Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2017, 4(10):454-465**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Study on the Bond Strength between Porous Asphalt and Asphalt Concrete Layer

Xiaotian Jiang*[1], Futao Chen[2], Jun Li[2], Mingliang Li[2], Dongwei Cao[2]

*[1]School of Civil Engineering, Chongqing Jiaotong University, No. 66 Rd. Xuefudadao, Nanan District, Chongqing, 400074, China

[2]Research Institute of Highway Ministry of Transport, No. 8 Rd. Xitucheng, Haidian District, Beijing, 100088, China

Abstract The weakness of waterproof and cohesive layer is the main reason for the disease of porous asphalt such as pot hole and water damage. The excellent performances of porous asphalt such as skid resistance and noise reduction are impaired by these diseases. Therefore, the quality of bond strength between the surface layer and middle layer becomes an important issue. To study the interface behaviour between porous asphalt and asphalt concrete layer, indoor tests were conducted. Different types of bond materials with different tack coat rates were tested by shear-type interface test and tensile-type interface test. The bond material was made of SBS modified asphalt. Three variables including particle size of gravel, the dosage of asphalt and coverage of gravel were considered. The results show how tensile strength and shear strength change with these variables and give advice for achieving excellent bond strength. Based on the advice, a test road with different kinds of waterproof and cohesive layers was constructed to test the bond strength. The performance of SBS modified asphalt was compared with bond material made of SBS modified emulsified asphalt and rubber asphalt. According to the results, three optimal combination schemes for SBS modified asphalt were decided, which provide a quantitative reference for the interlayer construction of porous asphalt overlay on old pavement. The optimal dosage of SBS modified asphalt is 1.2kg/m^2, particle size of 3-5mm and 5-10mm are recommended, and optimal coverage of gravel is 70% and 80%.

Keywords Porous asphalt; Bond strength; Shear test; Tensile test; SBS modified asphalt

1. Introduction

The waterproof and cohesive layer is an important part of porous asphalt structure. It is between porous asphalt surface layer and middle layer. It consists of asphalt or asphalt and precoated gravel. It has two primary functions. First, waterproofness. As surface layer, porous asphalt drains water from the surface, therefore waterproof and cohesive layer should isolate the water from the middle layer. Otherwise, water will erode middle layer and other pavement structures. At the same time, assurance of the bond strength is another critical function of the waterproof and cohesive layer. According to *Specifications for Design of Highway Asphalt Pavement*, in the design process of pavement interfaces are assumed to be well bonded by default [1]. However, most cases indicate that this assumption is hard to realize. Poor bond quality between pavement layers significantly reduces the service life of pavement system. When pavement layers are well bonded, maximum tensile strain occurs at the bottom of the pavement. If not, it occurs at the weakness of the pavement, so mostly the bottom of the surface layer. In that case, it will cause a lot of diseases which decrease the performance of the pavement, including slippage cracking, top-down cracking, premature fatigue cracking, pothole development, and even complete delamination [2]. According to the research of Khweir and Fordyce, poor bond quality could reduce the service life of the pavement by 40%-83% [3]. Poor bond quality between layers could also result in rutting, especially in the environment of high temperature [4]. On Xu-Huai highway, Jiangsu province of China, because of the hot weather of eight days in a sequence which was higher than 35 degrees Celsius, the rutting depth reached over 10 centimeters as figure 1(a) shows. The core broke at about 9 centimeters below the surface where is the interface between the middle layer and bottom layer. It means poor bond quality made the location of the maximum shear stress rise from the bottom of asphalt pavement. With the increasing emission of carbon, hot temperature becomes more and more common in summer, how to prevent this disease from happening is a critical issue. As figure 2 shows, due to the high design air void ratio of porous asphalt which is between 15% and 20%, the contact area between the surface layer and the middle layer is less than dense pavements [5]. In this situation, it is challenging to assure bond strength and prevent water entering. Therefore, the waterproof and cohesive layer for porous asphalt should reach a high standard of waterproofness and coherence. Base asphalt used as interlayer material shows poor bond performance [6]. In the construction process of the interlayer of a new road, modified emulsified asphalt is recommended. For heavy traffic road and overlay of an old road, hot modified asphalt such as rubber asphalt and SBS modified asphalt are recommended, their performances are proven in engineering practice.

(a) The rutting depth (b) Core from the field

Figure 1: Rutting disease

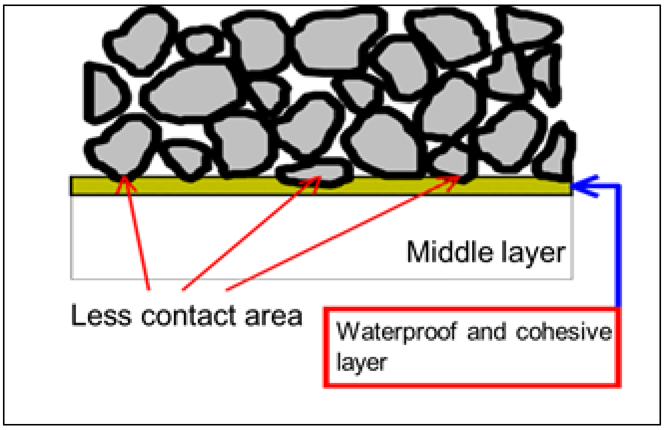


Figure 2: Waterproof and cohesive layer

In China, the importance of tack coat has been realized. According to *Technical Specifications for Construction of Highway Asphalt Pavements (JTGF40—2004)*, asphalt pavements should be constructed layer by layer, before the construction of new layer, the sub-layer should keep clean. Spray penetrated oil between the base and bottom layer, spray tack coat between layers. It also regulates the type of material and gives a range of the tack coat rate. However, there is no specific reference value for tack coat rate and it does not provide the test method of bond strength. Therefore, there is not an evaluation index of bond strength.

Most researchers take both shear strength and tensile strength as evaluation indicators of bond strength. The shear strength is used to evaluate the stress state of the pavement under the vehicle load, different laboratories have developed different methods to test it. Test methods of shear strength are not uniform now. Shear testing devices without vertical loading were developed first, including direct shear test (DST) [7], double shear test [8] and simple shear test (SST) [9]. Then researchers began to focus on the simulation of the wheel load in real condition, interface shear testing device (ISTD) [10], Coaxial shear test (CAST) [11] and Ancona shear testing research and analysis (ASTRA) [12] were developed. Tensile strength is an indirect evaluation index of the inter-layer bond state, and the test method is simple and uniform, pull-off tests are the most commonly used, including Louisiana tack coat quality tester (LTCQT) [13], tack coat evaluation device (TCED) [14] and Interface bond test (IBT) [15].

The objective of this paper is to investigate the bond strength between AC layer and porous asphalt. The waterproof and cohesive layer consists of SBS modified asphalt. The bond strength of interface without tack coat at the temperature of 5°C, 25°C, 40°C and 65°C was also investigated as a comparison. Find one or several optimal combinations of bond materials by considering three factors including tack coat rate, the particle size of gravel and coverage of gravel. Finally, verify the quality of optimal combinations by constructing a test road. The outdoor experiment results show that the optimal combination of bind materials can achieve excellent performance. Moreover, it can provide a practical reference for the application of waterproof and cohesive layer with SBS modified asphalt in the future.

2. Test Program and Method

2.1. Test Plans

2.1.1 Specimen Moulding

(1) Form the AC-20 layer in the rutting plate with a size of 300mm x 300mm x 50mm.

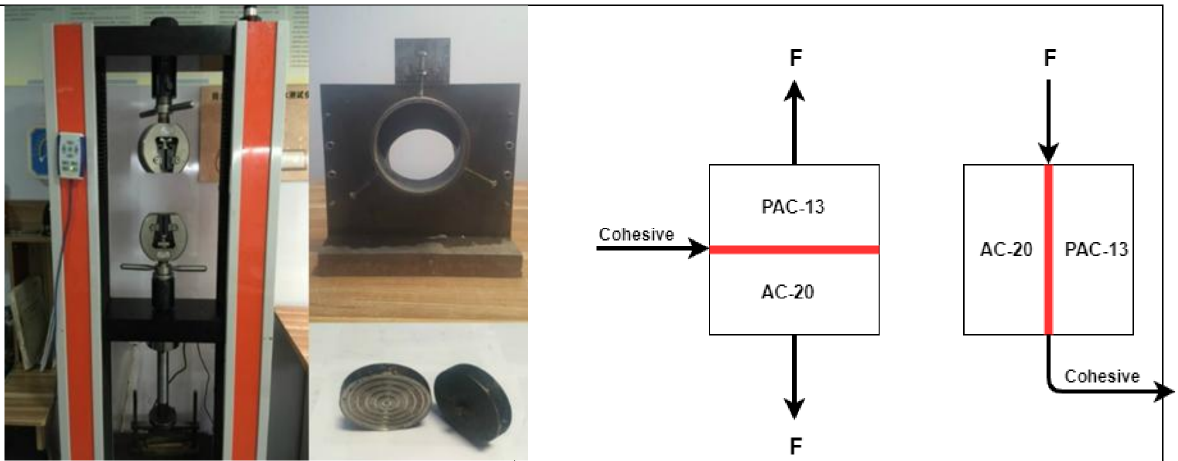
(2) Apply the waterproof and cohesive material to the AC-20 layer.

(3) Put asphalt concrete slab to 300 mm * 300 mm * 100 mm rutting plate, overlay 5cm thick hot PAC-13 asphalt mixture.

(4) Drill cores specimens with a size of Φ 10 x 10 cm (each rutting plate drill four cores) for shear test and tensile test.

2.1.2. Test method

Shear test and tensile test were applied by WDW-100 universal testing machine with special clamps which is developed by the lab. The test equipment and principles are shown in the figure 3.



(a) Test equipment (b) Test principles

Figure 3: Test equipment and principles

2.1.3. Influential factors design

There are many factors that influence the shear strength and tensile strength; this paper investigates four main factors below.

(1) Temperature

In hot summer, the temperature of asphalt pavement surface is over 60°C, and this condition often lasts more than two hours per day. In winter, the temperature of asphalt pavement surface of the cold region is under 0°C. To comprehensively evaluate the bond properties of interlayer materials, consider the worst-case scenario. Carried out the tensile test and shear test under 5°C, 25°C, 40°C and 65°C to study the effect of temperature on both tensile strength and shear strength.

(2) The dosage of SBS modified asphalt

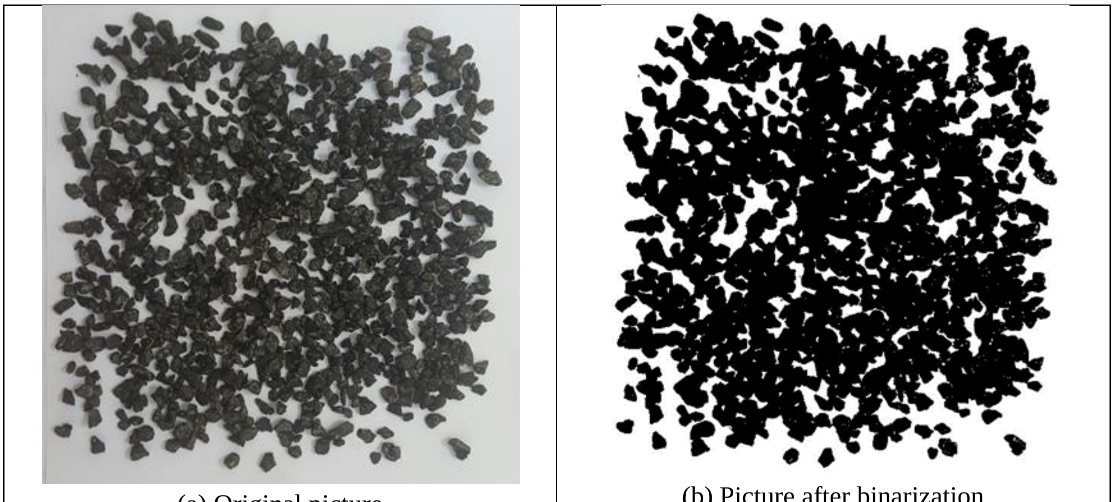
Tack coat rate has a great influence on the bond performance of asphalt pavement layers [16]. Excessive tack coat could create a slip plane between layers, causing displacement of one layer with respect to the other, whereas insufficient tack coat rate leads to the debonding of layers [17]. Varied the application of SBS modified asphalt from 0.6 kg/m^2 to 1.5kg/m^2 to study the effect of asphalt dosage on bond strength.

(3) The particle size of gravel

Waterproof and cohesive layer with modified hot asphalt requires a certain amount of gravel or precoated asphalt gravel. Precoated gravel refers to the gravel that is precoated by SBS modified asphalt and asphalt aggregate ratio is 0.5%. To study the effect of particle size of gravel on interlayer adhesion, three kinds of gravel were selected, including 2.36-4.75mm (from now on referred to as 3-5mm), 4.75-9.5mm(from now on referred to as 5-10mm) and 9.5-13.2mm(from now on referred to as 10-15mm).

(4) Coverage of gravel

To study the effect of coverage of gravel on interlayer adhesion, four kinds of coverage were selected, from 50% to 80%. To achieve the desired result, made a background by paper with the same size (30cm x 30cm) of rutting plate, and took the picture after spreading gravel. Then, the image was pretreated with MATLAB software to reduce the noise, and then obtained the binarization of image by otsu threshold algorithm, as shown in figure 4 [18]. The percentage of black pixels to the total pixels is the coverage of gravel. The relationships between the coverage of gravel and the mass of gravel are shown in table 1.



(a) Original picture (b) Picture after binarization

Figure 4: Coverage detection

Table 1: Coverage of gravel and mass

Particle size	Coverage	Mass/g	Particle size	Coverage	Mass/g
3-5mm	60%	266		50%	330
5-10mm	60%	410	5-10mm	70%	495
10-15mm	60%	720		80%	603

2.2. Material Design

2.2.1. Design of Tack Coat Material

The experimental results and technical specifications for SBS modified asphalt are shown in Table 2.

Table 2: Technical indexes of SBS modified asphalt

Pilot project	**Unit**	**Testing value**	**Standard**
Penetration 25 ºC, 100 g, 5 s	0.1mm	52.5	≥50
Penetration index (PI)	ºC	84.2	≥75
Ductility (ºC, 5 cm/min)	cm	23.9	≥20
Solubility	%	99.6	≥99
Elastic recovery (25 ºC)	%	95	≥90
Dynamic viscosity (135 ºC)	Pa·s	2.820	2.2~3.0
Relative density(25 ºC)		1.021	
TFOT (or RTFOT) residue			
Quality loss	%	+0.08	±1.0
Penetration ratio 25 ºC	%	81	≥65
Ductility (5 ºC, 5 cm/min)	cm	15.8	≥15

2.2.2. Design of asphalt surface materials

The aggregate gradations of PAC-13 and AC-20 asphalt surface materials are shown in Table 3.

Table 3: Aggregate gradation

Sieve size/mm	**26.5**	**19**	**16**	**13.2**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
	Passing percentage/%											
PAC-13			100	89.1	57.1	15.3	10.5	7.7	6.1	5.4	4.9	4.1
AC-20	100	96.5	87.6	75.8	60	40.4	29.1	20.3	15.4	10.3	7	4

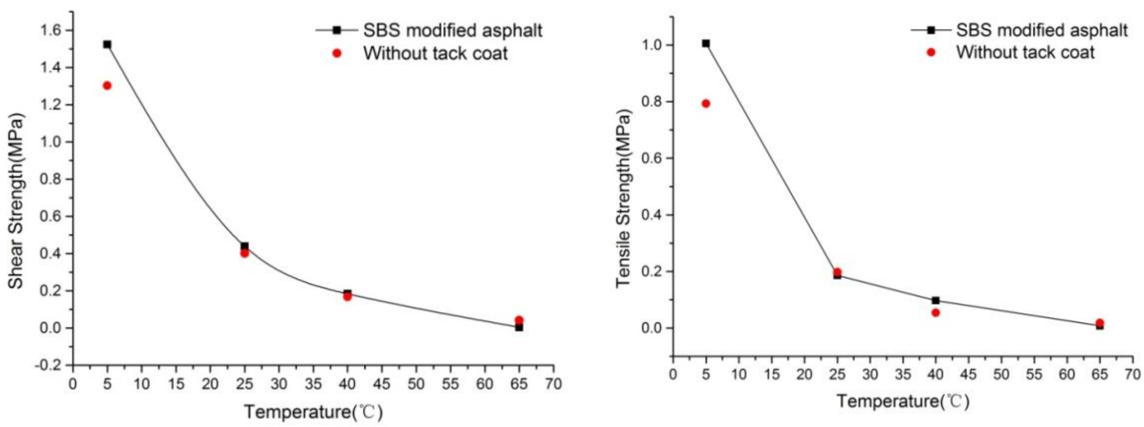
3. Analysis of the results

3.1. Effect of Temperature

The dosage of SBS modified asphalt is 0.9kg/m^2, the particle size of gravel is 5-10mm and the coverage of gravel is 60%. Table 4 shows that shear strength and tensile strength decrease significantly with the increase of temperature. Bond strength of interlayer with SBS modified asphalt is always stronger than the situation without tack coat.

Table 4: Bond strength at different temperatures

Temperature/ºC	**5 ºC**	**25 ºC**	**40 ºC**	**65 ºC**
Shear strength/MPa	1.524	0.439	0.184	0.004
Tensile strength/MPa	1.006	0.186	0.097	0.008



(a) Shear strength (b) Tensile strength

Figure 5: Effect of temperature on interface bond strength

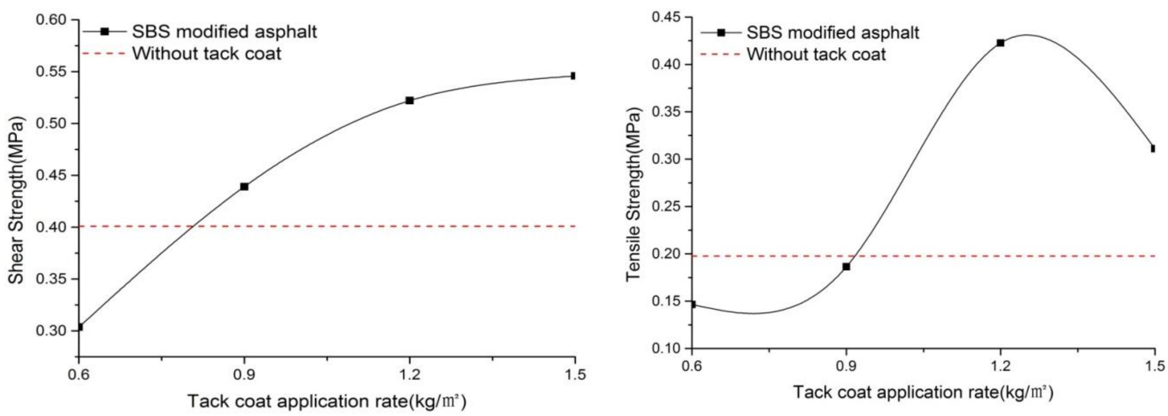
Clearly, the adhesion property of asphalt is affected by the temperature. Adhesion material made of asphalt becomes soft at high temperature, and it becomes brittle and hard at low temperature. Therefore, its viscosity shows different performances at different temperatures. At 5 ºC, shear strength is 1.524MPa, and tensile strength is 1.006MPa. However, at 40 ºC, they become 0.184MPa and 0.097MPa which means fall 88% and 90% respectively. At 65 ºC, two specimens were cut off by the gravity of shear equipment without the application of stress by test machine. High temperature makes the interlayer very brittle. As a result, it is more important to investigate the bond performance of waterproof and cohesive layer at high temperature. Because the bond performance at normal temperature is difficult to reflect the worst working condition of the real pavement.

3.2. Effect of Asphalt Dosage

The dosage of SBS modified asphalt varied from 0.6kg/m^2 to 1.5kg/m^2, the particle size of gravel is 5-10mm, and the coverage of gravel is 60%. Temperature condition was at the level of 25°C. The results are shown in table 5. Figure 6 presents the variation of shear strength and tensile strength of different tack coat application rates at 25°C.

Table 5: Bond strength of different tack coat rates

Tack coat application rate (kg/m^2)	**0**	**0.6**	**0.9**	**1.2**	**1.5**
Shear strength/MPa	0.401	0.304	0.401	0.522	0.546
Tensile strength/MPa	0.198	0.146	0.135	0.423	0.311



(a) Shear strength (b) Tensile strength

Figure 6: Effect of tack coat application rate on interface bond strength

It can be seen that with the increase of dosage of tack coat, shear strength and tensile strength increase at the same time. However, when the tack coat application rate reaches 1.2kg/m^2, shear strength continues to rise and tensile strength decreases. As the slopes of the curves indicate, when the dosage of SBS modified asphalt changes from 0.9kg/m^2 to 1.2 kg/m^2 the bond strength increases most. Therefore, under this circumstance (25 ºC, particle size of gravel is 5-10mm, coverage of gravel is 60%), consider 1.2kg/m^2 as optimal asphalt dosage.

The main reason that the shear strength increases with the increase of asphalt dosage is that the shear strength of the interlayer material depends on its cohesion and internal friction angle [19]. When the dosage of interlayer material is small, with thin oil film between the layers, the cohesive strength is small, the shear strength mainly depends on the friction between the layers and the internal friction angle of aggregates, in that case, the shear strength is small. With the increase of asphalt, the oil film becomes thick, the interlayer materials gradually form a robust structure, the cohesive strength and internal friction angle increase, so the shear strength increases.

3.3. Particle Size of Gravel

The particle size of gravel is at the level of 3-5mm, 5-10mm and 10-15mm. The dosage of SBS modified asphalt is 0.9 kg/m^2. The coverage of gravel is 60%. Temperature condition was at the level of 25°C. The results are shown in table 6. Figure 7 presents the variation of shear strength and tensile strength of different particle sizes of gravel at 25°C.

Table 6: Bond strength of different particle sizes of gravel

Particle size of gravel	0 (without gravel)	3-5mm	5-10mm	10-15mm
Shear strength/MPa	0.428	0.501	0.401	0.336
Tensile strength/MPa	0.191	0.276	0.135	0.179

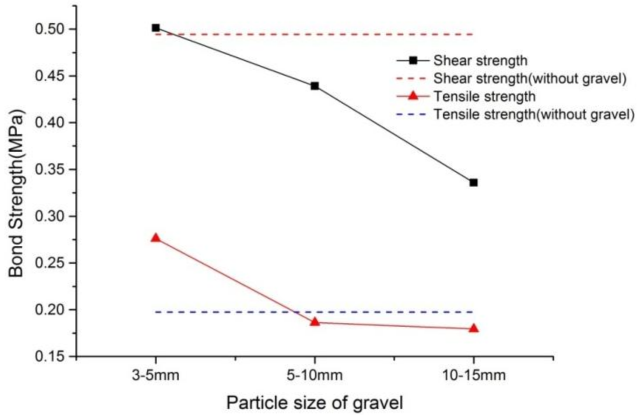


Figure 7: Effect of particle size of gravel on interface bond strength

One of the main reasons for using gravel is that it can protect the waterproof and cohesive layer from the crushing of construction vehicles. If the asphalt at high temperature is applied without spreading gravel, it will be adhesive to the tires of vehicles and tracks of pavers. At the same time, gravel should at least do not decrease bonding strength dramatically. It can be seen that with the increase of particle size, both tensile strength and shear strength decrease. And compared with the condition that without the application of gravel, only using gravel with the size of 3-5mm can make sure the bond strength is higher than it. It improves the tensile strength by 0.073MPa. For gravel with the particle size of 5-10mm, it decreases the shear strength by 0.085MPa. Therefore, gravel with 3-5mm particle size is recommended. However, 3-5mm size of gravel is too small to stick to the surface tightly. Considering that, 5-10mm size of gravel is mostly used.

3.4. Coverage of Gravel

The particle size of gravel is at the level of 5-10mm. The dosage of SBS modified asphalt is 0.9kg/m^2. The coverage of gravel varies from 50% to 80%. Temperature condition was at the level of 25°C. The results are shown in table 7. Figure 8 presents the variation of shear strength and tensile strength of different coverages of gravel at 25°C.

Table 7: Bond strength of different coverages of gravel

Coverage of gravel	0 (without gravel)	50%	60%	70%	80%
Shear strength/MPa	0.401	0.323	0.401	0.534	0.417
Tensile strength/MPa	0.198	0.535	0.186	0.381	0.235

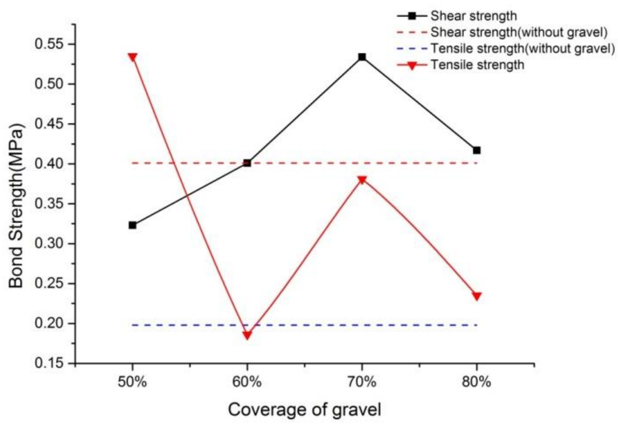


Figure 8: Effect of coverage of gravel on interface bond strength

It can be seen that with the increase of gravel, shear strength and tensile strength fluctuated. When the coverage of gravel reaches 70%, shear strength rise to the highest and shear strength decreases. As the slopes of the curves indicate, when the coverage of gravel changes from 60% to 70% the bonding strength increases most. Therefore, under this circumstance (25°C, particle size of gravel is 5-10mm, the dosage of asphalt is 0.9kg/m^2), consider 70% and 50% as optimal coverage of gravel.

3.5. Correlation of Shear Strength and Tensile Strength

In this study, investigate bond strength by shear test and tensile test. In most cases, shear strength and tensile strength increase together. To verify the correlation of shear strength and tensile strength, analyse them at different levels of temperature by SPSS. The results are shown in table 8.

Table 8: Data and results

Temperature/°C	5 °C	25 °C	40 °C	65 °C
Shear strength/MPa	1.524	0.439	0.184	0.004
Tensile strength/MPa	1.006	0.186	0.097	0.008

Correlations

		Shear strength	Tensile strength
Shear strength	Pearson correlation	1	0.994**
	Sig.(2-tailed)		0.006
	N	4	4
Tensile strength	Pearson correlation	0.994**	1
	Sig.(2-tailed)	0.006	
	N	4	4

**. At the 0.01 level (2-tailed), the correlation is significant.

The results (Pearson correlation coefficient is 0.994, significance level is 0.006) indicate that shear strength and tensile strength have significant positive correlation. It means interlayer materials with excellent shear strength have strong tensile strength as well.

4. Outdoor Tests

Based on the results of indoor tests, when the temperature is 25°C, consider 1.2kg/m^2 as the optimal dosage of SBS modified asphalt, 3-5mm and 5-10mm as optimal particle size, and optimal coverage of gravel is 70% and 80%. To validate these conclusions, constructed test road with the applications of waterproof and cohesive layer combinations. Three types of asphalt were considered: SBS modified asphalt, rubber asphalt and SBS modified emulsified asphalt. The particle size of gravel is at the level of 3-5mm and 5-10mm. Coverages of gravel are 0%, 40% and 80%.

4.1. Construction Scheme

The test road stimulated the construction of porous asphalt overlaying on the old road. First, milled the old road(kept it clean after milling); Paved 5cm AC-20 as the middle layer; Applied waterproof and cohesive layer(the area of each combination is 20cm×100cm); Paved 4cm PAC-13 as the surface layer; Finally, drilled cores to test shear strength and tensile strength.

The cores were cut into 9cm high. Before shear test and tensile test, put cores in the high-low temperature test chamber at the level of 25℃ for 7 hours, the endurance of a single test should be less than 5minutes to avoid cooling.

(a) Tack coat application

(b) Construction of porous asphalt layer

(c) Drill cores

(d) Cores

Figure 9: Construction of test road

4.2. Waterproofness Verification

As it is mentioned before, the waterproof and cohesive layer must prevent water from entering middle layer, even when heavy traffic load causes high pressure that pushes pore water in the surface layer rush into the middle layer. In this study, used seepage meter to verify the waterproofness. Applied the waterproof and cohesive layer material on a kraft paper with the same size of rutting plate, after 12 hours put it under the rutting plate. Made infiltration test on the rutting plate to see if the other side of kraft paper become moist [20]. The results show that all combinations performance excellent waterproofness.

4.3. Analysis of the Results

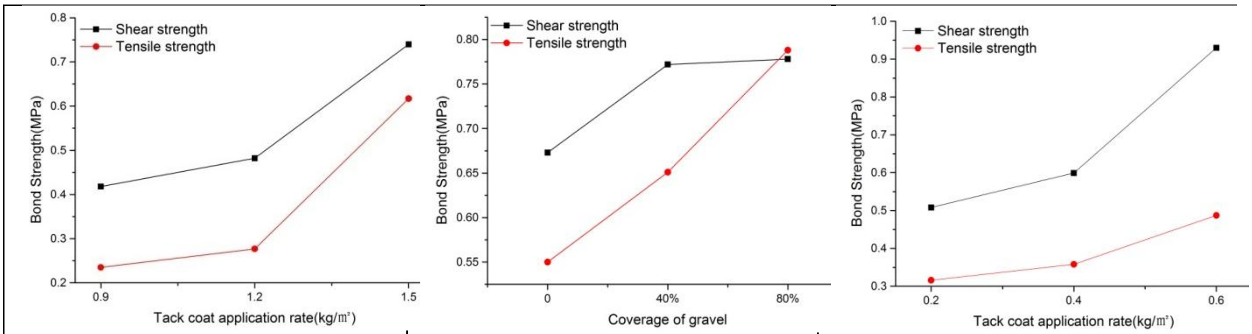
The results of tensile test and shear test are shown in table 9 and table 10.

Table 9: Bond strength of SBS modified asphalt and rubber asphalt

	Tack coat application rate (kg/m^2)	**Particle size of gravel (mm)**	**Coverage of gravel**	**Shear strength(MPa)**	**Tensile strength(MPa)**
SBS modified asphalt	1.5	5-10	80%	0.740	0.617
		-	0	0.992	0.607
	1.2	5-10	40%	0.791	0.612
			80%	0.482	0.277
		3-5	80%	1.095	0.622
	0.9	5-10	80%	0.418	0.235
Rubber asphalt	1.5	5-10	0	0.673	0.550
			40%	0.772	0.651
			80%	0.778	0.788

Table 10: Bond strength of SBS modified emulsified asphalt

	Tack coat application rate (kg/m^2)	Shear strength(MPa)	Tensile strength(MPa)
SBS modified emulsified asphalt	0.2	0.508	0.316
	0.4	0.599	0.358
	0.6	0.930	0.487



(a) SBS modified asphalt (b) Rubber asphalt (c) SBS modified emulsified asphalt

Figure 10: Bond strength of rubber asphalt and SBS modified emulsified asphalt

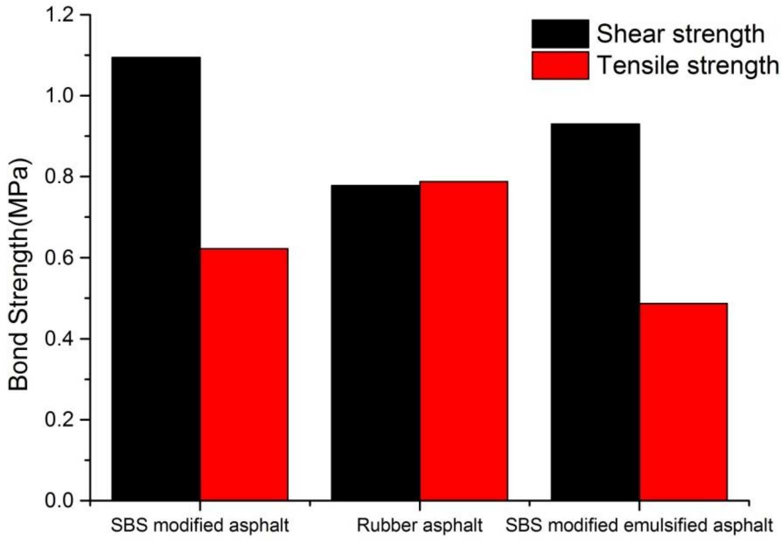


Figure 11: Bond strength of three types of asphalt

In the process of old road reconstruction by porous asphalt overlay, *Technical Specifications for Design and Construction of Porous Asphalt Pavement* recommends the material type and dosage of the waterproof and cohesive layer. On driving lane, it recommends $1.5kg/m^2 \pm 0.2kg/m^2$ rubber asphalt with the thicMPaess of 5mm, the particle size of gravel is 5-10mm, and the coverage of gravel is 60% to 70%. On emergency lane, it recommends $0.3kg/m^2 \pm 0.05kg/m^2$ SBS modified emulsified asphalt. Therefore, take these two kinds of materials as a comparison to verify if SBS modified asphalt could reach or surpass their bond strength.

(1) Figure 11 compares three optimal combinations of three types of asphalt. From figure 11, it is noticeable that waterproof and cohesive layer made of SBS modified asphalt experiences a stronger shear strength than rubber asphalt and SBS modified emulsified asphalt.

(2) For SBS modified asphalt, in table 9 it can be seen that the dosage of asphalt is $1.2kg/m^2$, the particle size of gravel is 3-5mm and coverage of gravel is 80% reaches the best performance of bond strength. It meets the conclusions obtained above. The failure surfaces were uneven, which also shew excellent bond strength. Compared with rubber asphalt and SBS modified emulsified asphalt, as figure 11 and table 9 show, the shear strength is the strongest, the tensile strength is lower than rubber asphalt. Therefore, three combinations that can

achieve a similar level of bond strength are recommended. Also, as figure 10(a) shows, the bond strength increases with the increase of dosage of asphalt.

(3) For SBS modified asphalt with 80% coverage of 5-10 mm gravel, when the tack coat rate reaches 1.2kg/m^2, the optimal dosage, compared with 40% coverage of gravel the shear strength and tensile strength decrease 40% and 55% respectively.

(4) For rubber asphalt, as figure 10(b) shows the bond strength increases with the increase of coverage of gravel, and its tensile strength is the strongest among these three bond materials.

(5) For SBS modified emulsified asphalt, as figure 10(c) shows, the bond strength increases with the increase of dosage of asphalt.

Conclusions

(1) In this study, the bond strength between porous asphalt and asphalt concrete was investigated by conducting indoor tests and outdoor tests. And the factors affecting bond strength were analysed. When the temperature rose from 25℃ to 40℃, the maximum shear strength and maximum tensile strength decreased 59% and 47% respectively. The results clearly show that the strength of tack coat material is affected by the temperature most.

(2) Considering three factors, obtained conclusions on bond strength by indoor tests. When temperature is 25°C, 1.2kg/m^2 is the optimal dosage of SBS modified asphalt, 3-5mm and 5-10mm are recommended particle size, and optimal coverage of gravel is 70% and 80%.

(3) By conducting infiltration test, all the combinations of tack coat shew excellent waterproofness.

(4) Based on the conclusions of indoor tests, a test road was constructed. Three combinations made of SBS modified asphalt are recommended, which can achieve the similar quality of bond strength compared with rubber asphalt and SBS modified emulsified asphalt. These combinations are 1.2kg/m^2 asphalt with 80% coverage of 3-5mm gravel, 1.2kg/m^2 asphalt with 40% coverage of 5-10mm gravel and 1.2kg/m^2 asphalt without gravel.

References

[1]. Ministry of Communication, Specifications for Design of Highway Asphalt Pavement (JTD D50–2006), China Communication Press, Beijing, China, 2006

[2]. Romanoschi, S. A. Characterization of Pavement Layer Interfaces. PhD dissertation. Louisiana State University, Baton Rouge, 1999.

[3]. Khweir, K., and D. Fordyce. Influence of Layer Bond on the Predictionof Pavement Life. Proceedings of the Institution of Civil Engineering–Transport, Vol. 156, 2003, pp. 73–83.

[4]. Papagiannakis A T, Tashman L, Nam K. Evaluation of the Influence of Tack Coat Construction Factors on the Bond Strength Between Pavement Layers [J]. Milling, 2006.

[5]. Yang J. Bond condition between surface layer and immediate layer in porous asphalt pavement [J]. Journal of Southeast University (English Edition), 2007.

[6]. Chen J S, Huang C C. Effect of Surface Characteristics on Bond Properties of Bituminous Tack Coat [J]. Transportation Research Record Journal of the Transportation Research Board, 2010, 2180(-1):142-149.

[7]. Yildirim Y, Smit AdF, Korkmaz A. Development of a laboratory test procedure to evaluate tack coat performance. Turk. J. Eng. Environ. Sci. 2005; 29:195–205.

[8]. Diakhaté M, Millien A, Petit C, et al. Experimental investigation of tack coat fatigue performance: towards an improved lifetime assessment of pavement structure interfaces. Constr. Build. Mater. 2011; 25:1123–1133.

[9]. Junior MSM. Evaluation of bond performance of an ultra-rapid setting emulsion for tack coat applications. State College, PA: The Pennsylvania State University; 2009.

[10]. Al-Qadi IL, Hasiba KI, Cortina AS, et al. Best practices for implementation of tack coat: part I-laboratory study. Rantoul, IL: Illinoise Center for Transportation; 2012. (Research Report: no. FHWA-ICT-12-004)

[11]. Sokolov K, Gubler R, Partl M. Extended numerical modeling and application of the coaxial shear test for asphalt pavements. Mater. Struct. 2005; 38:515–522.
[12]. Santagata E, Canestrari F. Tensile and shear tests of interfaces in asphalt mixes: a new prospective on their failure criteria. 2nd International Symposium Highway Surfacing; 1994;
[13]. Mohammad LN, Bae A, Elseifi MA, et al. Evaluation of bond strength of tack coat materials in field. Transport. Res. Rec.: J. Transport. Res. Board. 2009; 2126:1–11.
[14]. Woods ME. Laboratory evaluation of tensile and shear strengths of asphalt tack coats. Mississippi State University Starkville; 2004.
[15]. Hakimzadeh S, Kebede NA, Buttlar WG, et al. Development of fracture-energy based interface bond test for asphalt concrete. Road Mater. Pavement Des. 2012; 13:76–87.
[16]. Liu P, Hu J, Wang D, et al. Modelling and evaluation of aggregate morphology on asphalt compression behavior [J]. Construction & Building Materials, 2017, 133:196-208.
[17]. Rahman A, Ai C, Song J, et al. Characterization of Interface Bonding in Asphalt Pavement Layers Based on Direct Shear Tests with Vertical Loading[J]. Journal of Materials in Civil Engineering, 2017, 29(9).
[18]. Garcia D. Image segmentation using Otsu thresholding [J]. Image Processing, 2010.
[19]. Raposeiras A C, Ángel Vega-Zamanillo, Calzada-Pérez M Á, et al. Influence of surface macro-texture and binder dosage on the adhesion between bituminous pavement layers [J]. Construction & Building Materials, 2012, 28(1):187-192.
[20]. He Liangjie. The properties and application of high viscosity asphalt binder for bridge deck [D]. Changsha University of Science and Technology, 2009.