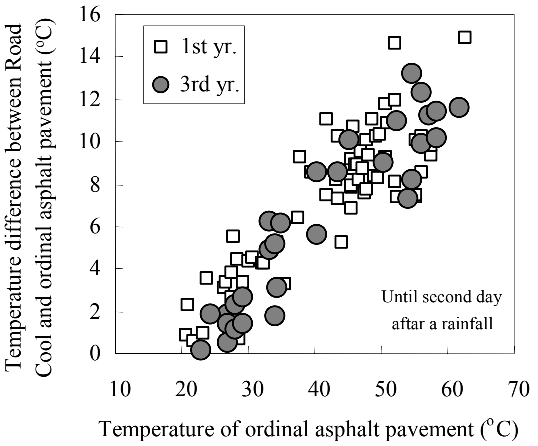

Figure5: The relation of the temperature difference between the water-retentive pavement and the dense-graded asphalt pavement in the second day after a rainfall.

4 SIMULATION OF ROAD COOLING EFFECT

4.1 Calculation Condition

The road cooling effect of the water-retentive pavement using and the sustainability of the effect were examined using a vertical one-dimensional heat balance model. The underground heat balance is expressed by the following heat conduction equations:

$$\frac{\partial (c_g(z)\rho_g(z)T(z))}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T(z)}{\partial z}\right) + Q_{surf} - Q_W \quad (1)$$

$$Q_{surf} = R_n^{\downarrow} - Q_H - Q_E \quad (2)$$

where $c_g(z)$ is the specific heat of the ground at depth z, $\rho_g(z)$ is the density of the ground at depth z, $T(z)$ is the temperature at depth z, Q_{surf} is the sum of the heat balance on the surface, Q_w is the quantity of heat removed by the supply of water, $R_n^{\downarrow}$ is the net amount of radiation, Q_H is sensible heat transport, Q_E is latent heat transport. Q_{surf} is given only for the surface. It has an assumption that the voids are filled with water completely in the nighttime at the same temperature as the road surface, therefore Q_w is considered to 0.

In a macro-analysis, the evaporation from the water-retentive pavement is generally modeled by a bulk equation based on the humidity of right over the pavement surface and its saturated humidity (Kimura et al., 1987). In an individual analysis, however, the effect of the water content of the water-retaining layer must be considered. A model estimating the amount of evaporation considers the moistness of the soil and introduces the ratio between the weight water content and the saturated weight water content as a linear coefficient (Tanimoto et al, 1997). A laboratory evaporation test has ascertained that the amount of evaporation decreases as drying proceeds (Yamazaki et al., 2008).

In our experiment, we measured the amount of evaporation from a saturated water-retentive pavement in each time zone, and we assume that the measured amount of evaporation was determined by the combined effects of the ambient temperature, mass-transfer coefficient, humidity, and other conditions. The amount of evaporation per unit time E was determined by multiplying this amount of evaporation by the water content.

$$E = (k_c \cdot I_{DR} + C) \cdot \frac{W}{W_F} \quad (3)$$

where, k_c is a proportionality constant for the amount of incoming radiation and the amount of evaporation (6.5×10^{-7} kg/J), C is the equivalent amount of evaporation in the nighttime (2.0×5 kg/m^{2}s), W is the water content of the water-retentive material, and W_F is the maximum water content of the water-retentive material. For the water content of the water-retentive material, we assume that the voids are completely filled with water at 12:00 on the first day of calculation, that the water content of the water-retentive material decreases by evaporation from the surface alone, and that no water is received from or released into the surrounding area. For physical properties such as heat capacity and specific gravity, we use those calculated according to the water content.

In the calculation of the ground surface excluding evaporation, the amount of received heat is calculated based on data from the Japan Meteorological Agency on the amount of solar radiation, and the sensible heat transport with the air was calculated using the convention heat transfer coefficient found by Jurges equation.

4.2 Calculation Results

Figure 6(a) shows the calculation results of the surface temperatures of the water-retentive pavement using BSF and dense-graded asphalt pavement on a day when the voids are filled with water. The road surface temperature is approximately 14°C, which agrees well with the measurement result. In the case of the 10 cm pavement, the temperature difference in the nighttime clearly appears, that suggests the water-retentive pavement seems to be effective not only in mitigating heat island phenomenon in daytime but also in alleviating the heat on sweltering nights, compare with the ordinal asphalt pavement with large heat accumulation.

Figure 5(b) shows the observed and calculated values of the surface temperature difference between water-retentive pavement and ordinal asphalt pavement after a single rainfall. Although they vary with changes in the amount of rainfall, the evaporation condition on the previous day, solar radiation conditions, and other factors, the calculated results correspond closely with the observed values. Both the moisture evaporation from the water-retentive material and the reflection of solar radiation contribute importantly to the cooling effect of the water-retentive pavement, and the former decreases as days elapse after a rainfall. In the case of the 10 cm pavement, the temperature difference from the dense-graded asphalt pavement is calculated on the order of 6°C when the amount of retained water is 0, therefore the effect in suppressing the temperature rise of the pavement by evaporations can be expected to last for about one week.

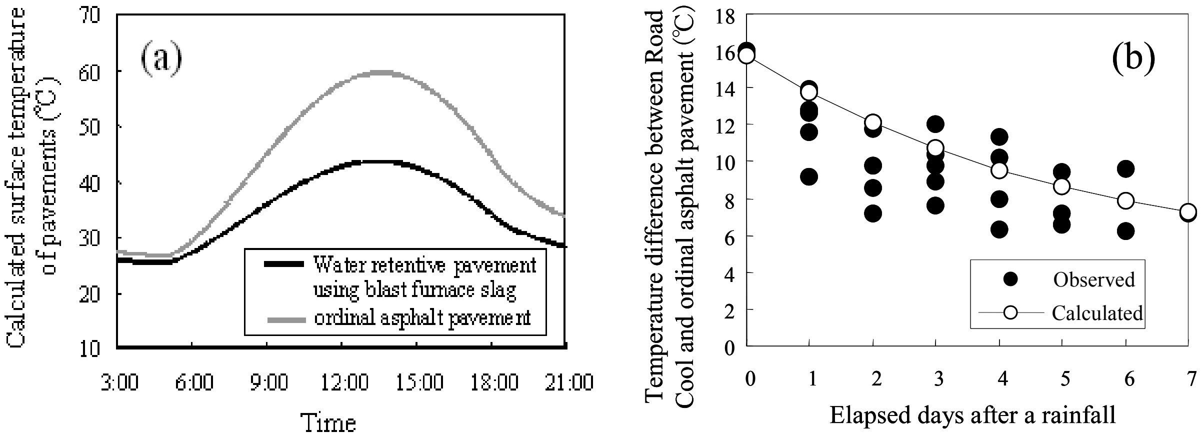

Figure6: Calculated surface temperature of water retentive pavement using blast furnace slag and ordinal asphalt pavement (a), and surface temperature difference between these pavements via elapsed days after a single rainfall (b).

5 CONCLUSIONS

The water-retentive material produced with blast furnace slag as a raw material, is used to suppress the heat-island phenomenon. It has been applied to national roads, prefectural and city roads, and various types of parking areas, parks, and other paved surfaces. The temperature suppressing effect of the pavement was evaluated to determine its long-period durability, temperature rise suppression after a single rainfall, and sustainability.

(1) The water-absorbing properties were evaluated by accelerated curing at 60°C. This clearly showed that the properties after accelerated curing sometimes vary greatly even when the initial characteristics are equivalent.

(2) The water-absorbing properties of water retentive material using blast furnace slag change only slightly after accelerated curing, and the effect of the water-retentive pavement with the BFS containing material in suppressing rises of road temperature after three summers was found to be similar to the effect immediately after the construction.

(3) The rises in road temperature are suppressed via the combined effect of water evaporation and reflection of solar radiation. Direct observations and calculated results on the effects of

cooling by evaporation suggest that this suppressive effect last for about one week for pavement.

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