Effect of Anti-Stripping Agent with Bipolarity to Strip-Ravelling Damage Caused by Surface Shear Stress

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Abstract. The stripping is one of serious distresses because it causes the decline in the bearing capacity of the asphalt pavement. As the result of evaluation of the bearing capacity of the pavement by FWD, the dissipation amount of work becomes larger at the stripping area in comparison with non-stripping area. An anti-stripping agent is effective for preventing such stripping in advance. The new anti-stripping agent which used in this research forms the strong electrochemical bonding between the asphalt and the aggregate by giving bipolarity to the asphalt. Furthermore, it is clarified that the new anti-stripping agent can give improve and enhance the shear strength of the asphalt as well. The shear strength is closely related to the rutting and the fretting of the asphalt pavement in accordance with past research. Therefore, enhancing the shear strength should contribute to not only the improvement in the rutting and the fretting but also the prevention of the strip-ravelling that the fine aggregates and the asphalt mortar are washed out from the pavement surface and it often takes place in Malaysia and Asian countries. In this research, we will focus on the strip-ravelling of the asphalt pavement, and simulate the strip-ravelling by using an immersed-wearing tester. As a result, this research clarifies the relationship between the shear strength of the asphalt and the strip-ravelling of the asphalt mixture.

1. Introduction
The stripping in asphalt pavement is one of the serious distresses because it occurs at the bottom or in the middle of the asphalt mixture layer and causes the decline in the bearing capacity of the asphalt pavement. As the result of evaluation of the bearing capacity of the pavement by the dissipation amount of work, which is obtained by FWD, the dissipation amount of work becomes larger at the area where the stripping is taking place in comparison with the non-stripping area.

In order to obviate such stripping which declines the bearing capacity of the pavement, it is widely known that the anti-stripping agent is very effective. The newly developed anti-stripping agent used in this research gives bipolarity to asphalt and forms electrochemical bonding between the aggregate and the asphalt. Furthermore, this new agent improves and enhances the shear strength of asphalt in addition to the anti-stripping efficiency.

In the past paper, authors already reported that the shear strength of asphalt was closely related to the rutting and the fretting of the asphalt pavement [1]. Therefore, enhancing the shear strength of asphalt should lead to the prevention of the strip-ravelling, which is caused by the friction between the tire and the surface of the pavement as shown in figure 1, as well as the rutting and the aggregate fretting.
Figure 1. Photos of strip-ravelling at surface of asphalt pavement

In this research, we focus on the strip-ravelling, which is the typical distress of asphalt pavement in Malaysia and other Asian countries, and evaluate the anti-stripping performance of asphalt mixture by the immersed wearing test simulating the strip-ravelling.

In this paper, it is clarified that there is the close relationship between the shear strength of the asphalt and the strip-ravelling, and the strip-ravelling is caused by the decline in the anti-stripping property of the asphalt mortar in the asphalt mixture, which is brought by the decrease in the shear stress of the asphalt.

2. Decline of bearing capacity by stripping

2.1. Dissipation amount of work by FWD
The dissipation amount of work expresses the energy dissipated into the pavement when subjected to the loading of 49 kN by FWD. As shown in figure 2, on the coordinates where the deflection is on the horizontal axis and the load is on the vertical axis, the dissipation amount of work is expressed by the area of hysteresis loop obtained from the chronological value of the load and the deflection when the loading values are positive. The area of the hysteresis loop is expressed as the difference in the loads at loading process and unloading process, and it is calculated by equation (1).

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\text{Dissipation amount of work (kN \cdot mm)} = \sum [(q1 + q2) \times (d2 - d1)/2]
\]  

(1)

Figure 2. Dissipation amount of work (the relation between deflection and load)

2.2. Dissipation amount of work at stripping area
The dissipation amount of work depends on the bearing capacity of the asphalt pavement, and if the pavement is distressed by the fatigue cracks, the dissipation amount of work becomes larger [2]. Therefore, we measured the dissipation amount of work by FWD at the area where stripping occurred in order to grasp the influence of the stripping of asphalt mixture on the bearing capacity of pavement. The stripping area was specified by the observation of the road surface condition and the section of core taken from the pavement.
Figure 3 shows the relationship between the thickness of the asphalt mixture layer and the dissipation amount of work. This figure shows the measurement results of the dissipation amount of work on 10 stripping areas and 10 non-stripping areas each. As shown on the left side of figure 3, the dissipation amount of work at the stripping area is obviously larger than that at the non-stripping area. And, the right side of figure 3 shows the difference in the size of the dissipation amount of work. Therefore, the stripping, as well as the fatigue cracks, can be regarded as one of serious distress which will bring the decrease in the bearing capacity of the pavement. Once such stripping occurs on the surface of the pavement, the distress will expand widely to the middle and the bottom of the asphalt mixture layer and bring the early deterioration of the pavement. Therefore, it is essential to obviate preventively the occurrence of the stripping.

3. Mechanism of stripping and anti-stripping

The aggregate with the main ingredient of SiO2 charges negatively because Oxygen with the negative charge is allocated on the surface of the aggregate. Therefore, if the asphalt mixture using such aggregate is immersed in water, Hydrogen of H2O will adhere to the surface of aggregate instead of asphalt due to the electronegativity of Oxygen. As a result, the asphalt around the aggregate is stripped from the aggregates by the hydrogen bonding, which is stronger than the intermolecular force between aggregate and asphalt, as shown on the left side of figure 4. In contrast, if the anti-stripping agent which gives the bipolarity to the asphalt, the electrochemical bonding between the aggregate and the asphalt is formed as shown on the right side of figure 4. Since such electrochemical bonding is stronger than the hydrogen bonding, the asphalt with the anti-stripping agent which provides the asphalt with the electrochemical bipolarity can exert the high anti-stripping performance.

![Figure 3. Dissipation amount of work at stripping area](image)

![Figure 4. Mechanism of stripping and anti-stripping](image)
4. Materials used and general properties

4.1. Materials used

In general, Granite and Andesite are known as the aggregates which easily arise the stripping. In this research, Andesite is used for the coarse aggregate and the fine aggregate because Granite is hardly used as aggregates for asphalt pavement in Japan. Calcium carbonate is used as a mineral filler.

Type of the asphalt mixture used for this research is dense-graded asphalt mixture (DAM). The asphalt used is straight asphalt with penetration 60-80 (StAs60-80). And, the anti-stripping agent used is “Tough Fix Hyper (TFH)” which can give bipolarity to asphalt [3]. The mix proportion and the lithology of the aggregates used for this research and the mix gradation are shown in Table 1 and Table 2, and the asphalt properties after adding TFH into StAs60-80 are shown in Table 3.

Table 1. Mix proportion and lithology of aggregates

| Material          | Lithology | Mix proportion (%) | Crushed stone (13) | Crushed stone (5) | Coarse sand | Screenings | Filler |
|-------------------|-----------|--------------------|---------------------|-------------------|-------------|------------|--------|
| Andesite          | Andesite  | 37.0               | 15.5                | 29.0              | 14.5        | 4.0        |
|                  | Calcium   |                    |                     |                   |             |            |
|                  | carbonate |                    |                     |                   |             |            |

Optimum asphalt content: 5.8%

Table 2. Mix gradation of dense graded asphalt mixture (DAM)

| Sieve size (mm) | Passing weight percentage (%) | Gradation envelope (envelope, %) |
|-----------------|-------------------------------|---------------------------------|
| 19.0            | 100                           | 100 95-100 55-70 35-50 18-30 10-21 6-16 4-8 |
| 13.2            | 98.5                          | 95-100                          |
| 4.75            | 64.1                          | 55-70                           |
| 2.36            | 46.0                          | 35-50                           |
| 0.6             | 23.5                          | 18-30                           |
| 0.3             | 15.2                          | 10-21                           |
| 0.15            | 9.4                           | 6-16                            |
| 0.075           | 5.9                           | 4-8                             |

Table 3. Properties of straight asphalt using TFH

| Base asphalt      | Straight asphalt 60-80 |
|-------------------|------------------------|
| TFH content (%)   | 0.0 0.1 0.15 0.2       |
| Penetration (1/10mm) | 62 57 58 59            |
| Softening point (°C) | 47.0 48.5 48.5 48.0    |
| Ductility (cm)     | >100 >100 >100 >100    |
| Viscosity at 135°C (mPa·s) | 366 366 368 368       |
| Viscosity at 160°C (mPa·s) | 132 128 128 130      |
| G*/sinθ at 64°C (Pa) | 1781.3 1944.2 2318.3 2412.6 |

As shown in table 3, the elastic component of the complex shear modulus “G*/sinθ” becomes higher along with the increase in TFH. It is considered that because the shear strength of the asphalt is becoming stronger due to the bipolarity brought from TFH.

4.2. General property for resistance to stripping

4.2.1. Test method of immersed wheel tracking test.

The immersed wheel tracking test is normally adopted to evaluate the anti-stripping property of asphalt mixture in Japan. In this test, the stripping would be caused at the middle and the bottom of the asphalt mixture by moving a wheel longitudinally and transversely in hot water of 60 °C. Table 4 shows the test conditions and two kinds of water level for the tests. The anti-stripping performance is evaluated by measuring the stripping area percentage obtained from the specimen after the test. The stripping area percentage is obtained by checking the stripping parts in the cross-section of the specimen on the sheet with 5 mm mesh. And the stripping area percentage is calculated by equation (2) [4].
Table 4. Condition of immersed wheel tracking test

| Item                      | Condition | Water level       |
|---------------------------|-----------|-------------------|
| Wheel weight (N)          | 686       | bottom of specimen|
| Contact pressure (MPa)    | 0.63      | top of specimen   |
| Curing temperature (°C)   | 60        |                   |
| Curing time (hours)       | 12 (air)/1 (water) |             |
| Test temperature (°C)     | 60        |                   |
| Test time (hours)         | 6.0       |                   |

4.2.2. Effect of anti-stripping agent “Tough Fix Hyper”.

The immersed wheel tracking test is normally adopted to evaluate the anti-stripping property of asphalt mixture in Japan. In this test, the stripping would be caused at the middle and the bottom of the asphalt mixture by moving a wheel longitudinally and transversely in hot water of 60 °C. Table 4 shows the test conditions and two kinds of water level for the tests. The anti-stripping performance is evaluated by measuring the stripping area percentage obtained from the specimen after the test. The stripping area percentage is obtained by checking the stripping parts in the cross-section of the specimen on the sheet with 5 mm mesh. And the stripping area percentage is calculated by equation (2) [4].

\[
\text{Stripping area percentage (\%)} = \frac{\text{Stripping area}}{\text{Sectional area}} \times 100 \quad (2)
\]

Figure 5. Relationship between TFH content and stripping area percentage

5. Evaluation of strip-ravelling

It is important to obviate and mitigate the risk of the occurrence of the strip-ravelling because the strip-ravelling may cause the serious distress of the asphalt pavement in the future as shown in figure 1. At present, however, the resistance to the strip-ravelling cannot be evaluated properly because the suitable test method is not established. Thus, in the following study, we will establish the test method to be able to simulate the strip-ravelling and will develop the asphalt mixture with the superior resistance to this problem.

5.1. Immersed wearing test

5.1.1. Test equipment and evaluation method.

The strip-ravelling is the distress in which only the fine aggregate and the asphalt mortar are worn away from the surface of the asphalt pavement. And it would become worse by the being subjected to the friction (shear) between the tire and the surface of the pavement. In this research, therefore, using the equipment which is normally adopted for the evaluation of the aggregate fretting of porous asphalt mixture, we evaluate the strip-ravelling as shown in figure 6. Furthermore, the loading weight, the rotational radius, and the rotational speed were in accordance with the conventional method of the
porous asphalt mixture [5]. The test situation and the specimen after the immersed wearing test are shown in figure 7.

Figure 6. Equipment of immersed wearing test

Figure 7. Test situation and specimen of immersed wearing test

The strip-ravelling is evaluated by the wearing depth obtained by comparing the surface shapes of the specimen before and after the test. Such wearing depths are measured on the same line before and after the test as shown on the left side of figure 8. And, the average of the wearing depths of all points measured on the horizontal axis at the intervals of 5 mm are adopted as the index value of the strip-ravelling (mm) as shown on the right side of figure 8 in this research.

Figure 8. Evaluation for strip-ravelling

5.1.2. Curing temperature and curing time. The curing temperature and the curing time of specimens are very important because they would influence significantly on the anti-stripping performance of the asphalt mixture. Hence, in order to determine these two conditions for the curing of the specimens, referring the curing conditions for ASTM D 1559 Residual Marshall Stability, we have carried out several types of immersed wearing test in advance based on the conditions of the curing temperature of 60 °C and the curing time of 48 hours.

The relationship among the curing temperature, the curing time, and the strip-ravelling is shown in Figure 9. In this case, the test temperature is provisionally set at 20 °C and the test time is set to 1 hour, the validity of these conditions will be re-examined in the next section. As shown in this figure, the strip-ravelling shows a tendency to converge to a certain value by setting the curing temperature to 60 °C and the curing time to 48 hours or more. Therefore, the curing temperature shall be set to 60 °C and the curing time to 48 hours in this research.
5.1.3. Test temperature and test time. It is also important in order to evaluate the strip-ravelling to decide the test conditions like the test temperature and test time as same as to have decided the curing conditions as mentioned above. Especially, the test temperature should be examined carefully because this research is aimed to evaluate only wearing of fine aggregate and asphalt mortar. Specifically, it is necessary to set the temperature which would not cause the rutting and the aggregate fretting of the asphalt mixture.

The relationship among the test temperature, the test time, and the strip-ravelling is shown in figure 10. The specimens used in this test have been cured at 60 °C for 48 hours. As shown in this figure, the strip-ravelling increases with the rise of the test temperature. However, the wearing depths of more than 5 mm, which shows the fretting of the coarse aggregates, were observed in several points and the plastic deformation like the rutting was also occurring at the test temperature of 40 °C. Therefore, the test temperature was set to 30 °C because this temperature did not provoke such distresses on the specimens. And, the test time was set to 1.0 hour because there was no significant difference between 1.0 hour and 2.0 hours.

5.2. Effect of anti-stripping agent “TFH” on strip-ravelling
The strip-ravelling when adding TFH of 0.1 to 0.25 % into StAs60-80 is shown in figure 11. As shown in this figure, the strip-ravelling is greatly improved by the addition of TFH of 0.15 % or more, and the strip-ravelling is able to be reduced by 1/2 compared with the case of no addition.
This result shows that the shear strength is improved at the same time as the anti-stripping performance, such improvement in the shear strength will be proved by the increase in the elastic component of the complex shear modulus, $G^*/\sin\delta$ as having shown in table 3.

**Figure 11.** Relationship between TFH content and strip-ravelling

6. Influence of asphalt mortar on strip-ravelling
The immersed wearing test was able to simulate the wearing of the fine aggregate and the asphalt mortar of the asphalt mixture as having shown in figure 1, and it was clarified that the relationship between the strip-ravelling and the shear strength of asphalt. Such an improvement in the shear strength of asphalt, which is provided by the addition of TFH, is brought from the improvement in the anti-stripping performance by forming the electrochemical bonding between the aggregate and the asphalt as having shown in figure 4. Therefore, the stripping test of the asphalt mortar was carried out in order to verify how TFH would result in the effects against the fine aggregates and the asphalt mortar, which would be worn by the strip-ravelling.

6.1. Residual Marshall Stability test using asphalt mortar
Dense-graded asphalt mixture (13) using the coarse aggregate and the fine aggregate of Andesite as shown in table 1 or 2 has been evaluated in this research so far. In this section, the specimens using only the coarse sand in the aggregates constituting the dense graded asphalt mixture (13) were fabricated in order to evaluate the anti-stripping performance of the asphalt mortar consisted of only coarse sand of Andesite. And such asphalt mortar consisting of only the coarse sand is evaluated by Residual Stability after the curing times of 48 and 96 hours referred to ASTM D1559. Furthermore, the optimum asphalt content of the asphalt mortar consisting of only the coarse sand is set to 6.6 % so that the thickness of asphalt film is 9.5 μm as the same as that of dense graded asphalt mixture (13) by the calculation of the gradation of the coarse sand.

6.2. Effect of anti-stripping agent “TFH” on Residual StabilityDense-graded
The Residual Stability of the asphalt mortar consisting of only the coarse sand when adding TFH of 0.15 % into StAs60-80 is as shown in figure 12. And in this test, the Residual Stabilities of the dense graded asphalt mixture (13) shown in table 1 or 2 are also evaluated as the comparison as well as the asphalt mortar.

As shown in this figure, the Residual Stability tends to decrease with the increase in the curing time from 48 to 96 hours. And the Residual Stability of asphalt mortar consisting of only coarse sand shows the bigger decrease than that of the dense graded asphalt mixture (13). Therefore, the strip-ravelling will be caused by the low anti-stripping performance of asphalt mortar like coarse sand. In contract, it is clarified that the resistance to the strip-ravelling is improved by using TFH because TFH added into StAs60-80 would be able to restrain the decrease in the Residual Stability.
7. Conclusion
The findings in this research are as follows:

a) The stripping is the serious distress which causes the decline in the bearing capacity of the pavement. The increase in the dissipation amount of work by FWD will explain clearly such a fact.

b) The strip-ravelling occurring in Asian countries can be recreated properly by the immersed wearing test carried out on the conditions that the specimens are cured at 60 °C for 48 hours are tested at 30 °C for 1 hour.

c) The strip-ravelling is clearly related to the shear strength of asphalt. And, the shear strength and anti-stripping performance of the asphalt are significantly improved by adding TFH of 0.15 % into StAs60-80.

d) The Residual Stability of the asphalt mortar is easily to decrease by the stripping. And the stripping of the asphalt mortar causes the stripping of the asphalt mixture. Therefore, it is necessary to prevent the stripping by adding TFH into StAs60-80.

e) In this research, we have focused on the stripping and the strip-ravelling in case of using StAs60-80. Hereafter, it will be necessary to expand the scope of the research to the modified asphalt and others.

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