Control of Pavement-Surface Temperature-Rise Using Recycled Materials

Satoru Ishiguro¹ and Masayoshi Yamanaka²

1. Graduate School of Bioresources, Mie University, Tsu 514-8507, Mie, Japan
2. Asahidoboku Co. Ltd., Yokkaichi 510-0033, Mie, Japan

Abstract: High temperatures of the asphalt concrete pavements in summer contribute to the heat island phenomenon in the urban areas. The effective cool-pavement technologies are sought to mitigate the pavement environment. In this paper, developed heat-reflective pavements are constructed from open-graded asphalt concrete, in which voids in the upper part of the pavement are filled with a cement mortar, containing recycled materials as a fine aggregate. The recycled materials used in this study are: crushed oyster shells, roof tile debris, pottery debris, glass cullet, crushed escallops and coral sand. The temperature reduction of the pavement surfaces at an open site is measured in the summer. The results show that the maximum surface temperature of the pavements falls by approximately 8~10 °C compared to the asphalt concrete pavement. Furthermore, it is found that the temperature reduction is mainly due to the increased solar radiation reflectance of the pavement surface.

Key words: Heat-reflecting pavement, asphalt concrete pavement, filling mortar, oyster shell, recycled materials.

1. Introduction

Asphalt concrete pavements generally tend to absorb solar radiation heat because they are black, and the temperature can rise to a maximum of 60 °C or above at the surface in daylight in summer. This high temperature of the asphalt concrete pavement can cause rutting, asphalt aging, heat island phenomenon and fire accidents [1]. In particular, asphalt aging can reduce the ductility and increase the risk of cracking in the pavements [1]. Cracking can be crucial in the asphalt concrete pavements of the reinforced concrete bridge decks, in which it can accelerate the rebar corrosion process and reduce the durability and the service life of the structure [2].

In order to control the pavement surface temperature rise, cool-pavement technologies, such as solar heat-blocking pavement and water-retaining pavement, have been developed [3, 4]. In the former pavement, a reflective paint with a high reflection rate in a near-infrared wavelength band is used on the pavement surface. Cool pavements can also be created with existing paving techniques of asphalt and concrete, as well as new techniques, such as the use of coatings [5, 6]. Among the wide variety of existing materials, concrete is a suitable cool pavement material since it can create high reflective surfaces with the use of lighter cements and aggregates [7]. A high reflective concrete surface can be also achieved by using a cement replacement, such as ground granulated blast furnace slag which is a waste product from the steel industry [8, 9].

Nowadays, there is increasing interest in the utilization of waste materials. In the case of the construction industry, a growing trend exists towards the recycling of waste or by-products as supplementary construction materials [10, 11]. In the area of Mie Prefecture, Japan, for example, oyster farming constitutes a major fisheries activity and produces a large quantity of oyster shells. Some of the shells are pulverized in a factory after removing salt and later utilized as oyster shell lime. However, most oyster shells end up as industrial waste materials without being reused. Fig. 1 shows piles of oyster shells
gathered at a factory site of Toba Kakigara Center, Toba City, Mie Prefecture, Japan. The factory produces 6,000 t of oyster shell lime, annually.

In a previous study, the authors reported that heat-reflecting pavements using oyster shell lime reduce surface temperatures by up to approximately 12 °C compared with new dense-graded asphalt pavements [12]. Crushed escallop and coral sand were also demonstrated to be useful as a fine aggregate for the filling mortar of heat-reflecting pavements [13]. In a recent study, it was found that mortars made by the oyster shell aggregate and ground granulated blast furnace slag could be effectively utilized as a filler mortar of the heat-reflecting pavement [14].

In this study, heat-reflecting pavements using recycled materials, such as crushed pottery debris, glass cullet and roof tile debris, have been investigated and compared with the pavement using oyster shells. All of the recycled materials were produced at factories located in Mie Prefecture. The reduction in the pavement-surface temperature-rise is evaluated by both field experiments and laboratory tests.

2. Experimental Program

2.1 Sample Preparation

A cross section of the pavement tested in this study is shown in Fig. 2. The heat-reflecting pavement is an open-graded asphalt concrete, in which voids in the upper part of the pavement are filled with a cement mortar, containing recycled materials. The pavements have 50-mm thickness and were placed on a 100-mm-thick crushed stone bed. A maximum aggregate size of 13 mm or 20 mm is used for the open-graded asphalt concrete pavement. The top 10 mm to 15 mm of the open graded asphalt pavement is filled with mortars by using a vibrator. The pavement surfaces treated by grinding after hardening of the filling mortar. Fig. 3 presents the grinded surface of the pavement filled with oyster shell mortar.

Fig. 4 shows the materials utilized as a fine aggregate for mortars. Different types of recycled materials are used for the filling mortar. Oyster shells, a waste product from oyster farming, are pulverized into a fine powder with a particle size of less than 2 mm to form the lime used as a fine aggregate for the filling mortar in this study. Other recycled materials, such as roof tile debris, pottery debris and glass cullet, are also pulverized as fine aggregates with a particle size of less than 3 mm. Natural river sand is employed as a control
in this study. In the filling mortar mixture, ordinary Portland cement and the recycled materials are used as the binder and fine aggregate, respectively. Table 1 shows the properties of the filling mortars with different aggregates. The aggregate-to-cement ratio of 2:1 was used for mixtures. Different water-to-cement ratios ($W/C$) were used to make the filling mortar so that the mixtures had similar workability. Chemical admixtures, such as super plasticizers, were not used in the mixture design. The compressive strength of mortars was measured at the age of 7 days that the pavement surfaces were subjected to grinding treatments. The results showed that the mortars with oyster shell and escallop aggregates have high water-to-cement ratios ($W/C$) and the compressive strengths were lower than those of the other mortars.

### 2.2 Test Procedure

Fields experiments were performed to evaluate the surface heat reduction of asphalt concrete pavements in the summer. The pavements were constructed at the Mie University testing site located in Tsu City, Mie Prefecture, as shown in Figs. 5 and 6, to monitor the surface temperature in summer. In this experiment, Section A is the open-graded asphalt concrete pavement with a maximum aggregate size of 13 mm, and the other sections (Sections B-F, H and I) had maximum aggregate size of 20 mm. The dense-graded asphalt pavement (Section G), with a maximum aggregate size of 20 mm, was utilized as a control one. The oyster shell sections (Sections A and B), the escallop section (Section H), and the coral sand section (Section I) were filled with mortar in June 2011. These sections had an area of 1.5 m × 1.5 m. The heat-reflecting pavements (Sections C-F), made with a cement mortar, containing various recycled materials, were filled in June 2012. This section had an area of 0.75 m × 0.75 m. The temperature measurements were conducted in late July 2012, via thermocouples attached to the pavement surfaces; a data logger recorded the temperature at 1 min intervals. The air temperature and solar radiation intensity were monitored at the same time.

Brightness and color tests for the pavement surfaces were performed with a digital color reader (CR-13, Konica Minolta Optics Inc.) by the direction of the instrument manufacturer. The average values in different points on every pavement surface are calculated and evaluated using the parameters of an $L^*$, $a^*$ and $b^*$ color space [15].

Spectral reflectance was determined by a spectral reflectometer of UV-3100PC and MPC-3100 for the dense-graded asphalt and the hardened and dried mortars.

### Table 1  Properties of mortar with different aggregates.

<table>
<thead>
<tr>
<th>Aggregate type</th>
<th>Maximum particle size (mm)</th>
<th>$W/C$ (%)</th>
<th>Aggregate cement ratio</th>
<th>7-day compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oyster shell</td>
<td>2</td>
<td>110</td>
<td>2:1</td>
<td>6.97</td>
</tr>
<tr>
<td>Roof tile debris</td>
<td>3</td>
<td>95</td>
<td>2:1</td>
<td>16.1</td>
</tr>
<tr>
<td>Pottery debris</td>
<td>3</td>
<td>83</td>
<td>2:1</td>
<td>17.0</td>
</tr>
<tr>
<td>Glass cullet</td>
<td>2.5</td>
<td>55</td>
<td>2:1</td>
<td>24.3</td>
</tr>
<tr>
<td>Escallop</td>
<td>2</td>
<td>110</td>
<td>2:1</td>
<td>9.39</td>
</tr>
<tr>
<td>Coral sand</td>
<td>2.5</td>
<td>58</td>
<td>2:1</td>
<td>27.1</td>
</tr>
<tr>
<td>River sand</td>
<td>5</td>
<td>50</td>
<td>2:1</td>
<td>32.9</td>
</tr>
</tbody>
</table>
3. Results and Discussions

3.1 Surface Temperature

The surface temperature changes of pavements Sections B-G, air temperature and solar radiation are shown in Fig. 7. There was no rainfall during the measurement period.

The surface temperature of the black dense-graded asphalt reached a maximum of 63.1 °C on July 26, whereas the surface temperature of the heat-reflecting pavements did not exceed 54.3 °C. The heat-reflecting pavements were up to approximately 9 °C lower than that of the dense-graded pavement on a fine day. This temperature reduction is as a result of the higher solar reflectance due to the lighter colored mortar.

The maximum surface temperatures of the pavements in the three consecutive days from July 26 to July 28 are indicated in Fig. 8. The numerical values represent the average of the three consecutive days. The maximum measured daily temperatures of the heat-reflecting pavements fell by approximately 8~10 °C compared with that of the dense-graded asphalt. The pavement filled with the escallop mortar exhibited the lowest surface temperature. The maximum temperature of the pavement using the pottery debris was slightly lower than that using the other recycled materials. The variations in the temperature difference are partly due to variations in the

The specimens were 30 mm × 30 mm × 20 mm in size. Wavelength for this test was 380~2,600 nm.

The skid resistances of the pavements were tested in accordance with ASTM E303 (standard test method for measuring surface frictional properties using the British pendulum tester).

Wheel-tracking tests were performed under defined standards of Japan Road Association. The specimens with a maximum aggregate size of 20 mm, which was filled with the oyster shell mortar, were prepared and tested.
results of the field experiments reveal that the surface temperatures of the heat-reflecting pavements under summer sunlight irradiation decrease during the days and nights. Therefore, it can increase the durability of the pavement and reduce the urban heat island effect.

3.2 Brightness and Color

Fig. 9 shows the surface patterns and colors in the area of 15 cm × 15 cm on pavements Sections A-I. The average values of the brightness and colors in 20 different points on every pavement surface are listed in Table 2. Brightness value \( L^* \) is expressed in the range from 0 (black) to 100 (white). The \( a^* \) value presents from green \((-a^*)\) to red \((+a^*)\) and the \( b^* \) value from blue \((-b^*)\) to yellow \((+b^*)\). The results show that the brightness of the pavement surface filled with the pottery debris and escallop mortars are rather higher than the other heat-reflecting pavements, and the dense-graded asphalt has the lowest \( L^* \).

3.3 Spectral Reflectance

Fig. 10 presents the spectral reflectance of the dense-graded asphalt and the mortars with different aggregates. The spectral reflectance in the near-infrared region is 5~10% for the dense-graded asphalt. On the other hand, the spectral reflectance of mortars is significantly different from that of the dense-graded asphalt. The reflectance value of the
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Table 3  BPN (British pendulum number) of the pavements obtained by skid resistance test.

<table>
<thead>
<tr>
<th>Section</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPN</td>
<td>80</td>
<td>79</td>
<td>77</td>
<td>77</td>
<td>80</td>
<td>73</td>
<td>88</td>
<td>74</td>
<td>80</td>
</tr>
</tbody>
</table>

Fig. 11  Pavements constructed by the top-filling of oyster shell mortar: (a) parking lot; (b) sidewalk.

3.4 Skid Resistance

The results of a skid resistance test in a wet condition are summarized in Table 3. The test results show that the BPN (British pendulum number) values of the heat-reflecting pavements are higher than the value of 40 required for pedestrian roads [16].

3.5 Dynamic Stability

The average value of the dynamic stability was 21,000 times per millimeter under the test temperature of 60 °C. The durability of pavement against rutting was considerably improved by top-filling of the oyster shell mortar.

4. Case Study

Figs. 11a and 11b show the heat-reflecting pavements constructed by top-filling of the oyster shell mortar in a parking lot and a sidewalk, which are located in Yokkaichi City and Ise City, Mie Prefecture. These pavements have been constructed by a road-paving company under the supervision of authors. A maximum aggregate size of 13 mm and 20 mm are used for the open-graded asphalt concrete pavement. The surface pattern of the pavement in the parking lot with a maximum aggregate size of 13 mm is shown in Fig. 3. In constructing of the parking lot, in order to get the enough workability for the mortar, a super plasticizer was used in the mixture.

The temperature reduction of the pavement surfaces at the parking area was evaluated experimentally by taking measurements for a week in early August. The results revealed that the maximum surface temperature of the pavement fell by approximately 8–10 °C compared with that of an asphalt concrete pavement set up at a testing site.

Pavements made with top-filling of mortars may cost up to two times more due to the filling and grinding treatment. However, it offers several key advantages, including an improvement in durability and the creation of beautiful surface-patterns.

5. Conclusions

Heat-reflecting pavements using recycled materials have been developed, and the temperature reduction
effect was evaluated by field experiments and laboratory tests. The results of this study are summarized as follows:

(1) The surface temperatures of the heat-reflecting pavements are approximately 8–10 °C lower than that of the dense-graded asphalt pavement. This is mainly due to the increase in the solar radiation reflectance;

(2) The heat-reflecting pavement filled with mortar containing crushed shell or pottery debris is lighter in color and has a higher solar reflectance compared with those of other recycled materials;

(3) Beautiful patterns were produced by grinding the pavement surface after hardening the filling mortar;

(4) The heat-reflecting pavements using recycled materials are environmentally friendly and contribute to promoting the effective use of waste products.

Acknowledgments

The authors wish to express their gratitude for the financial support of the Japan Society for the Promotion of Science.

References


