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Comparative Study on the Early Stage of Skid Resistance Development Between Polyurethane-bound Porous Mixture and Asphalt Mixture

Jiachen Shi[1], Lin Cong[2], Fan Yang[3], Tongjing Wang[4], Le Tan[5], Meng Yu[6]

[1] Ph.D. candidate, The Key Laboratory of Road and Traffic Engineering, Ministry of Education, Tongji University, 4800 Cao'an Rd., Shanghai, 201804, China. Email: s_jia_chen@tongji.edu.cn

[2] Professor, The Key Laboratory of Road and Traffic Engineering, Ministry of Education, Tongji University, 4800 Cao'an Rd., Shanghai, 201804, China. Email: conglin@tongji.edu.cn

[3] Ph.D. candidate, The Key Laboratory of Road and Traffic Engineering, Ministry of Education, Tongji University, 4800 Cao'an Rd., Shanghai, 201804, China. Email: 1810506@tongji.edu.cn

[4] Ph.D. candidate, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, Delft 2628 BL, The Netherlands Email: tongjing.wang@tudelft.nl

[5] Ph.D. candidate, The Key Laboratory of Road and Traffic Engineering, Ministry of Education, Tongji University, 4800 Cao'an Rd., Shanghai, 201804, China; Engineer, Highway Administration of Huzhou, Huzhou 313000, China. Email: tanle0572@163.com

[6] Engineer, State Key Laboratory of Special Functional Waterproof Materials, Beijing Oriental Yuhong Waterproof Technology Co. Ltd, Beijing, 100123, China. Email: yumeng@yuhong.com.cn

ABSTRACT

The polyurethane-bound porous mixture (PPM) is a new type of pavement materials, which has shown some potentials of overcoming common asphalt mixtures mechanical failures, but little research has been done on its skid resistance performance. This study conducted a comparative study of the skid resistance development between PPM and asphalt mixtures at their early stage. In this study, three mixtures bonded by polyurethane, 70# virgin bitumen and SBS modified asphalt, respectively, were compared and were named as PPM, BAM and SAM. A Taber Abraser was used to test the polishing property of binders. A Third-scale Model Mobile Loading Simulator (MMLS3) was used to simulate the traffic loadings on mixtures and then the British Pendulum Tester was used to measure the skid resistance of the three types of mixtures in the loading process. The binder polishing test results show a good linear relationship between the binder's mass loss and the polishing cycle. The slop of the fitting line of the two parameters was defined as Binder Coefficient (BC) to characterize the polishing property of binder. The mixture test results show that the skid resistance development trend (increase first, then decrease, and finally flatten) of three mixtures is similar, but the British

Pendulum Number peak value and stable value of PPM are lower than that of SAM. The order of the Number of Loading Times of Peak (NLTP) of three mixtures is SAM>PPM>BAM. Another good linear relationship is also found between BC and NLTP, and the R^2 of the fitting model is 0.85, which indicates the polishing property of binder is a good factor to predict the occasion that the skid resistance peak value occurs.

Keywords: Polyurethane-bound Porous Mixtures, Skid Resistance Development, Model Mobile Load Simulator Equipment, Polishing Property of Binder

INTRODUCTION

The polyurethane-bound porous mixture (PPM) is a new type of pavement materials. The benefits of PPM include great mechanical strength, high durability, and fast drainage ability, environmental-friendliness in the construction process (Chen, Yin, Wang and Ding, 2018, Cong, Wang, Tan, Yuan and Shi, 2018, Lu, Renken, Li, Wang, Li and Oeser, 2019). However, few studies have been done to explore the skid resistance development of PPM.

Research(Cong, Wang, Tan, Yuan and Shi, 2018) shows that the mechanical performance of PPM is close to asphalt mixtures than concrete, therefore, this paper aims to characterize the skid resistance of development of PPM and compare it with traditional asphalt mixtures. The common investigations of skid resistance development can be classified into two categories: field measurement and laboratory tests.

The field measurement is conducted by studying the influence of potential factors on skid resistance development over time. Ahammed et al. found that the skid resistance development has a strong correlation with the pavement temperature and aggregate, and proposed a simple linear model of skid resistance development and time which satisfy different asphalt mixture gradations (Ahammed and Tighe, 2009, Ahammed and Tighe, 2012). Echaveguren et al. presented a skid resistance development model considering the polishing effect of heavy loads by a polishing equivalence factor (Echaveguren, de Solminihac and Chamorro, 2010). The effects of maximum nominal particle size, fine aggregate content and traffic volume on skid resistance development of asphalt mixtures were studied as well. (Kotek and Florkova, 2014, Miao, Li, Zheng and Wang, 2016, Plati and Georgouli, 2014).

The laboratory studies characterize the physical processes of skid resistance development and build skid resistance development models for prediction. Xu et al. proposed that the polishing effects of same loading sequences with different order on the pavement are the same (Yang, HongXing, QiSen and ChongLu, 2010). Do et al. explored the long-term polishing process of aggregates with a Wehner/Schulze polishing machine and found that due to the differences of mineral, the polishing mechanisms of aggregate can be divided to “general polishing” and "differential polishing" (Do, Tang, Kane and de larrard, 2009). Do et al. also presented a two stages of asphalt mixtures polishing mechanisms (1) binder removal and (2) aggregate polishing (Do, Kane, Tang and de Larrard, 2009). Subsequent laboratory researches focused on quantitative studies of skid resistance development for certain material combinations (Asi, 2007, Kane and Edmondson, 2018, Wang, Chen, Yin and Steinauer, 2011).

It is general acknowledged that the skid resistance development of asphalt mixtures can be classified into three stages: (1) rapid increase (within half a year to two years) due to exposing the micro-texture of aggregates by polishing out the binder; (2) slow decrease (over five years) due to the polishing effects on aggregates; (3) stability since the surface texture almost disappeared. As the most commonly used materials in the pavement, the common asphalt mixtures' skid resistance development has basically thorough investigated. However, Qian's research on epoxy asphalt mixture shows that with the similar mixture gradation, the skid resistance development trend of epoxy asphalt mixture was the same as the asphalt mixtures but the peak value of epoxy asphalt mixture appeared later and also higher than that of the asphalt mixtures' (Zhen-dong, Yang, Chang-bo and Dong, 2016, Zheng, Qian, Liu and Liu, 2018). The macromolecular structure of Polyurethane and the binder-aggregate adhesion of PPM are different from that of asphalt mixtures and epoxy asphalt mixture, the difference of skid resistance development of PPM and asphalt mixtures is not clearly known.

The studies regarding the influence of asphalt binder properties on skid resistance development is a guide for evaluating PPM skid resistance. The effects of asphalt ageing, different asphalt properties and affinity of aggregate and asphalt on the skid resistance of asphalt pavement have been studied to a large extent. Zhao et al. found the ageing of asphalt led to a rise of skid resistance (Zhao, Kane and Do, 2010). Kane et al. thought the effect of time on skid resistance is reflected in the ageing of asphalt, and applied the effect of ageing in the Do-Kane model by making a parameter to be time-dependent (Kane, Zhao, Do, Chailleux and De-Lalarrard, 2010). Kane et al. also compared the changes in skid resistance and the carbonyl index, a chemical function linked to asphalt ageing and found that the ageing of the organic phase of the asphalt caused an increase of skid resistance in the first year (Kane, Zhao, Chailleux, Delarrard and

Do, 2013). Hadiwardoyo et al. investigated the relationship of skid resistance and asphalt penetration index, which shows a fairly strong correlation, the higher the penetration index, the larger skid resistance (Hadiwardoyo, Sinaga and Fikri, 2013). Wang et al. found the affinity of aggregate and asphalt affect the removal speed of the asphalt film, the maximum and the final value of skid resistance (Wang, Chen, Yin, Oeser and Steinauer, 2013). As the above studies have shown, different asphalts will lead to a difference in the skid resistance value and the skid resistance development in asphalt pavement. However, for the PPM and the asphalt mixtures, because of the difference of binder, the differences of skid resistance are still unclear. A comparative study on the skid resistance development between PPM and asphalt mixtures is necessary.

The objective of this study was to investigate the difference between the early stage of skid resistance development of PPM and asphalt mixtures. In this paper, the polishing property of three binders was tested by a Taber Abraser . A third-scale Model Mobile Loading Simulator (MMLS3) was used to simulate the vehicle loading on the pavement, and the British pendulum number (BPN) of three mixtures were measured to characterize the skid resistance of mixture in the loading process. In the end, a model between the polishing property of binder and early stage of skid resistance development of mixture is proposed by analyzing the test results.

METHODS

Materials

Three binders were used in this study, polyurethane, SBS (Styrene–Butadiene–Styrene) modified asphalt and 70# virgin bitumen. The polyurethane was developed by BASF Polyurethane Specialties (China) Company Ltd. (BASF). The coarse aggregates (size more than 4.75mm) are basalt from Guizhou, China and the fine aggregates are limestone from Jiangsu, China. The physical properties of raw materials are shown in Table 1. Three mixtures bonded by polyurethane, SBS modified asphalt and 70# virgin bitumen were compared in this study and were named PPM, SAM and BAM, respectively. The gradation of mixtures is OGFC-13 (Open Graded Friction Course) and is shown in Table 2. The volumetric properties of three mixtures are shown in Table 3.

Table 1. Physical properties of the raw materials

Item	Physical properties	Measured value	Test method
Basalt aggregate	Los Angeles abrasion value (%)	14.7	ASTM C131
	Crushing value (%)	10.2	ASTM C131
	Polished stone value (%)	46	ASTM D3319
polyurethane	Density (g/cm^3)	1.04	ASTM D1505
	Tensile strength (MPa)	25.3	ASTM D638
	Elongation (%)	67.2	ASTM D638
	E-modulus (N/mm^2)	390	ASTM D638
	Flexural strength (MPa)	10.7	ASTM D790
	Flexural modulus (MPa)	526	ASTM D790
SBS modified asphalt	Penetration (25°C, 100g, 5s)	55	ASTM D5-06
	Softening point (°C)	68.5	ASTM D36
	Ductility (15°C, cm)	28	ASTM D113
70# virgin bitumen	Penetration (25°C, 100g, 5s)	76	ASTM D5-06
	Softening point (°C)	49.3	ASTM D36
	Ductility (15°C, cm)	>100	ASTM D113

Table 2. The gradation of the used OGFC-13

Sieve size (mm) / Percentage passing (%)	13	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Upper Limit	100	80	45	28	20	16	10	8	6
OGFC-13	95	70	21	16	12	10	8	6	4
Lower Limit	90	50	20	8	4	2	0	0	0

Table 3. The volumetric properties of three mixtures

Volumetric Properties	Mixture			Test Method
	PPM	SAM	BAM	
Binder-aggregate Ratio (%)	5.0	5.0	5.0	-
Bulk Density (g/cm^3)	2.09	2.11	2.12	ASTM D2726
Air Void Content (%)	17.7	16.9	17.3	ASTM D6926

Instruments and test methods

To investigate the effects of binders on the early stage of skid resistance development of the mixture, the polishing property of binder was evaluated using the ASTM D4060-14 method (ASTM, 2007). The method was used to measure the polishing property of traffic marking materials in China. Taber Abraser, the test instrument in this method, is shown in the of Figure 1a. The specimen holder and the abrading wheel rotate simultaneously to polish the binder coating on the round glass which is fixed on the specimen holder. The Mass Loss (ML) of the specimen (binder and round glass) is measured after polishing. The width, diameter of the abrading wheel and the diameter of the specimen are 12.7mm, 50mm and 100mm, respectively. The auxiliary weight is 1kg each side. The polishing cycles is 3500 which is confirmed by a pre-test.

The MMLS3 (Figure 1b) was used to simulate the long-term polishing of mixtures under vehicle loads and the British Pendulum Tester (Figure 1c) was used to measure the skid resistance of mixture. The MMLS3 is a unidirectional vehicle load accelerated pavement testing simulator including four bogies, and each bogie has one pneumatic tire. The tire is 300mm in diameter and 80mm in width. The surface contact pressure of tire was 0.7 MPa, and the running speed of tire was 7200 repetitions/h in this study. The MMLS3 can test three slabs in one time. The BPN of the mixture was tested in some certain loading number.

a) Taber Abraser b) MMLS3 c) British Pendulum Tester

Fig.1. Test instruments in this study

Test procedures

The tests in this paper can be categorized into the binder's polishing property test and the mixture's skid resistance development test.

The procedure for the binder's polishing property test is illustrated in Figure 2 and described below. The test temperature was around 20°C and there were three specimens for each binder.

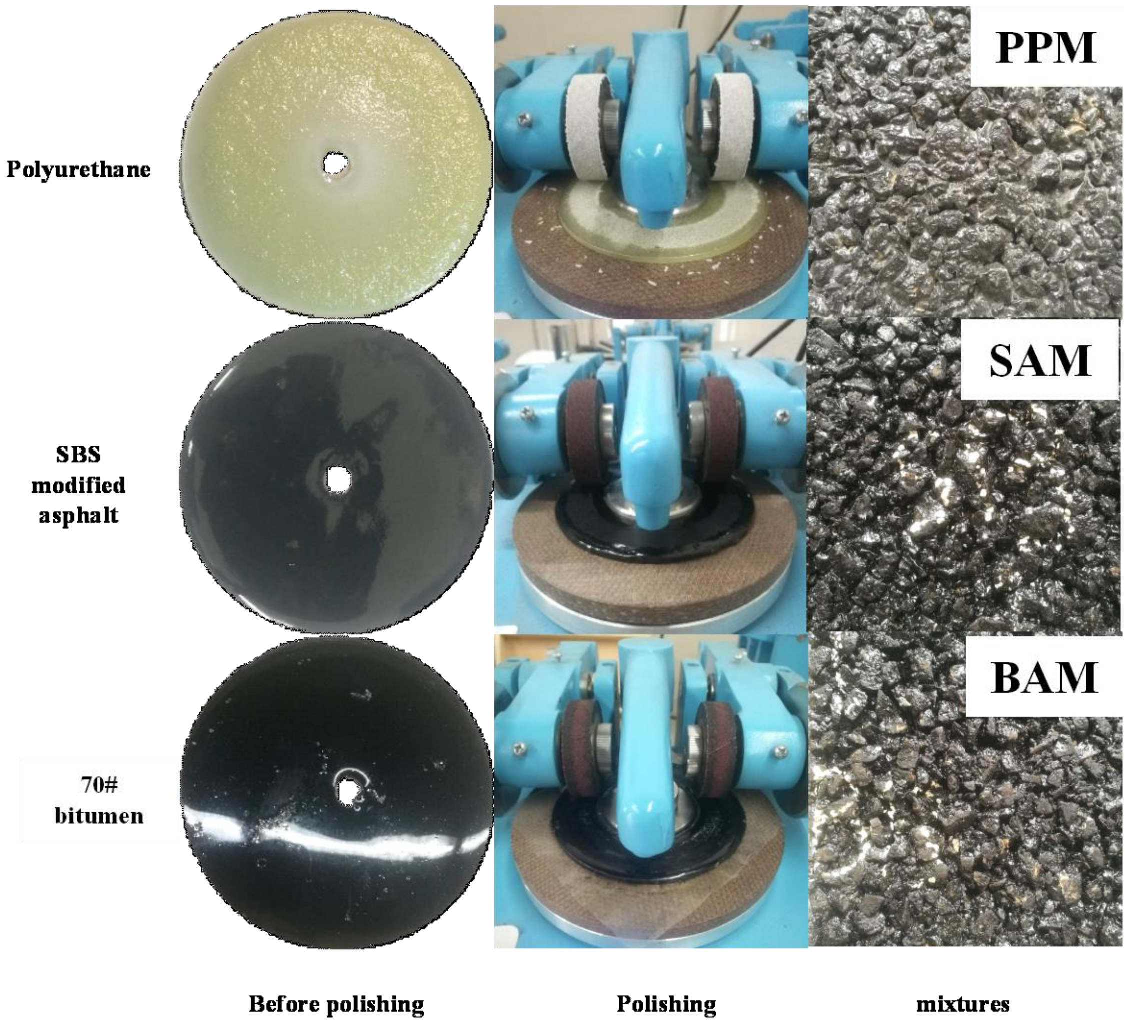


Fig.2. The different stages of the specimen in the polishing process

(1) Preparing the binder specimens. The raw materials, isocyanate and polyol were mixed with a ratio 100:60 to make the polyurethane and then the fluid polyurethane was uniformly coated on the round glass. The asphalt was heated before coating on the glass. The specimens were maintained in an indoor environment more than three days. The pictures in the first column of Figure 2 are the prepared binder specimens which is polyurethane, SBS modified asphalt and 70# virgin bitumen from top to bottom, respectively.

(2) Polishing the binder specimens. The specimen was fixed on the specimen holder and was polished after the Taber Abeaser operated. The second column in Figure 2 is the polishing process.

(3) Weighing the ML of the binder. The specimen was weighed after each hundred polishing

cycles. Before weighting, the debris on the specimen surface was cleaned by a brush. The polishing cycles of polyurethane and SBS modified asphalt are 3500 times. The polishing cycles of 70# virgin bitumen is 1700 times.

The procedure for the mixture's skid resistance development test includes the following parts. The test temperature was between 30-36℃ and measured by a thermometer. Each BPN was the average of five testing results.

(1) Preparing the mixture slabs. The mixture slabs (300mm × 300mm × 50mm) was made by the wheel rolling compactor. The compacting number was 24. The compacting temperature of PPM, SAM and BAM were 25℃, 110℃, and 110℃, respectively. The pictures in the third column of Figure 2 are the prepared mixture slabs.

(2) Cutting the mixture slabs. In order to put the slabs into the test platform of MMLS3, the standard size slabs were cut into 300mm × 250mm × 50mm slabs. The direction of the length corresponds to the direction of compaction and wheel running.

(3) Placing the mixture slabs and adjusting the MMLS3. The cut slabs were placed in the test platform, and the contact pressure and loading frequency were 0.7 MPa and 7200 repetitions/h, respectively.

(4) Measuring the BPN (to characterize the skid resistance of mixture). After loading a certain number of times, the slabs were taken out to measure the BPN in the wheel path. In this study, the total loading times are 300,000, and the test frequency of BPN in the early stage is higher than the frequency in the later stage.

RESULTS AND DISCUSSIONS

Binder polishing test results

The view of polished binders is shown in the last two columns of Figure 3, and the results of binders polishing are shown in **Figure 3** and **Table 4**.

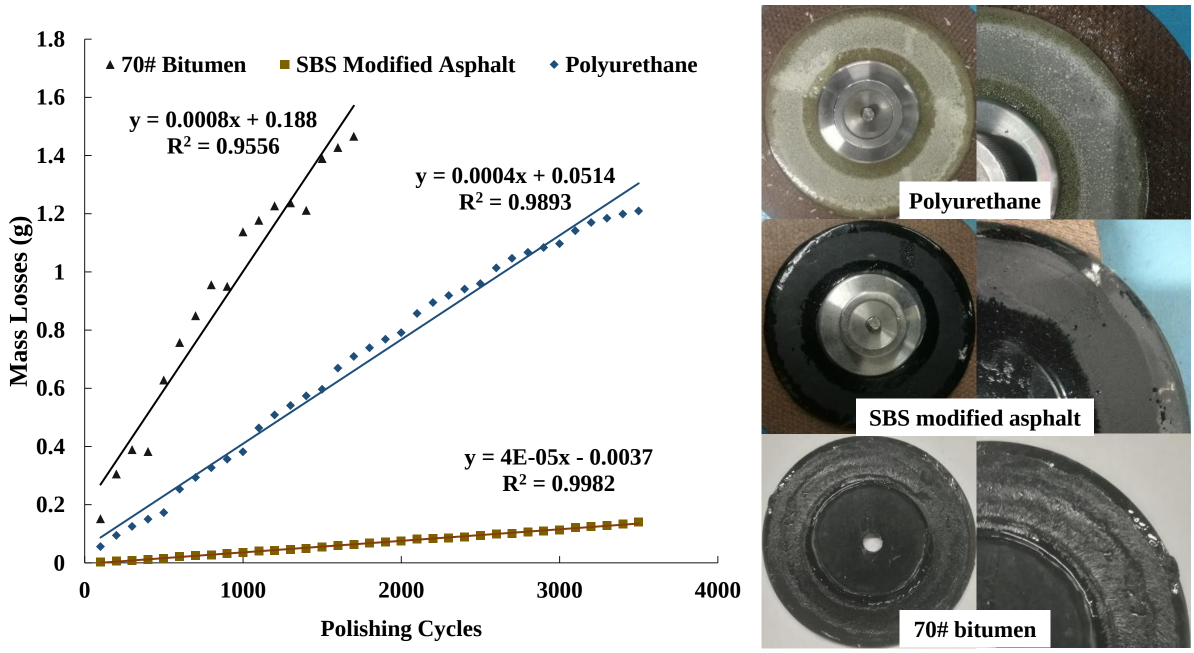


Fig.3. The polishing results of binders

Table 4. The result of binders polishing

	Polyurethane	SBS modified asphalt	70# virgin bitumen
Fitting equation	ML = 0.0004PC + 0.0514	ML = 0.00004PC − 0.0037	ML = 0.0008PC + 0.1880
R^2	0.9893	0.9982	0.9556
BC	0.0004	0.00004	0.0008

As shown in Figure 3, the three binders show different appearances after polishing. Both the polyurethane and 70# virgin bitumen showed a deep rut on the surface, but SBS modified asphalt only showed a little polish. The loss binders of 70# and SBS modified asphalt adhered to the abrading wheels, but the loss polyurethane adhered to the abrading wheels and scattered around. The polyurethane was polished to powders and showed a rigid characteristic, which is like polished cement. The SBS modified asphalt was like an elastomer in the polishing process, and only the surface was polished and became smooth. The 70# virgin bitumen had a strong viscosity and a deep rut after the polishing process, which caused large ML. During the test on

70# virgin bitumen, the polishing texture on the surface gradually disappeared and became smooth again.

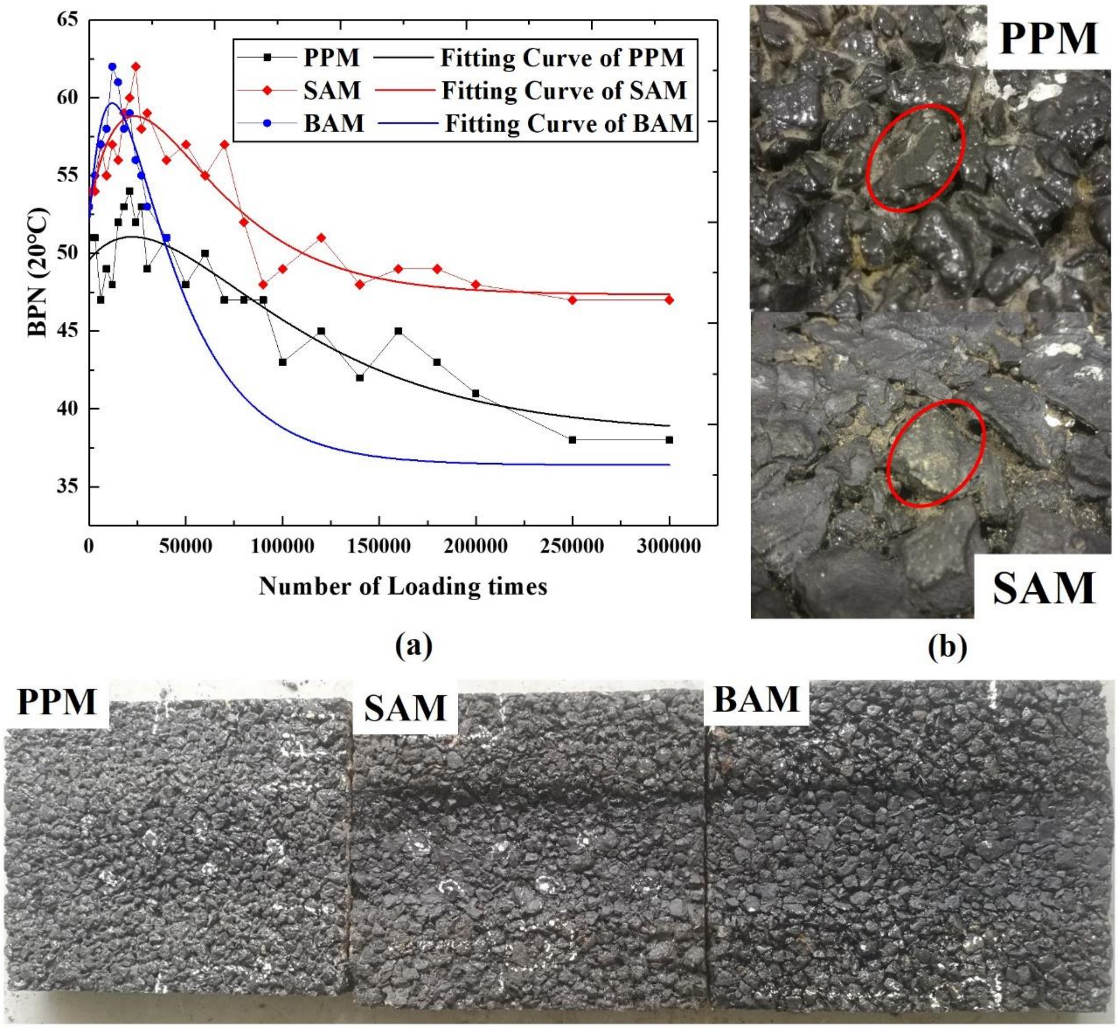
As shown in Figure 3, the horizontal and vertical axes are the polishing cycles and the ML of binder specimen, respectively. There is a good linear relationship between the ML and the polishing cycles for the three binders. The order of slopes is 70# virgin bitumen > polyurethane > SBS modified asphalt. After polished 3500 times, the polyurethane in the wheel track disappeared, and the underlying round glass was exposed. The SBS modified asphalt showed a similar result the polyurethane. The polishing cycles of 70# virgin bitumen was 1700 times, which is only half the cycles of polyurethane. As can be seen from Figure 3, five points are a group and increase a little value than the previous group. This is because in the ASTM D4060-07, the abrasive paper on the abrading wheels need to be replaced every 500 times to ensure the abrading wheels have a continuous abrading effect.

Table 4 shows the statistics of the regression equation for the result of binders polishing. The three rows are the regression equations, R2 and the slope of the line, respectively. The slope was defined as Binder Coefficient (BC) to characterize the polishing property of binder. The lower the BC is, the less the mass losses, which means the binder film in the mixture have a longer life under same traffic. When the polishing results are regressed to linear functions, all the R2 are bigger than 0.95, which indicated the linear function could competently describe the relationship between polishing cycles and ML. The 70# virgin bitumen has a BC double that of the polyurethane and ten times that of the SBS modified asphalt under the same polishing conditions.

Mixture skid resistance development test results

The mixture skid resistance development test results and the appearances of slabs after the test are shown in Figure5. The Figure 4a shows the BPN development of three mixtures with the increase of Number of Loading times (NL). As shown in the Figure 4a, the general trend of BPN development of three mixtures with the increase of NL are similar, increase first, then decrease, and finally flatten. As shown in Figure 4a, the increase and decrease speed of

PPM is higher than that of SMA and BAM. The peak of PPM is sharper than that of SAM and BAM. So, the BPN development of SAM and BAM are more similar than that with PPM. There was a large deformation in BAM when the NL is 4 × 104, so the test on BAM was finished in the early stage. The BPN value of PPM is lower than that of SAM and BAM, and the BPN peak value of SAM and BAM are similar. The order of the Number of Loading Times of Peak (NLTP) of three mixtures is SAM>PPM>BAM.



(c)

Fig.4. The polishing results of mixtures:(a) BPN results; (b) aggregate without binder coverage; (c) appearance of slabs after test.

The Figure 4b is the surface of mixture slabs when the NL of PPM is 8 × 104 and the NL of SAM is 1 × 105. It can be seen that the binder on the aggregate removed. The Figure 4c is the appearances of three mixture slabs after mixture's skid resistance development test. There is almost no rutting in PPM, and the rutting in BAM when NL is 4 × 104 is equivalent to the rutting in SAM when NL is 3 × 105. The rutting resistance of three mixtures in this study is consistent with the previous research (Cong, Wang, Tan, Yuan and Shi, 2018).

In order to describe the skid resistance development of the three mixtures, a fitting model proposed by Dawei Wang is used in this paper and is shown in Equation 1 (Wang, Chen, Yin, Oeser and Steinauer, 2013). Because the test instruments of the two studies are different, the model was shown in Equation 2. The fitting curves of three mixtures are shown with lines in the Figure 4a and the model parameters and R2 are shown in Table 5.

$$\mu(t) = \mu_0 + Aexp(-tB) + [Cexp(-tD) + F] \quad (1)$$

$$BPN(NL) = BPN_0 + Aexp(-NL \times B) + [Cexp(-NL \times D) + F] \quad (2)$$

In Equation 1, $\mu(t)$ is the skid resistance of mixture, and t is the polishing duration in minutes, and μ_0, A, B, C, D, F are coefficients. In Equation 2, $BPN(NL)$ is the BPN, and NL is the number of loading times of MMLS3, and BPN_0, A, B, C, D, F are coefficients.

Table 5. Parameters of the fitting models

	BPN_0	**A**	**B**	**C**	**D**	**F**	**R^2**
PPM	29.61578	-30	2.47E-05	41.20918	1.42E-05	9	0.8456
SAM	35.36337	-44.5195	4.33E-05	49.99997	2.53E-05	12	0.8782
BAM	29.04194	-34.3687	9.14E-05	49.99597	3.03E-05	7	0.8245

The polishing relationship between binder and mixture

Asphalt mixtures' skid resistance development is divided into three stages in the previous studies. The first stage is a rising stage and is caused by the binder removal (Do, Kane, Tang and de Larrard, 2009). The polishing property of binder (can be described by BC) decided the length of time required for the binder removal (can be described by NLTP). It can be seen from the mixtures polishing results that this is also the difference between the PPM and the asphalt mixtures in the early stage of skid resistance development. Equation 3 is obtained by deriving Equation 2. Equation 3 is to calculate the NLTP by the coefficients in the BPN development fitting model. The fitting line of the BC of three binders and the NLTP of three mixtures is shown in Figure 5. The linear model to describe the relationship of polishing property of binder and early stage of mixture's skid resistance development is shown in Equation 4.

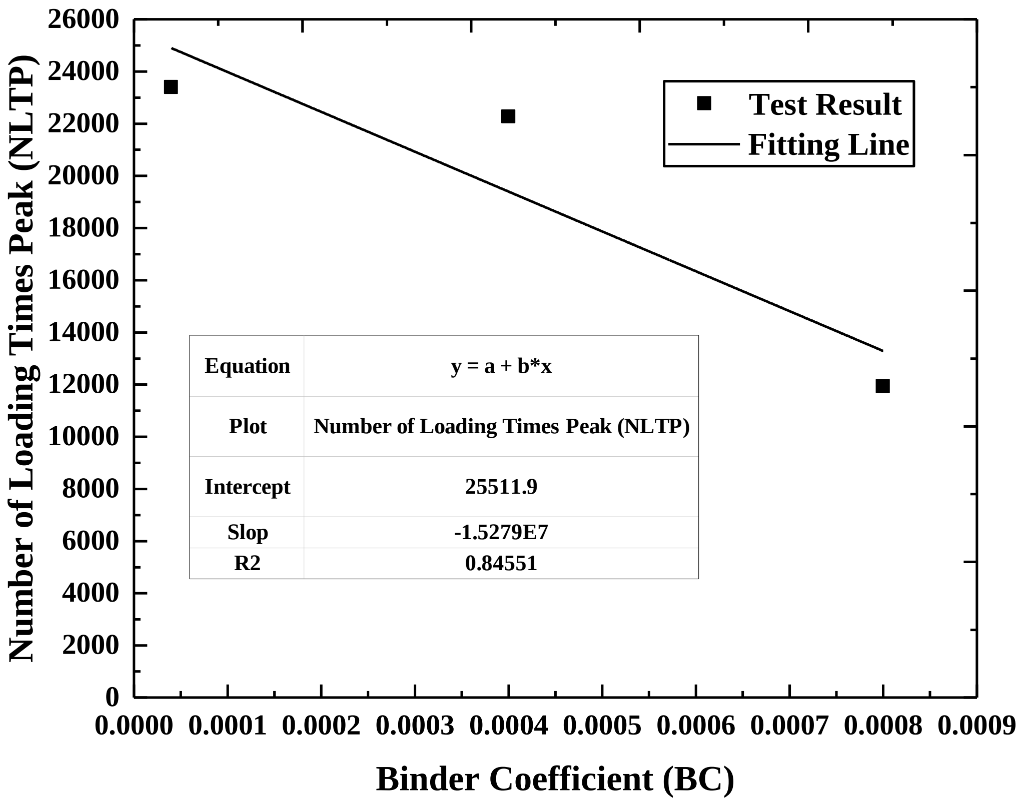


Fig.5. The relationship between BC and NLTP

$$NLTP = \frac{\ln(-AB) - \ln(CD)}{B - D} \tag{3}$$

In Equation 3, $NLTP$ is the NL when BPN reach the peak, and A, B, C, D are the coefficients in Equation 2.

$$NLTP = -15278970.02BC + 25511.9 \tag{4}$$

Where $NLTP$ is the NL when BPN reach the peak in Equation 2, and BC is the slope of ML and PC to characterize the polishing property of binder. The R2 of this linear fitting model is 0.85, which indicated the BC and NLTP has a good correlation. Because the fitting model is based on the results of polyurethane and asphalt materials, the model is suitable for OGFC-13 mixtures bonded by other binders. In addition, the form of this fitting model provides a reference for the similar research of different gradation mixtures. The occasion that the mixture skid resistance peak occurs can be predicted by the polishing property of binder which can guide the pavement management and maintenance.

CONCLUSIONS

In this paper, the differences of the skid resistance development between PPM and asphalt mixtures are investigated using MMLS3, and the relationship of polishing property of binder (characterized by BC) and the early stage of skid resistance development of mixture (characterized by NLTP) is analyzed. Several conclusions can be summarized as follows:

1. The Binder Coefficient can be used to characterize the polishing property of the binder. The BC of polyurethane is between that of the 70# virgin bitumen and SBS modified asphalt.

2. The early stage BPN of PPM satisfies the acceptance value in China, although it is weaker than that of asphalt mixtures. The BPN peak value and stability value of PPM is lower than that of SAM. The NLTP of PPM is higher than that of SAM and lower than that of BAM.

3. The three stages polishing mechanisms of asphalt mixtures is also applicable to the PPM. The polyurethane film in the PPM is easier to remove than the SBS modified asphalt film in the SAM under the axle load.

4. There is a good correlation between BC (characterizing the polishing property of binder) and NLTP (characterizing the early stage of skid resistance development of mixture). The R2 of the linear fitting model is 0.85 which means the occasion that the mixture skid resistance peak occurs can be predicted by the polishing property of binder used in the mixture.

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All the raw data that support the findings of this study are available from the corresponding author upon reasonable request.

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