Development of a Cool Pavement for Mitigating the Urban Heat Island Effect in Japan

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Pavements are considered to be one of the factors contributing to the urban heat island effect because their surface temperature exceeds 60°C on summer days and because the paved surface does not evapotranspire water, unlike soil and other natural land covers.

As a countermeasure to mitigate this urban heat island effect, the cool pavement has attracted attention in Japan as a way of decreasing road surface temperatures. Currently, cool pavements can roughly be categorized into two types, i.e., water retention pavements and heat-shield pavements. This paper reports on the outline and validation experiment results of the mixture-type heat-shield pavement, our cool pavement technique developed as a collaborative research project, conducted jointly with five private-sector companies.

1. Introduction

During the 20th century, the mean average air temperature in large cities in Japan showed a 2 to 3°C increase, while that of the entire globe rose about 0.6°C.[1)] In Tokyo and the surrounding vicinity, for example, there has been a tremendous increase in the number of hours for which the air temperature exceeded 30°C during the past decade (Figure 1). These phenomena are considered to be attributable to the urban heat island effect, in addition to the impact of global warming. The urban heat island effect is a phenomenon whereby air temperatures, mainly in large cities, become higher than those in the surrounding areas, with isotherms forming in the shape of an island. The causal factors are considered to include land cover modification due to an increase in artificial structures, as well as increased emissions of artificial waste heat from buildings and automobiles. It has been pointed out that this urban heat island effect has an adverse effect on humans, causing heat stroke and other health hazards, triggering localized torrential downpours, and affecting ecosystems.

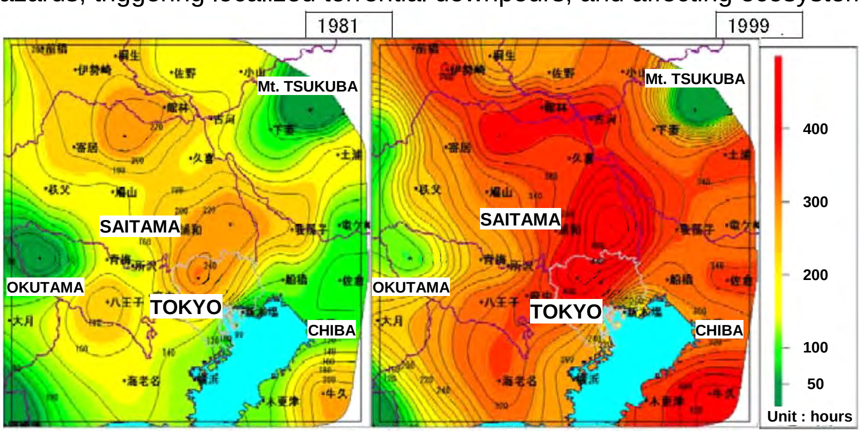


Figure 1: Change in the number of hours for which the air temperature exceeded 30°C in Tokyo and the surrounding vicinity[1)]

Pavement surface temperatures exceed 60°C on some days in summer and the paved ground surface does not evapotranspire water, unlike soil and other forms of natural land cover. Accordingly, pavements are suspected to be one of the factors that contribute to the urban heat island effect. Given this situation, the development of cool pavements that decrease road surface temperatures has recently been promoted in Japan. Simulation results[2)] have shown that the application of cool pavements yielded an air temperature decrease of 0.73°C at a height of 1.5 m and 2.13°C at a height of 0.5 m above ground level, in comparison to conventional pavements (Figure 2), thereby attracting attention as a promising technology for mitigating the urban heat island effect.

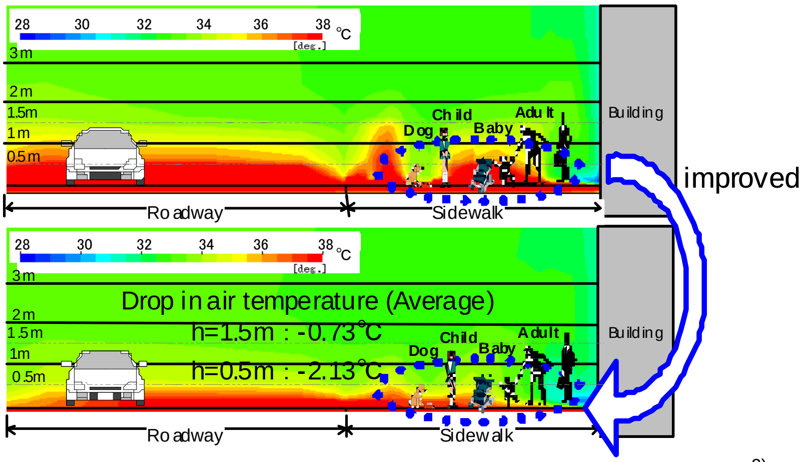


Figure 2: The effect of air temperature reduction (simulation results)[2)]

Currently available cool pavement techniques can roughly be categorized into two types, i.e., water-retention pavements and heat-shield pavements (Figure 3). With the water-retention pavement, water is stored inside the pavement material and the heat of evaporation is used. With the heat-shield pavement, special paint is used to reflect near-infrared radiation (NIR). The application of these cool pavement techniques to actual roadways has increased steadily, such cool pavements are built mainly by central and municipal governments on a trial basis.

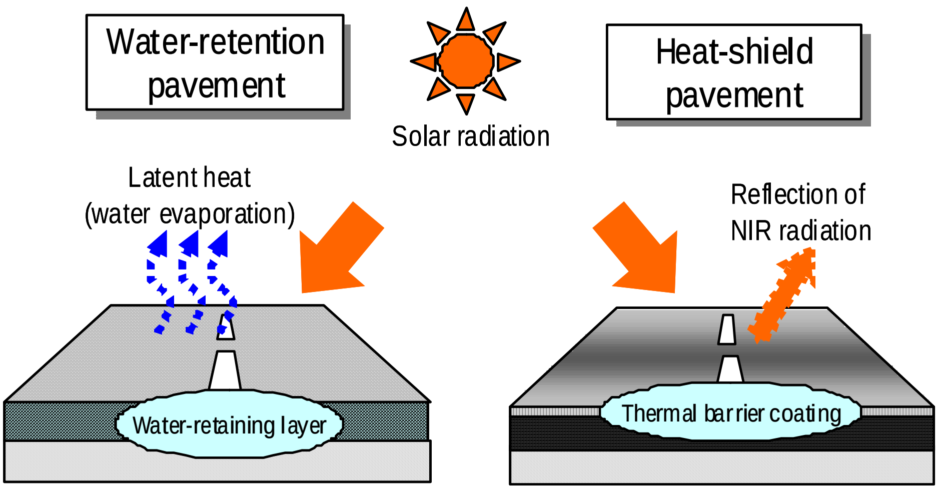


Figure 3: Conceptual drawing of water-retention and heat-shield pavements

In urban areas in Japan, on the other hand, drainage pavements have recently been used to replace conventional dense-graded pavements. The drainage pavement has been increasingly employed as a means of improving the roadside living environment because of its effect of reducing road traffic noise, in addition to its effect of improving vehicular traffic safety by promptly draining rainwater from the road surface. This shows that environmental improvement functions are important factors required for paving techniques in Japan, in addition to durability, which is the primary intended performance of pavements.

Therefore, the Public Works Research Institute (PWRI) developed a mixture-type heat-shield pavement by improving the performance of heat-shield pavements while incorporating the functionality of drainage pavements mentioned above. This development was undertaken from fiscal year 2003 to 2004 by organizing a collaborative research group with five private-sector companies. This paper reports on the technological outline of this mixture-type heat-shield pavement, as well as the results of various validation experiments implemented on the Pavement Test Field at PWRI.

2. Outline of the study

With a heat-shield pavement, the road surface temperature can be reduced to a greater extent than that of a conventional pavement because the pavement surface is coated with special paint that enhances solar reflectance (albedo). This pavement technique may improve the thermal environment in large cities because the effect of road surface temperature reduction can be obtained merely by applying this special paint to existing, ordinary pavement surfaces. Nevertheless, there are several problems to be solved, e.g., abrasion of thermal barrier coating materials caused by vehicular traffic, which leads to a lowering of thermal barrier functions, and the labor-saving process of applying thermal barrier coating materials, which need to be handled manually under present circumstances.

To resolve these problems, we aimed to discover a solution that retains the albedo and luminosity of the road surface as high as the initial levels, even after vehicular traffic, and that can be machine-applied as with conventional paving techniques. In addition, we aimed to achieve a 10°C or more reduction in the road surface temperature.

In this study, the structure and materials used for the heat-shield pavement were examined, and then validation experiments were conducted on the Pavement Test Field (Figure 4) located within the grounds of PWRI. To validate the effect of road surface temperature reduction, pavement specimens each measuring 4 m in length and 4 m in width were placed on the ground of the Outdoor Exposure Field to measure the road surface temperature (Figure 5). Meanwhile, to evaluate the durability and other originally intended pavement performance, accelerated loading tests were conducted by running trucks over the Pavement Test Field (Figure 6), to investigate how abrasion and dirt from vehicular traffic would affect the thermal barrier coating materials.

In the accelerated loading tests conducted on the Pavement Test Field, heavy loading vehicles were driven over the test pavement, which was applied to the test track in exactly the same manner as an actual roadway. Trucks of the most commonly used type in Japan were modified for use as heavy loading vehicles for unmanned operation. Four heavy loading vehicles were operated automatically at the same time to drive at a speed of 40 km/h.

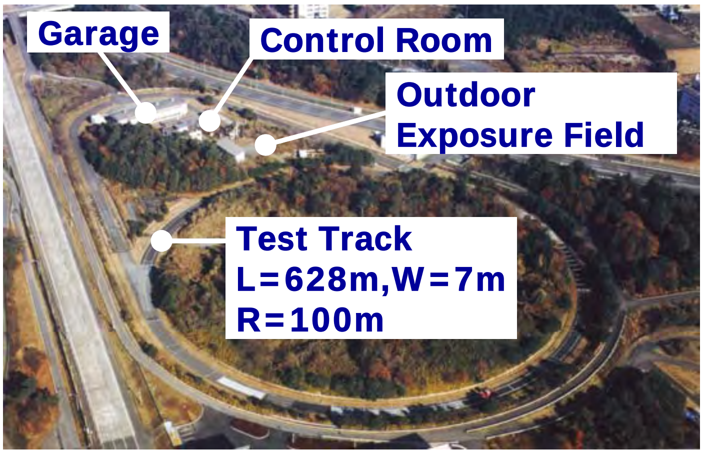


Figure 4: Facility configuration of the Pavement Test Field

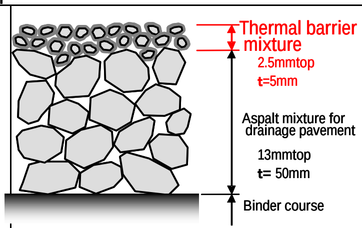
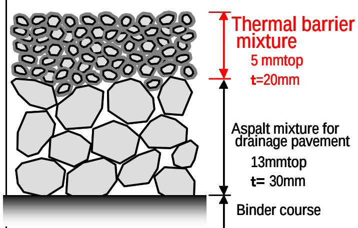
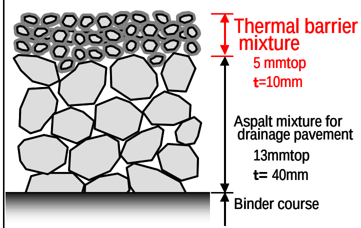
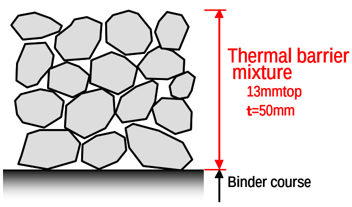
Figure 5: The 4 m x 4 m pavement specimens

Figure 6: A heavy loading vehicle and test track

3. Features of the mixture-type heat-shield pavement

The structure and features of four types of mixture-type heat-shield pavement developed in this study are shown in Table 1. The structure of this pavement is characterized by the fact that each piece of aggregate is coated with thermal barrier paint and constitutes a layer in the thermal barrier mixture, although with the conventional heat-shield pavement, the heat barrier materials are applied only to the pavement surface. With Types A, B, and C, special light-colored aggregates were used to enhance the sustainable performance of suppressing a rise in temperature, even if the thermal barrier materials on the pavement surface are abraded by the passage of vehicles. For Types B and D, an asphalt finisher can be used, which reduces the amount of work required in comparison to existing heat-shield pavement techniques.

Table 1: Structure and features of the four types of mixture-type heat-shield pavement

Type		Features
A		・The surface is paved with a thermal barrier mixture (2.5 mm top) that forms a thin layer (t = 5 mm). ・Resin is used. ・Special light-colored aggregates are used. ・Permeability is attained. ・Coloring in various colors is feasible.
B		・The surface is paved with a thermal barrier mixture (5 mm top) that forms a thin layer (t = 20 mm). ・High-viscosity decolorized asphalt is used. ・Special light-colored aggregates are used. ・Simultaneous work execution with a double-layer asphalt finisher is feasible. ・Permeability is attained. ・Coloring in various colors is feasible.
C		・The surface is paved with a thermal barrier mixture (5 mm top) that forms a thin layer (t = 10 mm). ・Resin is used. ・Special light-colored aggregates are used. ・Permeability is attained. ・Coloring in various colors is feasible.
D		・The surface is paved with a thermal barrier mixture (13 mm top) to a thickness of 50 mm. ・High-viscosity decolorized asphalt is used. ・A once-off application using a general asphalt finisher is feasible, for which labor is almost halved in comparison to that of a spreading-type heat-shield pavement. ・Permeability is attained. ・Coloring in various colors is feasible.

4. Results of various experiments conducted on the Pavement Test Field at PWRI

4.1 Measurement results of the road surface temperature

To confirm the effect of temperature reduction in an outdoor environment, pavement specimens each measuring 4 m in length and 4 m in width were placed on the Outdoor Exposure Field to measure the albedo, luminosity, and road surface temperature. A specimen of drainage pavement was also prepared for use as a control for comparing the measured data. The road surface temperature was measured using thermocouples at thirty-minute intervals.

The results of measuring the albedo of the respective specimens are shown in Figure 7. The albedo of the respective types ranged from 0.46 to 0.57. Despite the difference in measurement dates, the values turned out to be higher than 0.07 of the drainage pavement measured for comparison. For Type A, in particular, the albedo reached 0.57, which was the highest value.

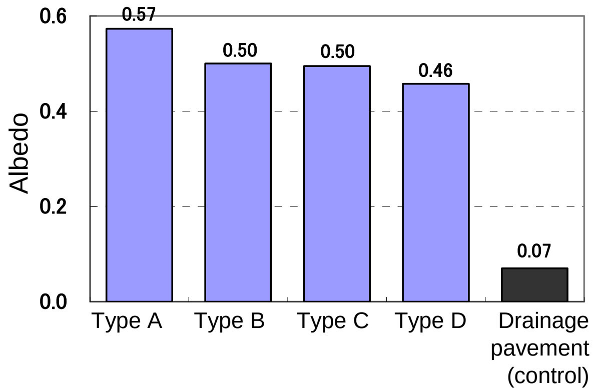


Figure 7: Albedo (4 m x 4 m specimens)

Figure 8 shows the mean average of the maximum temperature differences between the mixture-type heat-shield pavement and the drainage pavement, obtained by extracting the days when the maximum temperature of the drainage pavement exceeded 60°C from the data of surface temperature measurements.

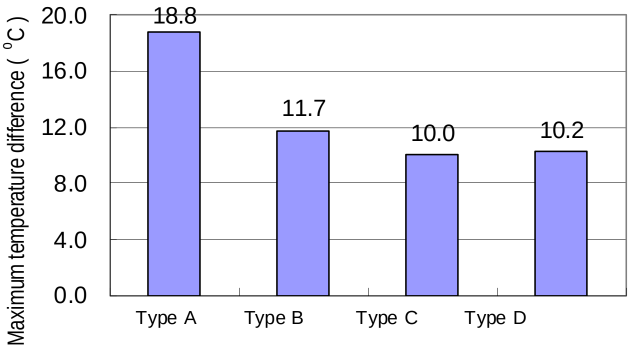


Figure 8: Maximum temperature difference in comparison to the drainage pavement (mean average)

These measurement results showed that the temperature difference was around 20°C at maximum for Type A, which presented the highest albedo value, whereas the temperature difference for Types B, C, and D was 10 to 13°C at maximum. Thus, these results prove that a temperature suppression effect of 10°C or over, which was our primary objective, was successfully attained.

4.2 Results of accelerated loading tests conducted at the test track

To evaluate the pavement durability, the influence of abrasion of the thermal barrier coating materials due to vehicular traffic, and various road surface properties, a mixture-type heat-shield pavement was applied to the test track in the Pavement Test Field with the same pavement structure as that applied to actual roadways. The heavy loading vehicles used were two-axle trucks with a 117.6 kN axle load, and the vehicles were driven automatically to cover the equivalent of 400,000 49 kN wheel loads.

The measurement results of the rut depth, cracking ratio, luminosity, albedo, on-site permeability, and skid resistance are shown below.

Figure 9 shows the rut depth. The results were favorable because the occurrence of rutting was low in comparison to drainage and dense-graded pavements, even after the passage of 400,000 wheel loads. This is considered to be due to the increased resistance to plastic deformation because the road surface temperature was lower than that of drainage and dense-graded pavements.

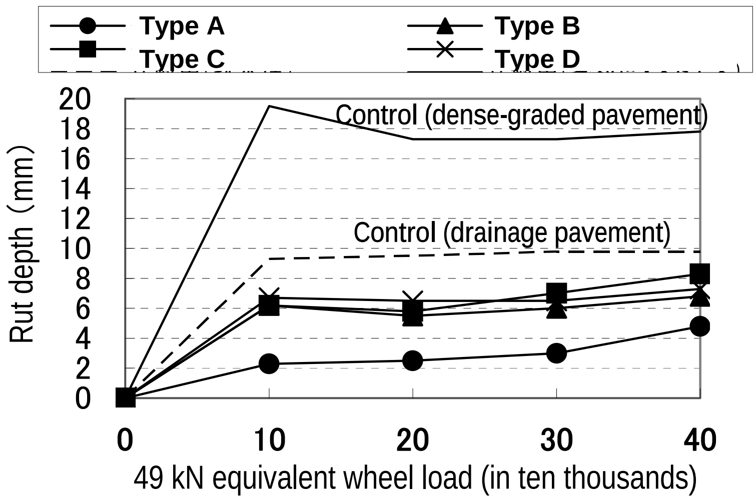


Figure 9: Rut depth

The cracking ratio is shown in Figure 10. For Types A and C, cracks increased in line with the increase in wheel load of the heavy loading vehicles. Accordingly, the cause of crack occurrence was studied exclusively for these two types of pavement. The results revealed that the major cause of cracking for Type A was the fact that the wheel-rolling position coincided with the positions of construction joints, whereas the cause for Type C cracking was considered to be defective workmanship in applying the binder course. Cracking of these pavement types is therefore considered to be avoidable if work is carefully executed, taking these causes into account.

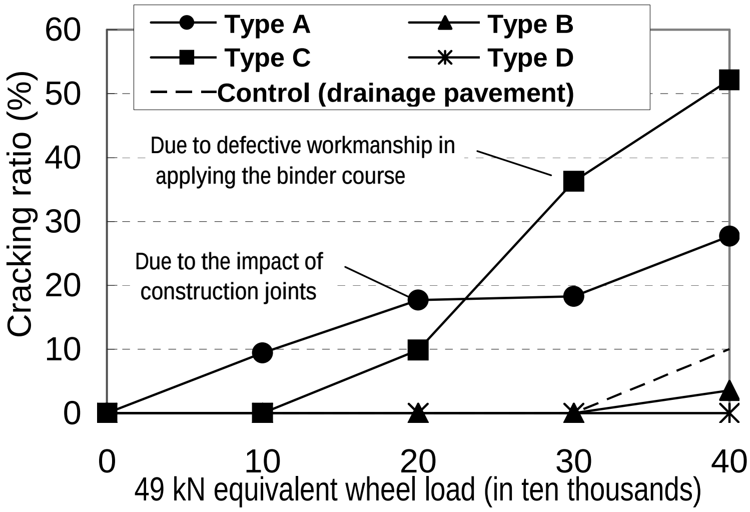


Figure 10: Cracking ratio

Figure 11 and 12 shows the change in albedo and luminosity due to the passage of the heavy loading vehicles. No major difference was observed between OWP, IWP and BWP, and no significant lowering of albedo and luminosity was observed, even after the heavy loading vehicles were run over the test pavement of 400,000 wheel loads.

These albedo and luminosity measurement results showed that the suppression of road surface temperature was sustainable.

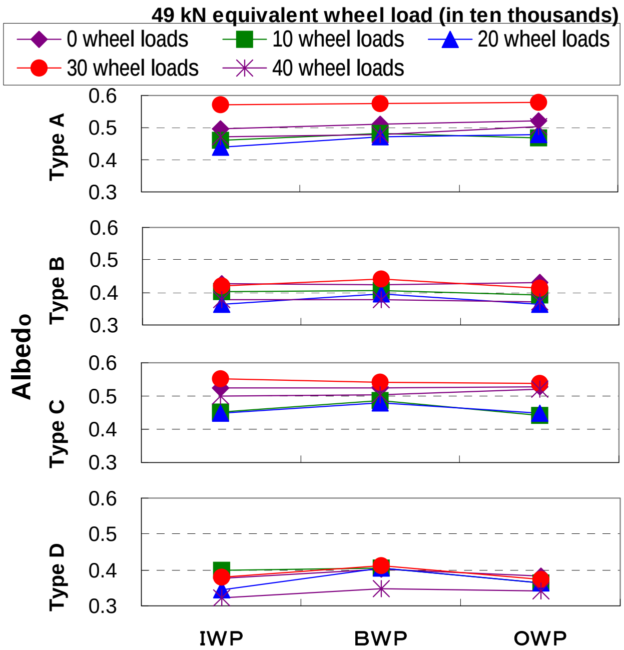


Figure 11: Change in albedo due to the passage of heavy loading vehicles

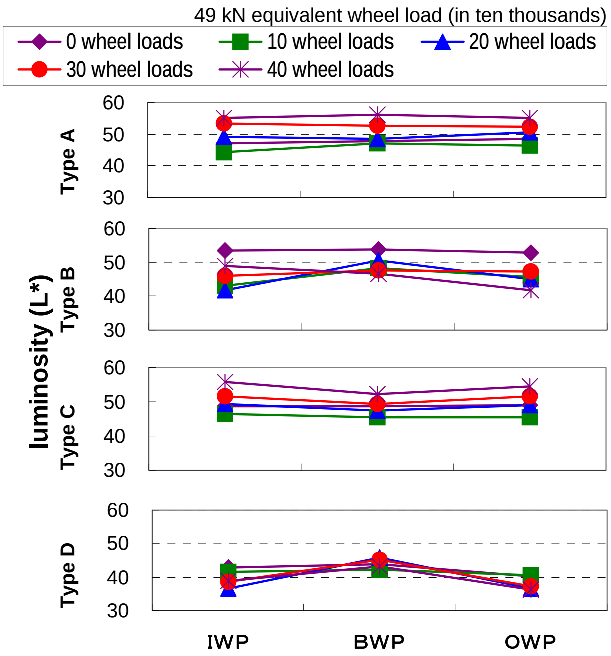


Figure 12: Change in luminosity due to the passage of heavy loading vehicles

Figure 13 shows the on-site permeability of the sections that the wheels rolled over. The results were favorable, because a permeability of 1,000 ml/15 sec or higher was retained, even after the passage of 400,000 wheel loads of heavy loading vehicles.

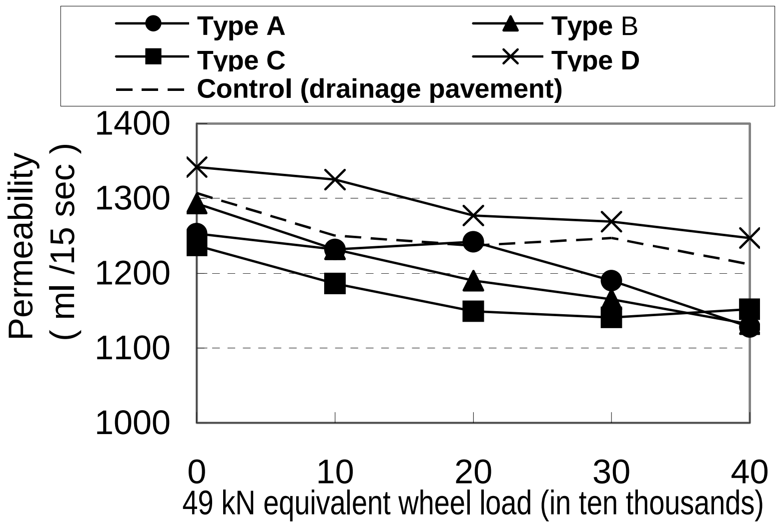


Figure 13: On-site permeability (OWP)

Figure 14 shows the results of measuring skid resistance of the sections that the wheels rolled over, using a DF tester. The results were favorable, because the skid resistance was the same or higher than that of drainage pavements, even after the passage of 400,000 wheel loads of heavy loading vehicles.

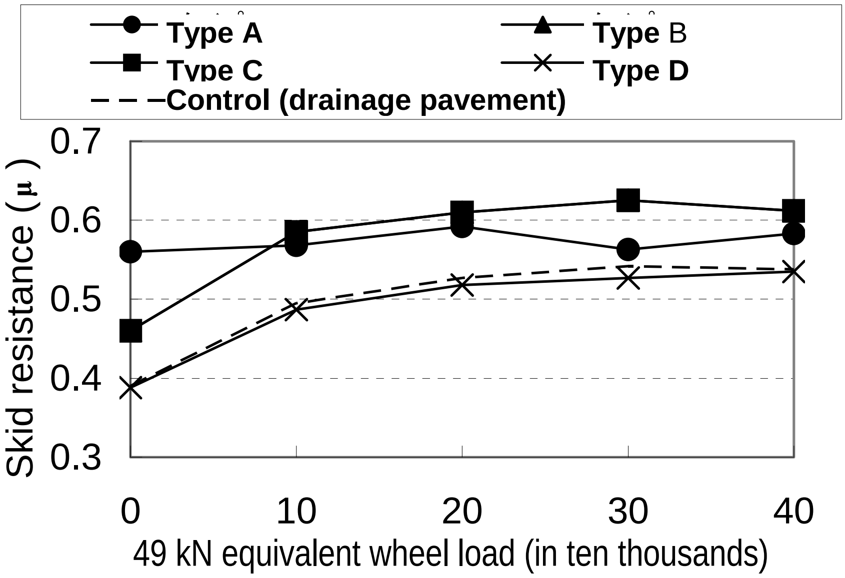


Figure 14: Skid resistance (OWP) 60 km/h

5. Results and discussion

In this collaborative research, all four types of the mixture-type heat-shield pavement technique satisfactorily met the primary objective of suppressing temperature by 10°C or more, in comparison to conventional pavements.

With regard to the work execution method, which is similar to that of conventional paving techniques, a once-off application of the surface layer is feasible with Types B and D, thus eliminating the spreading-work process of conventional work when using a existing heat-shield pavement. As for Types A and C, on the other hand, the work process could not be simplified because the highest priority was given to improving temperature suppression. However, a technique by which the maximum temperature difference reached 20°C in comparison to drainage pavements, could be developed.

These results are briefly summarized below:

1) The effect of temperature suppression obtained by the mixture-type heat-shield pavement was 10 to 20°C at maximum, in comparison to conventional drainage pavements. With Type A, in particular, a temperature suppression effect of 20°C was achieved.

2) As for Types B and D, improved temperature reduction performance and the labor-saving process. The effect of temperature suppression reached 10 to 13°C at maximum, and the thermal barrier mixture could be mechanically applied with an asphalt finisher.

3) Regarding the long-term sustainability of temperature reduction performance, luminosity scarcely decreased after the passage of 400,000 wheel loads of heavy loading vehicles, so the temperature reduction effect seems sustainable.

4) The road surface properties, including rut depth, on-site permeability, and skid resistance, remained favorable, even after the passage of 400,000 wheel loads of heavy loading vehicles.

5) Although partial cracking due to the passage of heavy loading vehicles occurred with specimens of Types A and C, such cracking is considered to be avoidable if pavement work is executed carefully, taking this problem into account.

6. Conclusion

This study was conducted as a collaborative research project entitled “Development of pavement mixture for suppressing the road surface temperature rise (fiscal year 2003 to 2004)” and conducted jointly with NIPPO Corporation, Nagashima Special Paint Co., Ltd., The Nippon Road Co., Ltd., Maeda Road Construction Co., Ltd., and Seikitokyukogyo Co., Ltd.

A new heat-shield pavement was developed from this collaborative research. To date, our paving technique has been used in Ishikawa Prefecture (Figure 15), and the effects of temperature suppression and applicability to in-service roadways are now being examined.

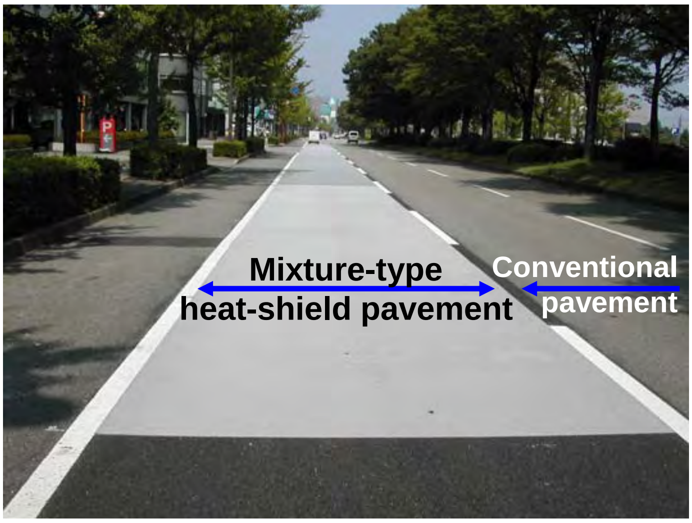


Figure 15: View of a roadway paved with our mixture-type heat-shield pavement technique (Kanazawa City, Ishikawa Prefecture)

Remaining issues to be examined in future studies include ways to reduce the initial costs and the air temperature reduction effects.

We intend to continue our research on cool pavement as a technology to mitigate the urban heat island effect.

7. References

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2. Study on pavement technologies to mitigate the heat island effect and their effectiveness, K. Kubo, H. Kido, M. Ito, 10th ICAP2006
3. Development of pavement mixture for suppressing the road surface temperature rise (fiscal year 2003 to 2004) (in Japanese), Incorporated Administrative Agency Public Works Research Institute, NIPPO Corporation, Nagashima Special Paint Co., Ltd., The Nippon Road Co., Ltd., Maeda Road Construction Co., Ltd., and Seikitokyukogyo Co., Ltd., PWRI Joint research report 339, March 2005