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Road Temperature Mitigation Effect of "Road Cool," a Water-Retentive Material Using Blast Furnace Slag†

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Abstract:

JFE Steel developed water-retentive material using blast furnace slag for water-retentive pavement, which is applied for mitigating urban heat-island phenomenon, and commercialized with improved durability of temperature reducing effect. Water absorbing properties 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 that of initial stage. Both simulation and observation indicate that "Road Cool" pavements with 10 cm thickness keep its surface temperature low for almost a week after a single rainfall.

1. Introduction

The recent progress of urbanization has brought a host of urban environmental problems to the fore. The "heat-island" phenomenon is a typical example. "Heat island," temperature in urban area is higher than nearby outlying suburbs, have 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[1]. Based on definitions from the United Nations, populations in urban areas now account for about 50% of the world population overall[2]. 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 materials, 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 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.

JFE Steel developed a water-retentive material made from blast furnace slag[3] and marketed it as a new generation of improved-durability "Road Cool"[4]. 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 "Road Cool"

A fine blast-furnace powder generated by the blast-

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furnace process, an admixture used in cement and the like, is one of the main raw materials composing Road Cool.

Table 1 shows the basic properties of Road Cool. Road Cool is available in two types: the high water-retentive type with a higher water-retaining capacity, and the high-strength type designed with a slightly higher strength. Both types have volume absorption rates of at least 65%. **Photo 1** shows a scanning electron microscope (SEM) image of the micro structure of Road Cool after solidification. The presence of voids among fine particles was observed after solidification, and estimates suggest that water is retained in the voids. Road Cool is designed with a prevalent pore diameter of 2 μm[4)]. This ensures stable absorption and discharge of water and volume stability.

Table 1 Material properties of Road Cool

	High-water retentive type	High-strength type
Raw material	Blast furnace slag, Cement, Admixture	
Water/Powder (%)	100	
Slurry density	1.45	
7 days compressive strength (MPa)	1.6	2.7
10 cm-hight suction time (min)	66	75
Water absorbtion (volume%)	min. 70	min. 65

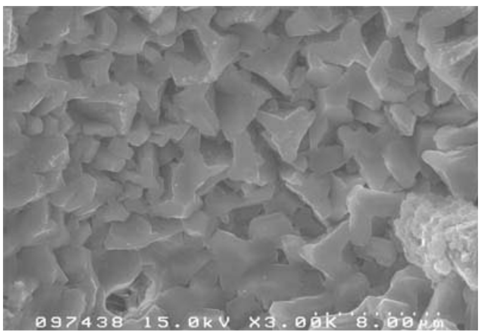

Photo 1 SEM image of Road Cool after solidification

Table 2 Result of reaching test of Road Cool

Element	Leaching value (mg/*l*)	Element	Leaching value (mg/*l*)
Cr (IV)	N. D.	As	N. D.
Hg	N. D.	CN^2	N. D.
Cd	N. D.	F	0.34
Pb	N. D.	B	N. D.
Se	N. D.	—	—

N. D.: Not detectable

Table 2 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.

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. The samples were dried in air at 40°C, and tested by the water-absorbing test. **Figure 1** shows a schematic diagram of the water-absorbing test. The 5 mm bottom sections of the samples were immersed in flowing water after the samples had dried and returned to room temperature, then the amount of water absorbed was measured based on the method proposed by Hosuisei-hosou-gijutsu-kyokai[5)]. Two sample materials were used: first, Road Cool; second, a test material with a high binder content and a water-absorbing speed comparable to that of Road Cool after room temperature curing.

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

A water-retentive pavement with Road Cool was prepared in the parking area of JFE Steel R&D Laboratories, and the pavement temperature was measured continuously for the next three years. **Figure 2** shows a schematic overview of the site. The temperature measurement was carried out with type K thermocouples

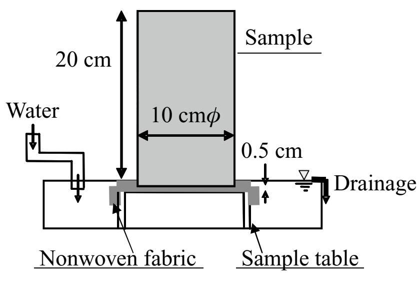

Fig. 1 Schematic diagram of water absorbing test

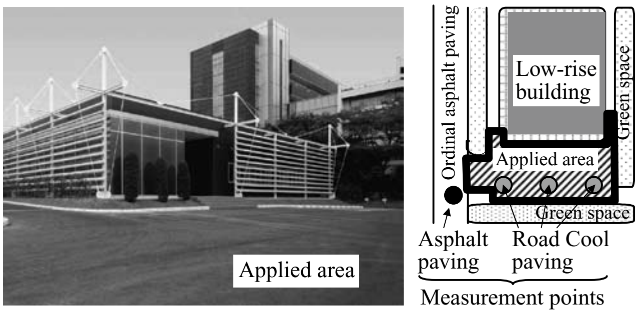

Fig. 2 Schematic overview of temperature measurement of water retentive pavement using Road Cool

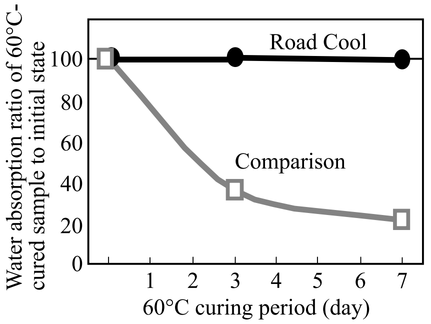

Fig. 4 24-hour water absorption of 60˚C-cured water retentive materials after various curing period

buried at a depth of 15 mm from the pavement surface.

3. Experiment Results

3.1 Water-Absorbing Properties of Water-Retentive Materials

Figure 3 shows the water-absorption behavior of the water-retentive materials obtained when the curing conditions were changed. In the Road Cool aged at 20°C, a layer of water of 20 cm in sample’s height was completely suctioned in less than 4 hours. In the Road Cool aged at 60°C, the water was initially suctioned at the same speed and sufficient water absorption performance was maintained until the water suction upto a height of 20 cm was about 2 hours late. In contrast, the water-absorbing speed of the comparative material with the higher binder content substantially decreased after curing at 60°C, while the water-absorbing speed of the sample cured at room temperature was almost the same.

Figure 4 shows the change in the 24-hour water absorption when the curing time was changed. In Road Cool, the initial level of water absorption was maintained even after the material was cured with water at 60°C 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 variation, and thus that the material performance should be investigated in actual use environments. The water-retaining capacity of Road Cool appears to maintain in high level over time.

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

The water-retentive pavement with Road Cool 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 5** shows examples of a daytime temperature change of the water-retentive pavement and a dense-graded asphalt pavement in the third summer. Road Cool continued to confer a cooling effect even in the third summer. In the case shown in Fig. 5, the difference in the maximum temperature between the water-retentive pavement and the dense-graded asphalt pavement was about 14°C.

Figure 6 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

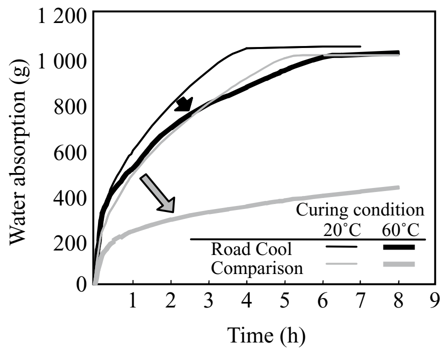

Fig. 3 Water absorption of water retentive materials after 20˚C and 60˚C during

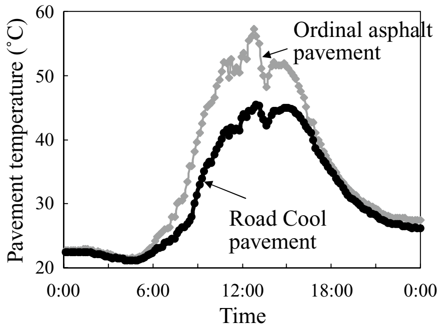

Fig. 5 Typical results of surface temperature of Road Cool pavement and ordinal asphalt pavement at third summer

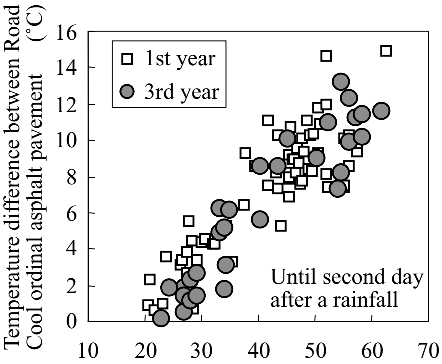

Fig. 6 Temperature difference between Road Cool pavement and ordinal asphalt pavement

basis, the properties of the water-retentive pavement can be assumed to have been maintained 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.

4. Simulation of Road Cooling Effect

4.1 Calculation Conditions

The road cooling effect of the water-retentive pavement of Road Cool 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:

$$\frac{\partial\left(c_g(z)\,\rho_g(z)\,T(z)\right)}{\partial t}=\frac{\partial}{\partial z}\left[\lambda\frac{\partial T(z)}{\partial z}\right]+Q_{\mathrm{surf}}-Q_{\mathrm{W}} \quad \cdots\cdots(1)$$

$$Q_{\mathrm{surf}}=R_{\mathrm{n}}{\downarrow}-Q_{\mathrm{H}}-Q_{\mathrm{E}} \quad \cdots\cdots(2)$$

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[6]. In an individual analysis, however, the effect of the water content of the water-retaining layer must be considered. A model by Tanimoto et al. for 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[7]. A laboratory evaporation test has ascertained that the amount of evaporation decreases as drying proceeds[8]. In our experiment, the amount of evaporation from a saturated water-retentive pavement in each time zone were measured, 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 the amount of evaporation by the water content.

$$E=(k_{\mathrm{c}}\cdot I_{\mathrm{DR}}+C)\cdot\frac{W}{W_{\mathrm{F}}} \quad \cdots\cdots(3)$$

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 (2.0×10^{-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 only from the surface, and that no water is received from or released into the surrounding area. Physical properties, such as heat capacity and specific gravity, are also calculated according to the water content.

In other calculation conditions, 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 7 shows the calculation results of the surface temperatures of the water-retentive pavement 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

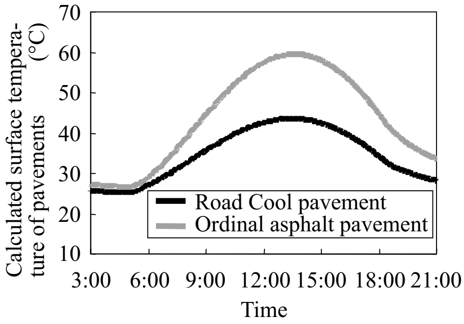

Fig. 7 Calculated surface temperature of Road Cool pavement and ordinal asphalt pavement

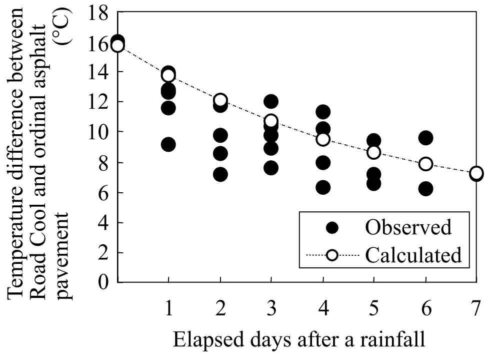

Fig. 8 Relationship between elapsed days after a single rainfall and reduced surface temperature by using Road Cool

in daytime but also in alleviating the heat on sweltering nights, compare with the ordinal asphalt pavement with large heat accumulation.

Figure 8 shows the observed and calculated values of the temperature-rise-suppressing effect of the 10 cm water-retentive pavement after a single rainfall. The calculated results correspond closely with the observed values, although they vary with changes in the amount of rainfall, the evaporation condition on the previous day, solar radiation conditions, and other factors. 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 with no retained water, the temperature difference from the dense-graded asphalt pavement is calculated on the order of 6°C, therefore the effect in suppressing the temperature rise of the pavement by evaporations can be expected to last for about one week.

5. Concluding Remarks

Road Cool, a water-retentive material produced with slag as a raw material, is used to suppress the heat-island phenomenon. As of this writing, it has been applied to national roads, prefectural and city roads, and various types of parking areas, parks, and other paved surfaces. The effect of Road Cool in suppressing increases in road temperatures was evaluated to determine its long-period durability, temperature rise suppression after a single rainfall, and its sustainability.

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

(2) The water-absorbing properties of Road Cool change onlyslightly after accelerated curing, and the temperature-rise-suppressing effect of the pavement with Road Cool 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 suggest that the cooling effect by evaporation last for about one week for pavement.

References

1) Hoyano, A. Midori No Dokuhon. 2001, no. 57, p. 337–344.
2) World Urbanization Prospects. The 2005 Revision Population Database. United Nations. 2006.
3) Takahashi, K.; Takagi, M.; Satoh, Y. The 24th Japan road conference. 2001, p. 274.
4) Hasegawa, K.; Takahashi, K. Environmental Solution Technology. 2006, vol. 5, no. 4, p. 19.
5) Hosuisei Hosou Gijyutsu Kenkyukai, public Works Management Journal. 2005, no. 326, p. 35.
6) Kimura, K.; Nagasawa, K.; Sugiura, S.; Ohba, K. Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan D. 2007, p. 875.
7) Tanimoto, J.; Hayashi, T.; Katayama, T. Journal of Architecture and Planning. 1997, no. 492, p. 23.
8) Yamazaki, M.; Miyawaki, T.; Satoh, Y.; Sakata, K.; Takahashi, K. Doboku Gakkai Ronbunshu G. 2008, vol. 64, p. 196.