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Effect of Simultaneous Application of Glass Fiber Reinforcement and Polymer-Modified Asphalt Emulsion on DBST's Resistance to Aggregate Loss Using Laboratory Investigation

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Abstract: Double bituminous surface treatment (DBST) has been a widely utilized pavement maintenance material due to its capability to restore the surface roughness of existing pavement and provide a layer of protection against weathering, aging, and moisture. However, DBST is highly prone to aggregate loss at an early stage, which is a very common problem experienced by surface treatment. Therefore, to lessen the aggregate loss and prolong the service life of DBST, fiber additive can be incorporated to strengthen the adhesion between the asphalt emulsion and aggregates. This study investigated the performance of glass fiber-reinforced polymer-modified DBST against aggregate loss by conducting laboratory tests using typical DBST as the benchmark of the test results. Four laboratory tests were chosen to represent different loading applications on the surface of the pavement: the bitumen bond strength (BBS) test, the sweep test, the Hamburg wheel-track test (HWT test), and a one-third-scale model mobile load simulator (MMLS3) model. Furthermore, the curing time of the asphalt emulsion was considered in the BBS test and sweep test. Based on all results from the conducted laboratory tests, polymer-modified DBST with glass fiber reinforcement presented an increased resistance to aggregate loss compared with typical DBST. Moreover, it was found that a longer curing time of the asphalt emulsion, whether it was typical or modified, strengthened the surface treatment's resistance to aggregate loss.

Keywords: double bituminous surface treatment; glass fiber reinforcement; polymer-modified asphalt emulsion; aggregate loss; bitumen bond strength test; sweep test; Hamburg wheel-track test; one-third-scale model mobile load simulator

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1. Introduction

As the demands on transportation infrastructure continue to evolve due to the increase in traffic and economic development, the efficient management of pavement systems becomes increasingly vital. The pavement management system (PMS) has been progressing in order to prolong the service life of the pavement [1]. Several techniques have been developed for preventive maintenance and rehabilitation methods that suit the necessary action to improve the current condition of the pavement. Other than that, the materials used in PMS are consistently developing to further prolong the service life of the pavement, and one of these preventive maintenance materials is the bituminous surface treatment (BST), also known as the chip seal.

BST is a common maintenance material composed of layers of aggregates and bitumen binder being used to provide a new wearing course on an old pavement to restore its surface roughness [2,3]. It is highly known as a durable wearing course that can resist weathering and serve as a protective layer against moisture and asphalt aging agents that promote oxidation [4]. To further strengthen the wearing course, most of the engineers prefer to apply double bituminous surface treatment (DBST). As the name suggests, two layers of aggregate and bitumen binder are applied to the pavement, with the last layer having finer aggregates [5]. DBST has been valued as a cost-effective solution for maintaining and extending the service life of roadways, particularly in moderate to high-traffic volume areas [6].

DBST, commonly known as double chip seal in other countries, is typically used in roads where higher traffic or steep slopes are present, requiring a higher durability for the surface of the pavement. Moreover, this surface treatment is more suitable for existing roads with moderate to severe cracking and roads that are openly textured or have heavily porous surfaces [7]. In this case, the single-layered BST's aggregate will only serve as a filler to the open voids and cracks of the surface of the existing pavement, thus failing to provide a new surface layer to the existing pavement. Compared with single-layered BST, DBST provides additional resistance to oxidation and moisture infiltration due to the finer aggregates applied at the second layer, thus prolonging the life of the pavement [8]. However, DBST is highly susceptible to aggregate loss in its early years, just like other surface treatments. This loss of aggregates lowers the surface treatment's surface roughness, thus defeating the purpose of applying it on the existing pavement.

Aggregate loss or stripping is the most common distress of DBST [9]. A wide variety of reasons can cause aggregate loss, ranging from poor construction and materials to external factors such as moisture, which break the adhesion between the asphalt and aggregates or cohesion within the asphalt binder [10]. With the absence of aggregate on the surface of the pavement, moisture can easily penetrate the pavement, causing major distress. Moreover, the skid resistance of the pavement decreases, resulting in higher instances of accidents, especially in the presence of water, snow, or black ice [11]. To address the problem, a number of research studies were dedicated to improve the resistance of surface treatment against aggregate loss.

In improving the resistance of aggregate loss in surface treatments, modifications were performed in the surface treatment's material composition. Several research studies focused on inspecting the aggregate component of the surface treatment. An example of this is a study conducted in 2013 [12], wherein the effects of aggregate surface properties on the resistance of chip seal were investigated. To assess the chip seal's adhesive performance in this study, an accelerated chip seal simulation device was developed, wherein a bidirectional vehicle load simulator is situated in a climate cabin to control the environmental condition while testing. Three different types of aggregates were compared during the experiment: clean, dusty, and pre-coated. It was found that the use of pre-coated aggregate mixed with modified binder provides the best performance in terms of chip retention. In addition, in 2014 [13], the stripping behavior of eight different types of granitic rocks was compared when used as aggregates for asphalt mixture. After assessing the chemical components, mineralogy, and physical properties of the aggregates, it was found that the aggregate stripping due to the presence of moisture is closely correlated with the aggregate's surface tension, while the aggregate stripping due to the application of traffic load is correlated with the aggregate's surface roughness. Moreover, the mineralogical and chemical composition of the aggregate affect both aggregate stripping phenomena. Although aggregate type and physical properties were found to have an effect on aggregate retention, the asphalt emulsion's properties were proven to have more significance in strengthening the resistance of surface treatment against aggregate loss [14].

Different modifications in the material composition of asphalt emulsion for surface treatments through additives or production methods have been used to improve its performance. A study from 2015 compared different production methods of bitumen emulsion for slurry seals, namely oxidated, distillation, and modified oxidated bitumens [15]. Another study in 2020 added hydrochloric and orthophosphoric acids in bitumen emulsions to produce a slow-setting slurry surfacing mix [16]. Moreover, in 2022, a study proposed the addition of Phenol-cresol-formaldehyde resins, a material obtained from the phenolic fraction of coal tar, to asphalt as an enhancer of its adhesive properties [17]. There are numerous modifications for bitumen, but the most popular is the addition of polymer.

Several studies have proven the positive effect of adding polymer as a modifier to asphalt emulsions of surface treatments. A study in 2010 [18] was conducted to evaluate the performance and cost-effectiveness of chip seals with polymer-modified asphalt emulsion. A one-third-scale model mobile load simulator was used to compare the typical and modified chip seal's rutting, bleeding, and aggregate retention performance. Considering both structural and functional performance, the modified chip seal showed an extended service life, and it was found that it is cost-effective if the modified chip seal reaches a service life year ranging from 5 years to 7 years. Moreover, a study in 2017 [19] investigated the bitumen aggregate adhesive performance of polymer-modified chip seal at low temperature with styrene-butadiene rubber (SBR) latex as an additive. The Vialit test was conducted on the polymer-modified ship seal. It was found that the addition of SBR increased the aggregate retention of the chip seal, and the effect is magnified as the amount of SBR in the asphalt emulsion increases. To further enhance the surface treatment's performance, additional modification can be applied to the surface treatment that is commonly used in typical asphalt mixtures, which is glass fiber reinforcement.

Glass fiber is an inorganic material with high tensile strength, making it an appropriate reinforcement for asphalt material [20]. Several studies have tested and proven the significant enhancement of glass fiber reinforcement regarding asphalt mixture's resistance to rutting [21], low-temperature cracking [22], moisture damage [23], and fatigue cracking [24]. A study from 2021 claimed to produce an asphalt mixture and described it in terms of its short- and long-term properties after reinforcing it with glass fiber [25]. The use of glass fiber has also been extended to the surface treatment as a reinforcement [26]. It has been found that glass fiber reinforcement improves the resistance of the surface treatment to reflective cracking [27], as well as improving its other structural properties [28]. However, there are no studies assessing the effect of glass fiber reinforcement on the aggregate retention of surface treatment. With the positive reviews on glass fiber reinforcement and its application to typical asphalt mixtures, its potential in increasing the surface treatment's resistance to aggregate loss is promising, especially when simultaneously applied with polymer additives.

In this study, a series of laboratory tests were conducted to investigate the performance of the glass fiber-reinforced polymer-modified DBST in terms of aggregate loss. Four different testing methods were conducted to measure the aggregate loss of the modified DBST on varying load applications. The severity of aggregate loss between the typical DBST and modified DBST were compared, and the effectiveness of the glass fiber reinforcement and polymer additive against aggregate loss was evaluated.

2. Materials and Methods

2.1. Materials

The glass fiber-reinforced polymer-modified DBST is basically composed of three materials: (1) aggregates, (2) asphalt emulsion, and (3) glass fiber. Figure 1 shows a diagram of the construction procedure of the modified DBST, which was also applied in the fabrication of the specimens for this study.

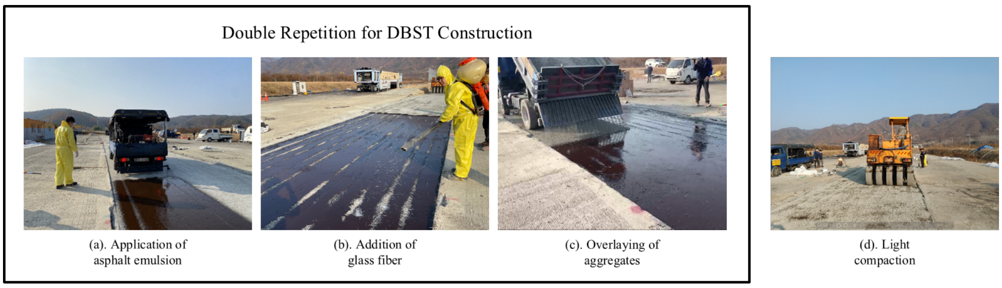


Figure 1. Glass fiber-reinforced polymer-modified DBST construction procedure.

2.1.1. Aggregates

In DBST, two binder–aggregate layers are overlaid on top of the existing pavement to renew its surface roughness and provide sufficient protection against weathering and moisture penetration that could promote the deterioration of the internal condition of the pavement [6]. The first layer of aggregate in the DBST is uniformly graded, which is similar to that of single-layer BST. The first layer of aggregates serves as the skeleton of the DBST that provides the surface roughness to the existing pavement. Meanwhile, the second layer is composed of smaller aggregates, usually about half the size of the aggregates from the first layer, to promote interlocking between the initial aggregate layer, thus providing stronger bonds that prevent the dislodging of aggregates from the surface treatment [7].

For the following laboratory tests, the aggregates used for specimen fabrication were natural limestone aggregates, which were sieved in accordance with the ASTM C136 standard [29]. The natural limestone aggregates were procured from a local quarry and supplier in South Korea. The aggregate size range for the first and second layers was 12.5 mm to 19 mm and 4.75 mm to 9.5 mm, respectively. The aggregate gradation for the first and second layers are summarized in Table 1. Moreover, the amount of aggregate for the first and second layers was set to 22.53 kg/m^2 and 12.16 kg/m^2, respectively.

Table 1. Aggregate gradation used for the specimen fabrication of laboratory tests.

Sieve Size (mm)	Percentage Retained for Aggregates on the First Layer (%)	Percentage Retained for Aggregates on the Second Layer (%)
19	0	0
12.5	90	10
9.5	100	90
4.75	100	100
2.36	100	100
1.18	100	100

Laboratory tests were conducted to determine the properties of aggregates such as median particle size, flakiness index, average least dimension, bulk specific gravity, absorption, loose unit weight, and void content. The summary of the aggregate properties is shown in Table 2.

Table 2. Properties of aggregates used in the specimens.

Properties	First Layer Aggregates	Second Layer Aggregates
Median particle size, mm	15.4	7.1
Flakiness, %	20.9	11.2
Average least dimension, mm	10.8	5.2
Bulk specific gravity	2.64	2.65
Absorption, %	1.9	1.01
Loose unit weight, kg/m^3	1502	1520
Void content, %	42.9	42.5

2.1.2. Asphalt Emulsion

Two types of asphalt emulsion were used in the specimen fabrication, CRS2 and CRS2P, for the typical and modified DBST, respectively. These asphalt emulsions were chosen as these are the most commonly used emulsions for surface treatment construction [30]. Both of the asphalt emulsions are cationic rapid-setting, water-based emulsified asphalt. In this type of emulsified asphalt, the emulsifying agent used to combine the asphalt binder in oil phase and water is positively charged, making it suitable for negatively charged aggregates in terms of bonding [31]. Moreover, both asphalt emulsions are rapid setting, which means that the asphalt emulsion breaks as soon as it is applied on any surface. The only difference between the two asphalt emulsions is the polymer modification for CRS2P. For the asphalt emulsion to improve its elasticity and durability, styrene butadiene styrene (SBS) latex was added to CRS2P to increase its resistance to aggregate loss.

SBS is a thermoplastic elastomer produced through the polymerization process of styrene and butadiene, two monomers [32]. It possesses characteristics of both plastics and rubbers, allowing for versatile applications. It is commonly used as a polymer modifier in asphalt, enhancing both its low-temperature and high-temperature properties [33,34]. This makes it widely utilized in the manufacturing of pavement materials and other related products. For CRS2P, the amount of SBS latex added was 5% of the weight of the asphalt emulsion.

The asphalt emulsions used in the experiments were supplied by a local asphalt plant in South Korea. Table 3 summarizes the properties of both asphalt emulsions. In fabricating the specimens for the laboratory tests, the application rates of the asphalt emulsion for the first and second layers were 1.75 kg/m^2 and 2.35 kg/m^2, respectively.

Table 3. Properties of asphalt emulsions used in the specimens.

Properties	CRS2	CRS2P
Viscosity, 122 °F, s.	150–400	150–400
Sieve test, %	0.1	0.1
Demulsibility, %	40	70
Storage stability, 1 day, %	1	1
Particle charge	Positive	Positive
Residue distillation, % by weight	65	65
Oil distillate, % by volume of emulsion	0.5	0.5
Penetration, 25 °C (77 °F), 100 g, 5 s	120–160	90–150
Ductility, 25 °C (77 °F), 5 cm/min, cm	100	50
Solubility in trichloroethylene, %	97.5	97

2.1.3. Glass Fiber Reinforcement

For the glass fiber reinforcement, discontinuous strands were used for the tests with a mean length of 25 mm and a diameter of 0.01 mm. The glass fiber has been outsourced from a local fiber supplier in South Korea. In the fabrication of the test specimens, the rate of application of the glass fiber has been set to be between 60 g/m^2 and 120 g/m^2. The physical properties of the glass fiber are summarized in Table 4.

Table 4. Physical properties of the glass fiber.

Properties	Values
Density	2.44 g/cm^3
Tensile strength	1700 MPa
Tensile elongation	<5%
Modulus of elasticity	73 GPa

2.2. Methods

2.2.1. Bitumen Bond Strength Test

A bitumen bond strength (BBS) test was conducted to evaluate the cohesive properties of the bitumen and the adhesive properties between the bitumen and aggregate in an asphalt mixture. The BBS test was derived from the pneumatic adhesion tensile strength testing instrument, commonly known as PATTI, which was originally utilized by the coating industry [35]. Based on the Superpave binder specification, the BBS test is the only material testing capable of quantifying the adhesive strength between asphalt and aggregates. Moreover, the BBS test's simplicity and repeatability prove its convenience and effectiveness for asphalt mixture testing [36].

According to AASHTO T 361 "Standard Method of Test for Determining Asphalt Binder Bond Strength by Means of the Binder Bond Strength (BBS) Test" [37], the test specimen setup is composed of a piston, a reaction plate, and a pull-off stub that is fixed to a rigid solid aggregate plate, called the substrate, with the asphalt binder that is to be tested. The geometrical measurements of the pull-off stub are shown in Figure 2. It is important to make sure that the asphalt binder specimen is not disturbed when placing the other parts of the test setup to prevent applying premature strains. The assembled test setup is shown in Figure 3.

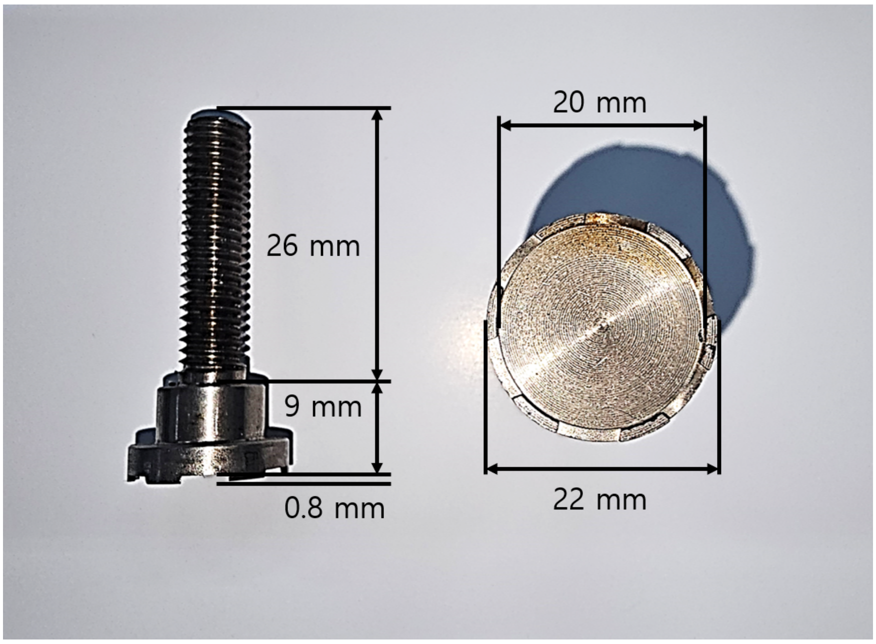


Figure 2. Pull-off stub geometry in mm.

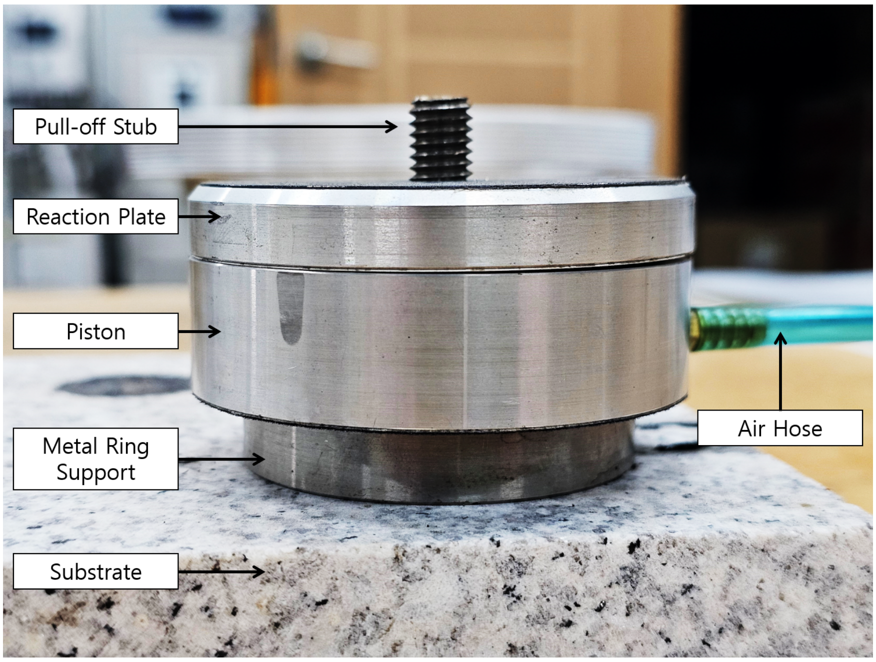


Figure 3. BBS test setup.

To compare the adhesive and cohesive properties of the typical DBST and modified DBST, the BBS test was conducted on both surface treatment specimens. The effect of curing time on the strength of the asphalt emulsion was also considered by making specimens with two varying curing times: 3 h and 24 h. Three repetitions of BBS tests were conducted for each combination of material and curing time; thus, a total of twelve specimens were fabricated.

The BBS test's final output is the air pressure applied at the failure of the asphalt binder specimen. After recording the air pressure at failure, the pull-off tensile strength (*POTS*) or the bond strength of the specimen is computed using the equation:

$$POTS = \frac{(BP \times A_G) - C}{A_{PS}} \tag{1}$$

where:

$POTS$ is the pull-off strength in kPa;
BP is the burst pressure in kPa;
A_G is the contact area of the gasket with the reaction plate in mm^2;
A_{PS} is the area of the pullout stub in mm^2;
C is the piston constant.

After the test, the failure mode can then be classified by inspecting the remaining amount of asphalt binder on the substrate. If more than 50% of the substrate surface is still covered by the asphalt binder, the failure mode is classified as cohesive or failure within the asphalt binder; otherwise, the failure mode is adhesive or failure at the interface of the aggregate and the asphalt binder.

2.2.2. Sweep Test

The sweep test was developed to effectively evaluate the adhesive performance of pavement surface treatment using asphalt emulsion as binder immediately after construction. It can also be used to assess the effect of curing duration on the adhesive property of the asphalt emulsion [38]. Due to its convenience and ease of experimental execution, it has been recommended as an appropriate testing method for the investigation of aggregate loss in an NCHRP report entitled, *Manual for Emulsion-Based Chip Seals for Pavement Preservation* [39]. In accordance with the ASTM D7000—19a "Standard test method for sweep test of emulsified asphalt surface treatment samples" [40], a brush attached to a mixer is used to apply shear stress on the surface treatment on the asphalt specimen disk to assess the film formation stage of the emulsified asphalt and its adhesive property with the aggregates, as shown in Figure 4.

Figure 4. Sweep test setup.

The procedure for the sweep test was as follows:

1. The asphalt specimen disk was prepared, and the weight before the application of the surface treatment was measured.
2. The surface treatment was applied on the disk and cured for 25 °C in an oven. In this experiment, two different curing times, 3 h and 24 h, of the asphalt emulsion were tested to see the effect of the curing time on the film formation and adhesive properties of the surface treatment.
3. The specimen was preconditioned at 35 °C in 30% relative humidity an hour before the start of the test.
4. The initial weight of the disk and the surface treatment was determined.
5. The sweep test was conducted at 0.83 gyrations per second for 60 s.
6. After the test, the specimen was weighed for the final reading.

Similar to the BBS test, the sweep test was conducted on both the typical and polymer-conducted DBST under two different curing durations, 3 h and 24 h. Three repetitions of the test were also performed for each combination of material and curing time.

To compute the aggregate loss, the percentage of the difference between the recorded initial weight and final weight was calculated, which can be represented in the equation as follows:

$$AL_S = \frac{W_{initial} - W_{final}}{W_{initial} - W_{AC}} \times 100 \tag{2}$$

where:

AL_S is the percentage of aggregate loss based on the initial weight of the specimen;
$W_{initial}$ is the initial weight of the specimen before loading;
W_{final} is the weight of the specimen after loading;
W_{AC} is the weight of the asphalt specimen disk.

2.2.3. Hamburg Wheel-Track Test

The Hamburg wheel-track (HWT) test simulates a vehicle load applied on the pavement to assess its performance in a controlled laboratory setup. The HWT device was developed by Helmut-Wind, Inc., a company situated in Hamburg, Germany, hence the name of the equipment [41]. Originally manufactured to predict the rutting performance of hot mix asphalt under wheel load, various additional properties of pavement materials were found to be applicable for evaluation using the HWT device, such as moisture susceptibility, aggregate stripping, bleeding, and overall stability [42].

As shown in Figure 5, the HWT device is composed of three main components: the wheel loading mechanism, the specimen in the mounting system, and the temperature control system. For a typical wheel loading mechanism of HWT, a steel wheel, placed at the center of the specimen, is used with a diameter of 203 mm and a width of 47 mm [43]. To mimic the breaking motion of the tire on the pavement in this experiment, the steel wheel was replaced with a rubber tire having a diameter of 200 mm and a width of 50 mm. Unlike the steel wheel, the rubber tires have grooves that promote the aggregate loss on the surface course of the pavement, which is the same as in the actual field condition. Because structural performance is not the main concern of the test, 10 loading cycles at 175 N of applied load were found to be sufficient in investigating the aggregate loss. With the replacement of the steel wheel for a rubber tire, the braking motion at typical loading cycles of the HWT test would result in the removal of almost all of the aggregates on the wheel path, leading to the same aggregate loss for both typical and modified DBST. Moreover, the testing temperature was set to 25 °C to simulate the ambient temperature under actual field conditions.

The testing specimen mounting has two different types based on the shape of the specimen: slab or cylindrical. In this study, laboratory-mixed cylindrical-shape specimens were used. Two cylindrical specimens of 13 mm HMA with 150 mm diameter, 62 mm thickness, and 7% air void were fabricated using the Superpave gyratory compactor, in accordance with AASHTO T324-22 [43]. These served as the asphalt surface course of the specimen. To fit to the mounting system, the cylindrical specimens were cut along equal secant lines that created a gap width of no greater than 7.5 mm between the two cylindrical molds. Because cutting the cylindrical specimen involves using water, the specimens were air-dried for 48 h at room temperature to remove unnecessary moisture. Afterwards, the DBST and modified DBST layers were applied on the asphalt surface course and cured in the oven at 25 °C for 24 h. Three repetitions of HWT tests were conducted on both the typical and modified DBST, resulting in six specimens produced.

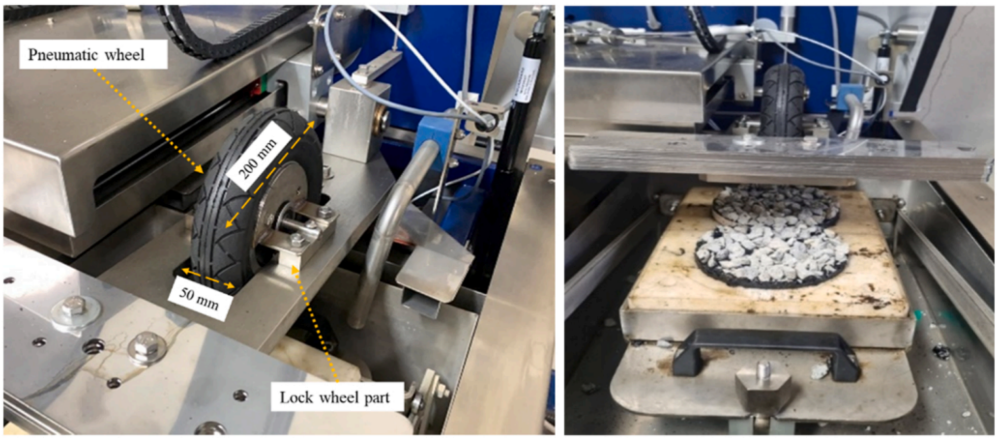


Figure 5. HWT test setup.

The conducted procedure for the HWT test experiment is as follows:

1. Cylindrical specimens were fabricated and securely placed in the mounting system. The weight of the asphalt surface course was determined before applying the surface treatment layer. After the application of the DBST on the asphalt surface course, the specimens were set aside to promote the curing process for 24 h at 25 °C.
2. After curing, the specimens were weighed for an initial reading.
3. The mounting system with the specimens was tightly fastened into the device with the height of the specimen being adjusted accordingly.
4. The temperature of the water bath was set to 25 °C. Before starting the actual test, a delay time of 45 min was set to ensure that the test specimens' temperature was uniform.
5. After the delay time, the HWT test started with a loading cycle and applied load set to 10 cycles and 175 N, respectively.
6. After the 10 loading cycles, the final weight of the specimens was determined.

The computation of the aggregate loss for the HWT test (AL_{HWT}) is the same as Equation (2), where $W_{initial}$ is the initial weight of the specimen before loading, W_{final} is the weight of the specimen after 10 loading cycles, and W_{AC} is the weight of the asphalt surface course.

2.2.4. MMLS3

The one-third-scale model mobile load simulator (MMLS3), a smaller-scale version of an accelerated pavement testing (APT) device, is typically used to assess the pavement's moisture susceptibility, rutting, and fatigue performance in various traffic loading and controlled environmental conditions. The testing device's portability makes it suitable for both laboratory and field test setups [44].

As shown in Figure 6, the loading mechanism of the MMLS3 is unidirectional, which mimics the rolling or passing motion of a vehicle. The specifications of the MMLS3 testing device are summarized in Table 5.

Figure 6. MMLS3 testing device.

Table 5. MMLS3 testing device properties [45].

Properties	Values
Loading application	Four pneumatic wheels in closed loop
Loading wheel diameter	300 mm
Loading wheel width	70 mm
Loading wheel spacing	1.26 m
Loading wheel inflation pressure	400–800 kPa
Axle wheel load	1.8–2.9 kN
Sinusoidal loading frequency	2 Hz
Resting time between loading	0.5 s
Loading wheel speed	1–9 km/h
Lateral wandering displacement	80–150 mm

A similar test using MMLS3 for assessing the aggregate loss on surface treatment was performed by Lee, J. and Kim, R. [46]. The test procedure was considered as a template for this experiment with the omission of some steps not concerning aggregate loss. The testing procedure conducted for this experiment was as follows:

1. Slab test specimens were fabricated for both typical and modified DBST. The weight of the asphalt surface course was determined before applying the surface treatment layer. After the application of the DBST on the asphalt surface course, the specimens were set aside to promote the curing process for 24 h at 25 °C.
2. Before testing, the initial weight of the specimen was measured.
3. The specimen was installed in the MMLS3 by placing it on the steel base plates and securely fastening it.
4. After installing the specimens, the whole MMLS3 setup was covered with the environment chamber using a crane. In this study, as the test is not concerned about the moisture resistance of the pavement material, the water bath was not utilized, and the temperature of the environment chamber was set to a typical ambient temperature of 25 °C. The specimen was kept inside the chamber for 3 h of conditioning.
5. After stabilizing the temperature of the specimen, the wheel load was applied to the specimen, and the test was started. Five loading cycles (1000, 2000, 5000, 8000, and 13,000) were assigned to be the checkpoints to weigh the specimen for the monitoring of aggregate loss.

One slab each was fabricated for the typical and modified DBST. To compute the aggregate loss, the percentage of the difference between the recorded initial weights and checkpoint weights was calculated, which can be represented in the equation as follows:

$$AL_{MMLS3} = \frac{W_{initial} - W_{checkpoint}}{W_{initial} - W_{AC}} \times 100 \tag{3}$$

where:

AL_{MMLS3} is the percentage of aggregate loss based on the initial weight of the specimen;
$W_{initial}$ is the initial weight of the specimen before loading;
$W_{checkpoint}$ is the weight of the specimen after a number of loading cycles;

W_{AC} is the weight of the asphalt surface course.

3. Results and Discussions

3.1. Bitumen Bond Strength Test

Figure 7 summarizes the results of the BBS test. For ease of comparison, the ratios of POTS with respect to the highest value of POTS among the four specimens were computed.

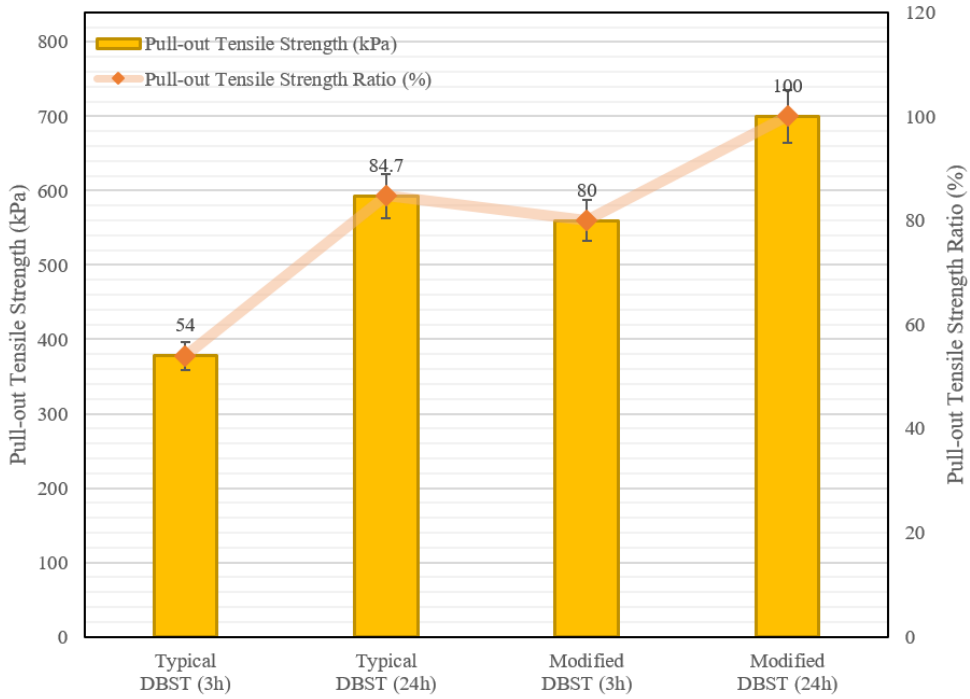


Figure 7. BBS test result comparison for typical and modified DBST after 3 h and 24 h of curing time.

As shown in the figure, the test specimen with the highest POTS is the modified DBST with 24 h of curing time, making this test specimen's POTS the basis of the computation for the POTS ratio. Based on the BBS test, it was found that the POTS of the modified DBST is significantly greater than the typical DBST for both 3 h and 24 h of curing time, with differences of 26% and 15.3%, respectively, in terms of the POTS ratio. This implies that the polymer effectively enhances the adherence of the asphalt emulsion to the aggregate and the coherence within the asphalt emulsion against the application of tensile stress.

Moreover, the POTS after 24 h of curing was found to be higher compared with the POTS after only 3 h of curing for both typical and modified DBST, with an increase in the POTS ratio of 30.7% and 20%, respectively. Based on the results of the BBS test, it can be concluded that longer curing time improves the adhesive and cohesive properties of DBST, regardless of the presence of polymer additive in the binder. Thus, when considering both the material and curing time, modified DBST with 24 h of curing time has the highest resistance to aggregate loss under the vertical tensile action.

After the BBS test, the remaining amount of asphalt binder on the substrate was inspected, and it was found that all of the test specimens still covered the whole area where it was initially applied before the test, as shown in Figure 8. Hence, the failure mode for all test specimens is cohesive, regardless of the presence of polymer additive and the curing time. Therefore, the adhesion of the asphalt emulsions to the aggregate is significantly stronger than the cohesion within the asphalt emulsion. This implies that the aggregate loss could likely be caused by the failure in the asphalt emulsion itself rather than the aggregate chipping out of the asphalt emulsion.

Figure 8. Failure modes of the specimens after the BBS test.

3.2. Sweep Test

Figure 9 shows the comparison of the specimens after being subjected to a sweeping action, while Figure 10 summarizes the results of the sweep test.


(**a**) (**b**)


(**c**) (**d**)

Figure 9. Test specimens after the sweep test. (**a**) Typical DBST (3 h). (**b**) Typical DBST (24 h). (**c**) Modified DBST (3 h). (**d**) Modified DBST (24 h).

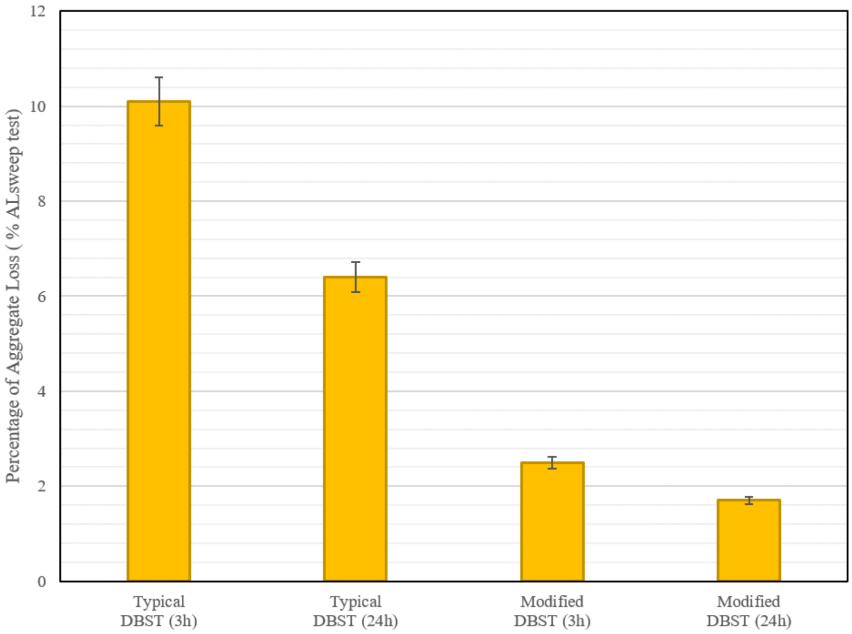


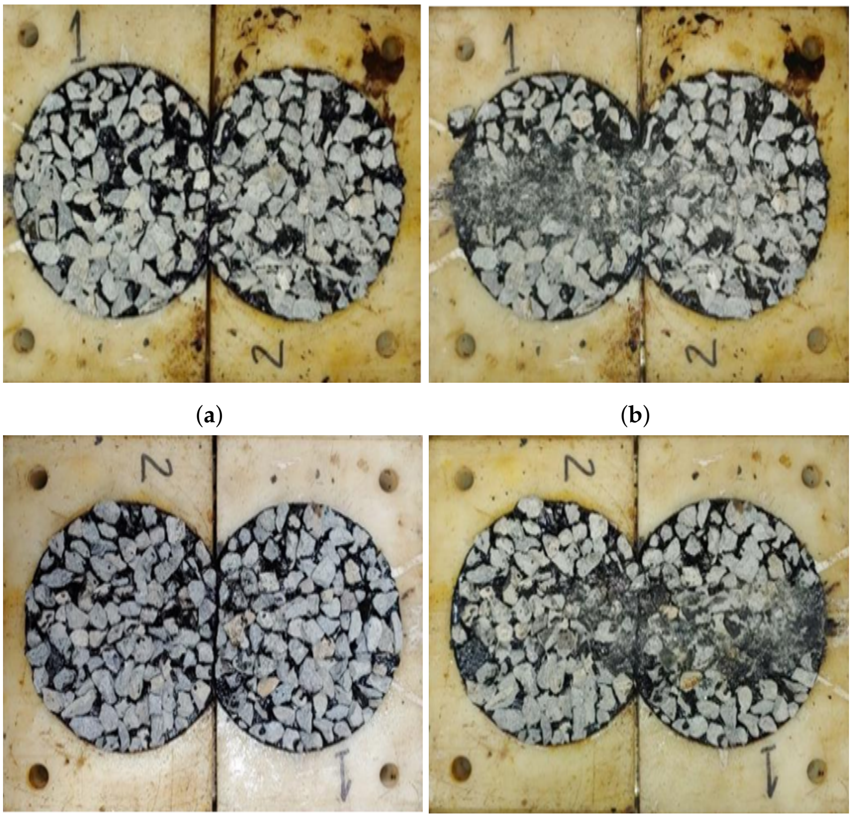
Figure 10. Sweep test result comparison for typical and modified DBST after 3 h and 24 h of curing time.

Comparing the AL_S of typical and modified DBST, typical DBST for both 3 h and 24 h of curing time has a higher percentage of aggregate loss than the modified DBST, with a difference of 7.6% and 4.7% for the 3 h and 24 h curing time cases, respectively. For both the 3 h and 24 h curing time cases, the aggregate loss from typical DBST is reduced by around 75% with the addition of polymer additive to the asphalt emulsion. This implies that modified DBST is better than typical DBST in terms of the resistance to aggregate loss under sweeping action. The adhesion between the aggregate and the asphalt emulsion was strengthened by the polymer additive, thus resulting in less aggregate loss. Moreover, the result of the sweep test agrees with the results of the BBS test when comparing the two materials.

In terms of the curing time, it is evident based on the results that curing the asphalt emulsion for 24 h improves the adhesion between the aggregate and asphalt emulsion when compared with the curing time for only 3 h. The difference in aggregate loss from 3 h to 24 h of curing time are 3.7% and 0.8% for typical and modified DBST, respectively, which calculates to an increase in aggregate loss resistance of 65% after longer curing time. In line with the BBS test, a longer curing time of the asphalt emulsion enhances the adhesion between the aggregate and asphalt emulsion. Therefore, as an application to actual practice, a longer time period, or at least 24 h, should be allotted before opening the constructed DBST to traffic after laying over the surface treatment to achieve its full resistance to aggregate loss.

3.3. Hamburg Wheel Track Test

The comparison of the specimens before and after the loading cycles in the HWT test are shown in Figure 11. The results of the HWT test is presented in Figure 12.



(**a**) (**b**) (**c**) (**d**)

Figure 11. Visual comparison of specimens before and after 10 cycles of HWT loading. (**a**) Typical DBST before loading. (**b**) Typical DBST after loading. (**c**) Modified DBST before loading. (**d**) Polymer-modified DBST after loading.

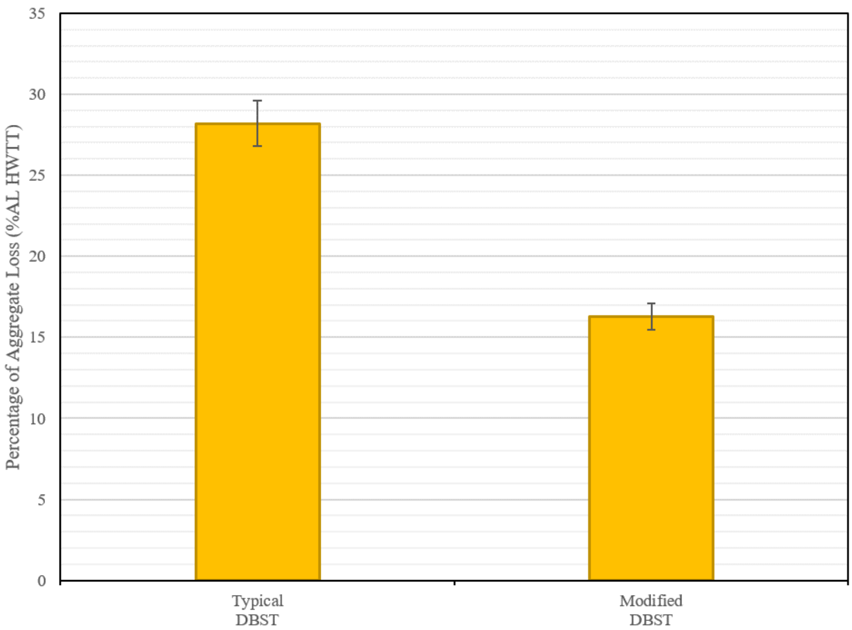


Figure 12. HWT test results for typical and modified DBST.

Based on the results, modified DBST has superior resistance to aggregate loss induced by braking action compared with the typical DBST with a percentage AL_{HWT} difference of 11.9%. Hence, the increase in the adhesive property that the polymer additive provides to the modified DBST has been effective in increasing the surface treatment's resistance to aggregate loss. Moreover, it can be noticed that the resulting percentage of aggregate loss in the HWT test is significantly higher than that of the other tests. The combination of the vertical wheel load of 175 N and the braking motion of the wheel induce a tremendous amount of shear stress on the surface of the pavement, thus incurring more aggregate loss.

Overall, the results of the HWT test support the conclusion of both previous tests showing that modified DBST has greater resistance to aggregate loss than typical DBST.

3.4. MMLS3

After obtaining the weight of the specimen for each loading cycle checkpoint in the MMLS3 test, the cumulative aggregate loss weight and percentage were computed, and the results are summarized in Figure 13. The appearances of the specimens after 13,000 loading cycles are shown in Figure 14.

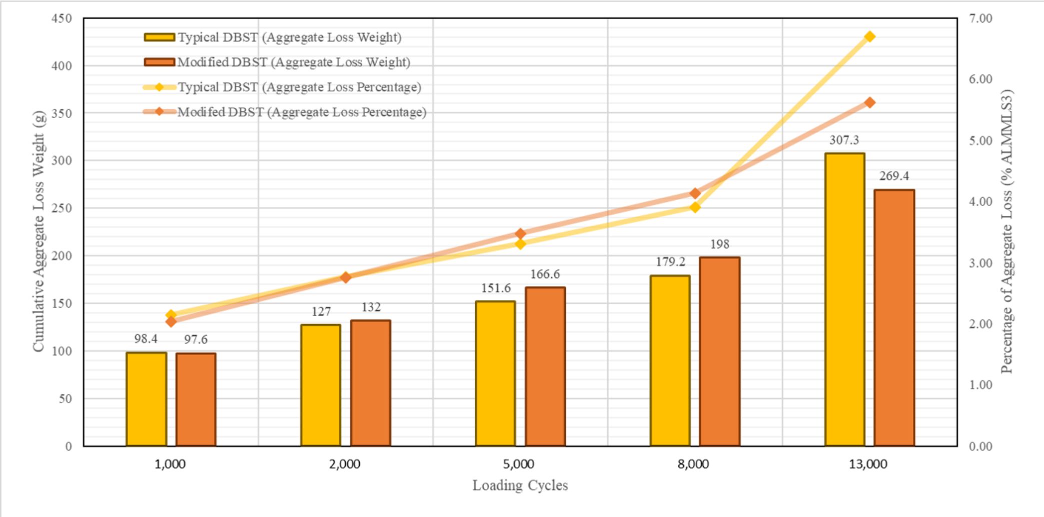


Figure 13. MMLS3 test results for typical and modified DBST.

(**a**) (**b**)

Figure 14. Specimens after MMLS3 loading. (**a**) Typical DBST. (**b**) Modified DBST.

As shown in the figure, the difference in the aggregate loss for typical and modified DBST is not significantly far from each other, with the modified DBST having a higher aggregate loss than the typical DBST with a maximum difference of 18.8 g (0.22%). However, in the final checkpoint of the MMLS3 test, the aggregate loss of typical DBST significantly surpasses that of the modified DBST with a difference of 37.9 g (1.08%). The AL_{MMLS3} of the typical DBST increases from 3.91% at 8000 loading cycles to 6.70% at 13,000 loading cycles, with a rate of AL_{MMLS3} change of 0.6% per 1000 loading cycles. Meanwhile, the AL_{MMLS3} of the modified DBST at 8000 loading cycle is higher than that of the typical DBST with a value of 4.13%. However, the rate of change in the AL_{MMLS3} of the modified DBST after 8000 loading cycle decreases at a rate of 0.3% per 1000 loading, which is half of the rate of change for the typical DBST, resulting in an AL_{MMLS3} lower than that of the typical DBST with a value of 5.62%. Therefore, considering the maximum number of loading cycles in the experiment, modified DBST performs better than typical DBST in terms of long-term aggregate loss resistance against rolling.

4. Summary and Conclusions

This study aimed to investigate the effect of the simultaneous application of glass fiber reinforcement and polymer modification in the asphalt emulsion of DBST in terms of aggregate loss by conducting four laboratory test methods that represent different actual tire–pavement interactions: the BBS test for vertical tensile action, the sweep test for sweeping action, the HWT test for braking action, and the MMLS3 model for rolling action. As a comparison, typical DBST was also tested to serve as the benchmark of the modified DBST and to quantify the improvement of the performance. Based on the results, the following conclusions were found regarding the performance of modified DBST:

- BBS test results showed that modified DBST had a greater resistance to vertical tensile action-induced aggregate loss than typical DBST. Moreover, based on the remaining amount of asphalt binder on the substrate after the failure of the asphalt emulsion due to vertical tensile action, the failure mode of all specimens was cohesive. This means that the adhesive bond between the aggregate and asphalt emulsion was stronger than the internal cohesion of the asphalt emulsion itself.
- Based on the sweep test results, modified DBST performed better than the typical DBST in terms of aggregate loss against sweeping action.
- Comparing the BBS test and sweep test results between 3 h and 24 h of curing time, it can be observed that a longer curing time of the asphalt emulsion led to greater resistance of the surface treatment to aggregate loss, regardless of the presence of an additive. As an application to actual pavement construction, a longer time should be allotted before opening newly constructed surface treatment for the asphalt emulsion to fully cure and reach its highest performance.
- The HWT test results presented superior resistance to aggregate loss induced by the braking action of modified DBST against typical DBST. Comparing the values of the aggregate loss percentage of the HWT test to other tests, it was observed that values were higher due to the tremendous shear that braking motion applies to the pavement in addition to the vertical load of the wheel.
- In the MMLS3 test, modified DBST and typical DBST were observed to have almost the same performance against aggregate loss at loading cycles of less than 8000, with modified DBST having higher aggregate loss. However, after 8000 loading cycles, typical DBST's aggregate loss abruptly increased, while modified DBST resulted in a lower aggregate loss at 13,000 loading cycles. Thus, modified DBST was found to be more resistant to long-term aggregate loss than typical DBST when the rolling load was applied after finishing 13,000 loading cycles.
- Based on the results of the tests, glass fiber-reinforced polymer-modified DBST shows a promising potential for actual application due to its positive results compared with typical DBST.
- Further tests can be conducted to support the results with more repetitions of the test procedure. Moreover, including other factors for future experiments, such as varying environmental conditions, the presence of moisture, and different levels of aging, would produce a more thorough investigation of the study.

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Abbreviations

The following abbreviations are used in this manuscript:

PMS	Pavement management system
BST	Bituminous surface treatment
DBST	Double bituminous surface rreatment
SBR	Styrene–Butadiene rubber
CRS	Cationic rapid-setting
SBS	Styrene-butadiene styrene
BBS	Bitumen Bond Strength
PATTI	Pneumatic adhesion tensile strength testing instrument
AASHTO	American Association of State Highway and Transportation Officials
POTS	Pull-off tensile strength
ASTM	American Society for Testing and Materials
HWT	Hamburg wheel-track

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