Cooling Effect of Water Retentive Pavement Utilizing Fly Ash

T. Shimpo
R&D Center, Tokyo Electric Power Company, Yokohama, Kanagawa, Japan

ABSTRACT: As a countermeasure to mitigate urban heat island and sustain high recycle rates of byproducts emitted from coal thermal power plants, a water retentive pavement utilizing fly ash has been designed. This water retentive pavement is composed of the asphalt surface course filled with slurries and the base course laying artificial crushed stones. The pavement materials, which are the slurries and the crushed stones, are made of fly ash and have high water absorption. Ideally, rainwater is reserved in the base course so that the water can be absorbed into the surface course due to the capillarity mechanism. Then, through a series of laboratory and field experiments, the cooling effect of the water retentive pavement utilizing fly ash has been investigated. The field experiments confirmed that the developed cool pavement lowers the surface temperature by about 10 degrees Celsius in maximum compared to common dense pavement.

KEY WORDS: urban heat island, fly ash, water retentive pavement, cooling effect.

1 INTRODUCTION

In fiscal 2007, approximately 8.8 million tons of fly ash was produced from the power industry in Japan, marking a 1.2-fold increase in five years. And then approximately 8.45 million tons of fly ash, which accounts for about 96% of the amount produced, was recycled. Of this, about 5.18 million tons (61%) was used in cement-related fields, including approximately 5 million tons as cement materials. Furthermore, about 1.3 million tons was recycled for improving the ground and other civil engineering purposes, including about 0.15 million tons as base course materials and asphalt fillers. In other words, the amount of fly ash recycled in the pavement field accounts for only about 1.7% of the total amount produced.

In the market, the artificial crushed stones produced from fly ash are disadvantageous to widely used alternatives in terms of costs. The crushed stones require additional costs for mixing several kinds of materials, solidifying, and crushing. In addition, the areas to which the stones can be supplied are also limited due to economic restrictions. In order to spread recycled materials, they should be utilized not as an alternative of currently used materials but as differentiated functional materials that have additional values.

Focusing on mitigation of urban heat island, the author has devised and investigated the use of the artificial crushed stones of fly ash as the base course of water retentive pavement. The crushed stones produced from fly ash are more water retentive than ordinary base course materials and are thus estimated to be effective for increasing the water retentive performance of pavement when lay under water retentive asphalt surface course so that the resultant pavement has a double water retentive structure (Shimpo 2006, Shimpo and Takahashi 2008). Besides, water retentive filling materials for porous asphalt surface course have been developed by utilizing the properties of fly ash. The water retentive performances of the developed water retentive pavement, which utilizes fly ash and retains rainwater in the base course, will be checked on community roads, plazas, pedestrian paths, etc.

This paper describes 1) the physical properties of the recycled fly ash materials, 2) the cooling effects of the water retentive pavement utilizing fly ash in laboratory, field and on-road demonstration tests, and 3) the effects of sprinkling water and storing rainwater on the performances of water retentive pavement constructed in a test yard.

2 PAVEMENT MATERIALS

2.1 Base Course Materials of Artificial Crushed Stones Produced from Fly Ash

The artificial crushed stones were produced by adding burnt lime and gypsum dihydrate to Class II fly ash, adding water and water reducing admixture, mixing, solidifying under steam curing, crushing so as to satisfy the required sizes of crushed stones for road, and adjusting the grain size. The physical properties of the artificial crushed stones used on a trial bases for public road in Ibaraki and Yokohama are shown in Table 1.

Fly ash was solidified in a concrete products plant by controlling the properties so that the compressive strength was at least 20 N/mm^2 to produce crushed stones of water absorption rate of at least 25% and abrasion loss of less than 35% on a test basis. The physical properties of the base course consisting of the artificial crushed stones produced from fly ash are shown in Table 2. Base course M-30 was prepared in a plant for producing recycled crushed stones, and M-40 was prepared using a movable rotary shredder mixer. However, special-purpose plants will be necessary for full-scale production.

The elution of trace components, such as arsenic, chromium (VI), fluorine compounds, boron, and selenium, could be controlled not to exceed the environmental soil quality standards by controlling the mix proportions and the quality.

Table 1: Physical properties of solidified fly ash and artificial crushed stones

State	Physical Property	IBARAKI	YOKOHAMA	Testing method
Solidified	Compressive strength (N/mm^2)	23.6	21.6	JIS A 1107
Crushed	Density (g/cm^3)	1.73	1.77	JIS A 1110
	Water absorption (%)	28.2	28.0	
	Abrasion loss (%)	33.0	32.4	JIS A 1121

Table 2: Physical properties of the base course

Test item	Physical property	IBAGAKI	YOKOHAMA
		M-30	M-40
Compaction test (JIS A 1210)	Optimum water content (%)	36.8	30.5
	Maximum dry density (g/cm^3)	1.241	1.304
Modified CBR test (Pavement Test Manual)	92-times dry density (g/cm3)	1.238	1.297
	Modified CBR (%)	96.8	132.6

2.2 Water Retentive Filling Materials

Water retentive filling materials (powder) were prepared by adjusting the amount of additives (portland blast furnace cement, gypsum hemihydrate and hydrated lime) mixed with fly ash so that the slurry and solid prepared by adding the predetermined amounts of water satisfied the required qualities (flowability, strength, water absorbability and environmental safety). Fly ash was added to account for 77 to 82% of the total weight of the powder materials to achieve a high recycling rate.

The qualities of the water retentive filling materials (slurry and solid) tested in Yokohama (construction area: about 690 m^2) were the time of flow (P funnel flow value) of 9.5 seconds, compressive strength (age: 28 days) of 2.7 N/mm^2, and maximum water absorption rate (age: 28 days) of 49.1%. The property values of the water retentive filling materials (slurry and solid) used in Komae (construction area: about 250 m^2) are shown in Table 3. The water retentive filling materials satisfied the standard property values stated in the specifications of the Tokyo Metropolitan Government for civil engineering materials. The water absorption by exposure was 3.4 l/m^2. Because the test was conducted using core specimens (φ10×5 cm) sampled at the age of 3 days, the measured values were slightly lower than the actual values due to fallout of water retentive filling materials near the surface of the cores. The water absorption of the specimen (30×30×5 cm) prepared at the site for quality control was 5.4 l/m^2.

The elution of trace components, such as arsenic, chromium (VI), fluorine compounds, boron, and selenium, could be controlled not to exceed the environmental soil quality standards by controlling the mix proportions and the quality.

Table 3: Quality of water retentive filling materials used in Komae

Item		Measured value	Standard property value (*)	Testing method
Slurry density (tf/m^3)		1.495	—	JIS A 1116
Time of flow (sec)		9.6	9～13	JSCE-F 521
Maximum water absorption (%)		56.4	At least 40	Guideline of the Tokyo Metropolitan Government (**)
Bending strength (N/mm^2)	Age: 7 days	0.40	At least 0.3	JIS R 5201
Compressive strength (N/mm^2)	Age: 7 days	0.76	At least 0.5	JIS R 5201
Water absorption by exposure (l/m^2)		3.4	At least 3.0	Guideline of the Tokyo Metropolitan Government (**)

*) Standard property value in the specifications of the Tokyo Metropolitan Government for civil engineering materials
**) Guideline of the Tokyo Metropolitan Government for designing and constructing water retantive pavement

3 IRRADIATION TEST

3.1 Test Conditions

The cooling effects of pavement that consisted of base and surface courses, which were both water retentive, were examined by conducting a comparative irradiation test on dense asphalt pavement and water retentive pavement. The temperature of the road surface was measured with thermocouples installed in the depth of 1 cm from the surface.

The specimens that simulated the pavements were prepared in acrylic molds (inside dimensions: φ30×30 cm, side plate thickness: 1 cm, bottom plate thickness: 2 cm) by spreading and compacting artificial crushed stones of fly ash to have a depth of 24 cm to form the water retentive base course and overlaying water retentive asphalt concrete or dense graded asphalt concrete to a depth of 5 cm. The void ratio of the porous asphalt where the water retentive slurry was filled up was about 23%.

To allow the base course to absorb water, the bottom plate of the mold had one hole (φ3 mm) at the center and 12 holes on the circumference of a circle of 7.5 cm radius. The specimens were covered by 10-cm thick polystyrene foam for heat insulation. The lights (150W) for irradiating the specimens were positioned so that the temperature at the surface of the dense graded asphalt pavement reached 60℃ in 6 to 7 hours and that the dense graded asphalt pavement and water retentive pavement received the same amount of irradiation.

The water retentive pavement was allowed to absorb water by filling water on the previous night so that the road surface submerged 1 cm under the water and saturating the water retentive surface course. During the test, the bottom of both specimens was submerged in water to allow the base course to gradually absorb water.

3.2 Cooling Effect

Changes in road surface temperature of the dense graded asphalt pavement and water retentive pavement, which were measured with thermocouples, are shown in Fig. 1 (irradiation: 1 cycle).

When the specimens were irradiated for about 6.5 hours, the temperature at the surface of the dense graded asphalt pavement reached 60℃, while the road surface temperature of the water retentive pavement was only slightly higher than 40℃. The water retentive pavement was thus capable of cooling the road surface by 18℃ (temperature difference between the dense graded asphalt pavement and water retentive pavement) when the surface course was saturated with water and water permeated from outside to the base course.

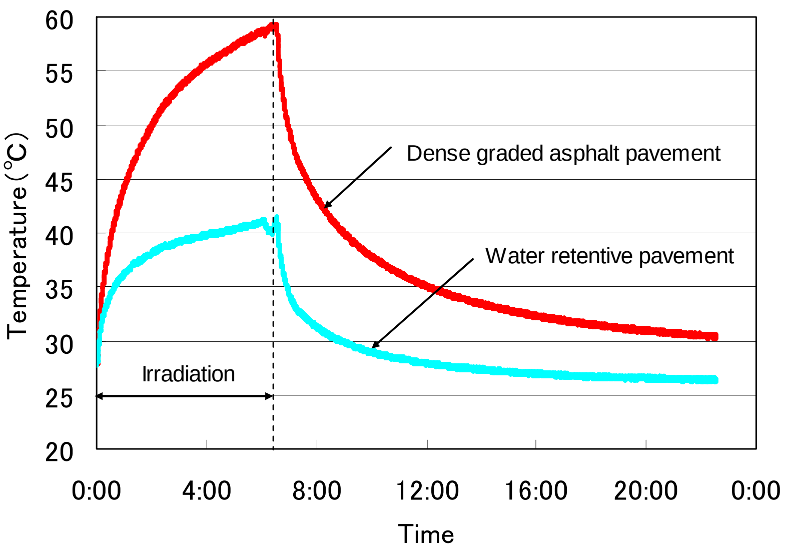
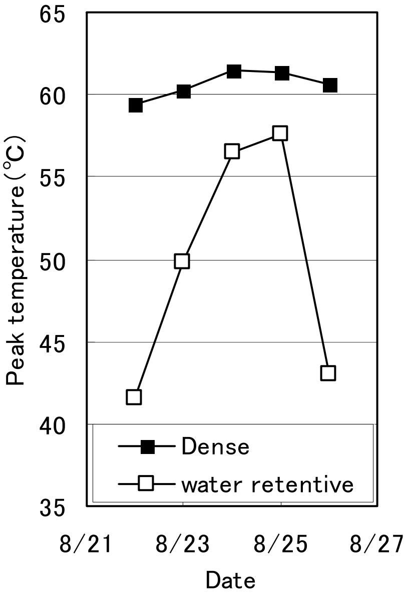


Figure 1: Changes in road surface temperature (irradiation: 1 cycle)

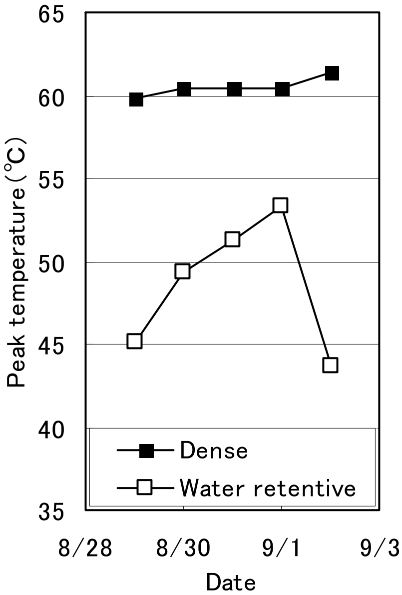
3.3 Continuance of the Cooling Effect

Fig. 2 compares the peak temperatures at the road surfaces of the dense graded asphalt pavement and water retentive pavement when the lights were irradiated for 5 continuous cycles. It also shows the effects of water absorption from the bottom on mitigating rises of road surface temperature.

The dense graded asphalt pavement and water retentive pavement were irradiated simultaneously for 5 continuous cycles with or without absorbing water from the bottom. The water retentive pavement was allowed to absorb water sufficiently on the night before the first irradiation. On the night prior to the fifth irradiation cycle, water was supplied on the road surface of the water retentive pavement to check the cooling effect of the surface course that was saturated again.



(a) Without absorbing water



(b) With absorbing water

Figure 2: Mitigation of rises in surface temperature by water absorption from the base course

When water was not absorbed from the bottom of the base course, the water retentive pavement cooled the road surface by 18℃ during the first irradiation cycle as shown in Fig. 2(a), but could control the temperature by only 11℃, 5℃ and 4℃ during the second, third, and fourth cycles, respectively. When the surface course was saturated again prior to the fifth cycle, the cooling effect was restored to 18℃.

On the other hand, when water was absorbed from the bottom of the base course (Fig. 2(b)), the cooling effects during the first and second cycles were 15℃ and 11℃, respectively. They were 9℃ and 7℃ during the third and fourth cycles, respectively, showing sustained cooling effect compared to that without water absorption from the bottom. The cooling effect was restored to 18℃ during the fifth cycle.

The test suggested that supplying water to the base course could improve the effect of the water retentive pavement in cooling the road surface.

4 FIELD EXPERIMENT

4.1 Cases Tested

The pavement cases tested at the outdoor experimental field are shown in Fig. 3. One section of dense graded asphalt pavement (Case 1) and two sections of water retentive pavement (Cases 2 to 3) were constructed. Each section had an area of 17.5 m^2 (5 m long and 3.5 m wide), and the depth of the asphalt surface course was 5 cm.

The two cases of water retentive pavement cases had mutually different conditions of the surface and base courses. Case 2 had 5-cm thick binder course (water impermeable one) under the water retentive surface course. Case 3 had 20-cm thick water retentive base courses (artificial crushed stones of fly ash) under the water retentive surface course.

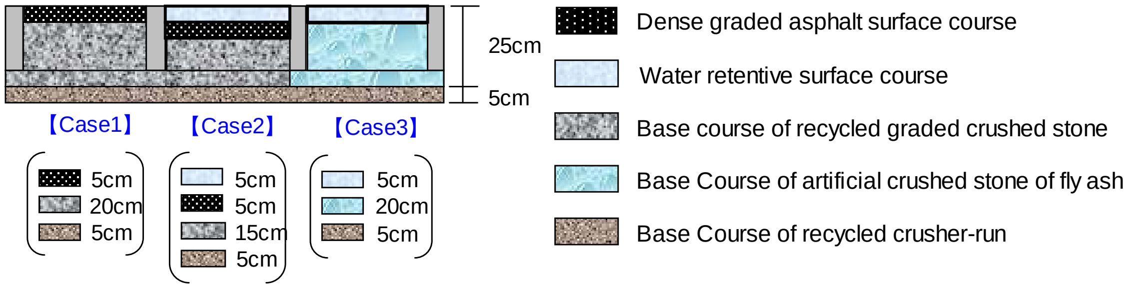


Figure 3: Pavement cases in field experiment

4.3 Cooling of the Road Surface

Changes in the temperature on the road surfaces of the dense graded asphalt pavement, water retentive pavement with binder course, and water retentive pavement with thick water retentive base course in 4 days at midsummer are shown in Fig. 4. The amount of precipitation and outdoor air temperature were monitored at the experimental yard.

It rained discontinuously but heavily from August 16 to the midnight of August 18, 2006, recording a total rainfall amount of at least 100 mm. After the rain, the road surface temperature of the dense graded asphalt pavement reached 53 to 57℃. On the other hand, it reached only 42 to 46℃ on the water retentive pavement with water retentive base course. As the peak temperature on the water retentive pavement with water impermeable course was higher than that with water retentive base course, the double structure of water retentive pavement was suggested to be effective.

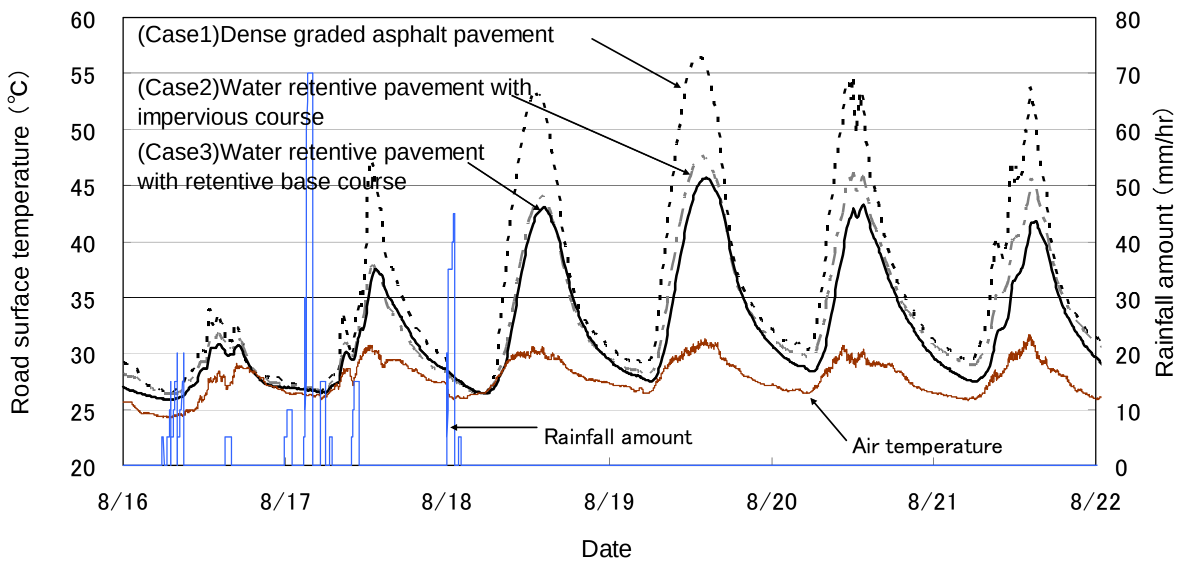


Figure 4: Changes in road surface temperature on dense graded and water retentive pavements

5 ON-ROAD DEMONSTRATION TEST

5.1 Test Conditions

While conducting the field experiment, an on-road demonstration test of water retentive pavement has also been conducted on a community road (width: 6.1 m, length: 113 m) in Naka-ku, Yokohama since July 2006. Two kinds of water retentive pavement were tested: water retentive surface course spread over the existing base course and double structure water retentive pavement consisting of water retentive base course of artificial crushed stones of fly ash and water retentive surface course. Time historical changes in road surface temperature were monitored for dense graded asphalt pavement, water retentive pavement on the existing base course, and water retentive pavement with water retentive base course. Thermocouples were installed at 1 cm from the road surface at two points in the southern pedestrian path of the dense graded asphalt pavement and at three points in the southern motorway of the water retentive pavement on the existing base course and of the water retentive pavement with water retentive base course, respectively.

5.2 Test Results

Changes in road surface temperature on the dense graded asphalt pavement and the two types of water retentive pavement are shown in Fig. 5, which were measured during the period of the field experiment shown in Fig. 4. The precipitation amount and outdoor air temperature were values monitored at the Yokohama Meteorological Observatory. Of the datasets of the water retentive pavements, the datasets at measuring points where morning temperature rises were similar to those of the dense graded asphalt were used. Because the surface temperature of the water retentive pavement was monitored at points north of the measuring points of the dense graded asphalt pavement, the temperature on the water retentive pavements exceeded that on the dense graded asphalt pavement at several points in the morning.

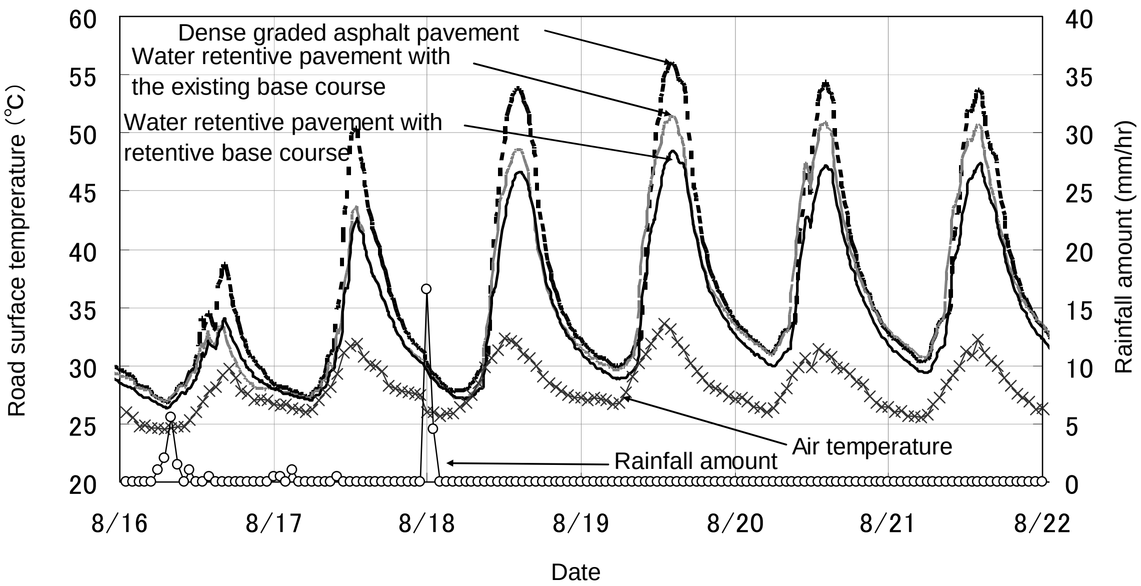


Figure 5: Changes in road surface temperature of dense asphalt and water retentive pavement

An hourly rainfall amount of 16.5 mm was recorded at 0:00 to 1:00 am on August 18, 2006. On the 4 subsequent days, the peak road surface temperatures were 54, 56, 54, and 54℃ on the dense graded asphalt pavement, 49, 51, 51 and 51℃ on the water retentive pavement on the existing base course, and 46, 48, 47 and 47℃ on the water retentive pavement with water retentive base course. On the public road, the water retentive pavement on the existing base course reduced the peak temperature by up to 3 to 5℃; and the water retentive pavement with water retentive base course reduced the peak temperature by up to 7 to 8℃. The cooling effects of the water retentive pavements were inferior to those in the field experiment but were still apparent. When data was organized for all measuring points of the demonstration test, the road surface temperature differences between the southern pedestrian path and the southern water retentive pavement fluctuated within a range of 1.5 to 8℃. The difference of sunshine condition was likely to be a cause.

6 EFFECTS OF STORING RAINWATER AND SPRINKLING WATER

6.1 Test Conditions

The temperatures of the road surface and base course were compared between three types of water retentive pavement (ordinary, rainwater storing, and water sprinkling) and dense graded asphalt pavement. The structures of the pavements and the positions of thermocouples are shown in Fig. 6. The area of each pavement was 17.5 m^2 (5×3.5 m). The pavement structure was 5-cm deep surface course laying over 20-cm deep base course. Each pavement section was surrounded by gutters to be separated from the rest. Thermocouples were installed 1 cm and 15 cm (within the base course) from the road surface. Water retentive base course was used only in the rainwater storing type.

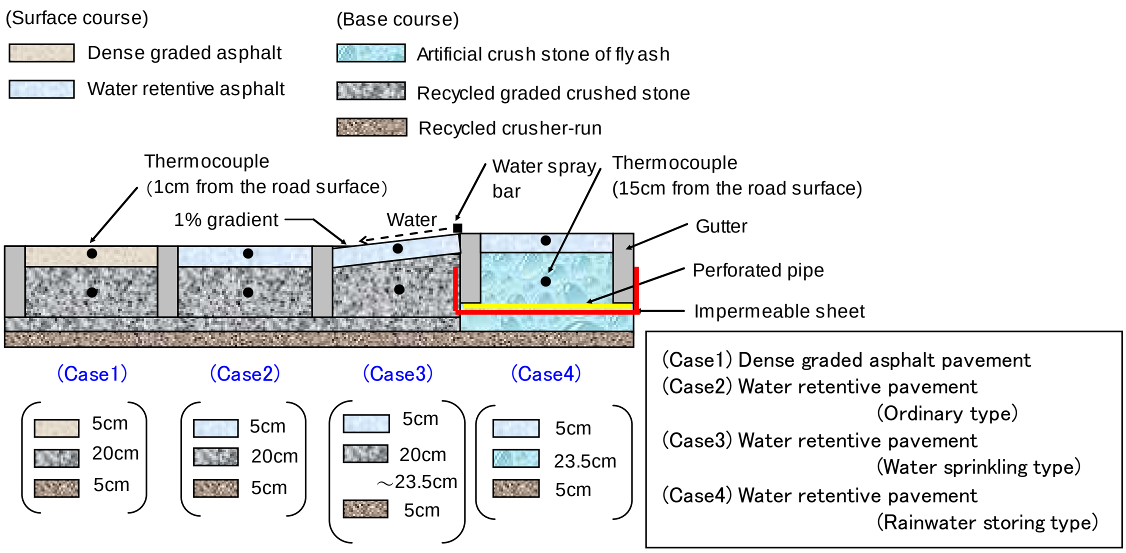


Figure 6: Pavement structure and positions of thermocouples (field experiment)

6.2 Effects of Storing Rainwater

To store rainwater in the base course of water retentive pavement, impermeable sheet was spread on the subgrade, and conducting pipes were laid and connected to gutters (inside dimensions: 250×175 mm, holes of φ30 mm on the bottom at 1-m intervals).

Time historical temperature changes of the road surface and base course of water retentive pavements (ordinary and rainwater storing types) and dense graded asphalt pavement are shown in Fig. 7. At 19:00 on August 10, there was a rain of about 25 mm. On the next day (August 11), the peak road surface temperature of the water retentive pavement of the rain water storing type was about 4℃ lower than that of the water retentive pavement of the ordinary type and was about 12℃ lower than that of dense graded asphalt pavement. The differences in road surface temperature narrowed thereafter. The peak base course temperature of the water retentive pavement of the rainwater storing type was about 2℃ lower than that of the water retentive pavement of the ordinary type and was about 6 to 7℃ lower than that of dense graded asphalt pavement.

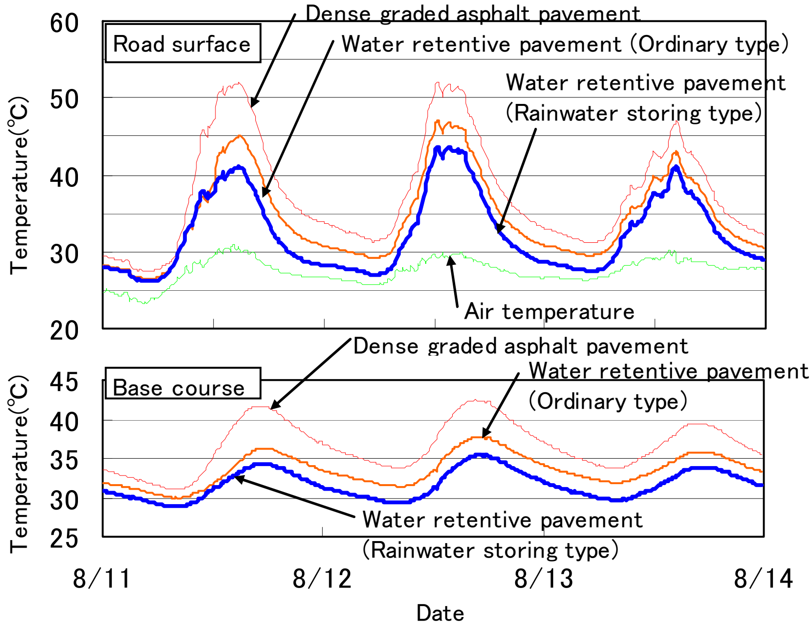


Figure 7: Effects of storing rain water (2008 field experiment)

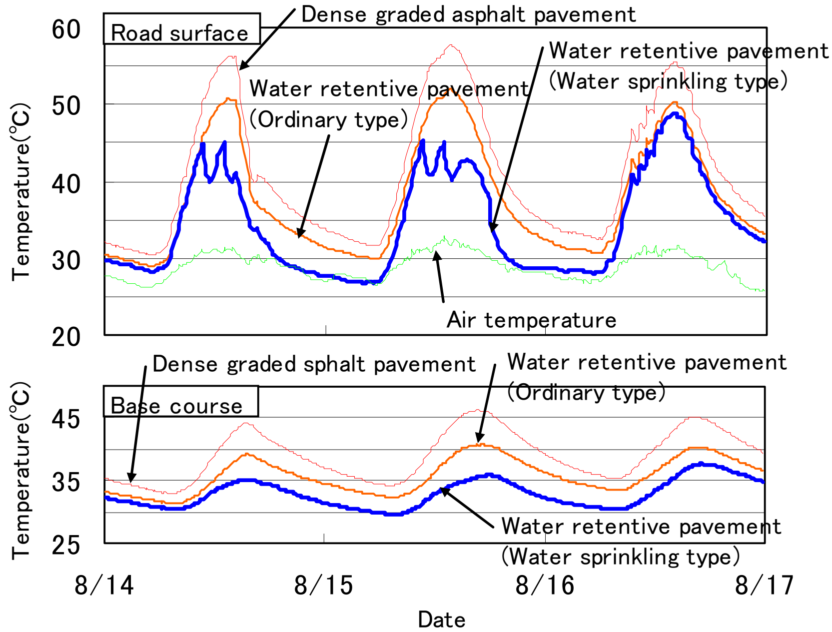


Figure 8: Effect of sprinkling water (2008 field experiment)

6.3 Effects of Sprinkling Water

Water sprinkling was automatically controlled so as to start sprinkling when the road surface temperature reached 45℃ and stop sprinkling when it dropped to 43℃. Water was sprinkled from one side of the road surface, which had 1% gradient, and the direction of sprinkling was adjusted so as to wet the entire road surface.

Time historical temperature changes of the road surface and base course of water retentive pavements (ordinary and water sprinkling types) and dense graded asphalt pavement are shown in Fig. 8. On August 14 and 15, the road surface temperature reached 45℃, and water was sprinkled twice a day slightly after 10:30 and at around 13:00. Approximately 40 l/m^2 of water was needed to be sprinkled, which took about 8 minutes, to lower the road surface temperature by 2℃. At nighttime, the road surface temperature of the water retentive pavement of the water sprinkling type dropped to almost the outdoor air temperature, and its peak temperature was about 9 to 10℃ lower than that of the dense graded asphalt pavement. However, the effects of sprinkling water hardly continued on the next day.

7 CONCLUSIONS

The cooling effects of water retentive pavement that had a double layer structure of water retentive base course and water retentive surface course were examined by conducting laboratory tests, field experiments, and on-road demonstration. The water retentive base course was shown to be effective for mitigating rises in road surface temperature. In order to make the best use of the cooling performances of water retentive pavement, methods are needed to be investigated for saturating the surface course at night by combining with techniques of utilizing rainwater.

The actual states of water retentive pavement that utilizes fly ash are as given below:

1) Use of artificial crushed stones produced from fly ash as base course materials is being tested in Ibaraki and Yokohama, and their in-service performances have been monitored since fiscal 2006.
2) Water retention filling materials have been used in Yokohama and Komae, and changes in water retentive performance have been monitored since fiscal 2006.
3) A structure that stores rain water in the base course was tested in an outdoor experimental field and was found to have certain effects in improving the water retentive performance.
4) The effects of sprinkling water on water retentive pavement were tested in an experimental yard. When optimized, sprinkling is likely to be effective in lowering the nighttime road surface temperature to almost the outdoor air temperature.

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