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## Mechanical Evaluation and Mechanism Analysis of the Stripping Resistance and Healing Performance of Modified Asphalt-Basalt Aggregate Combinations

--Manuscript Draft--

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<b>Abstract:</b>	<p>Asphalt modifications could contribute to the moisture susceptibility and fatigue resistance of asphalt mixtures. The study in this paper aims to investigate the effects of various asphalt modifications on the bond and healing properties of modified asphalt binders, as well as the mechanism of changes caused by the modification. Five modified asphalt binders were prepared in the laboratory for this study, including the SBS-modified asphalt, crumb rubber-modified asphalt, TB rubberized asphalt, high-density polyethylene (HDPE)-modified asphalt, and gilsonite-modified asphalt. A modified binder bond strength (BBS) test was applied to evaluate the bond and healing performance of five modified binders, at both dry and wet conditions. The surface free energy (SFE) test was conducted on the modified binders to investigate the changes in the cohesion/adhesion energy due to the binder modification. In addition, the ravelling resistance, moisture susceptibility, and fatigue life of asphalt mixtures prepared from the modified binders were measured by using the Cantabro test, Hamburg wheel-tracking test, and four-point beam fatigue test, respectively. The results of performance tests for the asphalt mixtures are employed to verify the findings of BBS and SFE tests for the modified binders. It is found that the modified BBS test provides a promising tool for evaluating the bond and healing properties of modified asphalt binders, and the SFE could help to explain the mechanism of binder modification. The testing results indicate that gilsonite enhanced the bond strength and surface energy of asphalt and high-density polyethylene significantly improve the healing performance.</p>

Dear Editor:

We submit our revised manuscript entitled “Mechanical Evaluation and Mechanism Analysis of the Stripping Resistance and Healing Performance of Modified Asphalt-Basalt Aggregate Combinations” to Construction and Building Materials for publication.

In this paper, the effects of five commonly used modifiers (SBS, crumb rubber, terminal blend rubber, high-density polyethylene, and gilsonite) on the asphalt cohesion/adhesion and healing properties were evaluated with the use of binder bond strength (BBS) test. Different dosages were investigated. The surface free energy test was conducted to reveal the mechanism of the performance variation of different asphalt-aggregate combinations in regard to cohesion/adhesion energy. Furthermore, the Cantabro test, Hamburg wheel-track test, and four-point beam fatigue-healing test were performed to estimate the ravelling resistance, moisture damage resistance, and fatigue healing property of the corresponding mixtures respectively. The correlation between the BBS test and the three mixtures tests were analyzed to validate the accuracy of the BBS test on the evaluation of stripping resistance and fatigue-healing performance of asphalt mixture.

All authors have read and approved this version of the article, and due care has been taken to ensure the integrity of the work. Neither the entire paper nor any part of its content has been published or has been accepted elsewhere. It is not being submitted to any other journal.

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Thank you very much for your attention and consideration.

Sincerely yours,

Quan Lv

1 **Mechanical Evaluation and Mechanism Analysis of the Stripping Resistance and Healing**

2 **Performance of Modified Asphalt-Basalt Aggregate Combinations**

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## Abstract

Asphalt modifications could contribute to the moisture susceptibility and fatigue resistance of asphalt mixtures. The study in this paper aims to investigate the effects of various asphalt modifications on the bond and healing properties of modified asphalt binders, as well as the mechanism of changes caused by the modification. Five modified asphalt binders were prepared in the laboratory for this study, including the SBS-modified asphalt, crumb rubber-modified asphalt, TB rubberized asphalt, high-density polyethylene (HDPE)-modified asphalt, and gilsonite-modified asphalt. A modified binder bond strength (BBS) test was applied to evaluate the bond and healing performance of five modified binders, at both dry and wet conditions. The surface free energy (SFE) test was conducted on the modified binders to investigate the changes in the cohesion/adhesion energy due to the binder modification. In addition, the ravelling resistance, moisture susceptibility, and fatigue life of asphalt mixtures prepared from the modified binders were measured by using the Cantabro test, Hamburg wheel-tracking test, and four-point beam fatigue test, respectively. The results of performance tests for the asphalt mixtures are employed to verify the findings of BBS and SFE tests for the modified binders. It is found that the modified BBS test provides a promising tool for evaluating the bond and healing properties of modified asphalt binders, and the SFE could help to explain the mechanism of binder modification. The testing results indicate that gilsonite enhanced the bond strength and surface energy of asphalt and high-density polyethylene significantly improve the healing performance.

**Key words:** asphalt bond; healing property; surface free energy; mixture stripping resistance; fatigue-healing performance.

## 1 Background

Ravelling and moisture damage that are two types of main distresses of asphalt pavements, are

1 mainly attributed to inner cohesion failure of asphalt binder and/or adhesion failure at the interface of  
2  
3 2 asphalt binder and mineral aggregates. Due to the traffic loading and environmental influence (e.g.  
4  
5  
6 3 moisture damage and oxidative aging), microcracks initial in the binder and binder-aggregate interface  
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9 4 and gradually develop into macrocracks as the pavement service time increases. It is also known that  
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12 5 with a rest time, asphalt materials have the ability to heal microcracks because of the viscoelasticity  
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15 6 nature of asphalt binder. Part of the bonding failure caused by the initiation and propagation of  
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18 7 microcracks could be restored within an available healing process of asphalt binder. Besides,  
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21 8 mechanical loading from traffic has an effect of re-bonding asphalt binder and aggregates under certain  
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24 9 conditions, and the meso cracks inside asphalt mixture even can close due to the binder flowability at  
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27 10 high pavement temperatures.

28 11 Many studies reported the bond and healing behavior of asphalt binders. In which, four main  
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31 12 theories are used to explain the asphalt bond mechanism, including the mechanical theory, chemical  
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34 13 reaction theory, surface energy theory, molecular orientation theory<sup>[1]</sup>. For the mechanism of asphalt  
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37 14 healing, the fracture surface energy theory, capillary theory, and interfacial diffusion theory are typically  
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39  
40 15 employed. Among those studies, the surface free energy (SFE) of asphalt binder and aggregates is  
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42  
43 16 mostly used and being considered as a very promising indicator in identifying the cohesive and adhesive  
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45  
46 17 energy of the binder-aggregate system<sup>[2]-[8]</sup>. The contact angle measured by using the Wilhelmy plate  
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48  
49 18 (WP) or Sessile drop (SD) methods<sup>[9]</sup> is employed for calculating the SFE components of both asphalt  
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52 19 binder and mineral aggregates, allowing for evaluating the moisture susceptibility of the asphalt mixture.

53 20 The SFE measurement has been conducted to investigate the moisture susceptibility of asphalt  
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56 21 mixture and to select asphalt binder and/or aggregates in some researches. For instance, the SHRP-A-  
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59 22 341<sup>[1]</sup> reports the analysis of adhesion between asphalt binder and aggregate and the SFE. In which both

1 the WP method and sorption method were conducted for the analysis. However, the calculation method  
2 used in that study is not easy to follow, neither the stripping resistance was included. Cheng<sup>[10]</sup>  
3 investigated the SFE of asphalt-aggregate system and correlated it with the performance of asphalt  
4 concrete. Through the study of asphalt-aggregate adhesion at both dry and wet conditions it was found  
5 that the SFE results were consistent with the findings from the mixture accelerated moisture damage  
6 testes. Bhasin<sup>[11]</sup> compared various aggregates in the SFE measurements and found that those aggregates  
7 showed significant differences in the adhesion energy when they were applied with the same asphalt  
8 binder. Jonathan<sup>[12]</sup> studied the influence of polymer-modified asphalt on the moisture damage of  
9 asphalt-aggregate systems. Wasiuddin et al.<sup>[13]</sup> investigated the compatibility ratio (CR) of different  
10 asphalt-aggregate combinations and proposed to use the SFE to screen the asphalt-aggregate  
11 combinations. In addition, many other studies<sup>[14][15]-[16]</sup> reported the influence of different binder  
12 modifiers on the moisture susceptibility of asphalt mixes. It is also confirmed that the SFE theory could  
13 be useful for determination of optimum combination of asphalt-aggregate system.

14 While, only few studies focus on quantitatively ranking the bond and healing properties of various  
15 modified asphalt binders. Most of those published studies report research methods of the DSR fatigue  
16 test<sup>[17][20]</sup> or four-point bending (4PB) test<sup>[21][22]</sup> for investigating the healing performance of asphalt  
17 binders and mixtures. In those fatigue-based healing tests, the binder/mixture samples are subjected to  
18 cyclic loading and healing. During the healing period, the specimens were rest at certain environmental  
19 conditions without mechanical loading<sup>[23]</sup>. The binder/mixture properties (e.g. modulus and peak load)  
20 at each load cycle were recorded for analyzing the healing performance<sup>[24]</sup>. It is noticed that the fatigue-  
21 based healing tests are very time-consuming, and the repeatability of testing data has a big concern in a  
22 long period. In recent years, the newly developed binder bond strength (BBS) test has become popular

1 in assessing the bond property of asphalt emulsions and modified asphalt binders<sup>[25][29]</sup> since the simple  
2 instrument used in the test and its ability of rapidly measuring the bond strength of asphalt-aggregate  
3 combination. The BBS test was originally designed for the coating industry and now it has been  
4 introduced into the asphalt industry as a standard test method in ASTM D 4541<sup>[30]</sup> for estimating the  
5 bond properties of asphalt binder. Several researchers<sup>[26][31]</sup> have reported that the BBS test could offer  
6 direct and quick measurement of bond strength at the asphalt-aggregate interface.

7 In this study, the BBS tests were employed for investigating the bond and healing properties of  
8 five representative modified binders, including the SBS-modified asphalt, crumb rubber-modified  
9 asphalt, TB rubberized asphalt, high-density polyethylene (HDPE)-modified asphalt, and gilsonite-  
10 modified asphalt. The optimum dosages of these five types of binder modifiers were determined based  
11 on the measured pull-off tensile strength (POTS) at both the dry and wet conditions. In addition, the  
12 SFE tests were conducted on these modified asphalt binders to understand their mechanism of changing  
13 the bond and healing properties of base asphalt binder. The Cantabro loss test, Hamburg wheel-tracking  
14 (HWT) test, and 4PB fatigue-healing test were performed on the mixtures prepared with these modified  
15 asphalt binders to evaluate the their ravelling resistance, moisture susceptibility and fatigue healing  
16 property, respectively. These mixture testing results are used for verifying the findings obtained from  
17 the BBS and SFE tests of modified asphalt binders.

## 18 **2 Objectives**

19 The main objectives of this study are as following:

- 20 1. To evaluate the cohesive/adhesive properties and the healing performance of five  
21 representative modified asphalt binders;

2. To investigate the mechanism of bond and healing properties of modified asphalt binders including various modifiers; and
3. To verify the findings of binder bond and healing properties from the BBS tests through assessing the corresponding mixture performance tests, including the ravelling resistance, moisture susceptibility, and fatigue healing property.

### 3 Experimental

#### 3.1 Materials

In this study, a PG 64-22 base asphalt and five commonly used binder modifiers were selected for preparing the modified asphalt binders in the laboratory. The modifiers, including the linear SBS, crumb rubbers, HDPE, and gilsonite, were applied at various dosages for the modification. Compared to the traditional crumb rubber-modified asphalt, the TB rubberized asphalt has a lower viscosity and better storage stability due to its specialized producing process, in which the crumb rubber is devulcanized at high temperatures and mixed with asphalt binder at high shear speed with an extended period during the modification. The Iranian gilsonite used in this study has a good compatibility with the base asphalt. The mixing conditions for these modified binders are listed in Table 1. It should be noted that all the modified binders were used for testing within 4 hours after they were produced in order to eliminate the influence caused by the possible inhomogeneity. For the mixtures and the aggregate substrates, basalt was chosen for its wide usage in road engineering projects.

Table 1 Summary of the selected asphalt and experimental dosages

Binder Types	Modified Asphalt Formulation	Dosages of Modifiers (%)
Base asphalt	—	—
SBS-modified asphalt	Linear SBS (varying dosages) +0.15% Sulfur	1.5, 3.0, 4.5, 5.5, 6.0, 7.5

Rubber asphalt	Crumb rubber	5, 10, 15, 18, 20
	TB rubber	5, 10, 15, 18, 20
HDPE-modified asphalt	HDPE	2, 4, 6, 8
Gilsonite-modified asphalt	Gilsonite	4, 8, 12, 20, 24

## 3.2 Methods

### 3.2.1 Binder bond strength (BBS) test

In this study, the BBS test was modified for assessing the binder healing property through introducing a cyclic pull-off tests with a healing setting between two standard testing procedures. The five types of laboratory prepared modified asphalt binders and basalt aggregate were used to prepare the asphalt-aggregate systems for BBS tests. The pull-off stubs were employed to apply an asphalt film at a thickness of 0.2mm (Figure 1-a) on the basalt aggregate substrate at a temperature of 150°C and then cooled down at room temperature. Detailed information for test sample preparation has been reported in the previous research<sup>[28]</sup>. The prepared asphalt-aggregate test samples were divided into two sets: one is for measuring the cohesion at dry condition and the other is for the adhesion at wet condition. The dry condition for testing samples was at 25°C for 24 h. The wet condition included the curing of samples in the water at 40°C for 24 h. The pull-off tensile strength (POTS) was measured using the Positest AT-A apparatus (Figure 1-b). In general, the testing samples that were cured under the dry condition showed the cohesive failure (Figure 1-c) while the samples after the wet conditioning showed the adhesive failure (Figure 1-d) due to the moisture damage.

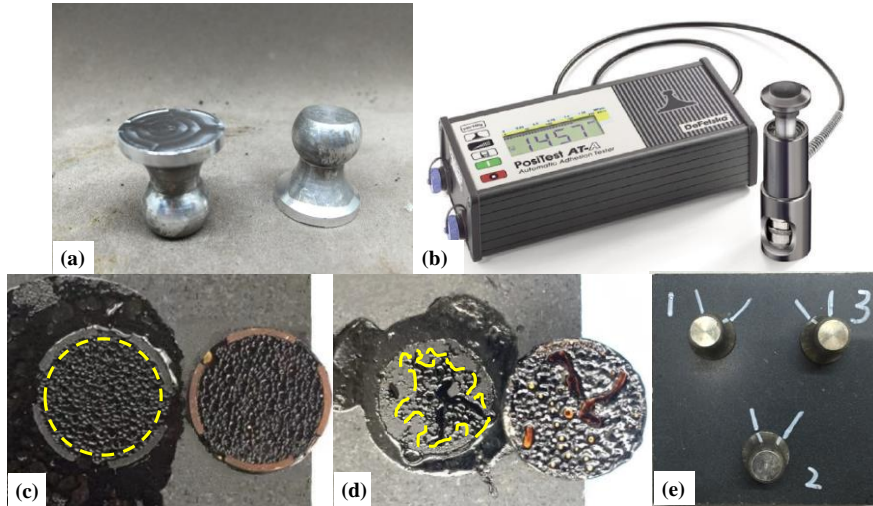


Figure 1 (a) Stubs and (b) Positest AT-A apparatus and (c) cohesive failure and (d) adhesive failure and (e) samples with marks

In order to applying for the healing procedure during the modified BBS test, the original locations of stubs were marked before the initial pull-off test (Figure 1-e) and the stubs were immediately placed at their original locations after the each pull-off cycle with a constant pressure applied on them. Then the tested asphalt-aggregate combinations were cured at different conditions for restoring the bond strength within the binder and/or between the binder and aggregate. For the testing samples in the dry conditioning set the healing condition was in the thermostatic chamber at 40°C for 12 hours. For the wet conditioning set the healing condition was in the water at 25 °C for 12 hours. The asphalt-binder combinations were pre-conditioned in the air at testing temperature of 25°C for 30 minutes before re-testing their POTS. In total, the asphalt-aggregate combinations were subjected to five healing cycles, and their bond strength after each healing cycle was measured. Thus, a healing ratio (HR) for each cycle could be calculated by using the equation (1). For each type of testing samples, three replicates were measured for the POTS values.

$$HR_i = \frac{POTS_{\text{Healing-}i}}{POTS_{\text{initial}}} \times 100\% \quad (1)$$

1 where,

2  
3 2  $HR_i$ — the healing ratio after i-th healing cycle;

4  
5  
6 3  $POTS_{Healing-i}$ — the pull-off tensile strength after i-th healing cycle (MPa);

7  
8  
9 4  $POTS_{initial}$ — the initial pull-off tensile strength (MPa).

### 10 11 12 5 3.2.2 Surface free energy (SFE) test

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14  
15 6 According to the acid-base theory, the surface free energy of any material can be divided into three  
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18 7 components based on the types of surface molecular forces: the non-polar component  $\gamma^{LW}$  (also  
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20  
21 8 known as van der Waals force or dispersion force component ), Lewis acid component  $\gamma^+$ , and Lewis  
22  
23  
24 9 basic component  $\gamma^-$ . The SFE of the material  $\gamma$  can be calculated according to equation (2):

$$25  
26 10 \gamma = \gamma^{LW} + \gamma^{AB} = \gamma^{LW} + 2\sqrt{\gamma^+\gamma^-} \quad (2)$$

27  
28  
29 11 According to the Young-Dupre equation, the adhesion work between the solid (aggregate) and  
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32 12 liquid (asphalt binder) can be written using equation (3):

$$33  
34  
35 13 W_{ls} = \gamma_l(1 + \cos\theta) \quad (3)$$

36  
37 14 where,  $W_{ls}$  represents the adhesion energy of asphalt-aggregate system;  $\gamma_l$  represents the SFE of the  
38  
39  
40 15 asphalt binder; and  $\theta$  represents the contact angle measured between the asphalt binder and aggregate.

#### 41 42 43 16 (1) Cohesion energy of asphalt binder ( $W_u$ )

44  
45 17 The cohesion energy of the liquid is defined as the work required for dividing a single liquid column  
46  
47  
48 18 into two parts along the unit cross section<sup>[32]</sup>. Therefore, the cohesion energy ( $W_u$ ) of a liquid can be  
49  
50  
51 19 calculated using equation (4):

$$52  
53  
54 20 W_u = 2\gamma_l \quad (4)$$

#### 55 56 57 21 (2) Wet adhesion energy of asphalt-aggregate system ( $W_{lsw}^{wet}$ )

Due to the higher adhesion energy between the water and aggregate, the bonding between asphalt and aggregate can be replaced by water, the work required for replacing asphalt binder is calculated using equation (5). A larger absolute value of  $W_{lsw}^{wet}$  indicates a lower resistant to stripping.

$$W_{lsw}^{wet} = W_{lw} + W_{sw} - W_{ls} - 2\gamma_w \quad (5)$$

where, subscript w refers to water, and

$W_{lw}$ —the interfacial energy between liquid-water;

$W_{sw}$ —the interfacial energy of solid-water;

$\gamma_w$ —the SFE of the water.

### (3) Compatibility ratio (CR)

Dallas et al.<sup>[33]</sup> introduced a parameter “compatibility ratio (CR)” to illustrate the moisture susceptibility of asphalt-aggregate system, in which the wettability of the asphalt over the aggregate is considered (as calculated in equation (6)). A higher CR value indicates a better adhesion performance of the asphalt-aggregate system and a lower moisture susceptibility.

$$CR = \left| \frac{W_{ls} - W_{ll}}{W_{lsw}^{wet}} \right| \quad (6)$$

#### ● SFE of modified asphalt binders

To calculate the cohesion energy of asphalt binder, wet adhesion energy of asphalt-aggregate system, and the compatibility ratio, the SFE components (LW, acid, and base) of modified asphalt binders were measured through solving the hyperstatic equations (7). In this study, the Wilhelmy plate (WP) method was used to obtain the advancing contact angle between the probe liquids (distilled water, formamide, glycerol, and ethylene glycol) and the modified asphalt binders. Four replicates were tested for each type of probe liquid.

$$\begin{bmatrix} \frac{(1 + \cos \theta_1)\gamma_{L1}}{2} \\ \frac{(1 + \cos \theta_2)\gamma_{L2}}{2} \\ \vdots \\ \frac{(1 + \cos \theta_n)\gamma_{Ln}}{2} \end{bmatrix} = \begin{bmatrix} \sqrt{\gamma_{L1}^{LW}} & \sqrt{\gamma_{L1}^-} & \sqrt{\gamma_{L1}^+} \\ \sqrt{\gamma_{L2}^{LW}} & \sqrt{\gamma_{L2}^-} & \sqrt{\gamma_{L2}^+} \\ \vdots & \vdots & \vdots \\ \sqrt{\gamma_{Ln}^{LW}} & \sqrt{\gamma_{Ln}^-} & \sqrt{\gamma_{Ln}^+} \end{bmatrix} \begin{bmatrix} \sqrt{\gamma_B^{LW}} \\ \sqrt{\gamma_B^+} \\ \sqrt{\gamma_B^-} \end{bmatrix} \quad (7)$$

where,  $\theta_1, \theta_2, \dots, \theta_n$  refer to the contact angle between the  $i_{th}$  probe liquid and asphalt binder; and subscript L1, L2, ..., Ln refer to the  $i_{th}$  probe liquid.

### ● SFE of aggregate

The or Sessile drop (SD) method was employed for measuring the contact angles between the basalt aggregate substrate and three probe liquids (distilled water, formamide, and ethylene glycol), and their results were used to calculate the SFE components of basalt aggregate using equation (7). The detailed sample preparation and the testing procedure have been reported in other studies<sup>[34]</sup>. Three replicates of samples with each probe liquid were tested.

#### 3.2.3 Cantabro loss test

Cantabro loss test was conducted on the asphalt mixtures in accordance with the standard method AASHTO TP 108-14. The asphalt concrete samples were conditioned at 25°C for 20 h prior to the test and then subjected to 300 revolutions in the Los Angeles abrasion testing machine at a rotating speed of 30rpm. The mass loss rate of the samples was calculated for determining the ravelling resistance of asphalt mixture. Four replicates were tested for each type of mixture.

#### 3.2.4 Hamburg wheel-tracking (HWT) test

The HWT test in accordance with the AASHTO T 324-14 was performed to evaluate the moisture susceptibility of asphalt mixtures. In this study, the samples were tested at 50°C in the wet condition until the wheel pass reaches to 20000 passes or the rut depth reaches to 20 mm. The “stripping inflection

1 point (SIP)” index was obtained, which is defined as the number of wheel load passes at the intersection  
2  
3 of creep slope and stripping slope and signifies the onset of mixture moisture damage. Two replicates  
4  
5 were tested for each mixture.  
6  
7

#### 8 3.2.5 Four-point beam (4PB) mixture fatigue-healing test

9 To study the healing performances of the mixtures, the modified 4PB fatigue test with an  
10 introduced healing period was conducted. The beam samples were subjected to dynamic four-point  
11 bending under the strain-control mode at a microstrain level of 1000 with a loading frequency of 10 Hz  
12 at 25°C. During the healing period, the specimens were cured at 50°C for 4h and afterward 25 °C for 24  
13 h. The traditional  $N_{f50}$  failure criterion was chosen for the analysis of the mixture prepared with base  
14 binder while the  $N_{fNM}$  failure criterion was employed for the mixtures prepared with the modified  
15 asphalt binders. Since it has been reported that the  $N_{fNM}$  failure criterion is more suitable for asphalt  
16 mixtures with modified binders<sup>[35][36]</sup>. The healing ratio of fatigue life for asphalt mixtures is calculated  
17 by using equation (8). Three replicates were tested for each mixture.  
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$$37 \quad HR_{4PB} = \frac{N_{f\text{-after}}}{N_{f\text{-initial}}} \times 100\% \quad (8)$$

38 where,

39  $HR_{4PB}$ — the healing ratio of the asphalt mixture;

40  $N_{f\text{-after}}$ — the fatigue life after healing;

41  $N_{f\text{-initial}}$ — the initial fatigue life.

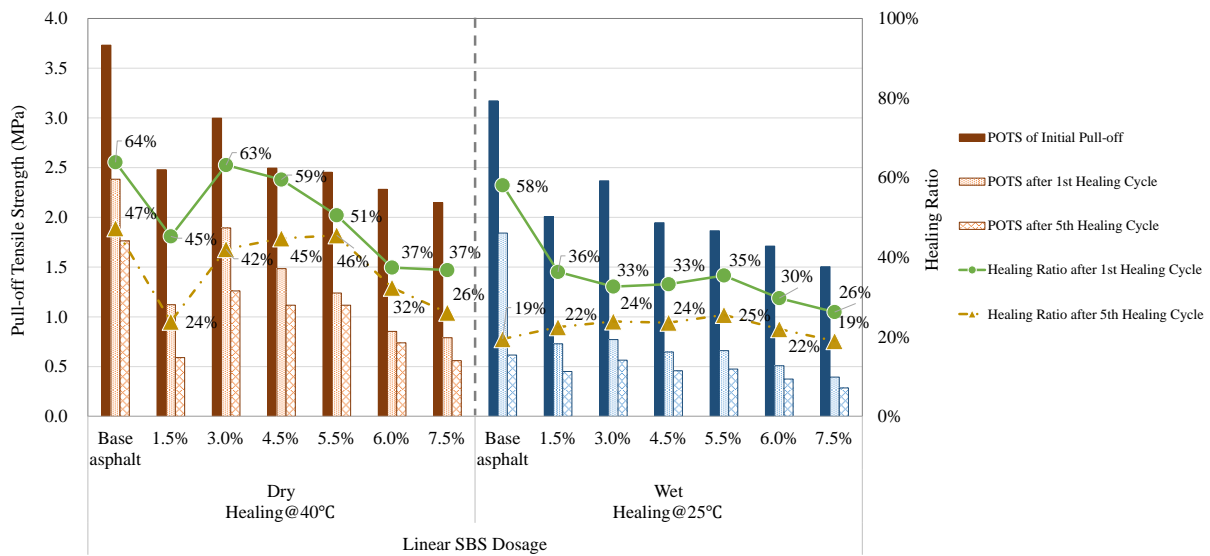
## 42 4 Results and discussion

### 43 4.1 BBS and SFE tests results of asphalt binders

44 The BBS test was performed to investigate the effects of different modifiers and their dosages on the

1 asphalt bond strength and healing property. Two healing conditions (dry and wet) and five healing cycles  
 2 were investigated. From Figure 2 to Figure 12, the POTS and HR values of different asphalt binders are  
 3 plotted separately. For each binder, only two healing POTS and healing ratio values in the 1st and 5th healing  
 4 cycle were presented and discussed. Also, the cohesion energy ( $W_{II}$ ), wet adhesion energy ( $W_{lsw}^{wet}$ ) and  
 5 compatibility ratio (CR) of each asphalt binder derived from SFE test were also shown and analyzed. The  
 6 error bar was omitted since the COV values of the testing results were less than 15% for all tested asphalt  
 7 binders. It should be noted that since only one aggregate type (basalt) was selected in this study, the following  
 8 results may be limited to this asphalt-aggregate system.

#### 9 4.1.1 Effects of linear SBS modification

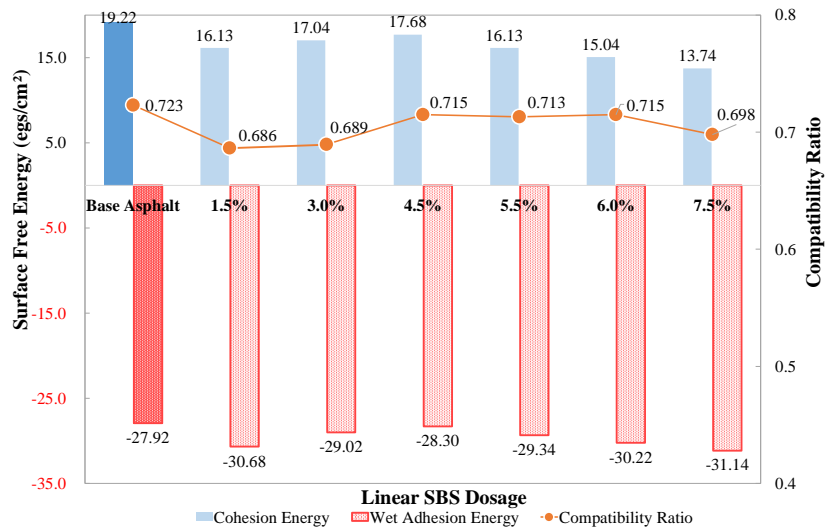


10  
11 Figure 2 BBS test results of linear SBS-modified asphalt.

12 Figure 2 shows the BBS test results of linear SBS-modified asphalt. The POTS and HR values of  
 13 linear SBS-modified asphalt are lower than those of the base asphalt, which manifests that linear SBS  
 14 modification harms the bonding strength and healing properties. It is also seen that POTS and HR  
 15 decrease with the increase of healing cycles. There is a notable drop in POTS values after the first

1 healing cycle. After that, the POTS values decrease in a much less range. This suggests the healing is a  
 2 long-standing behavior after multiple fractures. Besides, the HR values in the dry condition are always  
 3 higher than those in the wet condition, indicating the existence of water interferes with the asphalt  
 4 binder healing process.

5 As for the effects of modifier dosage, under dry conditions, the initial POTS and HR peak when  
 6 3.0% linear SBS is added. For wet conditions, the initial POTS peak at 3.0% dosage while HR remains  
 7 similar for different dosages. Therefore, it is recommended that 3.0% as the optimum SBS dosage in  
 8 terms of bond and healing properties.



9  
10 Figure 3 SFE test results of linear SBS-modified asphalt.

11 Figure 3 shows the SFE test results of linear SBS-modified asphalt at various dosages. The trend  
 12 of modification on the cohesion energy  $W_{II}$  is found to be consistent with the changes of POTS of SBS-  
 13 modified asphalt at dry condition, as well as their healing ratio. It is also found that the changes in the wet  
 14 adhesion energy  $W_{LSW}^{wet}$  and CR fall in the same trends as those of POTS and HR at wet condition,  
 15 respectively. These results indicate that BBS tests could match the principle changes of cohesion/adhesion  
 16 energies of SBS-modified asphalt binders.

1           The POTS of SBS modified asphalt at a dosage level of 1.5% shows a lower value than the base  
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3 binder at dry condition. And its cohesion energy is also lower than the base binder. This is because of  
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6 3       that the SBS polymer could not generate a stable grid structure enhancing the cohesive strength of  
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9 4       asphalt when the dosage is relatively low. Meanwhile, at low dosage level the SBS macromolecules  
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12 5       may cause an issue of inhomogeneity in the binder, which might result in stress concentration in the  
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14  
15 6       modified asphalt binder. On the other hand, SBS modification increases the viscosity of binder, leading  
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17  
18 7       to its poor flowability, which reduces the opportunity of asphalt to fully recreate the cohesive bond. In  
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20  
21 8       the dosage range of 3.0%~4.5%, SBS polymer could disperse uniformly in base asphalt and formulate  
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24 9       grid structure through the cross-linking reaction. Some saturates and aromatics in asphalt enter into the  
25  
26  
27 10       SBS network, which changes the component proportion of asphalt. The proportions of saturates and  
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29  
30 11       aromatics decrease while those of asphaltene and resin increase, which contain the most chemically  
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33 12       active components, such as asphaltous acid, asphaltous acid anhydrides, and other polar components,  
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36 13       which promotes the cohesion energy and strength of asphalt to some extent. When the SBS polymer  
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39 14       content is higher than 6.0%, the cohesion strength and healing performance of modified binder are  
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42 15       negatively affected due to the separation of SBS modifier and the increased viscosity of asphalt.

43           The trend of  $W_{lsw}^{wet}$  follows the POTS change of SBS-modified asphalt under the wet condition.  
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45 17       The SBS polymer itself does not adhere to aggregate, and the large molecules makes it difficult for  
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48 18       aggregate to adsorb SBS-modified asphalt, leading to the fact that SBS-modified asphalt is prone to be  
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51 19       stripped from aggregate by moisture. In addition, its large molecules limit the asphalt movements,  
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54 20       resulting in a relatively lower healing capability. Furthermore, it is observed that the index CR could  
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57 21       illustrate the variation of asphalt healing performance. CR reflects the asphalt wettability in wet  
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60 22       condition, which determines whether asphalt can penetrate the microstructure of the aggregate surface.

Higher CR implies that asphalt could recover the aggregate surface after adhesive fracture in the presence of water.

In consideration of bond strength as well as healing performance, it is concluded that 3.0%~4.5% is an optimum range of SBS dosage in terms of the results of BBS and SFE tests.

#### 4.1.2 Effects of crumb rubber modification

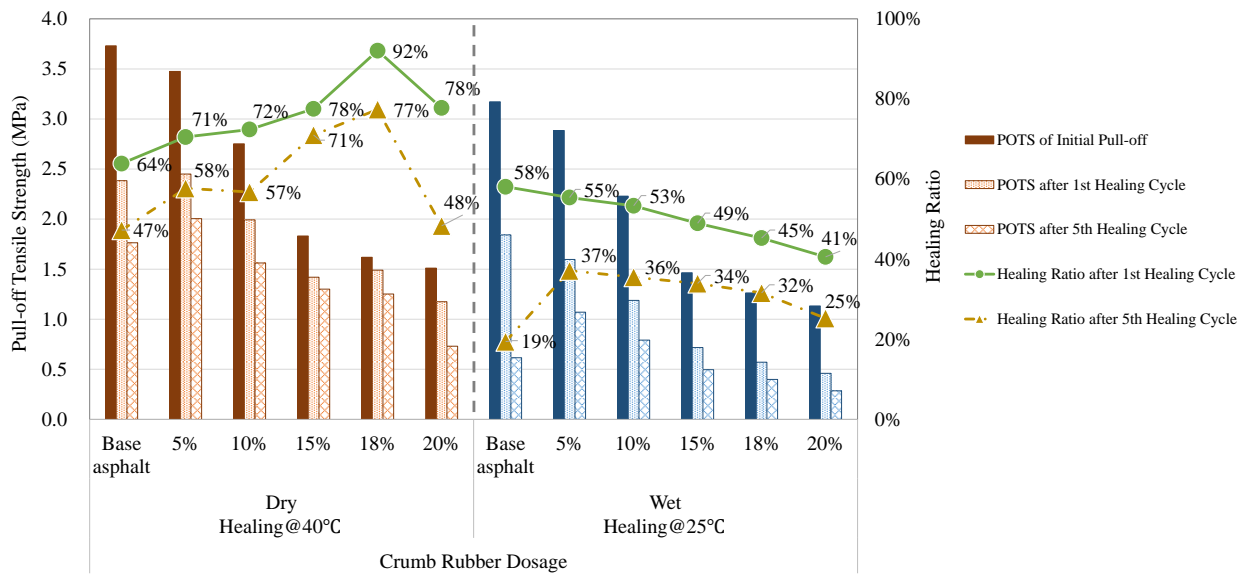


Figure 4 BBS test results of crumb rubber-modified asphalt.

According to Figure 4, crumb rubber has a negative effect on the asphalt binder bonding, which is similar to the SBS modifier. The POTS values decrease with the increase of crumb rubber dosage. The reason for this phenomenon is that the homogeneity of asphalt is seriously affected by the rubber with relatively larger particle size. Besides, the crumb rubber particle itself is not adhesive and could not provide extra bond strength between the asphalt and aggregate. In contrast, it occupies the area on the surface of aggregate which could be taken by asphalt binder.

It is also noted that crumb rubber-modified asphalt has much lower HR values at wet conditions in comparison with dry conditions, demonstrating that the healing property of crumb rubber-modified

1 asphalt is vulnerable to moisture. This is because that the existence of rubber particles causes a rugged  
 2 fracture surface after pull-off failure, and the gap between the cracks make the interface between asphalt  
 3 and aggregate prone to be intruded by water, interfering the asphalt infiltration to the aggregate.

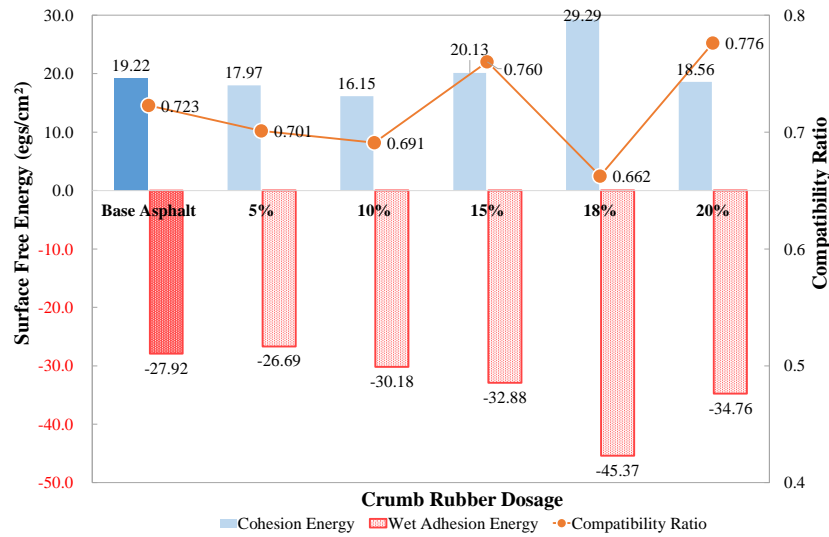


Figure 5 SFE test results of crumb rubber-modified asphalt.

6 However, no obvious regularity was found in the results of the SFE test according to Figure 5. This  
 7 is because of the effect of rubber particles on the smoothness of the glass slide surface and the sample  
 8 with a rough surface is prone to cause inaccuracy of test results. Figure 6 shows the comparison of the  
 9 glass slide with a rough surface (crumb rubber-modified asphalt) and the one with a smooth surface  
 10 (other asphalt).

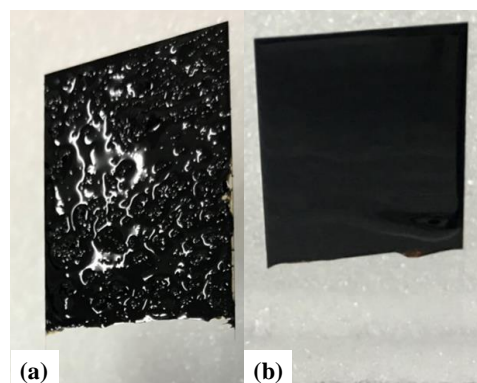


Figure 6 The appearance comparison of glass slides between (a) crumb rubber-modified asphalt and (b) other

asphalt.

To ensure the accuracy of the SFE test results, the surface of the prepared slide coated with asphalt should be as smooth as possible, any bubbles or granular substances attached to the slide should be avoided. For this reason, SFE is not a suitable measurement to evaluate the bond properties of crumb rubber asphalt-aggregate combinations.

#### 4.1.3 Effects of TB rubber modification

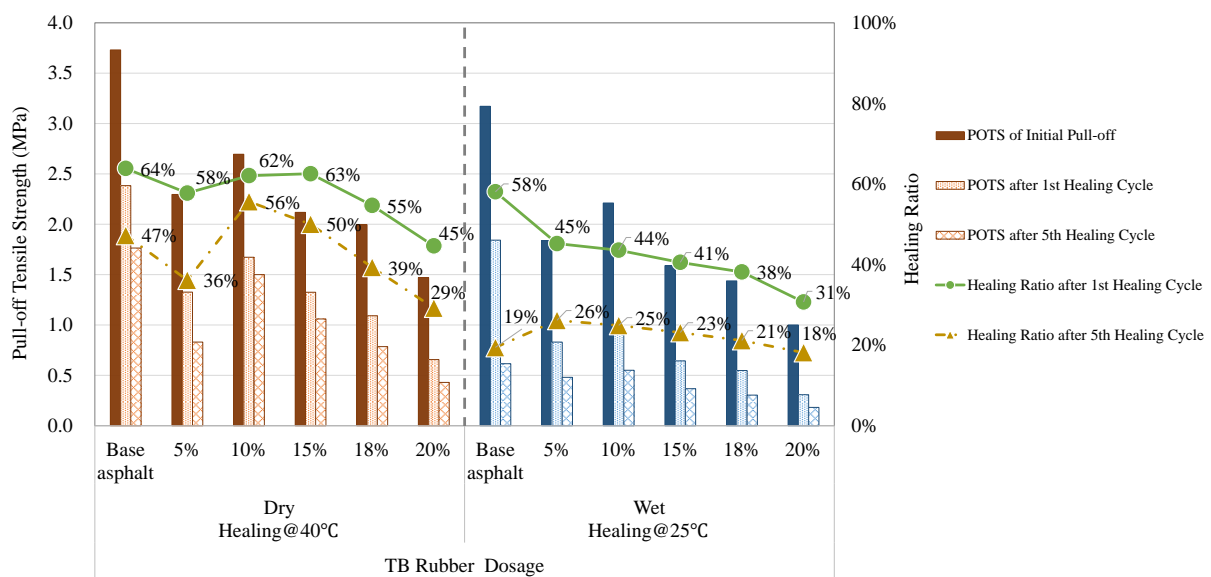


Figure 7 BBS test results of TB rubberized asphalt.

Figure 7 shows that TB rubber also negatively effects the bond and healing performance of asphalt. 10%~15% could be considered as the optimum dosage since the POTS and HR values of TB rubberized asphalt show preferable bond and healing performance within this concentration range.

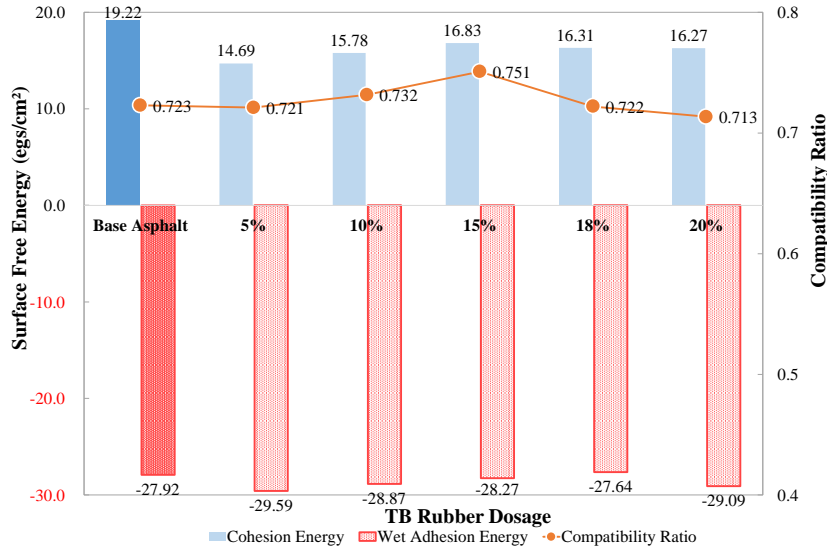


Figure 8 SFE test results of TB rubberized asphalt.

The SFE test results in Figure 8 show obvious regularity and consistency with the results of the BBS test. The accuracy of the SFE test results on TB rubberized asphalt could be ensured due to its much finer rubber particles and superior storage stability. 15% TB rubberized asphalt presents the highest cohesion energy and wet adhesion energy, which reconcile the variation of cohesive and adhesive strength in the BBS test.

The dosage of TB rubber has a double-sided effect on the POTS and SFE values of asphalt. TB rubberized asphalt is produced through devulcanizing crumb rubber at a very high temperature ( $\geq 220^{\circ}\text{C}$ ). The rubber particles become smaller molecular particles during the pyrolysis process and intermolecular interaction (van der Waals force) decreases. As the dosage increases, the bond strength and surface energy are enhanced as a result that some parts of the molecules get connected through chemical crosslinking or physical entanglement and form a spatial network structure, and the Lewis acidic component of TB rubberized asphalt increases as well. However, the adverse impacts of excessive TB rubber become prominent when the dosage is high. Therefore, it shows a trend of growth followed by decline.

Both traditional crumb rubber and TB rubber harm the asphalt bond strength. By comparing Figure

4 with Figure 7, it appears that TB rubberized asphalt binders at relatively high dosages generally have better bond and healing property than the crumb rubber-modified asphalt, which is attributed to the fact that the TB rubber can easily distribute in the asphalt due to its finer powder. The small TB rubber granule could swell well and form a better interface transition layer with asphalt, which could dissipate more stress and deflect the cracks under external force.

#### 4.1.4 Effects of HDPE modification

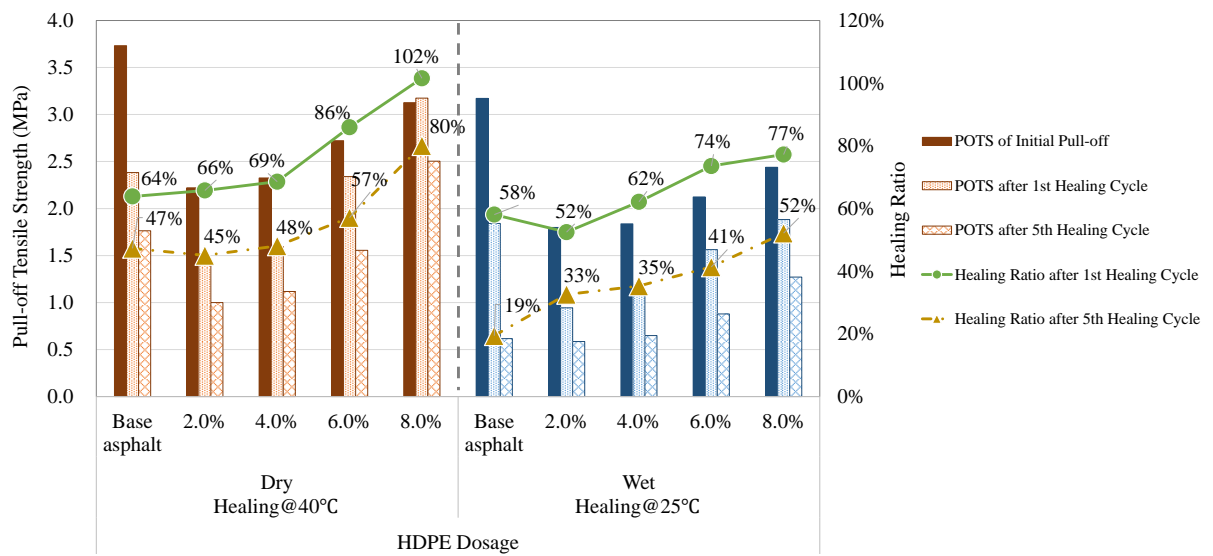


Figure 9 BBS test results of HDPE-modified asphalt.

According to Figure 9, the POTS and HR values of HDPE-modified asphalt keep increasing with the dosage from 2% to 8%. The HR value of 8% HDPE-modified asphalt at dry condition even reaches 102%, indicating the healing bond strength is even better than that before the initial fracture.

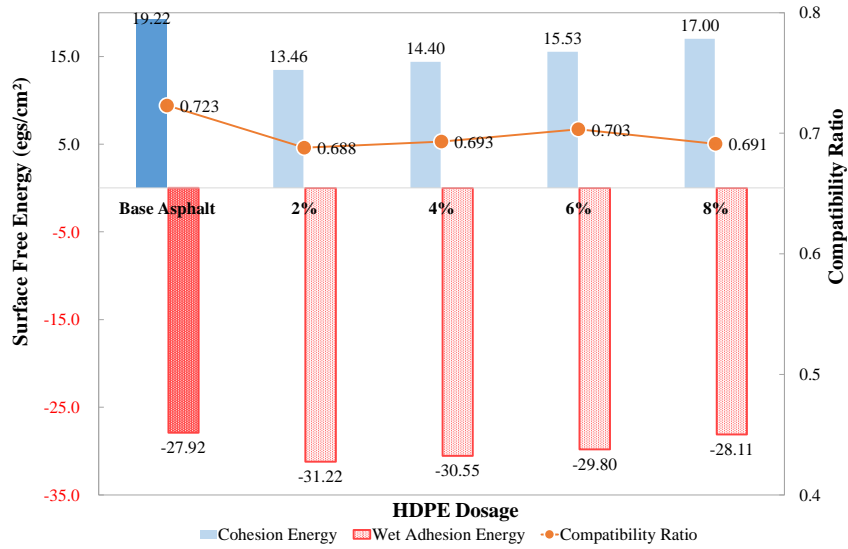
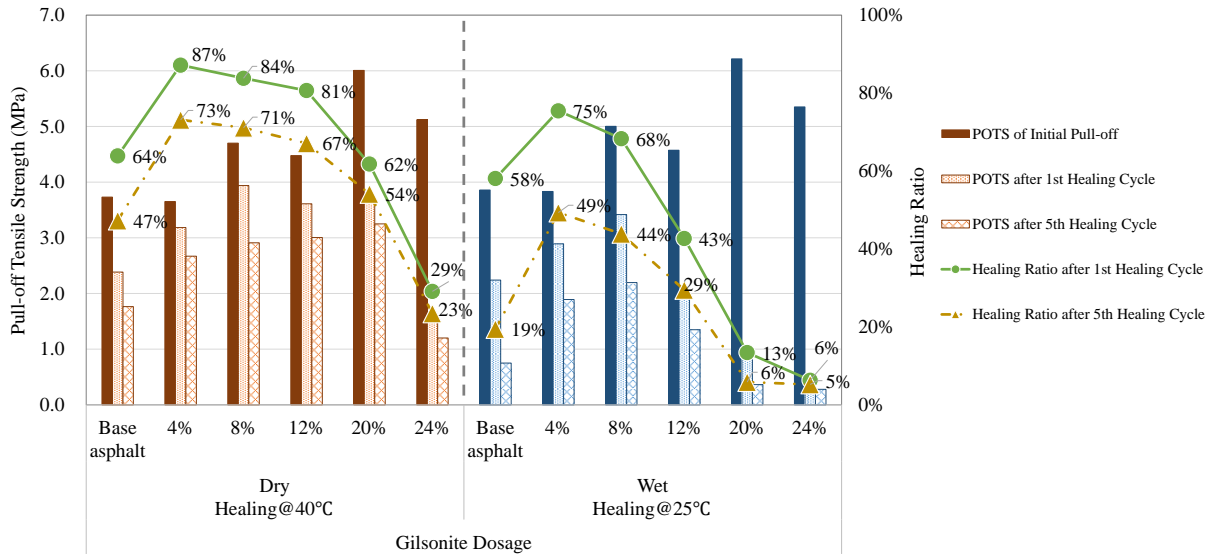


Figure 10 SFE test results of HDPE-modified asphalt.

Figure 10 demonstrates that the trend of SFE test result of HDPE-modified asphalt is in agreement with that derived from the BBS test. PE material has a low crystallinity and melting point and its solubility parameters and polarity are similar to those of wax components in asphalt. The introduction of HDPE into asphalt reduces the polarity and intermolecular interaction, also the chemical affinity between asphalt and aggregate as well. With the increase of dosage, HDPE chains get folded and form an interwoven structure, resulting in the improvement of surface energy.

The possible reason for the superior healing performance is that HDPE includes ethylene homopolymer, the copolymer of ethylene and a small amount of olefin. The molecular structure of HDPE is simple and symmetric, which contains very few short branches<sup>[37][38]</sup>. This kind of long-chain structure with few branches has superior molecular mobility, which results in a fast re-infiltration and re-bond of microcrack after the bond failure.

1 4.1.5 Effects of gilsonite modification



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Figure 11 BBS test results of gilsonite-modified asphalt.

According to Figure 11, gilsonite modification at a proper dosage ( $\leq 20\%$ ) can improve both the bond strength and healing performance of asphalt. However, excess gilsonite (e.g. 24%) significantly reduces the healing performance. During the test, it was observed that the fracture surface after the second pull-off test was nearly the same as that after the first pull-off test, indicating little asphalt flow and healing occurred during conditioning.

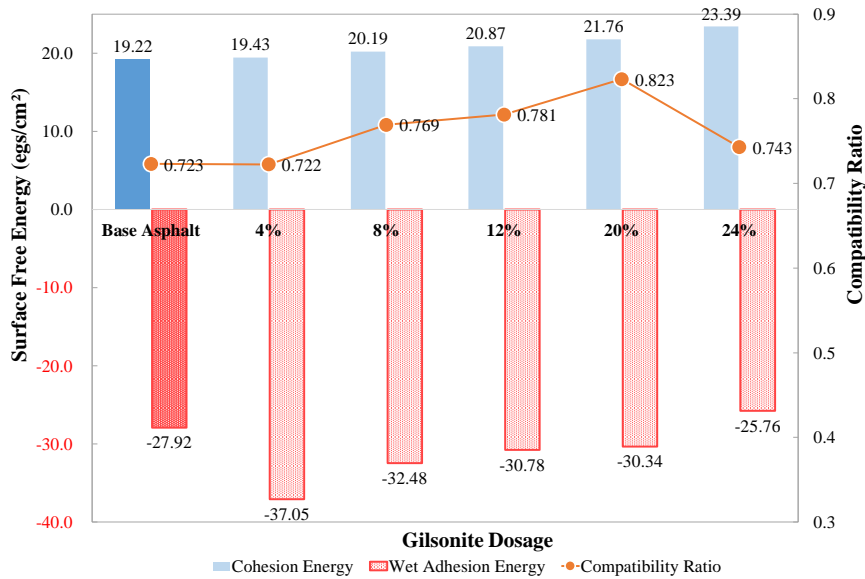


Figure 12 SFE test results of gilsonite-modified asphalt.

According to the SFE test results shown in Figure 12, the variation of cohesion energy chimes with the trend of dry POTS in the BBS test. However, the result of wet adhesion energy is inconsistent with that of wet POTS. This can be explained by the fact that some samples in the wet condition presented cohesive-adhesive combined failure rather than the total adhesive failure, which influenced the result of the SFE test. Also, there is no significant coherence between wet HR and CR. This phenomenon of inconsistency might be explained by the stiffness of gilsonite-modified asphalt. In spite that gilsonite-modified asphalt has good wettability with aggregate, its flowability is limited by high stiffness at 25°C (healing temperature), leading to the low HR values in the BBS test.

Compared with other modification, gilsonite modification can dramatically enhance the bond strength and cohesion/adhesion energy of asphalt for the following reasons:

- (1) high contents of metal and nitrogen elements increase the molecular polarity and wettability of asphalt, which brings high inner cohesion energy and adhesion performance.
- (2) gilsonite contains high contents of heavier components like asphaltene and resin because its

light components tend to volatilize due to the long-term exposure to nature. During the modification with asphalt, gilsonite absorbs the light components (nonpolar saturates and aromatics) in base asphalt after the shear mixing and swelling development and a blended asphalt system with a higher content of resin is formed, which is the strongest polar component among the four components of asphalt and has obvious promotion effect on the asphalt surface energy.

#### 4.2 Cantabro loss/ HWT and 4PB fatigue-healing tests results of asphalt mixtures

In this study, the base binder and modified binders at the recommended or commonly-used dosages (i.e. 4.5% SBS-modified asphalt, 15% TB rubberized asphalt, 24% gilsonite-modified asphalt, 8% HDPE-modified asphalt, and 18% crumb rubber-modified asphalt) were used to prepare HMA mixtures in the laboratory for their performance tests. The same source of aggregates and the Superpave-12.5 mix design were employed, except for the HMA mixture including the 18.0% crumb rubber modified binder. A gap graded mix design (ARAC-12.5)<sup>[39]</sup> was chosen for the crumb rubber modified asphalt mixture. The asphalt content for the crumb rubber modified mixture was 6.1% while it was 4.7% for the other modified asphalt mixtures and control asphalt mixture with base binder. The voids content of crumb rubber-modified asphalt mixture was 5.5%, and 4.0% for the other mixtures. The revelling resistance, moisture susceptibility and fatigue-healing behavior of asphalt mixtures were evaluated through the Cantabro loss test, HWT test, and 4PB fatigue-healing test respectively. The mean values of main testing results and their values of coefficient of variation are both shown in Table 2.

Table 2 Results and comparison of the mixture tests.

Binder	Cantabro Test		HWT Test		4PB Test			
	Cantabro loss	COV	SIP (passes)	COV	N <sub>f-initial</sub>	COV	HR <sub>4PB</sub>	COV

1	Base asphalt	25.4%	5.7%	7531	9.5%	23953	1.7%	47.9%	15.7%
2	4.5% SBS	22.3%	5.2%	8567	4.8%	381340	3.2%	53.0%	5.3%
3	18% Crumb Rubber	27.9%	6.2%	3895	13.5%	238860	7.8%	70.3%	2.5%
4	15% TB Rubber	26.3%	4.2%	3216	13.3%	190690	6.4%	61.4%	11.0%
5	8% HDPE	23.5%	5.8%	9063	9.8%	266650	6.5%	71.8%	3.0%
6	24% Gilsonite	15.9%	9.8%	13967	6.4%	89096	11.6%	35.4%	6.1%

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11 1 From Table 2, it can be seen that the SBS, HDPE and gilsonite modified asphalt mixtures show lower  
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14 2 values of Cantabro loss than the control mixture, illustrating an improved ravelling resistance. Their  
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16 3 relatively higher values of stripping inflection point indicate a better resistant to moisture damage. Among  
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19 4 all the tested asphalt mixtures, the gilsonite-modified asphalt mixture has the lowest value of Cantabro loss  
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22 5 and the highest SIP value, while the crumb rubber modified mixture and TB rubber modified mixture have  
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25 6 the highest values of Cantabro loss and the lowest SIP values. The gilsonite modification showed a superior  
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28 7 improvement of the ravelling resistance and moisture damage resistance of asphalt mixture. However, it  
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31 8 presents the lowest HR in 4PB fatigue-healing test due to the inferior mobility of asphalt. The crumb rubber  
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34 9 and TB rubber modifications have detrimental effects on the revelling resistance and moisture susceptibility  
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37 10 of the asphalt mixtures. The possible reason is that crumb rubber/TB rubber absorbed light molecular  
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41 11 components of asphalt binder resulting in less bonding between the binder and aggregates. while preferable  
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44 12 fatigue and healing performance were found on account of the fatigue stress absorbing of rubber and the  
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47 13 good mobility of TB rubberized asphalt.

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47 14 To verify the findings of the BBS and SFE tests on the asphalt-aggregate combinations, the mixture  
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50 15 performance test results are correlated with the corresponding POTS and cohesion/adhesion energies of  
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53 16 asphalt-aggregate combinations, as shown in Figure 13. It should be noticed that in the correlation analyses  
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56 17 the SFE data does not include the testing results of crumb rubber-modified asphalt binder due to its low  
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59 18 repeatability caused by the rubber particles.

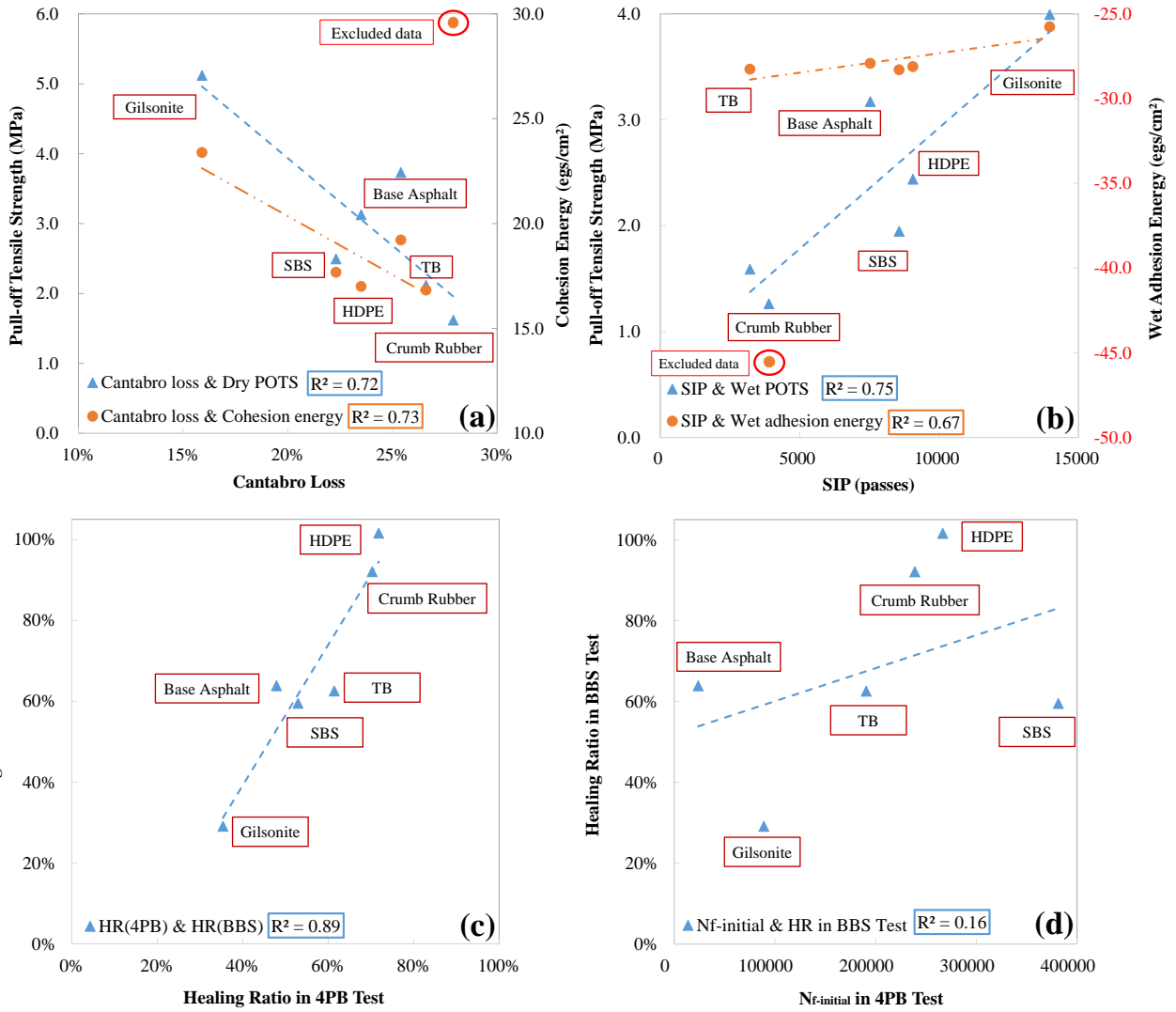


Figure 13 Correlation analysis of (a) Cantabro loss and dry POTS &  $W_{II}$ ; (b) SIP and wet POTS &  $W_{LSW}^{wet}$ ; (c)  $HR_{4PB}$  and  $HR_{BBS}$ ; (d)  $N_{f-initial}$  and  $HR_{BBS}$

The results and comparison presented in Figure 13 manifest that both the results of dry POTS in the BBS test and  $W_{II}$  in SFE test show similar correlation with Cantabro loss of asphalt mixtures ( $R^2=0.72$ ,  $0.73$  respectively) while for adhesion behavior, wet POTS shows better correlation ( $R^2=0.75$ ) than  $W_{LSW}^{wet}$  with SIP in HWT test, manifesting in spite that SFE test results could reveal and explain the mechanism of the variation tendency of bond performance of modified-asphalt binders with different dosages to some extent, the evaluation result of BBS test is closer to that derived from asphalt mixture tests by comparison. The standard 4PB fatigue test could not reflect the healing ability of asphalt according to the poor correlation

( $R^2=0.16$ ) between the HR in the BBS and the fatigue life in the 4PB test. The modified 4PB fatigue-healing test was performed to find the correlation between asphalt and mixture. The HR values in the modified 4PB test show an apparent correlation ( $R^2=0.89$ ) with BBS healing test (after 1 healing cycle, healed in dry condition), demonstrating that the BBS healing test could reflect the fatigue-healing performance of the corresponding asphalt mixture effectively. Based on the correlation analysis and comparison, and also considering the experimental efficiency and cost, the BBS test is suitable to predict the bond and fatigue healing behavior of asphalt pavements and could be determined as a screening experiment in practical engineering.

## 5 Conclusions

In this study, the BBS test and SFE test were performed respectively on asphalt binders to evaluate the bond and healing properties in terms of mechanical performance and mechanism analysis. Cantabro loss test, HWT test, and 4PB fatigue-healing test were conducted on asphalt mixtures to verify the evaluation accuracy of the two asphalt experiments on the cohesion, adhesion and healing properties of asphalt. The results from asphalt binders and asphalt mixtures were correlated. The following conclusions can be drawn from the results:

1. In the aspect of the bond property, according to the BBS test and SFE test, only gilsonite could enhance the cohesive/adhesive strength and surface energy of asphalt among all the tested modification methods, however, excessive gilsonite ( $>20\%$ ) would reduce this improvement. The other modifiers including linear SBS, crumb rubber, TB rubber, and HDPE have a negative effect on the bond performance and the effects vary with the dosages of the modifiers. Moreover, for each asphalt binder, the variations of its cohesion energy and wet adhesion energy in SFE test

1 are in accordance with those of the POTS in dry and wet conditions respectively, except for  
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9 2. In regard of asphalt healing performance, HDPE, crumb rubber and gilsonite ( $< 20\%$ )  
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11 modifications have a positive promotion effect, among which 8% HDPE-modified asphalt shows  
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13 the best healing performance (HR=102%) owing to the mobility enhancement effect of HDPE  
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15 on asphalt molecular. It is also noted that the variation trend of the SFE index “CR” is in  
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26 10 3. The Cantabro test, HWT test, and 4PB fatigue-healing test verify the accuracy of BBS testing the  
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28 cohesion/adhesion and healing properties. The correlations between Cantabro loss and dry POTS  
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30 ( $R^2=0.72$ ); SIP and wet POTS ( $R^2=0.75$ ); HR in 4PB mixture healing test and BBS healing test  
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32 ( $R^2=0.89$ ) indicate that the BBS test could reflect the stripping resistance and fatigue-healing  
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43 16 4. Based on the results of bond and healing performances, the recommended dosage for each  
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2  
3 acknowledge the financial support of the Postdoctoral Innovative Talent Support Program.  
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### 6 **Data availability**

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10 The data that support the findings of this study are available from the corresponding author, Quan  
11  
12 Lv, upon reasonable request.  
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**Response to editor:**

We thank the reviewers and the editor for their valuable comments.

Detailed responses to the reviewers' comments with the explanation of the revisions in the revised manuscript were given in this document.

## **Response to reviewer 1**

1. First of all: the language is a number of times so strange that the text is difficult to follow. Please have a native English speaking person check the document.

**Response:** Thanks for your careful reading and suggestion. We have revised the manuscript thoroughly and indicated the changes using MS revision mode. Also, a clean version of the revised manuscript has been submitted.

2. Title: the title is not covering the content of the paper well. Only one aggregate is used (basalt) and the bitumen is modified (sbs, gilsonite, CR, HDPE). So please rephrase the title.

**Response:** Thank you for the valuable suggestion. As you pointed that only basalt aggregate was used and most binders were modified. The title will be changed to “Mechanical Evaluation and Mechanism Analysis of the Stripping Resistance and Healing Performance of Modified Asphalt-Basalt Aggregate Combinations”.

3. The BBS test is performed with a thickness of 0.2 mm. What does that mean for the inhomogeneous binder and the addition of gilsonite?

**Response:** Thank you for the consideration about the inhomogeneity of binders. For some modified binders, such as SBS-modified asphalt and crumb rubber-modified asphalt, inhomogeneity occurs over time. In view of this, all the modified binders were used for testing within 4 hours after they were produced in the laboratory in order to eliminate the influence caused by the inhomogeneity. The freshly prepared asphalt has good homogeneity. Thus, accurate measurements could be obtained with the application of the thickness of 0.2mm. We would clarify this asphalt preparation and testing in the revised manuscript. As for the gilsonite, it is a petroleum-based solid which has a similar chemical structure with asphalt. Compared with other polymer modifiers, gilsonite has a better compatibility with base asphalt and can generate a stable system with asphalt. Therefore, the addition of gilsonite would not bring about inaccurate results when the thickness of 0.2 mm is used.

4. The interaction of the basic bitumen with the modifiers is not clear (is the binder suitable for the SBS used, did you use extender oil for the CR, etc). So the compatibility of the modifiers with the binder is not discussed and clear and can strongly influence the properties!!!! For example, the linear SBS used with the basic binder can be a bad combination because of compatibility reasons. The same for the CR. It is also not clear if the gilsonite contains a lot of fines (filler) or not.

**Response:** Thank you for pointing out this problem. The compatibility of the

modifiers with the binder does have a strong influence on the asphalt. In this study, the selected base asphalt is ESSO asphalt, which is produced by Exxon Mobil Corporation. Compared with other base asphalt binders which have the same PG grade (PG 64 -22), the content of aromatics in ESSO is relatively high (50.16%), which is favorable for the compatibility of the binder with the SBS modifier and crumb rubber. And this has been corroborated in many domestic engineering projects.

- (1) For the SBS-modified asphalt used in this study, 0.15% sulfur was added during process of asphalt preparation to guarantee its chemical stability.
- (2) For the crumb rubber-modified asphalt, the purpose of adding extender oil is to reduce the viscosity of asphalt and promote the swelling development of rubber. Due to the high content of aromatics in the base asphalt and the rubber dosage in this paper (less than 20%), additional extender oil is unnecessary in this study.
- (3) For the gilsonite-modified asphalt, the gilsonite used in this study was imported from Iran. The main characteristics of the gilsonite is as follows:

**Table 1 The main characteristics of the used gilsonite**

Test (%wt)	Result	Test method
Ash Content	≤5	ASTM-D3174
Solubility in CS <sub>2</sub>	88	ASTM-D4
Fixed Carbon	34	ASTM -D3172
Carbon Content	81	ASTM –D5291
Hydrogen Content	6.7	ASTM –D5291
Sulfur Content	2.1	Leco(s) Analyzer
Nitrogen Content	0.84	ASTM –D5291
Moisture Content	≤5	ASTM -D3173
Oxygen Content	2.3	ASTM –D5291
Volatile Matter	60	ASTM-D3175

Compared with other polymer modifiers, gilsonite is a petroleum-based solid with the similar chemical structure with asphalt and has a good compatibility with asphalt. From the Table 1, it can be seen that the ash content of the used gilsonite is less than 5% and could meet the specification requirements (≤20%). The fines with low content would not adversely affect the compatibility of the gilsonite and asphalt.

- (4) All the modified binders were used for testing within 4 hours after they were produced in the laboratory to reduce the experimental inaccuracy caused by the possible poor compatibility of base asphalt with modifiers.

We have added more detailed notes in the revised manuscript about the additives in various modified asphalt binders to show the compatibility of the basic bitumen

with the modifiers. Thank you very much for the reminder and suggestion.

5. The BBS test is a real failure test and the 4pb-healing is a test in which the stiffness is reduced to 50% (maybe some microcracks in the material. So the behaviour is different. The strain level of 1000 micron is extremely high for fatigue testing.

**Response:** Thank you for pointing out this problem. The BBS test is a real failure test while there is merely stiffness modulus reduction in the 4PB fatigue-healing test. So the failure mode is different. However, in a fracture-based healing method, the fractured parts of the mixture sample could not be perfectly put back in place during the healing period. Thus, the in situ-healing of the damaged interface might not be achieved, which would influence the healing effect and interfere with the experimental results. In consideration of this, the fatigue-based healing test (4PB test) was applied to the mixture samples in this study. Since the healing performances of the samples in the BBS test and 4PB fatigue-healing test are both related to the asphalt flowability and wettability, which play important roles in the healing process, we think both of the two tests could reflect the healing property of asphalt materials.

On the selection of strain level, the strain level of 1000  $\mu\epsilon$  was selected for the following reasons:

(1) In general, 250~750 $\mu\epsilon$  is used in the 4PB fatigue test. However, the excess freight of transport vehicles is quite common in China. According to the specific surveys from each province, the overload rate in most provinces reaches 40% ~ 80%. Some vehicles are overloaded 1~2 times, some even up to 3 times. We think it is necessary to consider the overload situation when studying the fatigue property of the asphalt mixture. Therefore, the high strain was selected in this study.

(2) For modified asphalt mixture, relatively low strain ( $< 1000\mu\epsilon$ ) will take too long in fatigue test while excessive strain ( $> 1500\mu\epsilon$ ) might cause data variability and inaccurate test results. The results of the previous experiments show that the variation trends of fatigue life under different strain levels are similar within the strain range of less than 1500  $\mu\epsilon$ . Based on this, 1000 $\mu\epsilon$  was applied to accelerate the progress of the fatigue experiment and reduce the cost.

(3) In this study, the purpose of the 4PB test was to compare the fatigue-healing property of different asphalt mixtures. Despite of the high strain, we think the comparison is still desirable since all the mixtures were tested under the same experimental condition.

6. CR modified bitumen contains a lot of carbon black and is an inhomogenous binder if the swelling parts are too large. Why then use the tests??

**Response:** The reason for using CR modified asphalt was to compare the test results of it with those of TB rubberized asphalt. As the reviewer pointed out, CR modified bitumen would be inhomogeneous if the swelling parts are too large. CR

modified asphalt could not be used in the SFE test because the rubber particles would cause inaccurate experimental results. In the BBS test and other mixture tests, the CR modified asphalt was heated to 165~170°C and stirred again before preparing the samples to avoid the inhomogeneity. In this way, the homogeneity issue of CR-modified asphalt could be addressed during the experimental measurement.

7. Why was basalt chosen as the aggregate for the mixtures?

**Response:** Basalt is a kind of high-quality stone for traffic construction, which has high compressive strength, superior wear resistance, and good adhesion with asphalt. In this study, basalt was selected for the mixtures and the aggregate substrates because of its wide usage in road engineering projects. The reason for choosing basalt as the aggregate for the mixtures has been added in the revised manuscript. Thank you for the reminder.

8. Two mixtures were used in the paper. For the CR-bitumen the binder content was much higher than for the other mixtures. No information on the voids content of the tested mixture samples is given. The voids content can play an important role in the test results.

**Response:** We are sorry that the voids content of the tested mixture samples was not given in the paper. Thank you for your reminder. The voids content of all the mixture samples was controlled at 4.0% except for the crumb rubber-modified asphalt mixture, which was 5.5%. The information on the voids content has been added in the revised manuscript.

9. Did you compare the BBS results with DSR results as the DSR is the usually used test??

**Response:** Thank you for your helpful suggestion. We have not yet performed DSR test to investigate the healing property of asphalt. In the next research work, we plan to study the asphalt healing property using DSR by setting a certain healing period between two loading periods. Then the asphalt property of each load cycle (e.g. modulus) will be recorded for self-healing performance analysis. In addition to the comparison between the results of BBS test and DSR test, the correlation between DSR healing test and 4PB fatigue-healing test will also be analyzed since both of the two tests are fatigue-based healing methods.

10. Pavement performance is very complex and needs more than just a comparison between the results on the binder and the mixture results as used in this paper. For example the combination of stiffness (is very important) and fatigue line will

determine the thickness of the asphalt layers in the pavement structure. No one will design the asphalt layer with 1000 microstrain, normally spoken. Besides, no field results are shown to show the validity of the results in this paper.

**Response:** Thank you for the thoughtful consideration. We agree with you that the evaluation of the pavement performance needs more than a comparison between the results of the binder and the mixture. Although no comprehensive field results were shown in this paper to validate the results. Some modified asphalt binders have been applied to highway sections in China and the application effect has been collected. For example, the SBS-modified asphalt and gilsonite-modified asphalt have been used in Jingfu Highway in Shandong province. After more than 3 years of vehicle operation, the monitoring data showed that the rutting depth of the gilsonite-modified asphalt section is smaller than that of the SBS-modified asphalt section. And gilsonite-modified asphalt section showed better stripping resistance under the same vehicle load conditions, which is consistent with the experimental results in this paper. Besides, a crumb rubber-modified asphalt section and a TB rubberized asphalt section are under construction in the Hebei province, which is based on the cooperation of the research projects between our research team and Hebei Transportation Investment Group Corporation. The response data of the pavement will be collected and the performance of the CR and TB asphalt mixtures will also be observed in the next few years to further validate the laboratory results in this paper. Thank you for your criticism.

As for the selection of the strain in 4PB fatigue-healing test, as mentioned in the fifth question, we chose 1000  $\mu\epsilon$  for several considerations:

- (1) A high level of strain was selected considering the serious problem of overloading on the highways in China.
- (2) The 4PB fatigue test would take too long if a low level of strain was used. The previous experimental results indicate that the variation trends of fatigue life under different strain levels are similar within the strain range of less than 1500  $\mu\epsilon$ . Thus, the higher strain was used to accelerate the progress of the fatigue-healing experiment.
- (3) In this study, the 4PB fatigue-healing test was used to evaluate and compare the healing property of different asphalt mixtures. All the samples were tested under the same experimental condition. Therefore, the comparison result was still reliable despite the high level of the strain.

As you pointed out that 1000  $\mu\epsilon$  is too high for the 4PB fatigue test and the pavement design, the lower strain will be used in the fatigue test in the future study to avoid the disagreements in this regard. Thank you very much for your comments and suggestions.

11. What surprises me is the argument from the authors that HDPE does not show

much crystallisation. My experience is that it is starting to crystallize very strongly below say 120 C and this can cause a lot of trouble in a binder.

**Response:** Thank you for the consideration of the HDPE crystallisation. In fact, the HDPE crystallization was not observed in this study, which was probably because of that all the modified binders would be used for testing within 4 hours after they were produced in the laboratory to avoid the segregation or the incompatibility of base asphalt with modifiers. During the sample preparation in the BBS test and SFE test, the modified binders will be heated to 160°C. In mixture tests, the modified binders will also be heated to at least 165°C. Thus, the crystallization would not occur when preparing the samples.

12. In general I propose that the authors explain that there results are only valid for the combinations as used in the paper and should be considered carefully with other components.

**Response:** Thank you very much for your suggestion. Only one type of aggregate (basalt) was used in this study so the results should only be considered for the tested modified asphalt and basalt aggregate combinations. We have also stated this in the revised manuscript.

We hope that the supplemented explanation and discussion would help to improve the paper. We would be glad to respond to any further questions and comments that you may have.

**Highlights:**

- Gilsonite improves the cohesive/adhesive strength and surface energy of asphalt
- High-density polyethylene and crumb rubber enhance the asphalt healing property
- Surface energy test reveals the mechanism of asphalt mechanical property variation
- The evaluation accuracy of binder bond strength test is verified



**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

### **Author contributions**

The authors confirm contribution to the paper as follows: study conception and design: Lu Zhou, Weidong Huang and Lijun Sun; data collection: Lu Zhou; analysis and interpretation of results: Lu Zhou and Quan Lv; draft manuscript preparation: Lu Zhou and Yuan Zhang. All authors reviewed the results and approved the final version of the manuscript.

# **Mechanical Evaluation and Mechanism Analysis of the Stripping Resistance and Healing Performance of Modified Asphalt-Basalt Aggregate Combinations**

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1 **Mechanical Evaluation and Mechanism Analysis of the Stripping Resistance and Healing**

2 **Performance of Modified Asphalt--Basalt Aggregate Combinations**

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## Abstract

~~The Asphalt modifications could contribute to the moisture susceptibility and fatigue resistance of asphalt mixtures. The study in this paper aims to investigate the effects of various asphalt modifications on the bond and healing properties of modified asphalt binders, as well as the mechanism of changes caused by the modification. Five modified asphalt binders were prepared in the laboratory for this study, including the SBS-modified asphalt, crumb rubber-modified asphalt, TB rubberized asphalt, high-density polyethylene (HDPE)-modified asphalt, and gilsonite-modified asphalt. A modified binder bond strength (BBS) test was applied to evaluate the bond and healing performance of five modified binders. Surface free energy test was conducted to reveal the mechanism of the performance variation of asphalt aggregate combinations in regard of cohesion/adhesion energy. The, at both dry and wet conditions. The surface free energy (SFE) test was conducted on the modified binders to investigate the changes in the cohesion/adhesion energy due to the binder modification. In addition, the ravelling resistance, moisture susceptibility, and fatigue life of asphalt mixtures prepared from the modified binders were measured by using the Cantabro test, Hamburg wheel-tracking test, and four-point beam fatigue test, respectively. The results of performance tests for the asphalt mixtures are employed to verify the findings of BBS and SFE tests for the modified binders. It is found that the modified BBS test provides a promising tool for evaluating the bond and healing properties of modified asphalt binders, and the SFE could help to explain the mechanism of binder modification. The testing results indicate that gilsonite enhanced the bond strength and surface energy of asphalt and high-density polyethylene significantly improve the healing performance in BBS test. The recommended dosages of different modifications were proposed. Furthermore, the Cantabro test, Hamburg wheel-tracking test, and four-point beam fatigue healing test verified the evaluation accuracy of BBS test on stripping resistance and~~

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healing performance.

**Key words:** asphalt bond; healing property; surface free energy; mixture stripping resistance; fatigue-healing performance.

## 1 Background

Ravelling and moisture damage ~~that are the two types of main causes~~ ~~distresses~~ of asphalt ~~pavement deterioration, which pavements~~, are mainly attributed to ~~the~~ inner cohesion failure of asphalt ~~binder and interface/or~~ adhesion failure ~~between asphalt and aggregate. Under the coupling influence of the repeated tension, compression and shear action at the interface of vehicle load asphalt binder and mineral aggregates. Due to the moisture traffic loading and aging caused by environmental change, the influence (e.g. moisture damage and oxidative aging), microcracks appear initial in the binder and binder-aggregate interface~~ and gradually develop into macrocracks ~~with as the increase of loading times pavement service time increases~~. It is ~~observed also known~~ that ~~given adequate with a rest time, the~~ asphalt materials have the ability to heal ~~owing to the infiltration and diffusive mobility, microcracks because of the viscoelasticity nature of asphalt binder. Part of the bonding can be failure caused by the initiation and propagation of microcracks could be restored during the within an available healing process of asphalt binder. Besides, mechanical loading from traffic has an effect of re-bonding asphalt binder will re-adhere to and aggregates under vehicle loads certain conditions, and the meso cracks inside asphalt will mixture even can close due to asphalt the binder flowability at high pavement temperatures.~~

Many studies ~~have been~~ reported ~~in investigating~~ the bond and healing behavior of asphalt binders. ~~At present, there are mainly~~ ~~In which~~, four ~~main~~ theories ~~that can be~~ used to explain the ~~asphalt bond~~

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mechanism of bond property, including the mechanical theory, chemical reaction theory, surface energy theory, molecular orientation theory<sup>[1]</sup>. And in the field of asphalt healing property, the main assumptions and research are based on the fracture surface energy theory, capillary theory, and interfacial diffusion theory, are typically employed. Among these studies, it is reported<sup>[2-8]</sup> that the surface free energy (SFE) of asphalt binder and aggregates is mostly used and being considered as a very promising indicator in identifying the cohesion and adhesive energy of an asphalt binder-aggregate system to evaluate the stripping resistance and moisture susceptibility of asphalt mixture, which could be assessed on the basis of the<sup>[2],[8]</sup>. The contact angle measurement through measured by using the Wilhelmy plate (WP) or Sessile drop (SD) methods<sup>[9]</sup> to calculate is employed for calculating the SFE components of the corresponding both asphalt and aggregate binder and mineral aggregates, allowing for evaluating the moisture susceptibility of the asphalt mixture.

Previous research has applied SFE measurements. The SFE measurement has been conducted to investigate the moisture sensitivity of asphalt mixture and the selection of asphalt aggregate. The reports binder and/or aggregates in some researches. For instance, the SHRP-A-341<sup>[1]</sup> analyzed the adhesion between asphalt and aggregate and proposed the evaluation method reports the analysis of adhesion between asphalt binder and aggregate and the SFE. In which both the WP method and sorption method were conducted for the analysis. However, the calculation method was complicated, and used in that study is not easy to follow, neither the process of asphalt stripping caused by moisture resistance was not included in the study. Cheng<sup>[10]</sup> developed the research work on investigated the SFE of asphalt-aggregate system and correlated it with the performance of asphalt and concrete. Through the study of asphalt-aggregate. The adhesion work under both dry and wet conditions were both calculated and it was found that the SFE results were consistent with that of the

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8 1 ~~findings from~~ the mixture accelerated moisture damage ~~testestest~~. Bhasin<sup>[11]</sup> compared ~~the adhesion~~  
9 ~~work of diversevarious~~ aggregates ~~in the SFE measurements~~ and ~~confirmedfound~~ that ~~there arethose~~  
10 2 ~~aggregates showed~~ significant differences in the adhesion energy ~~between different aggregates andwhen~~  
11 3 ~~they were applied with~~ the same asphalt. ~~Based on this research, binder~~. Jonathan<sup>[12]</sup> studied the  
12 4 influence of polymer-modified asphalt on the moisture damage ~~resistance~~ of asphalt-aggregate ~~systems~~.  
13 5 Wasiuddin et al.<sup>[13]</sup> investigated the compatibility ratio (CR) of different asphalt-aggregate combinations  
14 6 and ~~found that SFE could be helpfulproposed~~ to ~~determineuse~~ the ~~optimum selection ofSFE to screen~~  
15 7 ~~the~~ asphalt-aggregate combinations. ~~SimilarlyIn addition~~, many ~~other~~ studies<sup>[14][15]-[16]</sup> ~~have~~  
16 8 ~~investigatedreported~~ the influence of different ~~binder~~ modifiers on the moisture susceptibility of asphalt  
17 9 mixes ~~using the SD method. These studies indicate~~. It is also ~~confirmed~~ that ~~the~~ SFE theory could be  
18 10 ~~used as the compatibility checkuseful for determination of optimum combination~~ of asphalt-aggregate  
19 11 ~~combinations to achieve the optimum selectionsystem~~.

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21 13 ~~CurrentWhile, only few~~ studies ~~aboutfocus on quantitatively ranking~~ the bond and healing  
22 14 properties of ~~asphalt are limited to qualitative analysis and influence factors on the bond performances~~  
23 15 ~~while few studies are focusing on the quantitative rank evaluation on the bond and healing properties~~  
24 16 ~~of differentvarious~~ modified asphalt binders. ~~In terms ofMost of those published studies report~~ research  
25 17 methods, ~~most of the experiments on the healing performance of asphalt are conducted using of~~ the  
26 18 DSR fatigue test<sup>[17][20]</sup> or ~~asphalt mixture~~ four-point bending (4PB) test<sup>[21][22]</sup>. ~~In these- for investigating~~  
27 19 ~~the healing performance of asphalt binders and mixtures. In those~~ fatigue-based healing tests, the  
28 20 ~~binder/mixture~~ samples are subjected to ~~load, which are separated with certain rest/cyclic loading and~~  
29 21 ~~healing. During the healing periods. During healing periods, the specimen is healedperiod, the~~  
30 22 ~~specimens were rest~~ at certain ~~environmental~~ conditions without ~~mechanical~~ loading<sup>[23]</sup>. ~~Then theThe~~

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binder/mixture properties ~~of each load cycle~~ (e.g. modulus, and peak load) ~~are at each load cycle were~~ recorded for analyzing the healing performance ~~analysis~~<sup>[24]</sup>. ~~However, It is noticed that the~~ fatigue-based healing tests are very time-consuming, ~~the and the repeatability of testing data is not intuitive as well has~~ a big concern in a long period. In recent years, the newly developed binder bond strength (BBS) test has ~~been developed and introduced to study~~ become popular in assessing the bond property of asphalt-  
~~It is widely used in the field of emulsions and modified asphalt materials binders~~<sup>[25][29]</sup> ~~due to~~ since the ~~portability of the~~ simple instrument used in the test and its ability ~~to~~ rapidly ~~measure~~ measuring the bond strength of asphalt-aggregate combination. The BBS test was originally designed for the coating industry and now it has been introduced into the asphalt industry as a standard test method in ASTM D 4541<sup>[30]</sup> for estimating the bond properties of asphalt binder. ~~Several researchers~~<sup>[26][31]</sup> have reported that the BBS test could offer direct and quick measurement of bond strength at the asphalt-aggregate interface.

In this ~~paper study, the BBS tests were employed for investigating the~~ bond ~~(cohesion under the dry condition and adhesion under wet condition)~~ and healing properties of five representative modified binders ~~(, including the~~ SBS-modified asphalt, crumb rubber-modified asphalt, TB rubberized asphalt, high-density polyethylene (HDPE)-modified asphalt, and gilsonite-modified asphalt) ~~were investigated using BBS test. The influence of different. The optimum dosages was also explored. The of these five types of binder modifiers were determined based on the measured pull-off tensile strength (POTS) at both the dry and wet conditions. In addition, the SFE test was~~ tests were conducted on these modified asphalt binders to ~~reveal the~~ understand their mechanism of ~~asphalt~~ changing the bond and healing properties. ~~On the level of base asphalt mixture, binder. The Cantabro loss test, Hamburg wheel-tracking (HWT) test, and 4PB fatigue-healing test were performed~~ on the mixtures prepared with these modified

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~~asphalt binders~~ to evaluate the ~~their~~ ravelling resistance, moisture ~~damage resistance~~susceptibility and fatigue healing property ~~of the corresponding mixtures,~~ respectively ~~and to verify whether the BBS test.~~ These mixture testing results are used for verifying the findings obtained from the BBS and SFE test ~~could accurately reflect the mixture performance~~tests of modified asphalt binders.

## 2 Objectives

The ~~specific~~main objectives of this study are ~~listed~~as follows~~following~~:

1. To evaluate the ~~cohesion/adhesion~~cohesive/adhesive properties and the healing performance of five representative modified ~~binders using the modified BBS test. Different healing conditions (dry and wet) and modifier dosages were studied~~asphalt binders;
2. To investigate the mechanism of bond and healing properties ~~using SFE measurements and to correlate~~of modified asphalt binders including various modifiers; and
- 2.3. To verify the findings of binder bond and healing properties from the ~~result variation in~~BBS tests through assessing the BBS test with the parameters in the SFE test~~corresponding mixture performance tests, including the ravelling resistance, moisture susceptibility, and fatigue healing property.~~
3. ~~To correlate the BBS test results with those of mixture tests (Cantabro, HWT, and 4PB tests) to investigate the correlation of the bond and healing properties between asphalt binders and mixtures.~~

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## 3 Experimental

### 3.1 Materials

~~The~~In this study, a PG 64-22 base asphalt was and five commonly used binder modifiers were

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selected ~~to prepare for preparing the~~ modified asphalt binders. ~~Five commonly used~~ in the laboratory. The modifiers, including the linear SBS, crumb ~~rubber rubbers~~, HDPE, and gilsonite, were ~~employed applied~~ at various dosages for the modification ~~as shown~~. Compared to the traditional crumb rubber-modified asphalt, the TB rubberized asphalt has a lower viscosity and better storage stability due to its specialized producing process, in which the crumb rubber is devulcanized at high temperatures and mixed with asphalt binder at high shear speed with an extended period during the modification. The Iranian gilsonite used in this study has a good compatibility with the base asphalt. The mixing conditions for these modified binders are listed in Table 1. It should be noted that all the modified binders were used for testing within 4 hours after they were produced in order to eliminate the influence caused by the possible inhomogeneity. For the mixtures and the aggregate substrates, basalt was chosen for its wide usage in road engineering projects.

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Table 1 Summary of the selected asphalt and experimental dosages

Binder Types	Modified Asphalt Formulation	Dosages of Modifiers (%)
Base asphalt	—	—
SBS-modified asphalt	Linear SBS (varying dosages) +0.15% Sulfur	1.5, 3.0, 4.5, 5.5, 6.0, 7.5
Rubber asphalt	Crumb rubber	5, 10, 15, 18, 20
	TB rubber	5, 10, 15, 18, 20
HDPE-modified asphalt	HDPE	2, 4, 6, 8
Gilsonite-modified asphalt	Gilsonite	4, 8, 12, 20, 24

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~~TB rubberized asphalt is a promising alternative to the traditional crumb rubber modified asphalt for its lower viscosity and preferable storage stability, which is produced through devulcanizing crumb rubber at high temperatures and extending the shearing time during the production.~~

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## 3.2 Methods

### 3.2.1 Binder bond strength (BBS) test

The BBS test was originally designed for the coating industry and now it has been introduced into the asphalt industry as a standard test method in ASTM D 4541<sup>[29]</sup> for estimating the bond properties of asphalt binder. Previous papers<sup>[26][31]</sup> have reported that BBS could offer direct and quick measurement of bond strength at the asphalt aggregate interface. In this study, the BBS test was modified for asphalt assessing the binder healing property assessment by through introducing a sample cyclic pull-off tests with a healing setting after the initial bond strength between two standard testing-

The stubs with procedures. The five types of laboratory prepared modified asphalt binders and basalt aggregate were used to prepare the asphalt-aggregate systems for BBS tests. The pull-off stubs were employed to apply an asphalt film at a thickness of 0.2mm (Figure 1-a) were bonded to on the basalt aggregate substrate at high temperature ( $\geq 150^{\circ}\text{C}$ ), and then cooled down at room temperature. Detailed information for test sample preparation has been reported in the previous research<sup>[28]</sup>. After being cured at 25°C for 1 h, all the prepared asphalt-aggregate test samples were divided into dry and wet groups to study two sets: one is for measuring the cohesion and at dry condition and the other is for the adhesion properties of asphalt respectively. The at wet condition. The dry condition for testing samples in the dry group were cured was at 25°C for 24 h and. The wet condition included the curing of samples in the wet group were immersed in the water at 40°C for 24 h. The pull-off tensile strength (POTS) was recorded as the indicator of the bond performance measured using the Positest AT-A apparatus (Figure 1-b). Generally, In general, the testing samples that were cured under the dry condition showed the cohesive failure (Figure 1-c) while the ones in samples after the wet group presented conditioning showed the adhesive failure (Figure 1-d) due to the moisture damage.

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Figure 1 (a) Stubs and (b) Positest AT-A apparatus and (c) cohesive failure and (d) adhesive failure and (e) samples with marks

To prepare the test samples in order to applying for the healing study procedure during the modified BBS test, the original positions/locations of stubs and substrate were marked before the initial pull-off test (Figure 1-e). After initial testing, and the stubs were immediately returned to placed at their original positions and loaded at locations after the each pull-off cycle with a constant pressure to heal. The healing samples applied on them. Then the tested asphalt-aggregate combinations were cured under dry/wet at different conditions to restore the strength. The for restoring the bond strength within the binder and/or between the binder and aggregate. For the testing samples in the dry group were cured

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~~conditioning set the healing condition was~~ in the thermostatic chamber at 40°C ~~and the samples in the wet group were immersed for 12 hours. For the wet conditioning set the healing condition was~~ in the water at 25 °C. ~~After 12 h conditioning (which was considered as 1<sup>st</sup> healing cycle), the samples were tested again to measure the bond strength after healing. The~~ for 12 hours. The asphalt-binder combinations were pre-conditioned in the air at testing temperature of 25°C for 30 minutes before re-testing their POTS. In total, the asphalt-aggregate combinations were subjected to five healing cycles, and their bond strength after each healing cycle was measured. Thus, a healing ratio (HR) for each cycle could be ~~derived following~~calculated by using the equation (1). ~~In this study, 5 healing cycles were employed during the testing procedure. For each asphalt~~For each type of testing samples, three replicates were ~~tested~~measured for ~~calculating the average~~POTS values ~~of POTS~~.

$$HR_i = \frac{POTS_{Healing-i}}{POTS_{initial}} \times 100\% \quad (1)$$

where,

$HR_i$ — the healing ratio after i-th healing cycle;

$POTS_{Healing-i}$ — the pull-off tensile strength after i-th healing cycle (MPa);

$POTS_{initial}$ — the initial pull-off tensile strength (MPa).

### 3.2.2 Surface free energy (SFE) test

According to the acid-base theory, the surface free energy of any material can be divided into three components based on the types of surface molecular forces: ~~(1)the non-polar component~~,  $\gamma^{LW}$  (also known as van der Waals force or dispersion force component ~~( $\gamma^{LW}$ ), (2),~~ Lewis acid component ~~( $\gamma^+$ ),  $\gamma^+$ , and (3) Lewis basic component ( $\gamma^-$ ),  $\gamma^-$ . The SFE of the material  $\gamma$  can be calculated according to equation (2):~~

$$\gamma = \gamma^{LW} + \gamma^{AB} = \gamma^{LW} + 2\sqrt{\gamma^+ \gamma^-} \quad (2)$$

According to the Young-Dupre equation, the adhesion work between the solid (aggregate) and liquid (asphalt binder) can be ~~calculated by~~ written using equation (3):

$$W_{ls} = \gamma_l(1 + \cos\theta) \quad (3)$$

where, subscript  $l$  represents “liquid”, which refers to asphalt; subscript  $s$  represents “solid”, which refers to aggregate in this study, and

$W_{ls}$ —the adhesion energy of asphalt-aggregate combination;

system;  $\gamma_l$ — represents the SFE of the asphalt;

binder; and  $\theta$ — represents the contact angle measured between the asphalt binder and aggregate.

#### (1) Cohesion energy of asphalt binder ( $W_{ll}$ )

The cohesion energy of the liquid is defined as the work ~~which is needed to divide~~ required for dividing a single liquid column into two parts along the unit cross section<sup>[32]</sup>. ~~Thus~~ Therefore, the cohesion energy ( $W_{ll}$ ) of ~~asphalt is a liquid can be~~ calculated using equation (4):

$$W_{ll} = 2\gamma_l \quad (4)$$

#### (2) Wet adhesion energy of asphalt-aggregate ~~combination~~ system ( $W_{lsw}^{wet}$ )

~~During~~ Due to the ~~separation process of asphalt from~~ higher adhesion energy between the water and aggregate in, the ~~presence of~~ bonding between asphalt and aggregate can be replaced by water, the work ~~that is needed to replace~~ required for replacing asphalt ~~from aggregate by water~~ binder is calculated using equation

(5). A larger absolute value of  $W_{lsw}^{wet}$  indicates ~~that asphalt a lower resistant to stripping is more prone to~~ happen.

$$W_{lsw}^{wet} = W_{lw} + W_{sw} - W_{ls} - 2\gamma_w \quad (5)$$

where, subscript  $w$  refers to water, and

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1  $W_{lw}$ —the interfacial energy between liquid-water;

2  $W_{sw}$ —the interfacial energy of solid-water;

3  $\gamma_w$ —the SFE of the water.

### 4 (3) Compatibility ratio (CR)

5 Dallas et al.<sup>[33]</sup> introduced a parameter “compatibility ratio (CR)” to ~~better identify~~ illustrate the  
6 moisture ~~damage~~ susceptibility of asphalt-aggregate system, in which the wettability of the asphalt over  
7 the aggregate is considered (as calculated in equation (6)). A higher CR value indicates ~~an asphalt-~~  
8 ~~aggregate systems with~~ better adhesion performance of the asphalt-aggregate system and a lower  
9 moisture ~~damage~~ susceptibility.

$$10 \quad CR = \left| \frac{W_{ls} - W_{ll}}{W_{ls}^{wet}} \right| \quad (6)$$

#### 11 • SFE of modified asphalt binders

12 ~~Combined with Van der Waals force theory and Lewis acid-base theory presented in equation (2), to~~  
13 calculate the ~~indicators in equation (4), (5) and (6), the hyperstatic equations (7) are to be solved to~~  
14 ~~measure~~ cohesion energy of asphalt binder, wet adhesion energy of asphalt-aggregate system, and the  
15 compatibility ratio, the SFE components (LW, acid, and base) of modified asphalt binders ~~were~~  
16 measured through solving the hyperstatic equations (7). In this study, the Wilhelmy plate (WP) method  
17 was used to obtain the advancing contact angle ~~formed~~ between ~~each of~~ the probe liquids (distilled  
18 water, formamide, glycerol, and ethylene glycol) and the modified asphalt ~~evaluated~~ binders. Four  
19 replicates ~~of samples with~~ were tested for each type of probe liquid ~~were tested~~.

$$\begin{bmatrix} \frac{(1 + \cos \theta_1)\gamma_{L1}}{2} \\ \frac{(1 + \cos \theta_2)\gamma_{L2}}{2} \\ \vdots \\ \frac{(1 + \cos \theta_n)\gamma_{Ln}}{2} \end{bmatrix} = \begin{bmatrix} \sqrt{\gamma_{L1}^{LW}} & \sqrt{\gamma_{L1}^-} & \sqrt{\gamma_{L1}^+} \\ \sqrt{\gamma_{L2}^{LW}} & \sqrt{\gamma_{L2}^-} & \sqrt{\gamma_{L2}^+} \\ \vdots & \vdots & \vdots \\ \sqrt{\gamma_{Ln}^{LW}} & \sqrt{\gamma_{Ln}^-} & \sqrt{\gamma_{Ln}^+} \end{bmatrix} \begin{bmatrix} \sqrt{\gamma_B^{LW}} \\ \sqrt{\gamma_B^+} \\ \sqrt{\gamma_B^-} \end{bmatrix} \quad (7)$$

where,  $\theta_1, \theta_2, \dots, \theta_n$  refer to the contact angle between the  $i_{th}$  probe liquid and asphalt binder; and subscript L1, L2, ..., Ln refer to the  $i_{th}$  probe liquid.

● **SFE of aggregate**

The Sessile drop (SD) method was ~~applied to measure~~ employed for measuring the contact angles between the basalt aggregate substrate and three probe liquids (distilled water, formamide, and ethylene glycol), and their results were used to calculate the SFE components of basalt aggregate using equation (7). The detailed sample preparation and the testing procedure have been reported in other studies<sup>[34]</sup>. Three replicates of samples with each probe liquid were tested.

3.2.3 *Cantabro loss test*

Cantabro loss test was conducted ~~to evaluate on~~ the ~~ravelling loss of~~ asphalt ~~mixture~~ ~~following mixtures in accordance with~~ the standard ~~of method~~ AASHTO TP 108-14. The ~~mixture asphalt~~ ~~concrete~~ samples were ~~submerged in the water~~ conditioned at 25°C for 20 ~~before~~ prior to the test and then ~~were rotated~~ subjected to 300 revolutions in the Los Angeles abrasion testing machine ~~for 300~~ ~~revolutions~~ at a rotating speed of 30rpm ~~at 25°C~~. ~~Then the~~ The mass loss rate of the samples was calculated ~~after the rotation to characterize~~ for determining the ravelling resistance of asphalt mixture. Four replicates were tested for each ~~sample~~ type of mixture.

3.2.4 *Hamburg wheel-tracking (HWT) test*

The HWT test in accordance with the AASHTO T 324-14 was performed to evaluate the moisture

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1 ~~damage resistance~~susceptibility of asphalt mixtures ~~according to AASHTO T 324-14.~~ In this test, the sample  
2 ~~was submerged in study,~~ the ~~water~~samples were tested at ~~50 °C while being °C in the wet condition until the~~  
3 wheel ~~loaded repeatedly for pass reaches to~~ 20000 passes or ~~until~~ the rut depth ~~reached~~reaches to 20  
4 mm. The ~~index~~ “stripping inflection point (SIP)” index was obtained ~~and used in the analysis.~~ SIP shows,  
5 which is defined as the number of wheel load passes at the intersection of creep slope and stripping  
6 slope and signifies the onset of mixture moisture damage. Two replicates were tested for each  
7 ~~sample~~mixture.

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8 3.2.5 Four-point beam (4PB) mixture fatigue-healing test

9 To study the healing performances of the mixtures ~~corresponding to,~~ the ~~asphalt evaluated,~~  
10 ~~the modified~~ 4PB ~~mixture~~ fatigue ~~test with an introduced~~ healing ~~test~~period was conducted. The beam  
11 samples were subjected to dynamic four-point bending under the strain-control mode ~~with~~ a  
12 microstrain level of 1000 ~~at~~with a loading frequency of 10 Hz at 25 °C. During the healing period, the  
13 specimens were cured at 50 °C for 4h and afterward 25 °C for 24 h. ~~The~~The traditional  $N_{f50}$  failure  
14 criterion was chosen for the analysis of the mixture prepared with base ~~asphalt mixture and~~binder while  
15 the  $N_{fNM}$  failure criterion was employed for the mixtures prepared with the modified asphalt  
16 ~~since~~binders. Since it is concludedhas been reported that the  $N_{fNM}$  ~~definition of fatigue life~~failure  
17 criterion is more suitable for asphalt mixtures with modified binders<sup>[35][36]</sup>. ~~To study the healing behavior~~  
18 ~~of the mixture, a healing period was set after the fatigue test first reached termination and then the~~  
19 ~~loading cycle repeated.~~ During the healing period, the specimens were cured at 50 °C for 4h and  
20 afterward 25 °C for 24 h. The healing ratio of fatigue life for asphalt mixtures ~~could be~~is calculated  
21 as by using equation (8). Three replicates were tested for each ~~sample~~mixture.

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$$HR_{4PB} = \frac{N_{f\text{-after}}}{N_{f\text{-initial}}} \times 100\% \quad (8)$$

where,

$HR_{4PB}$ — the healing ratio of the asphalt mixture;

$N_{f\text{-after}}$ — the fatigue life after healing;

$N_{f\text{-initial}}$ — the initial fatigue life.

## 4 Results and discussion

### 4.1 BBS and SFE tests results of asphalt binders

The BBS test was performed to investigate the effects of different modifiers and their dosages on the asphalt bond strength and healing property. Two healing conditions (dry and wet) and five healing cycles were investigated. ~~From figure2 to figure4,~~ From Figure 2 to Figure 12, the POTS and HR values of different asphalt binders are plotted separately. For each binder, only two HRhealing POTS and healing ratio values ~~calculated for in~~ the 1st and 5th healing cycle were presented and discussed. Also, the cohesion energy ( $W_{II}$ ), wet adhesion energy ( $W_{ISW}^{wet}$ ) and compatibility ratio (CR) of each asphalt binder derived from SFE test were also shown and analyzed. The error bar was omitted since the COV values of the testing results were less than 15% for all tested asphalt binders. It should be noted that since only one aggregate type (basalt) was selected in this study, the following results may be limited to this asphalt-aggregate system.

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4.1.1 Effects of linear SBS modification

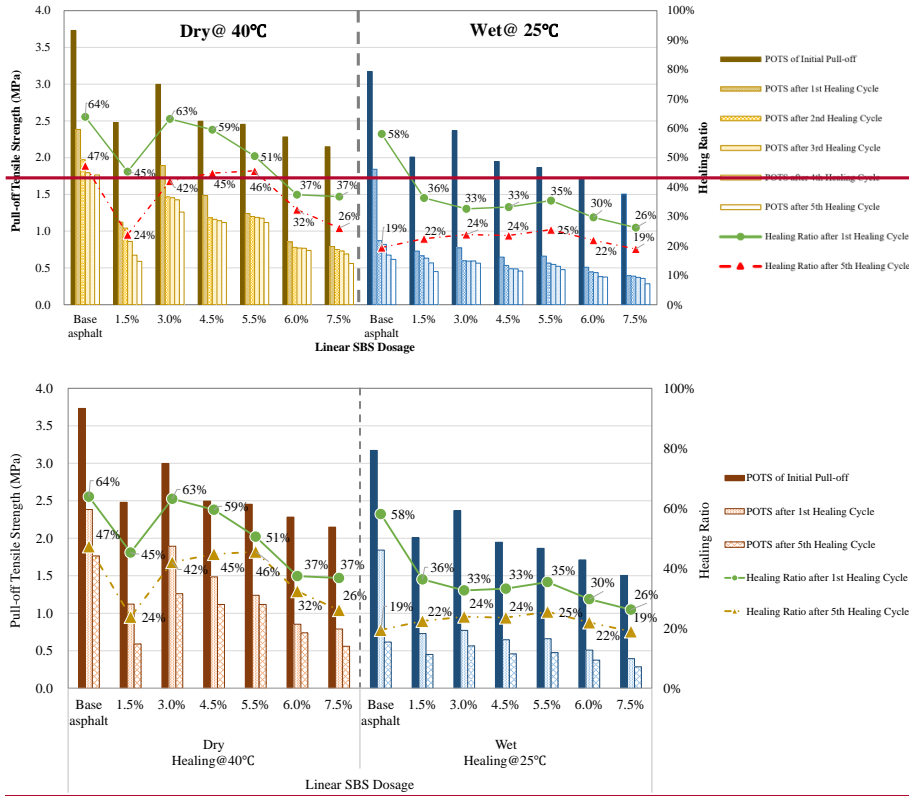


Figure 2 BBS test results of linear SBS-modified asphalt.

Figure 2 shows the BBS test results of linear SBS-modified asphalt. The POTS and HR values of linear SBS-modified asphalt are lower than those of the base asphalt, which manifests that linear SBS modification harms the bonding strength and healing properties. It is also seen that POTS and HR decrease with the increase of healing cycles. There is a notable drop in POTS values after the first healing cycle. After that, the POTS values decrease in a much less range. This suggests the healing is a long-standing behavior after multiple fractures. Besides, the HR values in the dry condition are always higher than those in the wet condition, indicating the existence of water interferes with the asphalt

binder healing process.

As for the effects of modifier dosage, under dry conditions, the initial POTS and HR peak when 3.0% linear SBS is added. For wet conditions, the initial POTS peak at 3.0% dosage while HR remains similar for different dosages. Therefore, it is recommended that 3.0% as the optimum SBS dosage in terms of bond and healing properties.

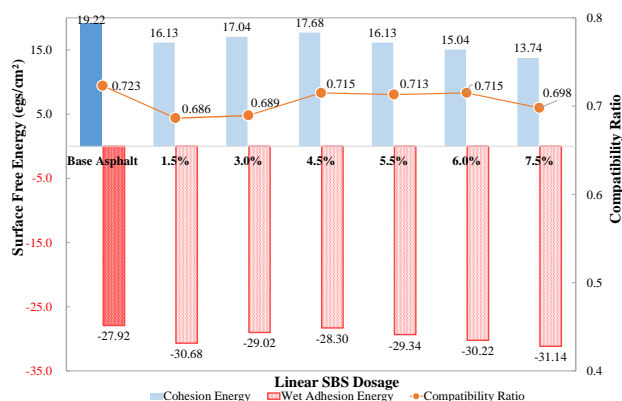


Figure 3 SFE test results of linear SBS-modified asphalt.

Figure 3 shows the SFE test results of linear SBS-modified asphalt at various dosages. The variation trend of modification on the cohesion energy  $W_{II}$  is found to be consistent with the changes of POTS and HR in of SBS-modified asphalt at dry condition, while as well as their healing ratio. It is also found that the changes of in the wet adhesion energy  $W_{Isw}^{wet}$  and CR coincide with fall in the same trends as those of POTS and HR in at wet the condition, respectively. These results indicate that BBS tests could match the principle changes of cohesion/adhesion energies of SBS-modified asphalt binders.

In terms The POTS of the changes of SBS modified asphalt cohesive POTS and  $W_{II}$  after SBS is added under at a dosage level of 1.5% shows a lower value than the base binder at dry condition. And its cohesion energy is also lower than the base binder. This is because of that the SBS polymer could

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1 not ~~form~~generate a stable grid structure ~~to enhance~~enhancing the cohesive strength of asphalt when the  
2 dosage is relatively low, ~~however~~. ~~Meanwhile, at low dosage level the SBS macromolecule hinders~~  
3 ~~the asphalt homogeneity~~macromolecules may cause an issue of inhomogeneity in the binder, which  
4 might ~~causer~~result in stress concentration in ~~asphalt and result in the lower  $W_{tt}$  and POTS values of~~  
5 ~~asphalt with lower SBS dosage~~the modified asphalt binder. On the other hand, SBS modification  
6 increases the viscosity of binder, leading to its poor flowability, which reduces the opportunity of asphalt  
7 to fully recreate the cohesive bond. In the dosage range of 3.0%~4.5%, SBS polymer could disperse  
8 uniformly in base asphalt and formulate grid structure through the cross-linking reaction ~~promotes the~~  
9 ~~formation of the grid structure~~. Some saturates and aromatics in asphalt enter into the SBS network,  
10 which changes the component proportion of asphalt. The proportions of saturates and aromatics  
11 decrease while those of asphaltene and resin increase, which contain the most chemically active  
12 components, such as asphaltous acid, asphaltous acid anhydrides, and other polar components, which  
13 promotes the cohesion energy and strength of asphalt to some extent. ~~However, When the SBS polymer~~  
14 content is higher than 6.0%, the cohesion strength and healing performance of modified binder are  
15 negatively affected ~~when SBS dosage is relatively high ( $\geq 6.0\%$ )~~ due to the separation of SBS modifier  
16 and the increased viscosity of asphalt.

17 The trend of  $W_{ISW}^{wet}$  follows the POTS change of SBS-modified asphalt under the wet condition.  
18 The SBS polymer itself does not adhere to aggregate, and the large molecules makes it difficult for  
19 aggregate to adsorb SBS-modified asphalt, leading to the fact that SBS-modified asphalt is prone to be  
20 stripped from aggregate by moisture. In addition, its large molecules limit the asphalt movements,  
21 resulting in a relatively lower healing capability. Furthermore, it is observed that the index CR could  
22 illustrate the variation of asphalt healing performance. CR reflects the asphalt wettability in wet

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condition, which determines whether asphalt can penetrate the microstructure of the aggregate surface.

Higher CR implies that asphalt could recover the aggregate surface after adhesive fracture in the presence of water.

In consideration of bond strength as well as healing performance, it is concluded that 3.0%~4.5% is an optimum range of SBS dosage in terms of the results of BBS and SFE tests.

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4.1.2 Effects of crumb rubber modification

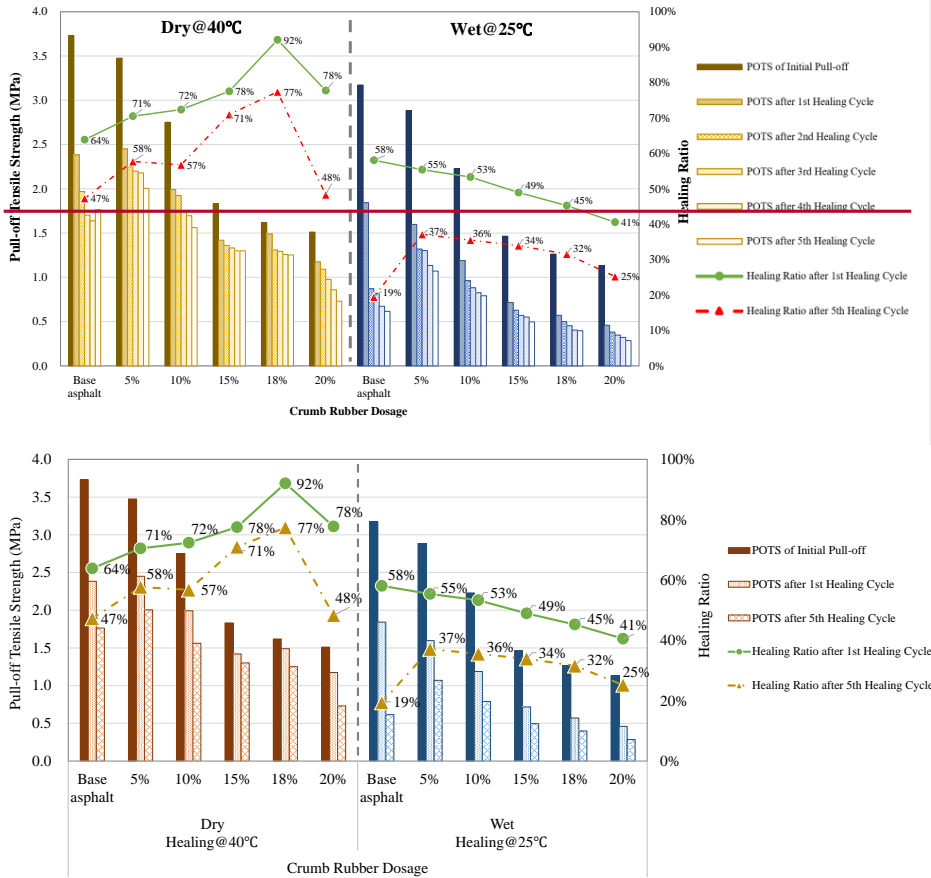


Figure 4 BBS test results of crumb rubber-modified asphalt.

According to Figure 4, crumb rubber has a negative effect on the asphalt binder bonding, which is similar to the SBS modifier. The POTS values decrease with the increase of crumb rubber dosage. The reason for this phenomenon is that the homogeneity of asphalt is seriously affected by the rubber with relatively larger particle size. Besides, the crumb rubber particle itself is not adhesive and could not provide extra bond strength between the asphalt and aggregate. In contrast, it occupies the area on the

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surface of aggregate which could be taken by asphalt binder.

It is also noted that crumb rubber-modified asphalt has much lower HR values at wet conditions in comparison with dry conditions, demonstrating that the healing property of crumb rubber-modified asphalt is vulnerable to moisture. This is because that the existence of rubber particles causes a rugged fracture surface after pull-off failure, and the gap between the cracks make the interface between asphalt and aggregate prone to be intruded by water, interfering the asphalt infiltration to the aggregate.

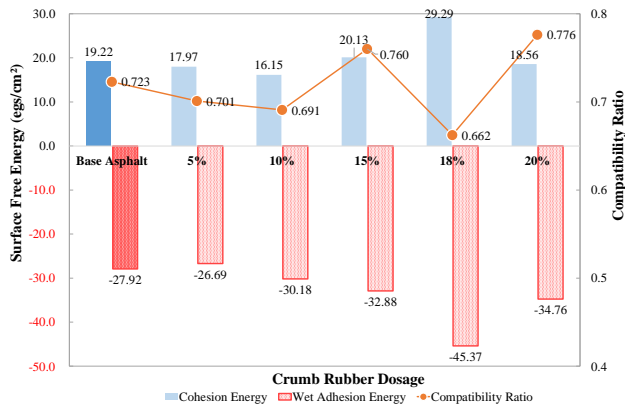
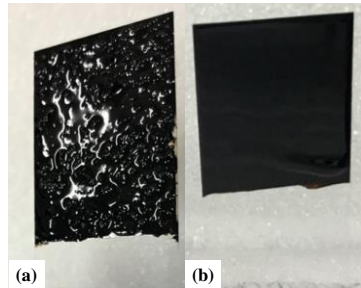


Figure 5 SFE test results of crumb rubber-modified asphalt.

However, no obvious regularity was found in the results of the SFE test according to Figure 5. This is because of the effect of rubber particles on the smoothness of the glass slide surface and the sample with a rough surface is prone to cause inaccuracy of test results. Figure 6 shows the comparison of the glass slide with a rough surface (crumb rubber-modified asphalt) and the one with a smooth surface (other asphalt).



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18 2 Figure 6 The appearance comparison of glass slides between (a) crumb rubber-modified asphalt and (b) other  
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22 4 To ensure the accuracy of the SFE test results, the surface of the prepared slide coated with asphalt  
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24 5 should be as smooth as possible, any bubbles or granular substances attached to the slide should be  
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26 6 avoided. For this reason, SFE is not a suitable measurement to evaluate the bond properties of crumb  
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28 7 rubber asphalt-aggregate combinations.  
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4.1.43 Effects of TB rubber modification

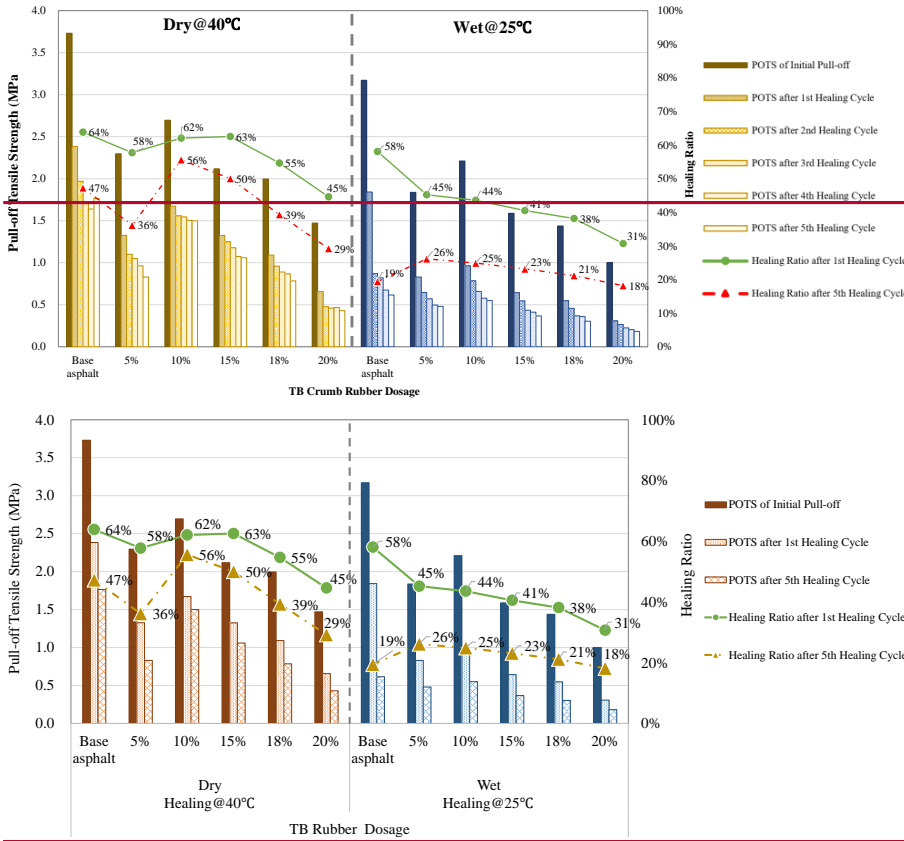


Figure 7 BBS test results of TB rubberized asphalt.

Figure 7 shows that TB rubber also negatively effects the bond and healing performance of asphalt. 10%~15% could be considered as the optimum dosage since the POTS and HR values of TB rubberized asphalt show preferable bond and healing performance within this concentration range.

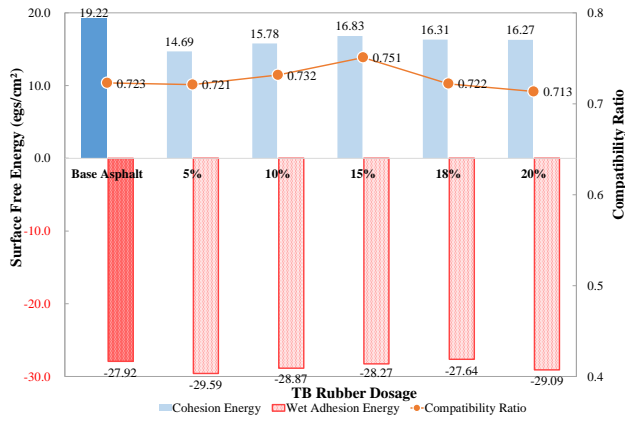


Figure 8 SFE test results of TB rubberized asphalt.

The SFE test results in Figure 8 show obvious regularity and consistency with the results of the BBS test. The accuracy of the SFE test results on TB rubberized asphalt could be ensured due to its much finer rubber particles and superior storage stability. 15% TB rubberized asphalt presents the highest cohesion energy and wet adhesion energy, which reconcile the variation of cohesive and adhesive strength in the BBS test.

The dosage of TB rubber has a double-sided effect on the POTS and SFE values of asphalt. TB rubberized asphalt is produced through devulcanizing crumb rubber at a very high temperature ( $\geq 220^{\circ}\text{C}$ ). The rubber particles become smaller molecular particles during the pyrolysis process and intermolecular interaction (van der Waals force) decreases. As the dosage increases, the bond strength and surface energy are enhanced as a result that some parts of the molecules get connected through chemical crosslinking or physical entanglement and form a spatial network structure, and the Lewis acidic component of TB rubberized asphalt increases as well. However, the adverse impacts of excessive TB rubber become prominent when the dosage is high. Therefore, it shows a trend of growth followed by decline.

Both traditional crumb rubber and TB rubber harm the asphalt bond strength. By comparing Figure

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4 with Figure 7, it appears that TB rubberized asphalt binders at relatively high dosages generally have better bond and healing property than the crumb rubber-modified asphalt, which is attributed to the fact that the TB rubber can easily distribute in the asphalt due to its finer powder. The small TB rubber granule could swell well and form a better interface transition layer with asphalt, which could dissipate more stress and deflect the cracks under external force.

4.1.54 Effects of HDPE modification

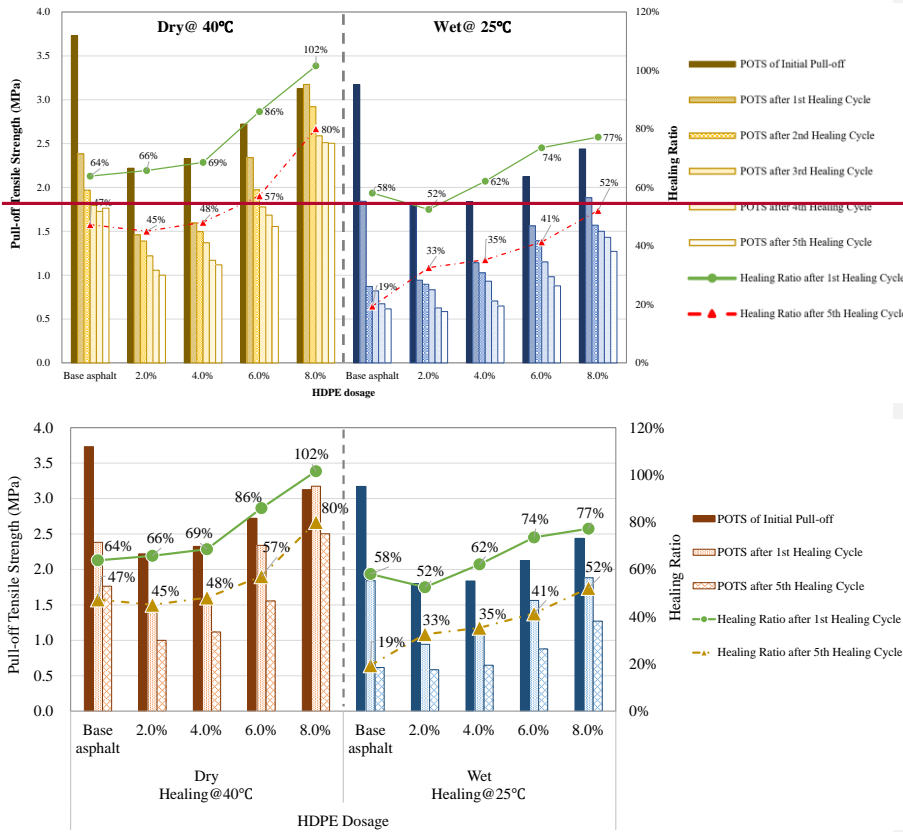


Figure 9 BBS test results of HDPE-modified asphalt.

According to Figure 9, the POTS and HR values of HDPE-modified asphalt keep increasing with

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the dosage from 2% to 8%. The HR value of 8% HDPE-modified asphalt at dry condition even reaches 102%, indicating the healing bond strength is even better than that before the initial fracture.

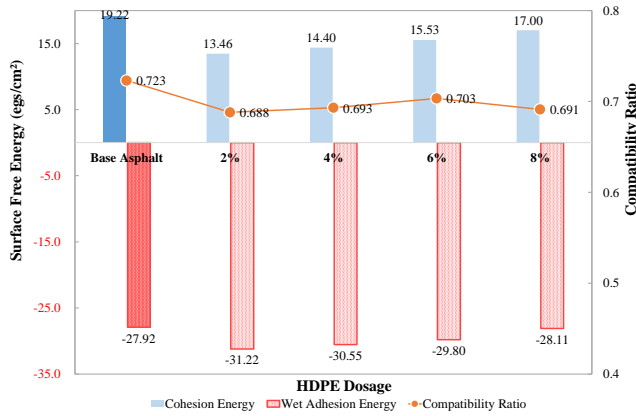


Figure 10 SFE test results of HDPE-modified asphalt.

Figure 10 demonstrates that the trend of SFE test result of HDPE-modified asphalt is in agreement with that derived from the BBS test. PE material has a low crystallinity and melting point and its solubility parameters and polarity are similar to those of wax components in asphalt. The introduction of HDPE into asphalt reduces the polarity and intermolecular interaction, also the chemical affinity between asphalt and aggregate as well. With the increase of dosage, HDPE chains get folded and form an interwoven structure, resulting in the improvement of surface energy.

The possible reason for the superior healing performance is that HDPE includes ethylene homopolymer, the copolymer of ethylene and a small amount of olefin. The molecular structure of HDPE is simple and symmetric, which contains very few short branches<sup>[37][38]</sup>. This kind of long-chain structure with few branches has superior molecular mobility, which results in a fast re-infiltration and re-bond of microcrack after the bond failure.

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4.1.65 Effects of gilsonite modification

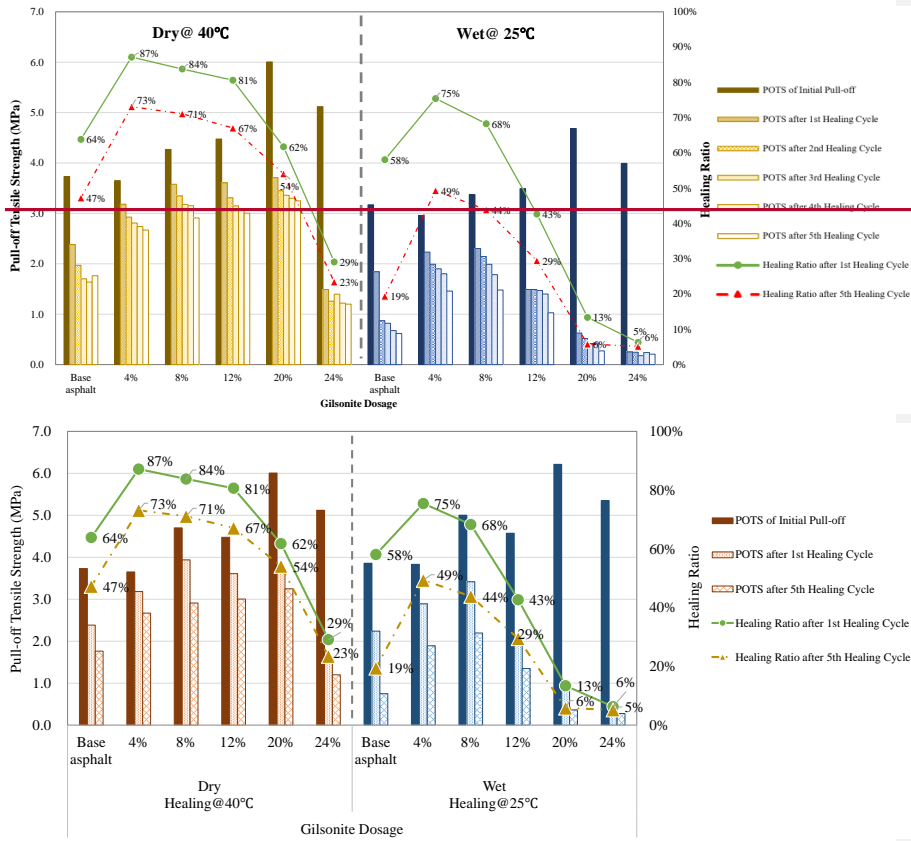


Figure 11 BBS test results of gilsonite-modified asphalt.

According to Figure 11, gilsonite modification at a proper dosage ( $\leq 20\%$ ) can improve both the bond strength and healing performance of asphalt. However, excess gilsonite (e.g. 24%) significantly reduces the healing performance. During the test, it was observed that the fracture surface after the second pull-off test was nearly the same as that after the first pull-off test, indicating little asphalt flow and healing occurred during conditioning.

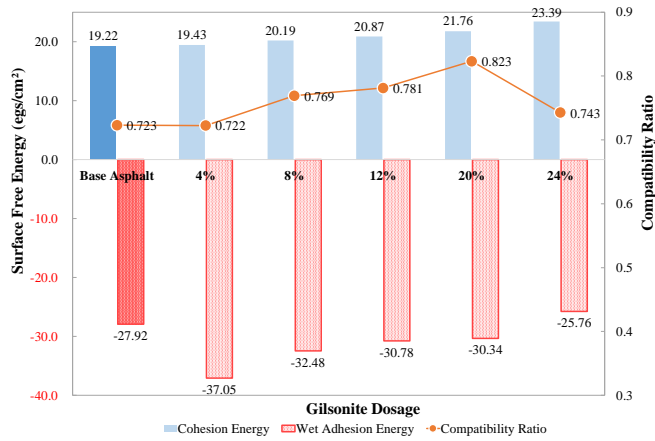


Figure 12 SFE test results of gilsonite-modified asphalt.

According to the SFE test results shown in Figure 12, the variation of cohesion energy chimes with the trend of dry POTS in the BBS test. However, the result of wet adhesion energy is inconsistent with that of wet POTS. This can be explained by the fact that some samples in the wet condition presented cohesive-adhesive combined failure rather than the total adhesive failure, which influenced the result of the SFE test. Also, there is no significant coherence between wet HR and CR. This phenomenon of inconsistency might be explained by the stiffness of gilsonite-modified asphalt. In spite that gilsonite-modified asphalt has good wettability with aggregate, its flowability is limited by high stiffness at 25°C (healing temperature), leading to the low HR values in the BBS test.

Compared with other modification, gilsonite modification can dramatically enhance the bond strength and cohesion/adhesion energy of asphalt for the following reasons:

- (1) high contents of metal and nitrogen elements increase the molecular polarity and wettability of asphalt, which brings high inner cohesion energy and adhesion performance.
- (2) gilsonite contains high contents of heavier components like asphaltene and resin because its

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8 1 light components tend to volatilize due to the long-term exposure to nature. During the  
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10 2 modification with asphalt, gilsonite absorbs the light components (nonpolar saturates and  
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12 3 aromatics) in base asphalt after the shear mixing and swelling development and a blended  
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14 4 asphalt system with a higher content of resin is formed, which is the strongest polar component  
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16 5 among the four components of asphalt and has obvious promotion effect on the asphalt surface  
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18 6 energy.

#### 20 7 **4.2 Cantabro loss/ HWT and 4PB fatigue-healing tests results of asphalt mixtures**

22 8 In this study, the base binder and modified binders at the recommended or commonly-used dosages  
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24 9 (i.e. 4.5% SBS-modified asphalt, 15% TB rubberized asphalt, 24% gilsonite-modified asphalt, 8%  
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26 10 HDPE-modified asphalt, and 18% crumb rubber-modified asphalt) were ~~selected~~ used to prepare HMA  
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28 11 mixtures ~~by using in the laboratory for their performance tests. The same source of aggregates and the~~  
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30 12 Superpave-12.5 mix ~~gradation design were employed, except for the HMA mixture including the 18.0%~~  
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32 13 crumb rubber modified binder, ~~for which a A gap graded gradation mix design (ARAC-12.5)<sup>[39]</sup> was~~  
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34 14 chosen. ~~The optimum asphalt content for mixtures was 4.7% while for for the crumb rubber- modified~~  
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36 15 asphalt- ~~mixture. The asphalt content for the crumb rubber modified mixture was 6.1% was determined.~~  
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39 16 ~~The cohesive bond (dry), adhesive bond (wet) and while it was 4.7% for the other modified asphalt~~  
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41 17 ~~mixtures and control asphalt mixture with base binder. The voids content of crumb rubber-modified~~  
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43 18 ~~asphalt mixture was 5.5%, and 4.0% for the other mixtures. The revelling resistance, moisture~~  
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45 19 ~~susceptibility and fatigue-healing behavior of asphalt mixtures were evaluated through the Cantabro~~  
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47 20 loss test, HWT test, and 4PB fatigue-healing test respectively. The ~~mixture mean values of main testing~~  
48  
49 21 results ~~and their values of coefficient of variation are both~~ shown in Table 2.

Table 2 Results and comparison of the mixture tests.

Binder	Cantabro Test		HWT Test		4PB Test			
	Cantabro loss	COV	SIP (passes)	COV	$N_{i-initial}$	COV	HR <sub>4PB</sub>	COV
Base asphalt	25.4%	5.7%	7531	9.5%	23953	1.7%	47.9%	15.7%
4.5% SBS	22.3%	5.2%	8567	4.8%	381340	3.2%	53.0%	5.3%
18% Crumb Rubber	27.9%	6.2%	3895	13.5%	238860	7.8%	70.3%	2.5%
15% TB Rubber	26.3%	4.2%	3216	13.3%	190690	6.4%	61.4%	11.0%
8% HDPE	23.5%	5.8%	9063	9.8%	266650	6.5%	71.8%	3.0%
24% Gilsonite	15.9%	9.8%	13967	6.4%	89096	11.6%	35.4%	6.1%

According to the results shown in From Table 2, it is concluded can be seen that 4.5% the SBS, 8% HDPE and 24% gilsonite modifications could improve modified asphalt mixtures show lower values of Cantabro loss than the control mixture, illustrating an improved ravelling resistance. Their relatively higher values of stripping resistance of asphalt mixture under both dry and wet conditions inflection point indicate a better resistant to moisture damage. Among all the tested asphalt mixtures, 24% the gilsonite-modified asphalt mixture holds has the lowest value of Cantabro loss and the highest SIP value, showing while the crumb rubber modified mixture and TB rubber modified mixture have the highest values of Cantabro loss and the lowest SIP values. The gilsonite modification showed a superior improvement of the ravelling resistance and moisture damage resistance of asphalt mixture. However, it presents the lowest HR in 4PB fatigue-healing test due to the inferior mobility of asphalt. By comparison, both 18% The crumb rubber and 15% TB rubber modifications have a detrimental effect effects on the bond behavior, ravelling resistance and moisture susceptibility of the asphalt-aggregate system, mixtures. The possible reason is that crumb rubber/TB rubber absorbed light molecular components of asphalt binder resulting in less bonding between the binder and aggregates, while preferable fatigue and healing performance was were found on account of the fatigue stress absorbing of rubber and the good mobility of TB rubberized asphalt.

To verify whether the findings of the BBS and SFE tests could accurately reflect the pavement on the

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1 ~~asphalt-aggregate combinations, the mixture~~ performance in terms of bond and healing properties, the  
2 ~~experimental test~~ results of Cantabro loss and dry POTS &  $W_{II}$ ; SIP and wet POTS &  $W_{Isw}^{wet}$ ;  $HR_{CIPB}$  and  
3  $HR_{BAS}$  (after 1 healing cycle, healed in dry condition) are correlated and compared with the corresponding  
4 POTS and cohesion/adhesion energies of asphalt-aggregate combinations, as shown in Figure 13. It is worth  
5 mentioning should be noticed that in the correlation analyses the SFE data does not include the testing results  
6 of crumb rubber-modified asphalt are excluded from the correlation binder due to the inaccurate  
7 experimental data its low repeatability caused by the rubber particles.

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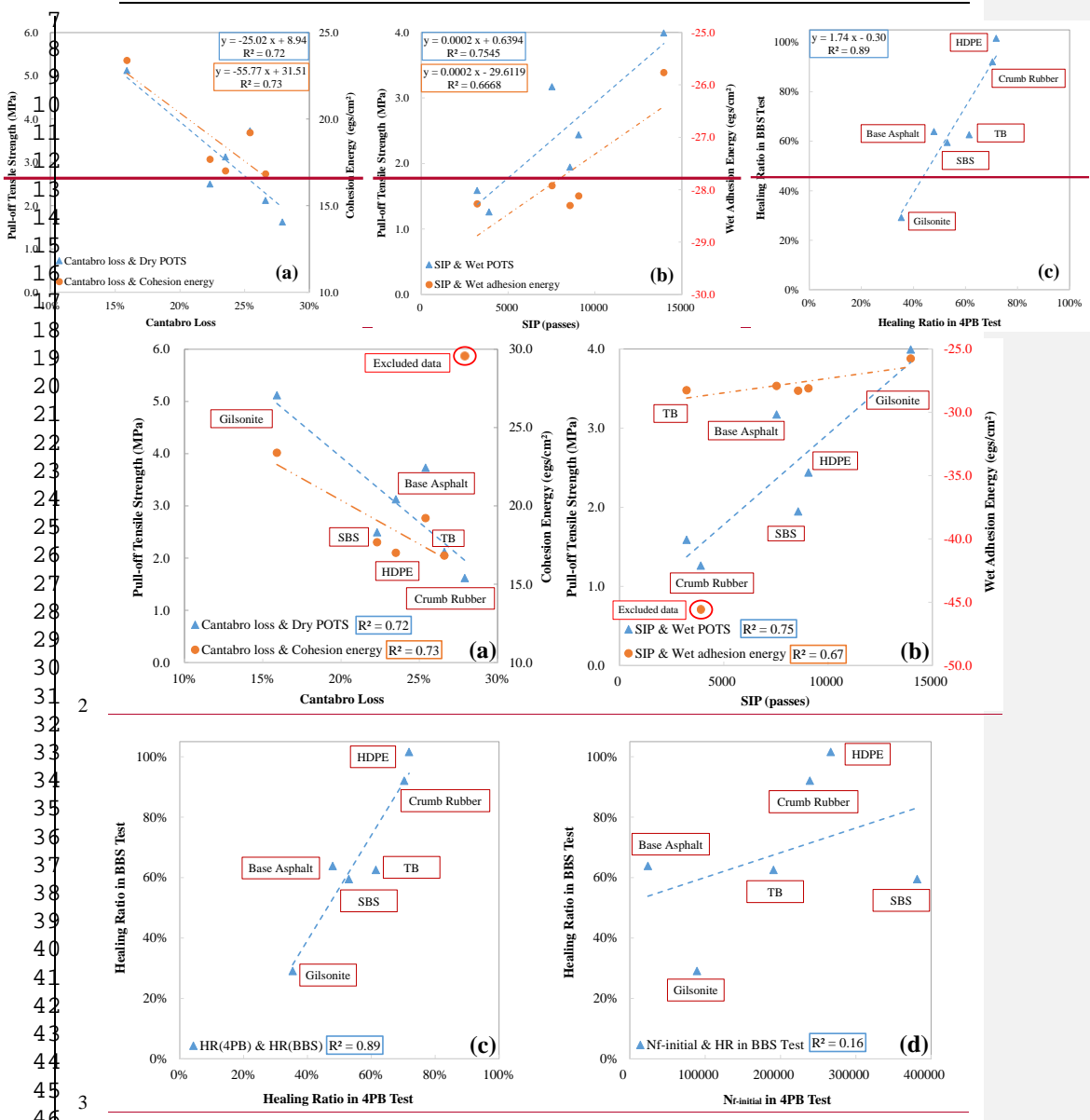


Figure 13 Correlation analysis of (a) Cantabro loss and dry POTS &  $W_{II}$ ; (b) SIP and wet POTS &  $W_{Isw}^{wet}$ ; (c)

HR<sub>4PB</sub> and HR<sub>BBS</sub>; (d) N<sub>F-initial</sub> and HR<sub>BBS</sub>

The results and comparison presented in Figure 13 manifest that both the results of dry POTS in the

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8 1 BBS test and  $W_{II}$  in SFE test show similar correlation with Cantabro loss of asphalt mixtures ( $R^2=0.72$ ,  
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10 2 0.73 respectively) while for adhesion behavior, wet POTS shows better correlation ( $R^2=0.75$ ) than  $W_{ls}^{wet}$   
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12 3 with SIP in HWT test, manifesting in spite that SFE test results could reveal and explain the mechanism of  
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14 4 the variation tendency of bond performance of modified-asphalt binders with different dosages to some  
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16 5 extent, the evaluation result of BBS test is closer to that derived from asphalt mixture tests by comparison.  
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18 6 ~~Moreover, The standard 4PB fatigue test could not reflect the healing ability of asphalt according to the poor~~  
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20 7 ~~correlation ( $R^2=0.16$ ) between the HR values of in the BBS test and 4PB the fatigue life in the 4PB test. The~~  
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22 8 ~~modified 4PB fatigue-healing test was performed to find the correlation between asphalt and mixture healing.~~  
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24 9 ~~The HR values in the modified 4PB test show an apparent correlation ( $R^2=0.89$ ) with BBS healing test (after~~  
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26 10 ~~1 healing cycle, healed in dry condition), demonstrating that the BBS healing test could reflect the fatigue-~~  
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29 11 healing performance of the corresponding asphalt mixture effectively. Based on the correlation analysis and  
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31 12 comparison, and also considering the experimental efficiency and cost, the BBS test is suitable to predict the  
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33 13 bond and fatigue healing behavior of asphalt pavements and could be determined as a screening experiment  
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35 14 in practical engineering.

## 37 15 **5 Conclusions**

40 16 In this study, the BBS test and SFE test were performed respectively on asphalt binders to evaluate  
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42 17 the bond and healing properties in terms of mechanical performance and mechanism analysis. Cantabro  
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44 18 loss test, HWT test, and 4PB fatigue-healing test were conducted on asphalt mixtures to verify the  
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46 19 evaluation accuracy of the two asphalt experiments on the cohesion, adhesion and healing properties of  
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48 20 asphalt. The results from asphalt binders and asphalt mixtures were correlated. The following  
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50 21 conclusions can be drawn from the results:

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1. In the aspect of the bond property, according to the BBS test and SFE test, only gilsonite could enhance the cohesive/adhesive strength and surface energy of asphalt among all the tested modification methods, however, excessive gilsonite (>20%) would reduce this improvement. The other modifiers including linear SBS, crumb rubber, TB rubber, and HDPE have a negative effect on the bond performance and the effects vary with the dosages of the modifiers. Moreover, for each asphalt binder, the variations of its cohesion energy and wet adhesion energy in SFE test are in accordance with those of the POTS in dry and wet conditions respectively, except for crumb rubber-modified asphalt, the SFE test result of which is not available since the rubber particles would interfere with the experimental accuracy.
  2. In regard of asphalt healing performance, HDPE, crumb rubber and gilsonite (< 20%) modifications have a positive promotion effect, among which 8% HDPE-modified asphalt shows the best healing performance (HR=102%) owing to the mobility enhancement effect of HDPE on asphalt molecular. It is also noted that the variation trend of the SFE index “CR” is in consistence with that of the HR under the wet condition in the BBS test (except for asphalt modified with crumb rubber and gilsonite).
  3. The Cantabro test, HWT test, and 4PB fatigue-healing test verify the accuracy of BBS testing the cohesion/adhesion and healing properties. The correlations between Cantabro loss and dry POTS ( $R^2=0.72$ ); SIP and wet POTS ( $R^2=0.75$ ); HR in 4PB mixture healing test and BBS healing test ( $R^2=0.89$ ) indicate that the BBS test could reflect the stripping resistance and fatigue-healing behavior of the corresponding asphalt mixture effectively, and could be determined as a screening experiment in practical engineering.
  4. Based on the results of bond and healing performances, the recommended dosage for each

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8 1 modified asphalt is as follows: 3.0% for linear SBS-modified asphalt, 15%~18% for crumb  
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10 2 rubber-modified asphalt, 10%~15% for TB rubberized asphalt, 8% for HDPE-modified asphalt  
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12 3 and 12%~20% gilsonite-modified asphalt.  
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18  
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21 7 acknowledge the financial support of the Postdoctoral Innovative Talent Support Program.  
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## 24 8 **Data availability**

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26 9 The data that support the findings of this study are available from the corresponding author, Quan  
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28 10 Lv, upon reasonable request.  
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