

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

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1 **Comparative Study on the Early Stage of Skid Resistance Development**

2 **Between Polyurethane-bound Porous Mixture and Asphalt Mixture**

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17 **ABSTRACT**

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

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

37

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

40 **INTRODUCTION**

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

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

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

61 The laboratory studies characterize the physical processes of skid resistance development and
62 build skid resistance development models for prediction. Xu et al. proposed that the polishing
63 effects of same loading sequences with different order on the pavement are the same (Yang,
64 HongXing, QiSen and ChongLu, 2010). Do et al. explored the long-term polishing process of
65 aggregates with a Wehner/Schulze polishing machine and found that due to the differences of
66 mineral, the polishing mechanisms of aggregate can be divided to “general polishing” and

67 “differential polishing” (Do, Tang, Kane and de larrard, 2009). Do et al. also presented a two
68 stages of asphalt mixtures polishing mechanisms (1) binder removal and (2) aggregate
69 polishing (Do, Kane, Tang and de Larrard, 2009). Subsequent laboratory researches focused
70 on quantitative studies of skid resistance development for certain material combinations (Asi,
71 2007, Kane and Edmondson, 2018, Wang, Chen, Yin and Steinauer, 2011).

72 It is general acknowledged that the skid resistance development of asphalt mixtures can be
73 classified into three stages: (1) rapid increase (within half a year to two years) due to exposing
74 the micro-texture of aggregates by polishing out the binder; (2) slow decrease (over five years)
75 due to the polishing effects on aggregates; (3) stability since the surface texture almost
76 disappeared. As the most commonly used materials in the pavement, the common asphalt
77 mixtures’ skid resistance development has basically thorough investigated. However, Qian’s
78 research on epoxy asphalt mixture shows that with the similar mixture gradation, the skid
79 resistance development trend of epoxy asphalt mixture was the same as the asphalt mixtures
80 but the peak value of epoxy asphalt mixture appeared later and also higher than that of the
81 asphalt mixtures’ (Zhen-dong, Yang, Chang-bo and Dong, 2016, Zheng, Qian, Liu and Liu,
82 2018). The macromolecular structure of Polyurethane and the binder-aggregate adhesion of
83 PPM are different from that of asphalt mixtures and epoxy asphalt mixture, the difference of
84 skid resistance development of PPM and asphalt mixtures is not clearly known.

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

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

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

112 **METHODS**

113 **Materials**

114 Three binders were used in this study, polyurethane, SBS (Styrene–Butadiene–Styrene)
115 modified asphalt and 70# virgin bitumen. The polyurethane was developed by BASF
116 Polyurethane Specialties (China) Company Ltd. (BASF). The coarse aggregates (size more
117 than 4.75mm) are basalt from Guizhou, China and the fine aggregates are limestone from
118 Jiangsu, China. The physical properties of raw materials are shown in Table 1. Three mixtures
119 bonded by polyurethane, SBS modified asphalt and 70# virgin bitumen were compared in this
120 study and were named PPM, SAM and BAM, respectively. The gradation of mixtures is OGFC-
121 13 (Open Graded Friction Course) and is shown in Table 2. The volumetric properties of three

122 mixtures are shown in Table 3.

123 **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

124

125 **Table 2.** The gradation of the used OGFC-13

Sieve size (mm)	13	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
	Percentage passing (%)								
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

126

127

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

128 Instruments and test methods

129 To investigate the effects of binders on the early stage of skid resistance development of the
130 mixture, the polishing property of binder was evaluated using the ASTM D4060-14 method
131 (ASTM, 2007). The method was used to measure the polishing property of traffic marking
132 materials in China. Taber Abraser, the test instrument in this method, is shown in the of Figure
133 1a. The specimen holder and the abrading wheel rotate simultaneously to polish the binder
134 coating on the round glass which is fixed on the specimen holder. The Mass Loss (ML) of the
135 specimen (binder and round glass) is measured after polishing. The width, diameter of the
136 abrading wheel and the diameter of the specimen are 12.7mm, 50mm and 100mm, respectively.
137 The auxiliary weight is 1kg each side. The polishing cycles is 3500 which is confirmed by a
138 pre-test.

139 The MMLS3 (Figure 1b) was used to simulate the long-term polishing of mixtures under
140 vehicle loads and the British Pendulum Tester (Figure 1c) was used to measure the skid
141 resistance of mixture. The MMLS3 is a unidirectional vehicle load accelerated pavement
142 testing simulator including four bogies, and each bogie has one pneumatic tire. The tire is
143 300mm in diameter and 80mm in width. The surface contact pressure of tire was 0.7 MPa, and
144 the running speed of tire was 7200 repetitions/h in this study. The MMLS3 can test three slabs
145 in one time. The BPN of the mixture was tested in some certain loading number.



146

147 a) Taber Abraser

b) MMLS3

c) British Pendulum Tester

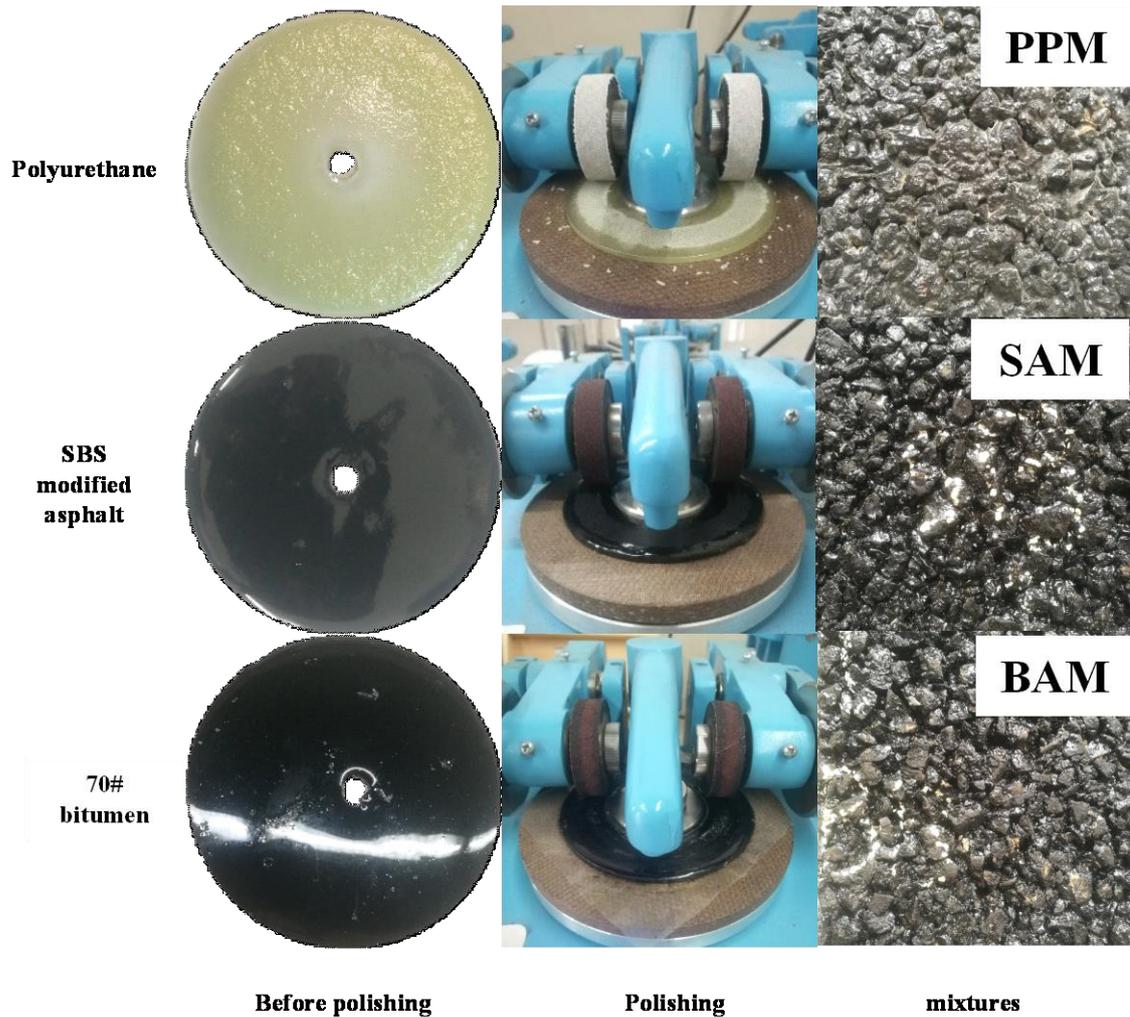
148

Fig.1. Test instruments in this study

149 **Test procedures**

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

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



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

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(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 Abreaser 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

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

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

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

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

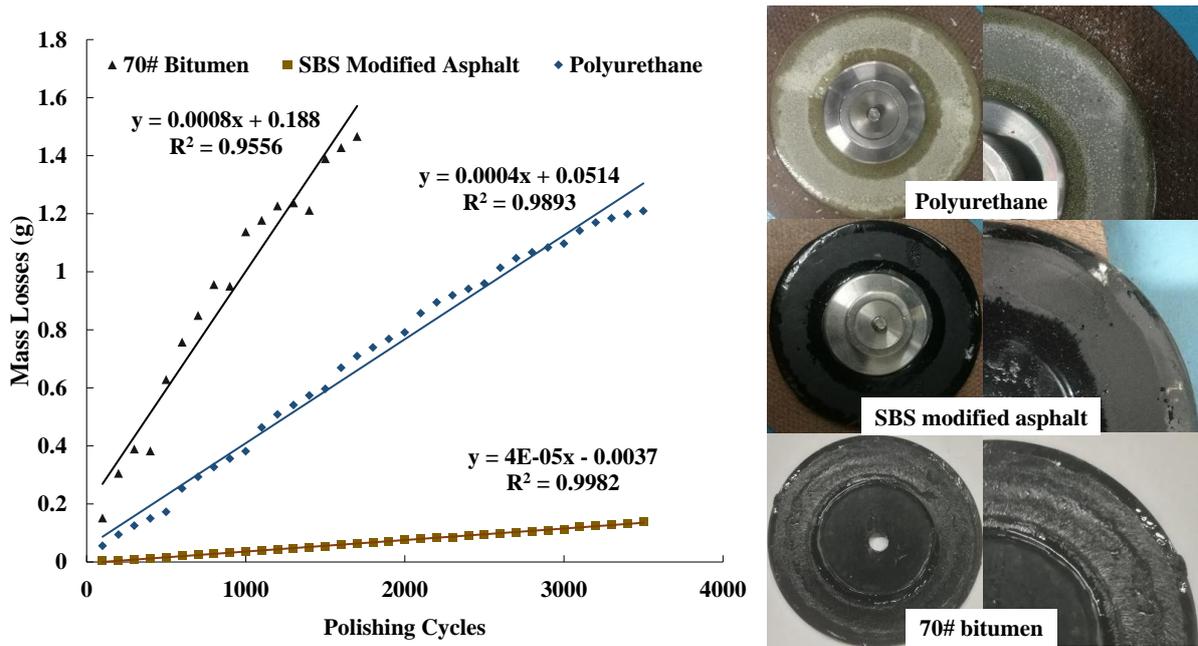
179 (3) Placing the mixture slabs and adjusting the MMLS3. The cut slabs were placed in the test
180 platform, and the contact pressure and loading frequency were 0.7 MPa and 7200 repetitions/h,
181 respectively.

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

186 **RESULTS AND DISCUSSIONS**

187 **Binder polishing test results**

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



190

191

Fig.3. The polishing results of binders

192

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

193

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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

201 70# virgin bitumen, the polishing texture on the surface gradually disappeared and became
202 smooth again.

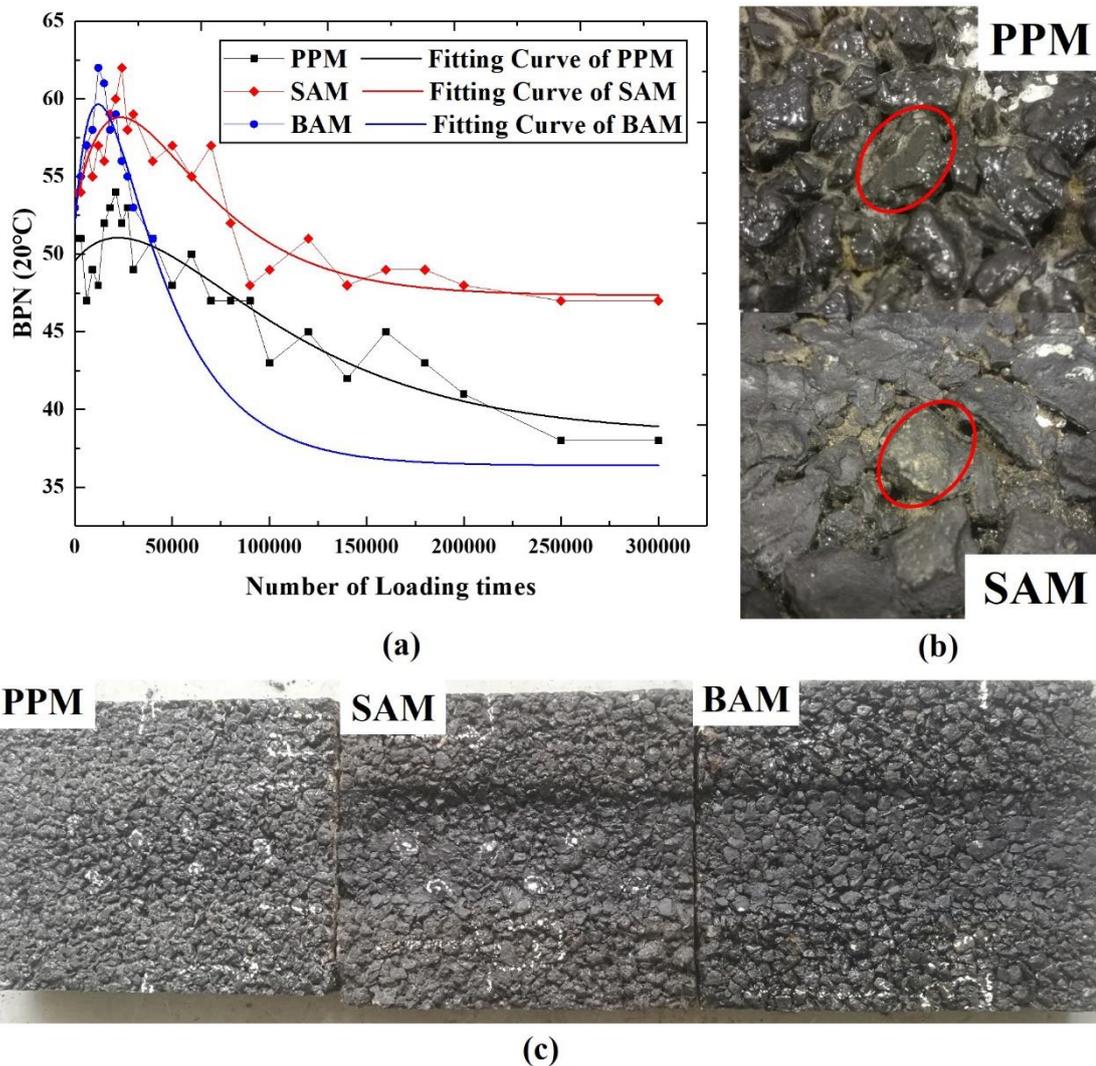
203 As shown in Figure 3, the horizontal and vertical axes are the polishing cycles and the ML
204 of binder specimen, respectively. There is a good linear relationship between the ML and the
205 polishing cycles for the three binders. The order of slopes is 70# virgin bitumen > polyurethane >
206 SBS modified asphalt. After polished 3500 times, the polyurethane in the wheel track
207 disappeared, and the underlying round glass was exposed. The SBS modified asphalt showed
208 a similar result the polyurethane. The polishing cycles of 70# virgin bitumen was 1700 times,
209 which is only half the cycles of polyurethane. As can be seen from Figure 3, five points are a
210 group and increase a little value than the previous group. This is because in the ASTM D4060-
211 07, the abrasive paper on the abrading wheels need to be replaced every 500 times to ensure
212 the abrading wheels have a continuous abrading effect.

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

222 **Mixture skid resistance development test results**

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

228 PPM is higher than that of SMA and BAM. The peak of PPM is sharper than that of SAM and
 229 BAM. So, the BPN development of SAM and BAM are more similar than that with PPM.
 230 There was a large deformation in BAM when the NL is 4×10^4 , so the test on BAM was
 231 finished in the early stage. The BPN value of PPM is lower than that of SAM and BAM, and
 232 the BPN peak value of SAM and BAM are similar. The order of the Number of Loading Times
 233 of Peak (NLTP) of three mixtures is SAM>PPM>BAM.



234
 235 **Fig.4.** The polishing results of mixtures:(a) BPN results; (b) aggregate without binder coverage;
 236 (c) appearance of slabs after test.

237 The Figure 4b is the surface of mixture slabs when the NL of PPM is 8×10^4 and the NL

238 of SAM is 1×10^5 . It can be seen that the binder on the aggregate removed. The Figure 4c is
 239 the appearances of three mixture slabs after mixture's skid resistance development test. There
 240 is almost no rutting in PPM, and the rutting in BAM when NL is 4×10^4 is equivalent to the
 241 rutting in SAM when NL is 3×10^5 . The rutting resistance of three mixtures in this study is
 242 consistent with the previous research (Cong, Wang, Tan, Yuan and Shi, 2018).

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

$$248 \mu(t) = \mu_0 + A \exp(-tB) + [C \exp(-tD) + F] \quad (1)$$

$$249 BPN(NL) = BPN_0 + A \exp(-NL \times B) + [C \exp(-NL \times D) + F] \quad (2)$$

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

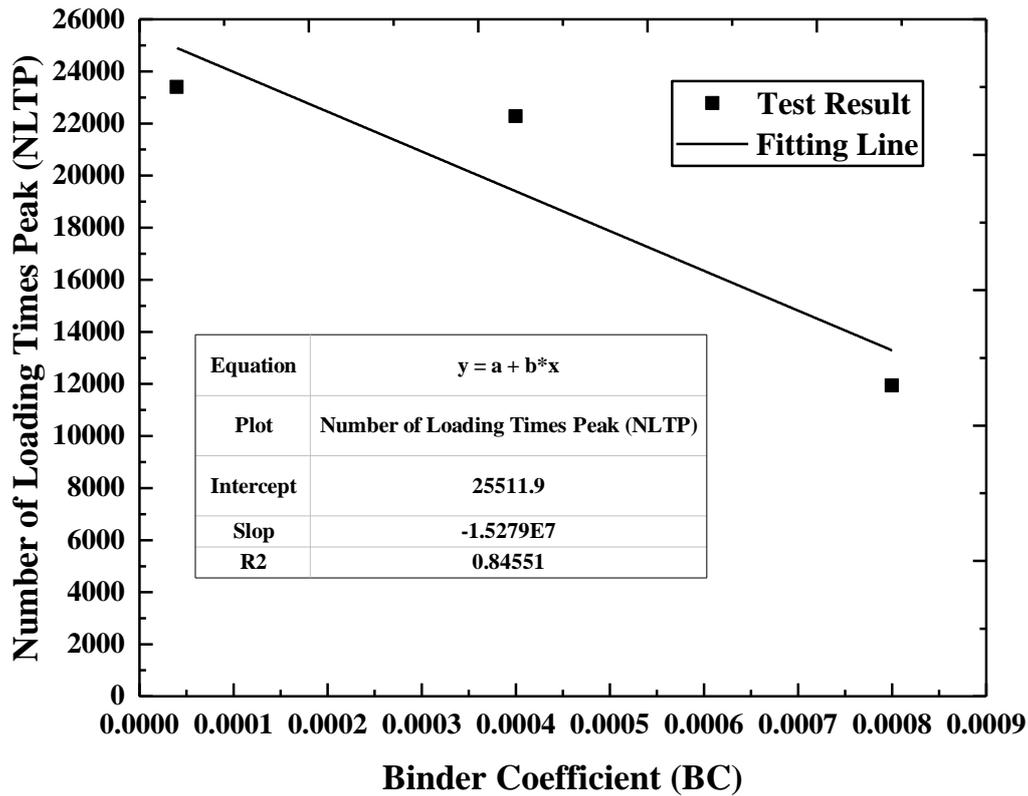
253 **Table 5.** Parameters of the fitting models

	BPN₀	A	B	C	D	F	R²
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

254 **The polishing relationship between binder and mixture**

255 Asphalt mixtures' skid resistance development is divided into three stages in the previous
 256 studies. The first stage is a rising stage and is caused by the binder removal (Do, Kane, Tang
 257 and de Larrard, 2009). The polishing property of binder (can be described by BC) decided the
 258 length of time required for the binder removal (can be described by NLTP). It can be seen from

259 the mixtures polishing results that this is also the difference between the PPM and the asphalt
 260 mixtures in the early stage of skid resistance development. Equation 3 is obtained by deriving
 261 Equation 2. Equation 3 is to calculate the NLTP by the coefficients in the BPN development
 262 fitting model. The fitting line of the BC of three binders and the NLTP of three mixtures is
 263 shown in Figure 5. The linear model to describe the relationship of polishing property of binder
 264 and early stage of mixture's skid resistance development is shown in Equation 4.



265

266

Fig.5. The relationship between BC and NLTP

267
$$NLTP = \frac{\ln(-AB) - \ln(CD)}{B - D} \quad (3)$$

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

270
$$NLTP = -15278970.02BC + 25511.9 \quad (4)$$

271 Where *NLTP* is the NL when BPN reach the peak in Equation 2, and BC is the slope of
 272 ML and PC to characterize the polishing property of binder. The R2 of this linear fitting model
 273 is 0.85, which indicated the BC and NLTP has a good correlation. Because the fitting model is

274 based on the results of polyurethane and asphalt materials, the model is suitable for OGFC-13
275 mixtures bonded by other binders. In addition, the form of this fitting model provides a
276 reference for the similar research of different gradation mixtures. The occasion that the mixture
277 skid resistance peak occurs can be predicted by the polishing property of binder which can
278 guide the pavement management and maintenance.

279 **CONCLUSIONS**

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

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

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

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

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

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

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