Progress has been made in the diversification and repeated reuse of reclaimed asphalt pavement (RAP) in recent years. However, evaluating the quality of RAP containing polymer-modified asphalt (RAPm) has been difficult, and no method has been established for its reuse as hot mix asphalt. We have been developing recycling technology to restore RAP to the original condition of each material by separating it into aggregate and asphalt using hot water, and have succeeded in restoring aggregate from RAP containing straight (nonmodified) asphalt (RAPs). In this paper, we examine the recovery of aggregate from RAPm using hot water and the restoration of asphalt quality using high-temperature, high-pressure water. This technology can be applied to RAPm to rejuvenate asphalt.

**Key Words:** hot mix asphalt, hot water rubbing method, polymer-modified asphalt, reclaimed asphalt pavement, separation recycling technology

### 1. INTRODUCTION

In Japan, full-scale development of recycling technology for reclaimed asphalt pavement (RAP) has been underway since the 1970s. Since 2000, more than 98% of RAP has been recycled according to the flow indicated in Fig.1, although the use of hot mix asphalt (HMA) containing various modifiers or recycled materials has spread since the 1990s (as shown in Fig.1a and 1b), as has ongoing diversification of pavement materials coupled with the repeated reuse of RAP. In Japan, a styrene-butadiene-styrene (SBS) block copolymer is mainly used as a modifier for polymer-modified asphalt, and the amount of modifier added is approximately 7%. The polymer-modified asphalt mixture accounted for 15% of the total shipment of asphalt mixtures in 2009. Porous asphalt mixture pavements are especially effective in improving driving safety and reducing traffic noise, and have seen widespread use in high-standard roadways, including highways. However, it is difficult to evaluate the quality of the RAP containing polymer-modified asphalt (RAPm) after use, and issues remain with the quality control of its recycling. Methods for recycling RAPm must be established before the time comes to update porous asphalt mixture pavements.

We have focused on the solvent capabilities of hot water and developed an evaluation of stripping resistance with pressurized hot water and a high-temperature, high-pressure water extraction test. In these processes, we have found that aggregate and asphalt are separated by stirring asphalt mixtures in pressurized hot water at 150°C, and that asphalt cracks as a result of reacting with supercritical water. Based on these findings, we have applied a series of separation and cracking processes to separation recycling technology for RAP. Here, ideal conditions for this technology would allow for continuous and efficient processing under atmospheric pressure, and decreases in solvent temperature when separating and cracking would reduce environmental stress and lower processing costs. Accordingly, we took inspiration from the rubbing method for manufacturing high-quality recycled aggregate from cement concrete chunks to develop a separation method. We call this the hot water rubbing method, which crushes RAP by stirring it in hot water while separating materials. We
confirm that aggregate is separated from RAP containing straight (nonmodified) asphalt (RAP) using the hot water rubbing method at 80°C to 90°C and is recovered to its original condition6).

In this study, we evaluate the aggregate separated and recovered from RAPm using hot water, along with HMA containing these recovered aggregates, and confirmed the applicability of the hot water rubbing method to RAPm. We also focused on the decomposition of subcritical water, which is cooler and easier to handle than supercritical water, and evaluated the effects of its temperature and pressure on asphalt composition.

2. AGGREGATE RECOVERED WITH THE HOT WATER RUBBING METHOD

(1) Experimental outline
We evaluated the properties and quality of aggregate recovered from RAPm. The procedures included
Table 1 Properties of R5–13_m and R0–5_m.

|                     | R0–13_m | R5–13_m | R0–5_m |
|---------------------|---------|---------|--------|
| Old asphalt content (%) | 4.25    | 2.95    | 7.08   |
| Particle quantity (%)  | 2.84    | 2.27    | 5.12   |
| Weight of fraction passing a sieve (%) |
| 13.2 mm             | 100.0   | 100.0   | 100.0  |
| 9.5 mm              | 81.5    | 76.5    | 100.0  |
| 4.75 mm             | 38.4    | 18.1    | 100.0  |
| 2.36 mm             | 23.1    | 12.4    | 67.9   |
| 1.18 mm             | 16.7    | 10.6    | 46.9   |
| 0.6 mm              | 13.2    | 9.1     | 35.4   |
| 0.3 mm              | 9.7     | 7.2     | 26.0   |
| 0.15 mm             | 6.5     | 5.5     | 18.0   |
| 0.075 mm            | 4.8     | 4.1     | 13.4   |

Table 2 Properties of SR5–13_m.

|                     | SR5–13_m | SR5–13_m |
|---------------------|----------|----------|
|                     | 80°C     | 90°C     |
|                     |          |          |
| Water content (after natural cooling) (%) | 0.23 | 0.17 |
| Asphalt content (%) | 0.87    | 0.7     |
| Particle quantity (%) | 0.1     | 0.1     |

Fig.6 Grain size distribution of SR5–13_m (After asphalt extraction).

in recovery with hot water rubbing are shown in Fig.2, and schematic representations of the devices involved are shown in Figs.3 and 4. In the hot water rubbing method, asphalt is softened in hot water, which suppresses deterioration and separates materials by rubbing them against each other over a sieve. Incidentally, SR is an abbreviation for separated and recovered. This method consists of a primary separation step, which yields 5–13 mm pieces of recovered aggregate (SR5–13_m), and a secondary separation step, which similarly yields 1–5 mm pieces of recovered aggregate (SR1–5_m) from RAP_m that have passed through the primary separation step. The asphalt content of pieces smaller than 1 mm (SR0–1_m) that passed through the secondary separation was checked using furnace-dried samples. Based on reported RAP_s findings, we set the stirring speed and duration for the primary and secondary separations as indicated in Fig.2, with separation temperatures of 80°C and 90°C.

To clarify the effects of the differences in asphalts, we used two pieces (totaling approximately 22 kg) of a dense-graded asphalt mixture (with a maximum aggregate size of 13 mm) as specimens in a wheel tracking test, in which recycled aggregates of 5–13 mm (R5–13_m) and 0–5 mm (R0–5_m) produced using current recycling methods (by mechanically crushing) from RAP_m were mixed. The properties of R5–13_m and R0–5_m are shown in Table 1. The RAP_m that was used was produced by simultaneously cutting a surface course containing type-H polymer-modified asphalt and a binder course containing type-II polymer-modified asphalt.

(2) Evaluating the recovered SR5–13 aggregate

a) Properties

The SR5–13_m reached a stable temperature after cooling for an hour. We then observed its appearance and evaluated its properties (water content, asphalt content, particle quantity, and grain size distribution). The properties are shown alongside those of previously reported aggregates recovered from RAP_s (SR5–13_s), and the effects due to differences in the asphalts were compared. The appearance of SR5–13_m is shown in Fig.5; its properties are shown in Table 2; and the aggregate grain size of the asphalt after Soxhlet extraction is shown in Fig.6. The aggregate grain size of SR5–13_m was also compared with that of R5–13_m using current recycling methods.

Although slight residues of the old asphalt were seen at both 80°C and 90°C, SR5–13_m showed no noticeable wear or damage, and compared favorably with virgin aggregates and SR5–13_s. A decline in water and asphalt content was shown with rising separation temperatures, while the aggregate grain size was roughly equivalent to that of virgin aggregate and SR5–13_s at both 80°C and 90°C and no differences due to separation temperature were observed. The grain size distribution of SR5–13_m contained a slight mix of 4.75 mm remnants in the aggregate recovered at 80°C, although it was more rigorously
The quality of SR5–13m was tested against quality target values for virgin aggregate (a density of 2.45 g/cm³ or higher, water absorption of 3.0% or lower, and an abrasion loss of 30% or lower), focusing on aggregate recovered at 90°C, for which the old asphalt content was relatively lower. Here, we evaluated the effects of polymer-modified asphalt based on a comparison with SR5–13s, evaluated in the same manner, and showed each of the results alongside the quality of R5–13m after undergoing Soxhlet extraction, approximating its original condition. The density and water absorption of SR5–13m are shown in Fig.7 and its abrasion loss is shown in Fig.8.

Whereas the density of SR5–13m was approximately equivalent to that of R5–13m following asphalt extraction, its water absorption declined relative to R5–13m, presumably due to remnants of the old asphalt impregnating the inner part of the aggregate. The abrasion loss of SR5–13m was slightly higher than that of R5–13m following asphalt extraction, which was also observed in aggregate recovered from RAP. While this difference was likely due to wear or peeling of the old asphalt remaining in the surface of SR5–13m, it easily satisfied the abrasion loss target of 20% or lower. These results affirm that SR5–13m separated and recovered from RAP roughly can be restored to its original condition and treated in the same manner as virgin aggregate, just as aggregate recovered from RAP can.

### (3) Evaluating the recovered SR1–5 aggregate

#### a) Properties

The properties of SR1–5 were evaluated with the same content and methods as those of SR5–13m. Water content, asphalt content, particle quantity, and grain size distribution are shown alongside those of recovered aggregate from RAP, already reported (SR1–5s), and the effects due to differences in the asphalts were compared. The appearance of SR1–5m is shown in Fig.9, its properties are shown in Table 3, and its aggregate grain size is shown in Fig.10. The aggregate grain size of SR1–5m was also compared with that of R1–5m using current recycling methods at both 80°C and 90°C.

|                | SR1–5m | SR1–5s |
|----------------|--------|--------|
| Water content (after natural cooling) (%) | 2.5    | 1.97   |
| Asphalt content (%)       | 0.07   | 0.01   |
| Particle quantity (%)      | 0.2    | 0.3    |

### b) Quality

The density of SR5–13m was approximately equivalent to that of R5–13m following asphalt extraction, its water absorption declined relative to R5–13m, presumably due to remnants of the old asphalt impregnating the inner part of the aggregate. The abrasion loss of SR5–13m was slightly higher than that of R5–13m following asphalt extraction, which was also observed in aggregate recovered from RAP. While this difference was likely due to wear or peeling of the old asphalt remaining in the surface of SR5–13m, it easily satisfied the abrasion loss target of 20% or lower. These results affirm that SR5–13m separated and recovered from RAP roughly can be restored to its original condition and treated in the same manner as virgin aggregate, just as aggregate recovered from RAP can.
As with SR5–13m, old asphalt residue was seen in parts of SR1–5m; however, there was no wear or damage to the aggregate. Although the water content cooling for an hour was higher than that of SR5–13m due to differences in grain diameter, the asphalt content was lower than that of SR5–13m at both 80°C and 90°C, suggesting that rubbing was more efficient for SR1–5m. The asphalt content of SR1–5m was also lower than that of SR1–5s, though their particle quantity was roughly equivalent at both 80°C and 90°C. The aggregate grain size of SR1–5 m did not depend on separation temperature, and was more rigorously classified than R1–5m at any temperature.

b) Quality

The density, water absorption, and abrasion loss of 2.5–5 mm recovered aggregate (SR2.5–5m) and 1–2.5 mm recovered aggregate (SR1–2.5m) recovered at 90°C, for which the asphalt content was lower, were tested against target values for virgin aggregate.

As with SR5–13m, the water absorption of SR2.5–5m was lower than that of the recycled aggregate following asphalt extraction, just as with SR5–13m. The abrasion loss of SR2.5–5m was almost equal to that of R2.5–5m following asphalt extraction, and satisfied quality targets for virgin aggregate. These results affirm that SR1–5m separated and recovered from RAPm can be roughly restored to its original material conditions and treated with the same procedures as virgin aggregate, just as with aggregate recovered from RAPs.

3. HMA CONTAINING RECOVERED AGGREGATE

(1) Experimental outline

We confirmed reports in earlier research that old asphalt coated in R5–13 might adversely affect the quality of recycled mixtures. We therefore evaluated the quality of recycled mixtures containing SR5–13m and examined the reuse of aggregate recovered from RAPm with the hot water rubbing method.

Three specimen types were prepared, namely, — recycled mixtures containing 30% SR5–13m, R5–13m, and a mixture consisting only of virgin aggregates. Their bending strengths were then compared. The formulation and name of each specimen are shown in Table 4. The bending test was conducted.
at temperatures of -10, 0, 5, 10, and 20°C, and the embrittlement point was confirmed. In addition, when the blend of recovered aggregates was designed, splitting tests confirmed that additives were not necessary for mixtures blended with R5–13m and SR5–13m.

(2) Evaluating HMA containing recovered aggregate

The relationship between temperature and bending strength is shown in Fig.14. As previously reported, the mixture blended with R5–13 showed a significant decrease in bending strength near the embrittlement point of the virgin mixture, but the mixture blended with recovered aggregate had similar strength8).

4. RESTORING ASPHALT PROPERTIES WITH HIGH-TEMPERATURE, HIGH-PRESSURE WATER

(1) Experimental overview

In developing separation recycling technology using hot water as a medium, we must examine the reuse of SR0–1 that contains old asphalt after secondary separation. Although combining SR0–1 in recycled mixtures can also be considered, in this study, we attempted to restore the properties of the old asphalt using high-temperature, high-pressure water to restore it to its original condition. For reference, the properties of 1 mm aggregate separated and recovered from RAP, (SR0–1,) are shown in Table 5.

The old asphalt contained in RAP indwelling deterioration with use and alteration from the rejuvenator, and these conditions are thought to build with repeated reuse. When combining into recycled mixtures, the miscibility between the virgin asphalt and the rejuvenator is unclear, making rigorous quality control even more challenging.

To make the initial properties homogeneous and clear, straight virgin asphalt 60–80 (virgin) forcefully heat-deteriorated in a thin membrane state with penetration to 20 (0.1 mm) was used as the specimen. The asphalt properties before and after heat deterioration are shown in Table 6. Experiments to restore these properties using high-temperature, high-pressure water were conducted according to the procedure shown in Fig.15.

Recovery temperatures were set to 200°C or higher—the range in which asphalt cracking effects could be expected based on preliminary experiments—but no higher than 350°C, ensuring that water was below the critical point; experiments were
conducted under saturation water vapor pressures of 1.55 MPa at 200°C, 3.98 MPa at 250°C, 8.59 MPa at 300°C, and 16.5 MPa at 350°C, respectively. The reaction time was determined to be 10 minutes, for which there has been a proven record in the development of asphalt extraction tests with subcritical water. Following the experiments, the asphalt contained approximately 25% moisture weight by volume, and in the dehydration process in Fig.15, we evaluated the material that reduced oxidative degradation due to superheated steam while rapidly drying as recovered asphalt. The recovered asphalts were labeled 200°C, 250°C, 300°C, and 350°C, and we confirmed the effects of high-temperature, high-pressure water on chemical properties based on compositional analysis using thin layer chromatography (TLC). Furthermore, we evaluated the recovery of physical properties by penetration and ductility tests. The specifications of the high-temperature, high-pressure water reaction device are shown in Fig.16.

(2) Composition of Recovered Asphalt

a) Chemical properties

The recovered asphalt composition is shown in Fig.17, and its colloidal index (Ic) calculated by Eq. (1) is shown in Fig.18. Based on comparisons with virgin and aged asphalt, heat degradation significantly reduced aromatic compounds, and a tendency to increase resin and asphaltene compounds was observed. However, the recovered asphalt contained more aromatic compounds relative to the deteriorated asphalt, and we observed a tendency for asphaltene and resin compounds to decrease. From the results of the composition analysis, it is considered that the hydrothermal decomposition reaction in high-temperature and high-pressure water decreased the high molecular component of asphalt, and the effect of inhibiting repoly-merization was observed simultaneously9). Further, Ic, which is also effective in evaluating the deformation followability and toughness of asphalt increases due to thermal degradation. These effects became more significant with increasing recovery temperatures, and the chemical properties of asphalt recovered at 350°C was very close to those of virgin asphalt.

\[
Ic = \frac{\text{Satiation compounds} + \text{Asphaltene compounds}}{\text{Aromatic compounds} + \text{Resin compounds}}
\]  

b) Physical properties

The penetration of recovered asphalt, shown in Fig.19, tends to recover with increasing temperature. Furthermore, for asphalt recovered at 350°C, at which penetration reached the maximum, we confirmed that ductility was recovered by ductility tests, as shown in Fig.20. Hence, old asphalt is roughly restored to its original chemical and physical properties as the result of reaction with high-pressure water at...
350°C, confirming its practical application in separation recycling technology.

5. CONCLUSION

We found that aggregate recovered from RAPm and RAPs using hot water rubbing at 90°C meets the same rigorous quality control as virgin aggregate and satisfies target quality values. Further, mixtures blended with the recovered aggregate have the same bending strength as virgin mixtures without additives. Changes to asphalt composition due to heat degradation can potentially be restored to roughly the same degree as virgin asphalt with a 350°C high-temperature, high-pressure water reaction; moreover, such reactions may recover not only the penetration, but also the ductility of old asphalt.

Based on the above results, the separation recycling technology that we have presented enables the recovery of 1–13 mm aggregate from RAP containing diverse types of asphalt. We also confirmed that the composition of old asphalt could be restored to its original condition. Moving forward, we will assess recycled mixtures containing aggregate recovered from RAPm using hot water rubbing.

Further examination of methods for restoring asphalt properties using high-temperature, high-pressure water from 1 mm recovered through hot water rubbing, is needed, as are methods for combining it into recycled mixtures. These questions all aim at the establishment of separation recycling technology that enables the quality control and use of recycled mixtures for diverse types of RAP.

ACKNOWLEDGMENT: This work was supported by JSPS KAKENHI Grant Numbers JP23760411 and JP26820179.

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(Received March 6, 2018)