

## Research Article

# Bonding Performance and Evaluation of Basalt Fiber Asphalt Macadam Seal

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To broaden the application of the basalt fiber in the preventive maintenance of asphalt pavement, this study investigated the bonding performance and evaluated the comprehensive performance of the basalt fiber asphalt macadam seal. Firstly, different types of basalt fiber asphalt macadam seal were prepared. The influences of content and length of the basalt fiber and dosage of emulsified asphalt on the bonding performance of the asphalt macadam seal were analyzed and compared. Next, by using the efficacy coefficient method, comprehensive performance considering both mechanical and economic characteristics of the basalt fiber asphalt macadam seal was evaluated. After that, reasonable content of each material was determined. Finally, the strengthening mechanism of the fiber on the bonding performance of macadam seals was revealed from a microscopic view. The results showed that compared with the ordinary asphalt macadam seal, the loss aggregate rate of the basalt fiber asphalt macadam seal was 11.0–30.5% lower, and the pull-out strength, shear strength, and torsional shear strength were 11.7–16.3%, 9.7–22.4%, and 4.2–20.6% higher, respectively. Considering the bonding performance and economic benefits, the optimal amount of emulsified asphalt and basalt fiber was 1.6 kg/m<sup>2</sup> and 70 g/m<sup>2</sup>, respectively. Basalt fiber increased the cohesion of the asphalt material and improved the bonding performance of asphalt macadam seals through formation of the three-dimensional network structure. This study can provide reference to the application of basalt fibers in asphalt pavement maintenance.

## 1. Introduction

An asphalt macadam seal is a thin layer formed by spreading well-graded aggregate on the asphalt binder [1]. As a new type of preventive maintenance technology for pavement, asphalt gravel seals are widely used because of their short construction period and low construction cost [2]. However, there are also a series of problems, such as insufficient adhesion between aggregate and asphalt and cracking of the macadam seal at low temperature [3]. Some researchers have tried to use high-viscosity asphalt to improve the bonding property of asphalt binders, but the effect is not ideal. However, adding fibers into asphalt materials to form “matrix + fiber” composite can make full use of the advantages of the two materials [4]. Fibers play the roles of adsorption, stability, reinforcement, crack resistance, and

toughening and effectively improve the bonding performance of asphalt materials [5].

Among many fiber materials, basalt fiber is often used as a reinforcement material for construction materials such as cement and concrete due to its excellent mechanical properties. Basalt fiber is a kind of high-performance fiber. It is made of basalt as a raw material, fused at high temperature, and then drawn with the platinum-rhodium alloy wire pull-out plate at high speed [6]. Basalt fiber and modified basalt fiber can significantly improve the tensile and bending properties of concrete, but the change of compressive properties was not obvious [7, 8]. By incorporating the basalt fiber into cementitious composites, the effect of the basalt fiber on the mechanical strength and microstructure of the composites was investigated. Results show that the addition of fibers can improve flexural strength and toughness of

cementitious composites, but when the fibers exceed the proper amount, the composites will agglomerate [9, 10]. Through adding the basalt fiber into concrete beams with recycled coarse aggregate, the experiment on bending behavior of concrete beams was carried out. The results indicate that not only the flexural strength of concrete with the basalt fiber is significantly improved but also fatigue cracking of concrete beams is reduced due to increased toughness [11]. To sum up, basalt fiber as a reinforcement material can improve the tensile strength, bending strength, and fatigue strength of brittle building materials such as cement and concrete, as well as improve toughness and ductility and hinder the development of cracks.

At present, basalt fibers are also widely used in asphalt and asphalt mixtures. The low-temperature performances of fiber-reinforced binding materials were studied by dispersing the basalt fiber into the asphalt binder and mastic. The results show that a proper amount of basalt fiber can restrain the axial strain of the asphalt binder and mastic and increase their rigidity modulus and fracture stress. In addition, the fibers reduce the concentrated stress among fillers and enhance the fatigue life of the asphalt binder and mastic [12]. The adhesion between fiber and asphalt was studied by blending the fiber treated with silane coupling agent KH550 into asphalt. It is concluded that KH550 solution can significantly improve the adhesion of the surface-modified basalt fiber to asphalt and improve the road performance [13]. The aging test of the fiber-asphalt mixture shows that the basalt fiber can delay the aging of the asphalt mixture and improve the low-temperature crack resistance and water stability of asphalt concrete [14]. By comparing the effects of basalt fiber, lignin fiber, and polyurethane fiber on the shear resistance, crack resistance, and high-temperature rheological properties of asphalt mastic, it was found that the basalt fiber significantly improved the performances of asphalt mastic, especially the crack resistance [15]. The reinforcement mechanism of the fiber to asphalt mortar was elucidated from the microscopic point of view. Mixing nano- $\text{TiO}_2/\text{CaCO}_3$  and basalt fiber into asphalt can improve its high-temperature stability and low-temperature crack resistance [16]. Basalt fiber can enhance the mechanical properties of asphalt and its mixture which are usually used in ordinary pavement structures. As a pavement maintenance structure, asphalt macadam seals are often destroyed due to insufficient bonding. However, there are few studies on the influence of the basalt fiber on the mechanical performance of asphalt macadam seals, so it is necessary to study the effect of the basalt fiber on the bonding performance. The bonding performance of the asphalt macadam seal consists of two parts. One part is the bonding performance between adhesive and aggregate, and the other part is the bonding performance between pavement structural layers.

Therefore, to study the influence of the basalt fiber on the two parts of bonding performance, basalt fiber was mixed into the asphalt macadam seal, and asphalt macadam seal specimens with different basalt fibers were prepared. The influences of basalt fiber content, basalt fiber length, and emulsified asphalt amount on the bonding performance

were compared and analyzed. And the evaluation model of the bonding performance of basalt fiber asphalt macadam seals based on the efficacy coefficient method was established. According to the model, the bonding performance was scientifically evaluated, and the reasonable content of each material was determined. The strengthening mechanism of the basalt fiber on the bonding performance of asphalt macadam seals was revealed. This work laid a solid foundation for further promotion and application of basalt fiber asphalt macadam seal.

## 2. Test Materials and Methods

**2.1. Test Materials.** In order to simulate the bonding performance between the basalt fiber asphalt macadam seal and the original asphalt pavement after the construction of the basalt fiber asphalt macadam seal, the test specimens were prepared in the combination structure form of "asphalt mixture + basalt fiber asphalt macadam seal."

According to JTG E20-2011 [17],  $300\text{ mm} \times 300\text{ mm} \times 40\text{ mm}$  asphalt mixture specimens were made. The binder is modified asphalt of SBS (I-D), and its performance parameters are given in Table 1. The aggregate is high-quality basalt, the density of the coarse aggregate is  $2.86\text{ g/cm}^3$ , the density of the fine aggregate is  $2.876\text{ g/cm}^3$ , and the mineral powder is high-quality limestone powder. Table 2 shows the grading type of AC13, and the optimum oil-stone ratio is 4.6%.

The binder of asphalt macadam seals is the quick-cracking cationic emulsified asphalt modified by SBR. The mass fraction of SBR is 2.5%. Its performances are shown in Table 3. The average particle size of latex is  $5.65\text{ }\mu\text{m}$ , and the maximum size is  $9.93\text{ }\mu\text{m}$ . All performances meet the requirements of JTG E20-2011. The amount of emulsified asphalt is  $1.2\text{--}1.8\text{ kg/m}^2$ . The aggregate is  $3\text{--}5\text{ mm}$  basalt gravel, and the aggregate spreading quantity is  $8\text{ kg/m}^2$ . The content of the basalt fiber is  $60\text{--}80\text{ g/m}^2$ , and technical indexes are shown in Table 4.

According to the construction technology of synchronous macadam seal and related literature [18], the basalt fiber asphalt macadam seal was partially laid on the  $40\text{ mm}$ -thick AC13 asphalt mixture. The preparation method of the test specimen is as follows. Firstly, take a proper amount of emulsified asphalt and divide it into two parts. Apply one part of emulsified asphalt on the surface of AC13 quickly and evenly with a brush. Randomly distribute basalt fibers on the emulsified asphalt. Spread another part of emulsified asphalt on the fiber layer. Then, spread the aggregate after the first step, and the aggregate should not be dropped from a higher place to prevent the sputtered stone particles from taking away part of emulsified asphalt. Finally, level the surface with the scraper, and roll the combined structure with the wheel roller. During the process, a  $10\text{ mm}$  rubber mat is laid on the basalt fiber asphalt macadam seal to isolate the macadam seal from the rolling wheel, so as to simulate the rolling condition of the rubber wheel on site and prevent the aggregate from being crushed (Figure 1). After demoulding the formed composite structure, a number of cylinder specimens with a diameter of  $101.6 \pm 0.2\text{ mm}$  are drilled for pull-out test, shear test, and torsion shear test.

TABLE 1: Basic properties of SBS-modified asphalt.

Indexes	Penetration (25°C, 100 g, 5 s) (0.1 mm)	Softening point (°C)	Ductility (5°C, 5 cm/min) (cm)	Mass loss (%)	RTFOT (163°C, 85 min)	
					Penetration ratio (25°C) (%)	Ductility (5°C) (cm)
Value	56	84	33	0.04	75	23

TABLE 2: Gradation of the asphalt mixture.

Gradation	Quantity percentage of passing (sieve mesh, mm) (%)									
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC13	100	97.5-100	70-74	33-37	24-30	20-22	16-18	11-13	8-10	7-8

TABLE 3: Performances of SBR-modified emulsified asphalt.

Indexes	Test value	
Residue on sieve (%)	0	
Evaporation residue (%)	54	
Standard viscosity (s)	21	
Evaporation residue	Softening point (°C)	53.6
	Penetration (100 g, 25°C, 5 s) (0.1 mm)	91
	Ductility (5°C) (cm)	>100
Storage stability	Stability after 1 day (%)	0.6
	Stability after 5 days (%)	3.5

TABLE 4: Technical parameters of the basalt fiber.

Density (g/cm <sup>3</sup> )	Tension strength (MPa)	Modulus of elasticity (GPa)	Elongation (%)	Diameter (μm)	Water absorbability (%)	Mass loss rate after boiling 3 h (%)	
						NaOH	HCl
2.78	4100-4800	93.1-109.5	3.1-3.2	100	1.5	2.8	2.2

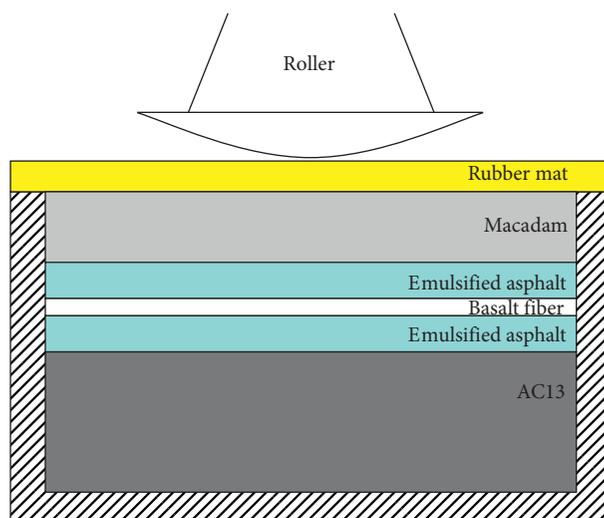


FIGURE 1: Structure and rolling test of the fiber macadam seal.

## 2.2. Test Method

**2.2.1. Plate Impact Test.** The common diseases of asphalt macadam seals are loose and potholes, which are especially common in large longitudinal slope, sharp turn, and accelerated braking section. On the one hand, the interlaminar shear stress caused by traffic load of the heavy road section is several times larger than that of the general road section. On the other hand, the bonding performance of sealing layers is insufficient [19]. Poor bonding performance between aggregate and asphalt will lead to the peeling of aggregate and the formation of pockmarked pavement. These damages seriously affect the road performance. Therefore, the plate impact test is used to systematically study the bonding performance between asphalt and aggregate [20]. The plate impact test is to evenly spread clean and dry gravel on the steel plate covered with emulsified asphalt and basalt fiber. After rolling and curing, the test specimen is put into the low-temperature environment box to cool for more than 12 h. Finally, the cooled specimen is taken out and placed on the plate impact test bench. The side of the steel plate with gravel is downward so that a 500 g steel ball can freely fall on the center of the steel plate from 50 cm height for three times. The quality of the fallen aggregate is weighed, and the aggregate loss rate is calculated. The loss aggregate rate is used as the evaluation index of the bonding performance of the basalt fiber asphalt macadam seal. The aggregate loss rate can be calculated by

$$\text{aggregate loss rate} = \frac{m_1}{m_0} \times 100\%, \quad (1)$$

where  $m_1$  is the quality of the dropped stone and  $m_0$  is the amount of the aggregate.

**2.2.2. Interlayer-Related Tests.** The poor bonding between sealing layers will cause U-shaped cracks, slippage, pavement potholes, and other diseases, which will affect the driving comfort and increase the risk of traffic accidents [21]. At present, there is no established test method to evaluate the interlayer performances of pavement structures [22]. Pull-out test, shear test, and torsion shear test are used to further analyze the interlayer bonding performance of the basalt fiber asphalt macadam seal and the original pavement.

Pull-out test, shear test, and torsion shear test can describe the bonding performance of asphalt macadam seals to a certain extent. However, the failure mode between layers is different from the actual situation. Pull-out test and shear test are widely used, and the pull-out strength and shear strength can be calculated by equations (2) and (3), respectively. However, the torsional shear test is mainly used to determine the interlaminar shear strength between the bonding layer and the bridge deck. Compared with pull-out test and shear test, torsional shear test has the following advantages. Firstly, torsional shear test is a kind of shear with normal stress. It can well simulate the actual stress condition of the gravel surface. And by adjusting the normal stress, it can simulate the influence of overload on the shear strength. Secondly, in the process of torsional shear, there is relative

sliding between the gravel surface and the original pavement. Relative sliding causes the specimen to be damaged, and this failure mode is similar to the actual situation. Thirdly, in the process of torsional shear test, the requirement of operation radius is low. The test specimen does not need to slide in the transverse direction, so it is more suitable for field tests than other similar equipment. The torsional shear test device consists of three parts: fixing device, connecting device, and torque measuring device. During the test, the normal stress is 0.7 MPa. Torque is gradually applied to the test specimen through the torque wrench until the asphalt pavement is separated from the macadam seal. The maximum torque is recorded as the shear resistance index between macadam seals.

$$C = \frac{F_{\max}}{A}, \quad (2)$$

where  $C$  is the pull-out strength,  $F_{\max}$  is the maximum pull-out force, and  $A$  is the pull-out area.

$$\tau = \frac{Q_{\max}}{A_t}, \quad (3)$$

where  $\tau$  is the shear strength,  $Q_{\max}$  is the maximum shear force, and  $A_t$  is the shear area.

**2.2.3. Microscopic Characterization.** JSM-6390A scanning electron microscope was used to characterize the micro-morphology of the basalt fiber in emulsified asphalt [23–25] to reveal the mechanism of the basalt fiber strengthening the adhesion of the macadam seal. The amplification of SEM analysis included 100 and 1500 times. The sample was sputtered to improve its electrical conductivity before SEM analysis [26].

## 3. Results and Discussion

**3.1. Bonding Performance of the Aggregate and Binder.** The plate impact test is a kind of test to detect the bonding performance of the aggregate and binder under impact load. The test scheme is designed as follows. Different types of basalt fiber asphalt macadam seals were prepared by using 10 mm, 15 mm, and 20 mm basalt fibers. The fiber contents were 60 g/m<sup>2</sup>, 70 g/m<sup>2</sup>, and 80 g/m<sup>2</sup>, and the emulsified asphalt contents were 1.2 kg/m<sup>2</sup>, 1.4 kg/m<sup>2</sup>, 1.6 kg/m<sup>2</sup>, and 1.8 kg/m<sup>2</sup>, respectively. The results are shown in Figure 2.

In Figure 2, as the content of emulsified asphalt increases, the loss aggregate rate of the specimen decreases. It indicates that, under the impact load, the bonding performance of the basalt fiber asphalt macadam seal increases with the increase of asphalt content. This is because when the fiber content is constant, the increase of emulsified asphalt content will increase the coverage area of the aggregate. It results in the increase of bonding between the two and the decrease of the loss aggregate rate. Therefore, the content of emulsified asphalt should be controlled between 1.6 and 1.8 kg/m<sup>2</sup>. The loss aggregate rate of asphalt macadam seals with the basalt fiber is 11.0–30.5% lower than that of the ordinary asphalt macadam seal. However, with the increase

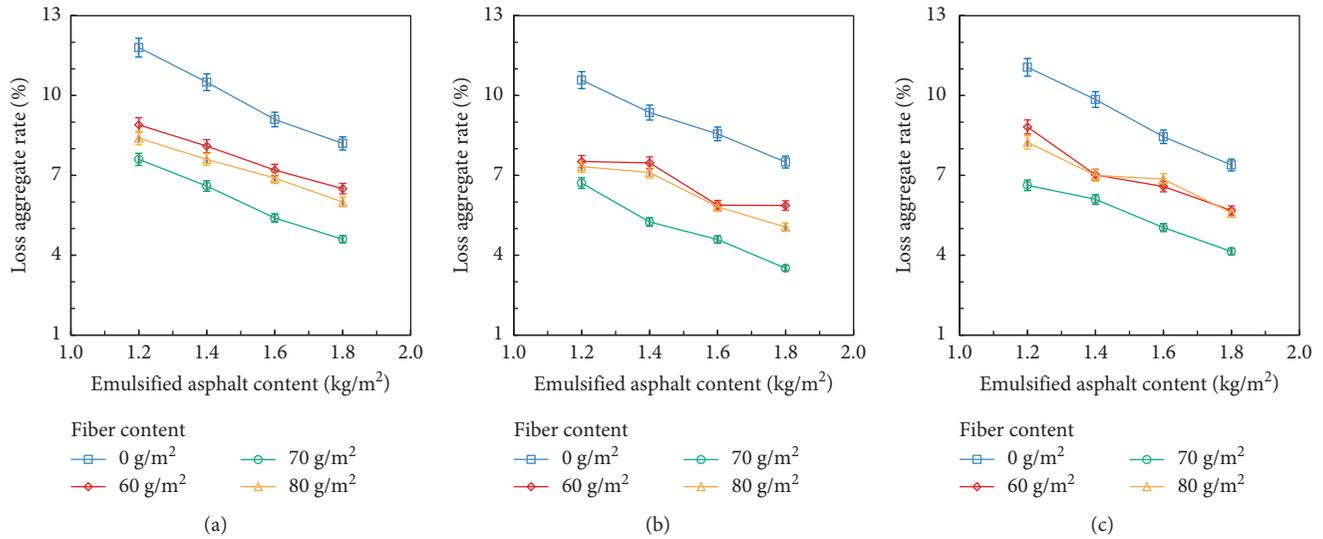


FIGURE 2: The loss aggregate rate with the basalt fiber. (a) 10 mm basalt fiber. (b) 15 mm basalt fiber. (c) 20 mm basalt fiber.

of basalt fiber content, the loss aggregate rate decreased and then increased. This is because the basalt fiber has a strong adsorption effect on asphalt, which makes extra oil in asphalt absorbed by the basalt fiber and effectively increases the bonding. However, excessive fiber will absorb part of normal oil, reduce the bonding between asphalt and aggregate, and increase the rate of loss aggregate. Therefore, it is advisable to control the dosage of the fiber at about 70 g/m<sup>2</sup>.

There is very little difference in the loss aggregate rate of asphalt macadam seals prepared from basalt fibers with different lengths. This indicates that the length of the basalt fiber has little effect on the bonding performance between aggregate and binder in the asphalt macadam seal. Therefore, the basalt fiber length can be within 10–20 mm, and 15 mm fiber was used to prepare for subsequent tests.

**3.2. Bonding Performance between Asphalt Macadam Sealing Layers.** It is necessary to further systematically analyze the bonding performance between the asphalt macadam seal and the original asphalt pavement through pull-out test, shear test, and torsion shear test.

**3.2.1. Pull-Out Test.** Based on the above research, the 15 mm basalt fibers are worth recommending. Basalt fiber contents of 60 g/m<sup>2</sup>, 70 g/m<sup>2</sup>, and 80 g/m<sup>2</sup> and emulsified asphalt with dosage of 1.2 kg/m<sup>2</sup>, 1.4 kg/m<sup>2</sup>, 1.6 kg/m<sup>2</sup>, and 1.8 kg/m<sup>2</sup> are used to prepare different types of specimens for pull-out test. The results are shown in Figure 3.

In Figure 3, the interlayer pull-out strength of asphalt macadam seals increases with the increase of the emulsified asphalt content. This is because the bonding between asphalt and aggregate will be enhanced, and the pull-out strength between layers will be increased with the increase of the asphalt content under the constant fiber content. Therefore, the content of emulsified asphalt should be controlled to between 1.6 and 1.8 kg/m<sup>2</sup>. With the increase of the basalt fiber content, the interlayer pull-out strength of asphalt

macadam seals increases and then decreases. When the fiber content is 60 g/m<sup>2</sup>, the peak value of pull-out strength is 0.285 MPa. This is because the crisscross fiber plays a role of reinforcement, increasing the pull-out strength between the asphalt macadam seal and the asphalt mixture. However, when the amount of the fiber exceeds an appropriate content, fibers will absorb a lot of asphalt, resulting in less asphalt bound with aggregate and reducing the bonding between layers. In addition, excessive fibers will form weak layers, which will lead to poor bonding between layers. When the fiber content is 60 g/m<sup>2</sup>, the pull-out strength of the asphalt macadam seal is 11.7–16.3% higher than that of the ordinary asphalt macadam seal. Therefore, only for pull-out strength, the amount of fiber should be controlled at about 60 g/m<sup>2</sup>.

**3.2.2. Shear Test.** Based on the bonding test of the aggregate and binder, different types of basalt fiber asphalt macadam seals are prepared, and the results are shown in Figure 4.

In Figure 4, initially, the interlaminar shear strength of the asphalt macadam seal increases with the increase of emulsified asphalt. This is because the bonding between asphalt and aggregate increases with the increase of the asphalt content, and the shear strength increases accordingly. However, when the amount of asphalt is too large, the surface friction and interlocking between asphalt and aggregate are relatively reduced, and the shear strength is correspondingly reduced. Therefore, the content of emulsified asphalt should be controlled to between 1.6 and 1.8 kg/m<sup>2</sup>. The regularity of shear strength of the asphalt macadam seal with the basalt fiber content is similar to that of pull-out test. The shear strength increases initially and then decreases with the increase of the basalt fiber content. When the fiber content is 80 g/m<sup>2</sup>, the shear strength peak value is 0.246 MPa. When the fiber content is 60 g/m<sup>2</sup>, the interlayer shear strength of the asphalt macadam seal is 9.7–22.4% higher than that of the ordinary asphalt macadam seal. Therefore, only for shear

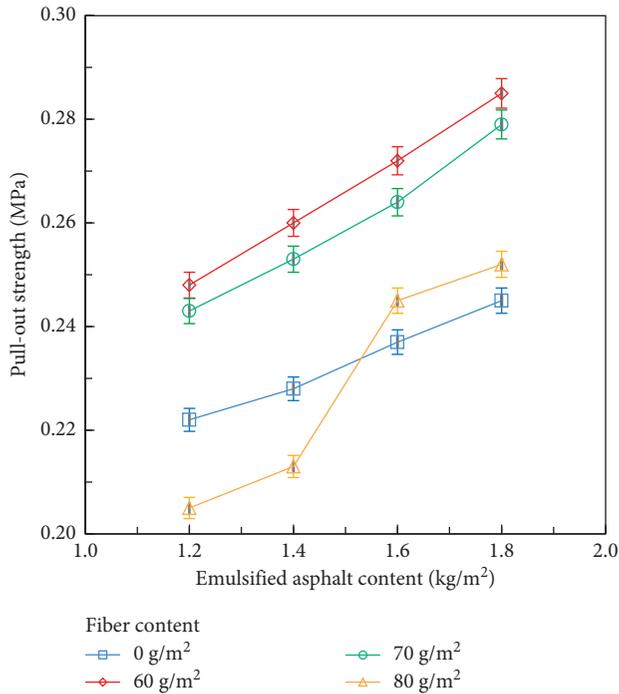


FIGURE 3: The results of pull-out test.

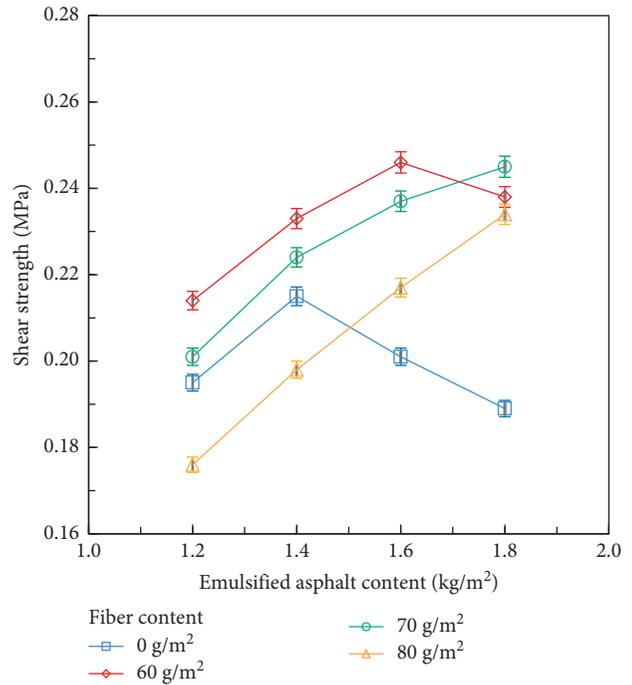


FIGURE 4: The results of shear test.

strength, the amount of fiber should be controlled at about 60 g/m<sup>2</sup>.

3.2.3. *Torsional Shear Test.* The type of the torsional shear test specimen is the same as that of shear test, and the results of torsional shear test are shown in Figure 5.

In Figure 5, with the increase of emulsified asphalt, the torsional shear resistance of the basalt fiber macadam seal increases and then decreases. The interlayer shear resistance mainly comes from the bonding between aggregate particles, the bonding between asphalt and aggregate, and asphalt itself. When the amount of emulsified asphalt in the seal layer is small, the increase of emulsified asphalt increases the contact area between asphalt and aggregate and increases the bonding of the two. When the amount of emulsified asphalt continues to increase, the interlayer free emulsified asphalt will increase. And the free asphalt will play a lubricating role in the interlayer, so the torsional shear strength will decrease. Therefore, the content of emulsified asphalt should be controlled at 1.6–1.8 kg/m<sup>2</sup>. The torsional shear strength increases at first and then decreases with the increase of the basalt fiber content. When the content of the basalt fiber is less, the reinforcement effect of the basalt fiber in asphalt increases the shear strength between sealing layers. When the content of the basalt fiber exceeds the optimal amount, the existence of fiber makes the integrity of the macadam seal worse. The weak layer makes its torsional shear strength lower. The best basalt fiber content is about 60 g/m<sup>2</sup>. When the fiber content is 60 g/m<sup>2</sup>, the torsional shear strength of the basalt fiber asphalt macadam seal is 4.2–20.6% higher than that of the ordinary macadam seal. Therefore, only for

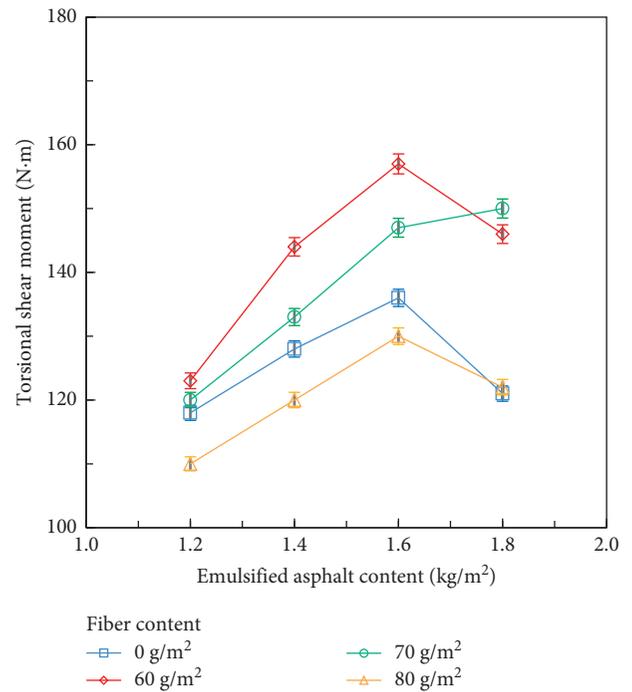


FIGURE 5: The results of torsional shear test.

the torsional shear strength, the amount of fiber should be controlled at about 60 g/m<sup>2</sup>.

3.3. *Determination of Optimum Content.* Compared with the above test results, it can be found that the amount of emulsified asphalt and basalt fiber corresponding to the optimal value of each test is different. Considering the

TABLE 5: Sample data.

Schemes	Content			Indexes			
	Basalt fiber (g/m <sup>2</sup> )	Emulsified asphalt (kg/m <sup>2</sup> )	Loss aggregate rate (%)	Pull-out strength (MPa)	Direct strength (MPa)	Torsional strength (N·m)	Cost increment (¥/m <sup>2</sup> )
1	60	1.2	7.5181	0.248	0.214	123	4.68
2	60	1.4	7.4717	0.260	0.233	144	5.28
3	60	1.6	5.8828	0.272	0.246	157	5.88
4	60	1.8	5.8687	0.285	0.238	146	6.48
5	70	1.2	6.7101	0.243	0.201	120	4.86
6	70	1.4	5.2459	0.253	0.224	133	5.46
7	70	1.6	4.5879	0.264	0.237	147	6.06
8	70	1.8	3.5102	0.279	0.245	150	6.66
9	80	1.2	7.3320	0.205	0.176	110	5.04
10	80	1.4	7.1069	0.213	0.198	120	5.64
11	80	1.6	5.8174	0.245	0.217	130	6.24
12	80	1.8	5.0558	0.252	0.234	122	6.84

economic factors, taking the price of the basalt fiber as 18 ¥/kg as an example, if 10 g basalt fiber is added to 1 m<sup>2</sup> macadam seal, the cost of the fiber will increase by 0.18 ¥/m<sup>2</sup>. At the same time, with the increase of the fiber content, emulsified asphalt content will also increase, and the overall cost will be greater. Based on the above research results, the efficacy coefficient evaluation system of 12 schemes and 5 indexes is constructed by using the efficacy coefficient method. It is built to comprehensively evaluate the bonding performance of the basalt fiber asphalt macadam seal [27–29]. Sample data are given in Table 5.

Based on the analysis of each evaluation index, the satisfaction value ( $X_{hi}$ ), disallowed value ( $X_{si}$ ), and average value ( $\bar{X}_i$ ) of the evaluation index are determined. These determined indexes are shown in Table 6.

According to equation (4), the single-effect coefficient ( $d_i$ ) of each index is shown in Table 7:

$$d_i = \frac{X_i - X_{si}}{X_{hi} - X_{si}} \times 0.4 + 0.6, \quad (4)$$

where  $X_i$  is the actual value of the  $i^{\text{th}}$  evaluation index;  $X_{hi}$  is the satisfaction value of the  $i^{\text{th}}$  evaluation index; and  $X_{si}$  is the disallowed value of the  $i^{\text{th}}$  evaluation index.

After the single effect coefficient is determined, according to the importance of each evaluation index, the coefficient of variation method is used to weigh each index. The weight ( $\omega_i$ ) of the  $i^{\text{th}}$  evaluation index calculated according to equations (5) and (6) is shown in Table 8:

$$v_i = \frac{\sigma_i}{\bar{X}_i}, \quad (5)$$

$$\omega_i = \frac{v_i}{\sum_1^n v_i}, \quad (6)$$

where  $v_i$  is the coefficient of variation of the  $i^{\text{th}}$  evaluation index,  $\sigma_i$  is the standard deviation of the  $i^{\text{th}}$  evaluation index,  $\sum_1^n v_i$  is the sum of the coefficient of variation of the  $i^{\text{th}}$  evaluation index, and  $n$  is the number of evaluation indexes.

The total efficacy coefficient ( $D_i$ ) can be calculated according to equation (7). The total efficacy coefficient of the basic performance of different schemes is shown in Table 9.

$$D_i = \sum_1^n \omega_i \sqrt{\prod_1^n d_i^{\omega_i}}, \quad i = 1, 2, \dots, n. \quad (7)$$

According to Table 9, the order of the total efficacy coefficient of different design schemes is  $8 > 3 > 7 > 4 > 12 > 2 > 6 > 11 > 1 > 10 > 5 > 9$ . Schemes 8 and 3 have higher total efficacy coefficients. Considering the road performance and economic benefits, the optimal amount of emulsified asphalt is 1.6 kg/m<sup>2</sup>, and the optimal amount of the basalt fiber is 70 g/m<sup>2</sup>. Considering the material cost in practical application, scheme 8 can be selected if the project cost is high, and scheme 3 is more appropriate if the project cost is low.

**3.4. Microscopic Characterization.** The morphology of the basalt fiber in emulsified asphalt was characterized to further explain the influence of the basalt fiber on the adhesion of asphalt macadam. The amount of emulsified asphalt is 1.6 kg/m<sup>2</sup>, and the amount of the fiber is 60 g/m<sup>2</sup>. The results are shown in Figure 6.

Figure 6(a) shows the basalt fiber is randomly distributed in emulsified asphalt and overlaps with each other to support the asphalt. Fiber, asphalt, and crushed stone form a three-dimensional network structure, which increases the overall stability of the seal. In Figure 6(b), the basalt fiber surface is surrounded by an asphalt layer. It can be seen from the interface infiltration theory [30, 31] that the asphalt molecules on the surface of the basalt fiber are rearranged under the adsorption of the fiber, and the formed structural asphalt layer reduces the content of free asphalt in the original asphalt. The addition of the basalt fiber increases the consistency and viscosity resistance of asphalt, improves the cohesion of asphalt, and then improves the adhesion performance of the macadam seal. When the content of the basalt fiber is less, the three-dimensional network structure and structural asphalt content increase with the increase of the fiber content, so the bonding performance between aggregate and binder and the bonding performance between macadam seal and asphalt mixture increase. When the content of the basalt fiber is excessive, the three-dimensional

TABLE 6: Standardization of evaluation index values.

No.	Evaluating indicator	Satisfaction value ( $X_{hi}$ )	Disallowed value ( $X_{si}$ )	Average value ( $\bar{X}_i$ )
1	Loss aggregate rate (%)	3.5102	7.5181	6.0090
2	Pull-out strength (MPa)	0.279	0.205	0.2516
3	Shear strength (MPa)	0.246	0.176	0.2219
4	Torsional strength (N·m)	157	110	133.5
5	Cost increment (¥/m <sup>2</sup> )	4.68	6.84	5.76

TABLE 7: Single-effect coefficient of evaluation indexes.

Schemes	Loss aggregate rate	Pull-out strength	Shear strength	Torsional strength	Cost increment
1	0.6000	0.8324	0.8171	0.7106	0.6000
2	0.6046	0.8973	0.9257	0.8894	0.7111
3	0.7632	0.9622	1.0000	1.0000	0.8222
4	0.7646	1.0324	0.9543	0.9064	0.9333
5	0.6806	0.8054	0.7429	0.6851	0.6333
6	0.8268	0.8595	0.8743	0.7957	0.7444
7	0.8924	0.9189	0.9486	0.9149	0.8556
8	1.0000	1.0000	0.9943	0.9404	0.9667
9	0.6186	0.6000	0.6000	0.6000	0.6667
10	0.6410	0.6432	0.7257	0.6851	0.7778
11	0.7697	0.8162	0.8343	0.7702	0.8889
12	0.8457	0.8541	0.9314	0.7021	1.0000

TABLE 8: The weight of evaluation indexes.

Evaluation index	Loss aggregate rate	Pull-out strength	Shear strength	Torsional strength	Cost increment
Weight	0.1518	0.0447	0.4785	0.1713	0.1537

TABLE 9: Total efficacy coefficient of comprehensive performance.

Schemes	1	2	3	4	5	6	7	8	9	10	11	12
Total efficacy coefficient	0.7332	0.8365	0.9350	0.9176	0.7095	0.8330	0.9187	0.9819	0.6131	0.7102	0.8211	0.8862

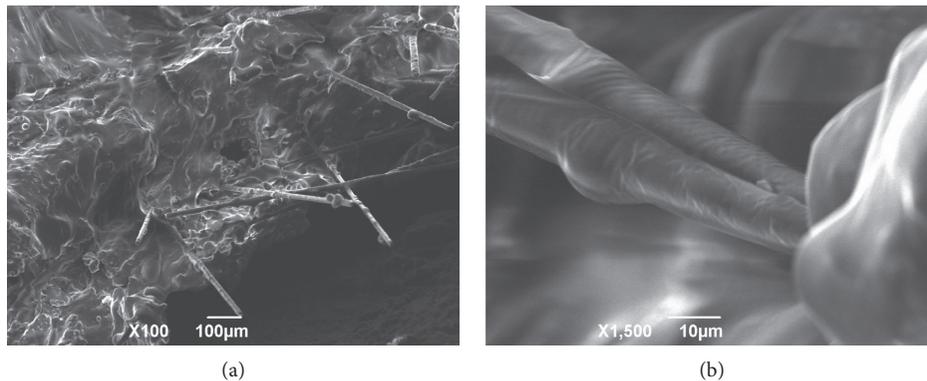


FIGURE 6: Micromorphology of basalt fiber and asphalt. (a) Distribution of the basalt fiber. (b) Interface morphology of the basalt fiber.

network structure is staggered and overlapped with each other, which make the fiber aggregation area weak and reduce the overall adhesion performance of the gravel seal.

#### 4. Conclusion

- (1) The length of the basalt fiber has little effect on the bonding performance of aggregate and binder

in the asphalt macadam seal. The basalt fiber length can be within 10–20 mm, and 15 mm is optional.

- (2) Comparing the ordinary asphalt macadam seal, the loss aggregate rate of the basalt fiber asphalt macadam seal is 11.0–30.5% lower. The bonding performance between aggregate and binder is improved significantly.

- (3) The addition of the basalt fiber increases the cohesion of emulsified asphalt, and the three-dimensional network structure of fiber, asphalt, and aggregate increases the overall cohesion of the seal.
- (4) When the basalt fiber content is 70 g/m<sup>2</sup>, the pull-out strength, shear strength, and torsional shear strength are 11.7–16.3%, 9.7–22.4%, and 8.5–15.6% higher, respectively. Considering the road performance and economic benefits, the optimal amount of emulsified asphalt is 1.6 kg/m<sup>2</sup>, and the optimal amount of the basalt fiber is 70 g/m<sup>2</sup>.
- (5) The mechanical properties and economic performance of the basalt fiber asphalt macadam seal are considered comprehensively when determining the optimal dosage of the basalt fiber and emulsified asphalt. The efficiency coefficient method is reasonable and reliable.
- (6) In the future, the dispersion of the basalt fiber in asphalt macadam seals should be studied. Furthermore, it is also necessary to analyze the correlation between the dispersion and the bonding performance of the seal.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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