

Research Article

Performance of Waterborne Epoxy Emulsion Sand Fog Seal as a Preventive Pavement Maintenance Method: From Laboratory to Field

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To preserve the existing asphalt pavement and extend its service life, various preventive maintenance methods, such as chip seal, slurry seal, fog seal, and microsurfacing, have been commonly applied. Sand fog seal is one of such maintenance methods, which is based on the application of bitumen emulsion and sand. Thus, its performance is largely dependent on the properties of the bitumen emulsion and sand. This study aims to develop an improved sand fog seal method by using waterborne epoxy resin as an emulsion modifier. To this end, both laboratory tests and field trials were conducted. In the laboratory, the wet track abrasion and British pendulum test were performed to determine the optimum sand size for the sand fog seal, and the rubbing test was carried out to evaluate the wearing resistance of the sealing material. In the field, pavement surface regularity before and after the sand fog seal application was measured using the 3 m straightedge method, and the surface macrotexture and skid resistance were evaluated with the sand patch method and British pendulum test, respectively. The laboratory test results indicated that the optimum sand size range is 0.45–0.9 mm, and the sand fog seal with waterborne epoxy resin showed good wearing resistance and skid resistance. The field test results verified that both the pavement texture and skid resistance were substantially improved after sand fog sealing.

1. Introduction

Asphalt pavement suffers from a series of distresses, such as rutting and cracking, because of vehicle loading and environmental effects. These distresses, if not treated in the early stage, can negatively affect the driving safety and pavement service life. To preserve pavement from further deterioration, preventive maintenance is commonly applied. Techniques like chip seal, slurry seal, fog seal, and microsurfacing have been proven to be effective for such purpose. Among these techniques, fog seal is a convenient and economical method, which has gained widespread applications [1, 2]. Many studies have shown that the application of fog seal with bitumen emulsion can help seal the small cracks, improve aggregate retention, and decrease the permeability of water and air [3–5]. Nevertheless, fog seal also faces some concerns, such as long curing time before traffic opening and

reduction of the skid resistance [3, 6, 7]. Correspondingly, sand fog seal, which applies both bitumen emulsion and sand, has been developed to address these concerns [8, 9]. The incorporation of sand into fog seal can increase the mechanical strength as well as the skid resistance of the pavement surface.

Cationic bitumen emulsion is commonly applied in fog seal to allow sufficient penetration of the emulsion into cracks and surface voids [10]. To further improve the inherent properties of bitumen emulsion, polymers or latexes have been added into the emulsion [10]. For mixing convenience with bitumen emulsion, latexes such as styrene-butadiene rubber (SBR) and natural rubber (NR) are commonly used [11–13]. These latexes can disperse easily in the water continuous phase of bitumen emulsion, and with the evaporation of water, the interconnected polymer networks can be formed within bitumen. In recent years, waterborne epoxy resin has

gained increasing interest due to its various advantages, such as convenience of application and improvement of strength and adhesion [14, 15]. As waterborne epoxy resin is soluble in water, it can be easily blended with bitumen emulsion. The epoxy starts to cure as it is in contact with hardener, and then the three-dimensional chemically interconnected epoxy polymer networks can be formed inside bitumen as water in emulsion evaporates. Such a polymer structure will lead to significant improvement of the bitumen mechanical properties. It has been reported that the incorporation of waterborne epoxy resin into bitumen emulsion substantially increased its high-temperature performance, adhesion with aggregate, and fatigue properties [14].

The objective of this research is to investigate the performance of the sand fog seal using waterborne epoxy modified bitumen emulsion as a preventive maintenance method for asphalt pavement. To achieve this object, both laboratory tests and field trials were conducted. In the laboratory, the wet track abrasion and British pendulum test were performed to determine the optimum sand size for the sand fog seal, and the rubbing test was carried out to evaluate the wearing resistance of the sealing material. In the field, pavement surface regularity before and after the sand fog seal application was measured using the 3 m straightedge method, and the surface macrotexture and skid resistance were evaluated with the sand patch method and British pendulum test, respectively.

2. Materials and Methods

2.1. Materials. Cationic bitumen emulsion was used in this research. Table 1 presents the main properties of the bitumen emulsion. The waterborne epoxy resin had two parts: Part A and Part B. Part A is the waterborne epoxy, and Part B is the amino curing agent. The weight ratio of Part A and Part B was 5:2 as recommended by the supplier. Table 2 presents the major properties of the waterborne epoxy resin. The black corundum sand, a very strong aggregate mainly composed of Al_2O_3 , was used as the “sand” for sand fog seal. Table 3 shows the main components and properties of the black corundum. According to the previous research [16], to achieve the optimum properties of the waterborne epoxy bitumen (WEB) emulsion, the solid residual weight of the waterborne epoxy resin system was 50% by weight.

2.2. Wet Track Abrasion Test. Wet track abrasion tests were conducted in this study to determine the optimum size of black corundum sand for the surface treatment according to ISSA TB 100. Five black corundum sand size ranges were considered, including 2.0–4.0 mm, 0.9–2.0 mm, 0.45–0.9 mm, 0.2–0.45 mm, and 0.15–0.2 mm, which are denoted as AS-1, AS-2, AS-3, AS-4, and AS-5, respectively, in this study. As Figure 1 shows, layer of WEB emulsion was first sprayed on the specimen holding plates, followed by spreading of the black corundum sand. Both the WEB emulsion and black corundum were applied at a rate of 700 g/m^2 . The specimens were then maintained at room temperature for 3 days to allow the evaporation of water and curing of waterborne

epoxy resin. The weight and skid resistance of all the testing samples prior to abrasion were measured using a weight scale and British pendulum tester, respectively. After soaking in water at 25°C for 60 min, the wet track abrasion was performed on the samples for 300 s. In the follow-up step, the samples were heat conditioned at 60°C until the weight became constant. Finally, the weight loss due to abrasion was calculated, and the skid resistance of these samples after abrasion was measured.

2.3. Skid Resistance Test. A British pendulum tester as shown in Figure 2 was used to measure the friction of the testing specimens according to ASTM E303. The specimens were fixed on the test table, which were then wetted thoroughly by water. Four swings were performed on each specimen, and the British pendulum number (BPN) was recorded.

2.4. Rubbing Test. To simulate the polishing of the pavement surface under repeated vehicle loading, a conventional rutting test machine was modified (Figure 3). An additional motor was installed to introduce a transverse movement of the tire, which is perpendicular to the original longitudinal movement. Figures 3(a) and 3(b) show the testing device and the moving track of the rubber tire, respectively. The horizontal movement was set to be 10 cm/min, while the longitudinal movement was 42 ± 1 times/min. In addition, a water bath was designed and installed to control the specimen temperature. The dense-graded bituminous mixture slabs with a size of $300 \text{ mm} \times 300 \text{ mm} \times 50 \text{ mm}$ were prepared, followed by spraying of the WEB emulsion and 0.45–0.9 mm black corundum onto the surface, both at a rate of 700 g/m^2 . The specimens were then kept at room temperature for 3 days. Rubbing tests were conducted at three different temperatures: 25°C , 40°C , and 60°C . During the rubbing tests, skid resistance tests were conducted using a British pendulum tester at 2 h intervals till the end of the tests.

2.5. Construction and Testing of the Trial Section. The trial section of the sand fog seal was conducted on a two-way six-lane asphalt pavement in Fo Shan, Guangdong Province, China, and the station number ranged from K17+600 to K18+000. The construction procedure mainly constitutes the following: (1) pretreatment of the old pavement, (2) grinding of the old pavement, (3) sand fog seal spraying, and (4) preservation before traffic opening (Figure 4). The pretreatment of the old pavement focused primarily on the cleaning of pavement surface and cracks sealing. Following light grinding of the pavement surface, the WEB emulsion and black corundum were sprayed with a construction speed of 6–8 km/h. The thickness of the sand fog seal was controlled at approximately 2 mm. Finally, the newly constructed sand fog seal was preserved until the surface dried.

3. Laboratory Test Results

3.1. Wet Track Abrasion. During the wet track abrasion, the surface aggregates are subjected to both lateral shearing stress and vertical stress. Thus, these aggregates become vulnerable and inclined to be stripped off the plate.

TABLE 1: Properties of bitumen emulsion.

Properties	Sieve test (%)	Demulsibility	Solid content (%)	Residue solubility (%)	Residue penetration (25°C, 0.1 mm)
Value	0.05	MS	60.0	98.4	82.0
Requirement	<0.1	—	50–70	—	—
Specification	ASTM D6933	ASTM D6936	ASTM D244	ASTM D2042	ASTM D5

TABLE 2: Properties of waterborne epoxy resin.

Properties	Color	Epoxy value (mol/100 g)	Amine value (mol/100 g)	Viscosity (mPa·s, 20°C)	Solid content (w%, ≥)
Part A	Milk white	0.12	—	543	51
Part B	Light yellow	—	0.073	59	22

TABLE 3: Main components and properties of black corundum sand.

Properties	Main components				Shore hardness	Mohs hardness	Los Angeles abrasion loss (%)
	Corundum (wt.%)	Quartz (wt.%)	Square iron ore (wt.%)	Magnetite (wt.%)			
Value	95.2	2.1	1.6	1.1	87	8.2	7.5
Specification	—	—	—	—	ASTM D2240	ASTM C1895	ASTM C131

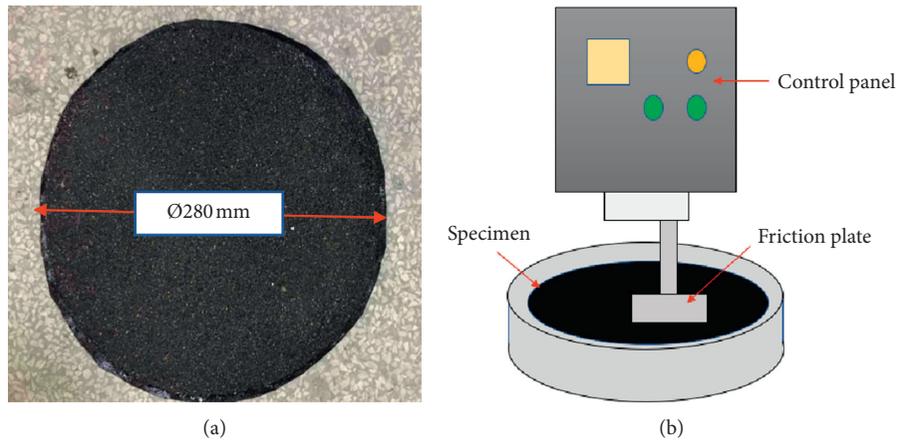


FIGURE 1: Wet track abrasion: (a) test specimen; (b) test equipment.



FIGURE 2: British pendulum tester.

Table 4 presents the abrasion loss of sand fog seal during the wet track abrasion test, as well as the coefficient of variances (COVs) of the test results. It shows that the larger-

sized black corundum sands were more likely to get detached compared with smaller-sized ones. The aggregate loss ratio of AS-5 was 0.7%, which was much lower than that of AS-1, which was 2.2%. This is mainly because larger-sized aggregates have smaller surface area than smaller aggregates. Thus, there is less and lower bonding between bitumen emulsion and larger-sized aggregate, leading to higher abrasion loss under the external force.

Table 5 presents the surface frictions of the sand fog seal with different sand sizes before and after the wet track abrasion in terms of BPN. It is clear that opposite to the abrasion test results, the sand fog seal with smaller-sized aggregate produced weaker skid resistance. The BPN of AS-5 was 66, which was 25% lower than that of AS-1. Comparing the BPN values before and after wet track abrasion, it can be seen that the abrasion process significantly reduced the skid resistance of all specimens, but the reduction rates of larger-sized aggregates (AS-1 and AS-2) were much more

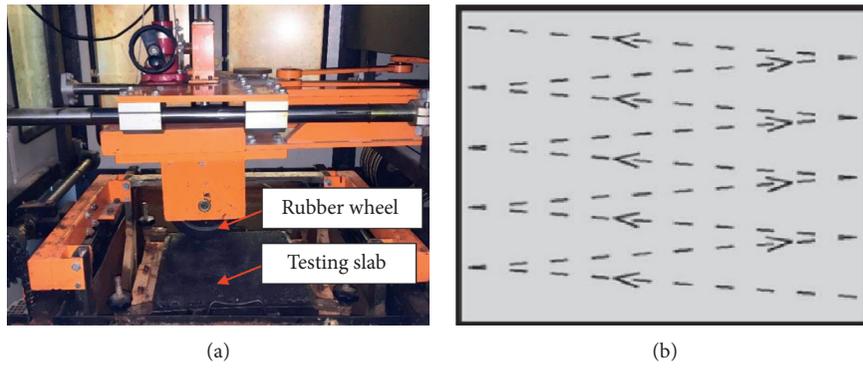


FIGURE 3: Rubbing test: (a) test equipment; (b) wheel moving track.



FIGURE 4: Construction of sand fog seal: (a) pretreatment of the old pavement; (b) surface grinding; (c) sand fog seal spraying; (d) preservation after sealing.

TABLE 4: Abrasion loss of sand fog seal of different aggregate sizes.

Properties	AS-1 (2.0–4.0)	AS-2 (0.9–2.0)	AS-3 (0.45–0.9)	AS-4 (0.2–0.45)	AS-5 (0.15–0.2)
Loss weight (g)	20.9	14.6	9.2	9.0	6.7
Loss ratio (%)	2.2	1.6	1.0	0.9	0.7
COV (%)	8.1	5.8	5.9	2.8	9.3

significant than those of the smaller-sized ones. Among all test groups, AS-3 showed the smallest BPN reduction value, and the best friction after abrasion. Although the smaller size corundum sand (AS-4 and AS-5) had better retention on WEB emulsion during the wet track abrasion test, the

skid resistance was slightly poorer than AS-3. Thus, comprehensively considering the results of the wet track abrasion tests and the skid resistance tests, the black corundum sand with the size of 0.45–0.9 mm was selected for the following tests.

TABLE 5: Skid resistance test results before and after abrasion.

Properties	AS-1 (2.0–4.0)	AS-2 (0.9–2.0)	AS-3 (0.45–0.9)	AS-4 (0.2–0.45)	AS-5 (0.15–0.2)
BPN before abrasion	88	84	78	77	66
COV (%)	0.57	2.38	1.92	1.30	2.27
BPN after abrasion	49	49	64	58	54
COV (%)	4.08	3.06	0.78	4.31	1.85
BPN reduction rate (%)	44.3	41.7	17.9	24.7	18.2

3.2. Wearing Resistance Analysis. Under the repeated vehicle tire loading, the surface of asphalt pavement becomes polished and its skid resistance declines over time, which leads to driving safety concern, especially under wet conditions. Therefore, at certain stage, it is necessary to treat the pavement surface with appropriate methods for protecting the surface texture and ensuring good friction properties. Figure 5 illustrates the change of BPN values during the polishing process in the rubbing tests at different temperatures up to 8 hours. Rapid friction drop can be observed within the first 2 hours, and then the declination rate became slow. It is worth noting that unlike conventional sand fog seal with raw bitumen emulsion, temperature did not significantly affect the polishing resistance of the WEB sand fog seal. The possible reason is that WEB is a thermal-setting material which has good thermal stability. Thus, good retention of the aggregates was achieved even at a high pavement service temperature of 60°C. This ensures that WEB sand fog seal will have good wearing resistance under different weather conditions. The underlying mechanism is that the bitumen emulsion with waterborne epoxy resin had strong adhesion to the existing pavement layer. Furthermore, the sand was also bonded together effectively by WEB. From our previous study [16], it was found that the continuous connected epoxy microstructure can be formed by the addition of 50 wt.% waterborne into bitumen emulsion. Such structure would provide the residual bitumen significant improvement on the mechanical performance as well as the adhesion with aggregates. Therefore, the WEB sand fog seal surface layer will not become loose easily. Thus, the WEB sand fog seal-treated pavement surface had good skid resistance and durability.

4. Trial Site Testing Results

4.1. Pavement Conditions Index. The existing pavement surface of the test trial site had been in service for more than 6 years, and cracking was the major type of distress as shown in Figure 6. In addition, some minor stripping was also observed. If not treated timely, the pavement surface was expected to deteriorate rapidly.

Table 6 presents the results of the pavement condition index (PCI) surveys of the existing pavement conducted according to ASTM D6433: Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys. In this table, “R” and “L” denote the right lane and left lane, respectively, and the follow-up number (1 or 2) indicates the lane number. It can be seen that all PCI values are larger than 70, indicating the pavement condition was “satisfactory” ($85 > \text{PCI} \geq 70$) or “good” ($\text{PCI} \geq 85$).

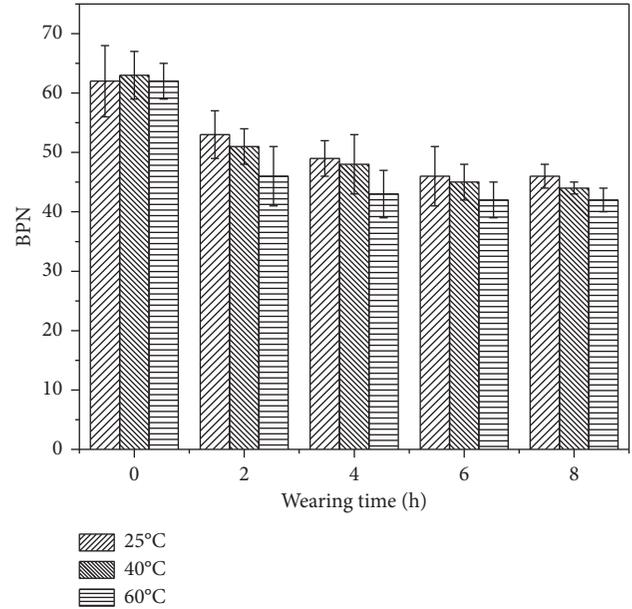


FIGURE 5: Skid resistance of WEB sand fog seal after different wearing periods at different temperatures.

4.2. Pavement Surface Regularity. The pavement surface regularity was measured using the 3 m straightedge method (Figure 7). The measurement was carried out every 100 m along the traffic direction (Figure 7(a)). The surface regularities of the pavement before and after the sand fog seal were measured and compared, as shown in Figure 8. It can be seen that the surface regularities were similar before and after treatment, with the deviations less than 3 mm for all the testing sites. The reason might be that the sand fog seal layer was very thin (around 2 mm), which would not cause significant change to the pavement surface regularity, and the existing pavement were in “satisfactory” and “good” conditions, which had relatively smooth surface.

4.3. Pavement Surface Texture Measurement. The pavement surface mean texture depth (MTD) was measured with the sand patch method according to ASTM E965. The locations for the MTD tests matched those of the pavement surface regularity tests as shown in Figure 7(a). The MTD was calculated by using the following equation:

$$\text{MTD} = \frac{4V}{\pi D^2}, \quad (1)$$



FIGURE 6: Pavement surface: (a) before WEB sand fog seal treatment; (b) after WEB sand fog seal treatment.

TABLE 6: Pavement condition index (PCI) of the old pavement.

Station number	Lane	PCI	Rating scale
K17 + 700	R1	77.92	Satisfactory
	R2	81.51	Satisfactory
	R3	89.05	Good
K17 + 800	R1	74.30	Satisfactory
	R2	78.72	Satisfactory
	R3	81.65	Satisfactory
K17 + 900	R1	76.03	Satisfactory
	R2	82.36	Satisfactory
	R3	86.67	Satisfactory
K17 + 000	R1	81.02	Satisfactory
	R2	78.44	Satisfactory
	R3	87.04	Good
K18 + 100	R1	78.13	Satisfactory
	R2	79.80	Satisfactory
	R3	86.84	Good
K17 + 700	L1	84.46	Satisfactory
	L2	87.84	Good
	L3	91.10	Good
K17 + 800	L1	86.14	Good
	L2	78.71	Satisfactory
	L3	88.18	Good
K17 + 900	L1	87.84	Good
	L2	79.13	Satisfactory
	L3	89.27	Good
K17 + 000	L1	79.72	Satisfactory
	L2	84.02	Satisfactory
	L3	88.33	Good
K18 + 100	L1	87.81	Good
	L2	82.02	Satisfactory
	L3	93.65	Good

where V is the volume of the testing material (mm^3) and D is the average diameter of the area covered by the testing material (mm).

Figure 9 presents the MTD values of the pavement surface before and different years after the sand fog seal. It can be seen that the average MTD values for all the sections were in the range of 0.8–0.9 mm prior to the treatment. The MTD values were increased to more than 1.0 mm right after the treatment, corresponding to an increment of 20–30%.

This result indicated that the pavement surface texture was significantly improved by the sand fog seal. The MTD values then started to decrease gradually under vehicle loading. However, all the MTD values were still significantly larger than those of the old pavement surface after 1.5 years of service. As discussed in one of the previous papers [16], the incorporation of waterborne epoxy resin into the sand fog seal significantly increased the adhesion between the seal layer and the original pavement surface. Thus, the pavement

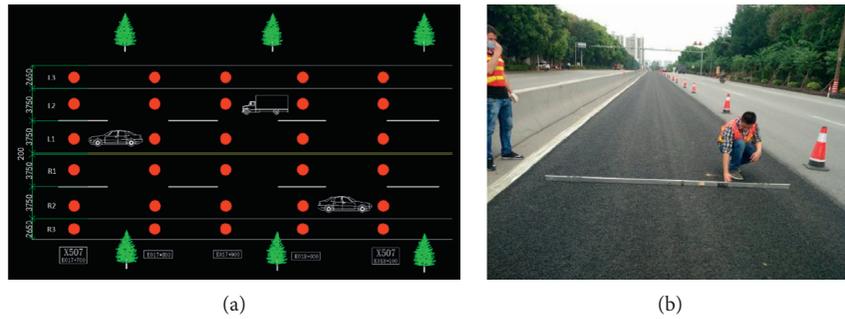


FIGURE 7: Pavement surface regularity test. (a) Selected testing spots. (b) 3 m straightedge.

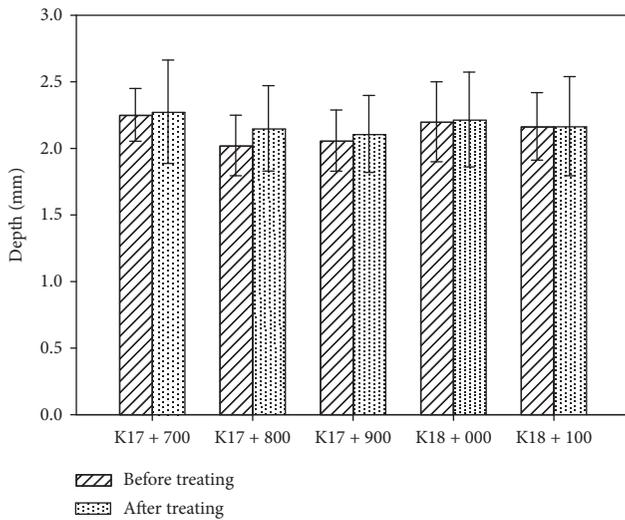


FIGURE 8: Pavement surface regularities before and after sand fog seal.

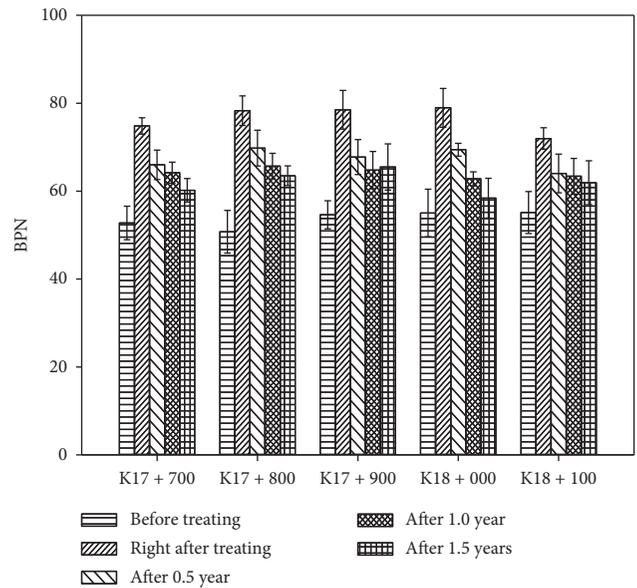


FIGURE 10: BPN values of pavement surface before and after sand fog seal.

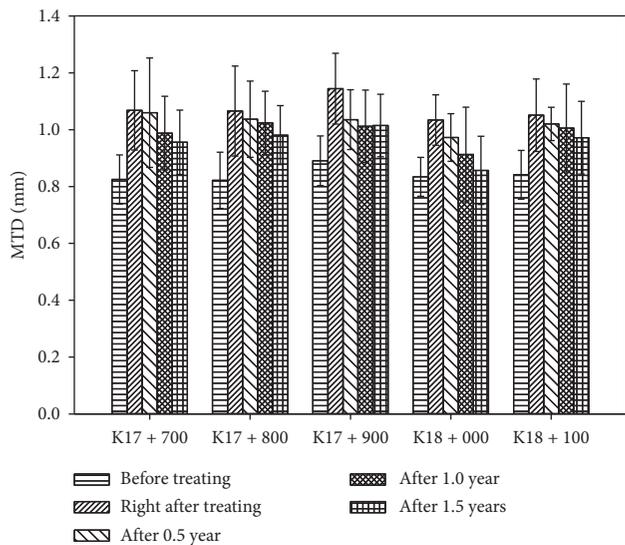


FIGURE 9: MTD values of pavement surface before and after sand fog seal.

surface profile becomes more robust and will not be worn out by tires easily, which helps preserve the texture of the pavement surface.

4.4. Skid Resistance of Pavement. The British pendulum tests were also conducted in the field trial sections. Figure 10 shows the BPN values measured before sand fog seal treatment and after treatment till up to 1.5 years of service. The BPN values were less than 60 for all the locations of the old pavement surface, which were significantly increased to around 80 right after the WEB sand fog seal treatment, verifying the effect of the sand fog seal in enhancing the skid resistance of the pavement surface. The BPN values then decreased with time after traffic opening. Nevertheless, the BPN values after 1.5 years of service were still significantly larger than those of the old pavement surface. This indicated that the WEB sand fog seal can maintain durable skid resistance for at least 1.5 years, which was mainly because the

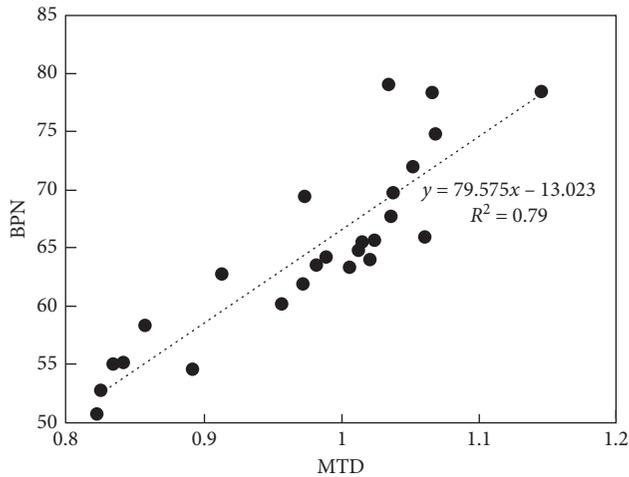


FIGURE 11: Correlation between MTD and BPN.

waterborne epoxy resin increased the adhesion among the aggregates as well as the bonding between the sealing layer and the pavement surface.

4.5. Relationship between MTD and BPN. Figure 11 illustrates the relationship between the field measured MTD and BPN, which can be approximately fitted by a linear equation with a regression coefficient of 0.79. A larger MTD corresponds to a larger BPN, i.e., the skid resistance of the pavement surface is positively influenced by the MTD of the pavement surface.

5. Conclusions

In this study, both laboratory tests and field trials were conducted to investigate the performance of the WEB sand fog seal as a preventive maintenance method. The following points summarize the major findings of this study:

- (i) The black corundum sand with the size of 0.45–0.9 mm provided the optimum WEB sand fog seal performance in terms of balanced skid resistance and abrasion resistance
- (ii) The WEB sand fog seal caused insignificant change to the surface regularity of the existing pavement in “satisfactory” and “good” conditions.
- (iii) The WEB sand fog seal significantly improved the pavement surface texture and skid resistance. The MTD was increased by 20–30%, and the BPN was increased by 50% right after the WEB sand fog seal is applied. After 1.5 years of service, both the surface texture and skid resistance were maintained a level much better than those of the old pavement surface, indicating good durability of the WEB sand fog seal.
- (iv) The MTD and BPN of the WEB sand fog seal surface are positively related, and a linear relation can be developed to describe their relationship.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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