Performance Characterization of Asphalt Mixture Modified with One-component Polyurethane

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Abstract: Using polyurethane (PU) modified asphalt for paving purposes has recently gained increasing interest in both academia and industry. This study aims to characterize the engineering performance of the asphalt mixture modified with one-component PU and explore its adhesive mechanism. To achieve this objective, PU modified bitumen and asphalt mixture of two different PU contents (10% and 30%) were prepared. Various laboratory material property tests, such as rotational viscosity test of binder, Marshall test, indirect tensile strength test, Hamburg wheel-tracking test, moisture susceptibility, and indirect tensile fatigue test of PU modified mixture, were performed. Fourier transform infrared spectroscopy test was carried out to explore the adhesive mechanism between PU-modified binder and aggregate. The results indicated that the overall performances of asphalt mixture were increased significantly by PU prepolymer, including increased Marshall stability, indirect tensile strength, and resistance to moisture damage, rutting and fatigue damage. It was found that PU prepolymer can react with the hydroxyl groups on the aggregate surface, which contributed to better performance of asphalt mixture. The findings of this study may facilitate the further practical applications of one-component PU-modified bituminous materials in the pavement industry.

Keywords: polyurethane; performance characterization; adhesive; bitumen & tar; pavements & roads; UN SDG 9

1 Introduction

Growing needs in mobility and the simultaneous decrease of natural resources require innovative and sustainable solutions in terms of transportation infrastructure. As a major type of transportation infrastructure, pavements are expected not only to carry more traffic load (longer durability), but also to provide sustainable benefits (such as low energy consumption and emission).

To meet the increasing requirements of pavement materials for future mobility, the incorporation of polymers, such as styrene-butadiene-styrene (SBS), crumb rubber (CR), polyethylene terephthalate (PET), and epoxy, in asphalt materials has been extensively studied. By adding these polymers, the properties of asphalt will be improved to varying degrees, and the durability of the pavement will be enhanced (Wang et al., 2020b, Leng et al., 2018, Airey, 2003, Wang et al., 2020a). However, there are still some environmental issues that need to be addressed. For instance, the blending and swelling of polymers in asphalt need high production temperatures, which consumes more energy, and the potential greenhouse gas emissions and the associated air pollutions from the asphalt binder and polymer itself at high construction temperatures have not been well studied (Zhu et al., 2019, Wang et al., 2018, Cao et al., 2019).

In recent years, polyurethane (PU) has been studied as a binder modifier to provide pavement materials with both superior functional properties and good mechanical performance (Hong et al., 2021a, Lu et al., 2019). PU binder is a compound containing urethane groups (-NHCOO-) in molecule chains stemming from the reaction of isocyanate-based materials (containing -NCO functional groups) with polyols (containing -OH groups). Due to the low viscosity of PU binder, it can be applied readily at ambient temperature. Hence, during the manufacturing process of PU pavement mixture, no heating is required, and the green-house gas (GHG) emissions can be eliminated (Cong

et al., 2019, Chen et al., 2018). As a sustainable and durable pavement material, PU binder has been extensively researched and its performance has been widely validated in engineering practices (Jin et al., 2020, Hong et al., 2021b).

However, due to the unit price of PU is much higher than that of asphalt, to completely replace asphalt by PU binder becomes impossible, except for some special application scenarios, which hinders the wider application of PU in practice. To address this problem, the application of PU-precursor-based or PU-based materials as a reactive asphalt modifier was further investigated (Fang et al., 2016, Singh et al., 2003). PU-precursor-based modifier (PUM) containing isocyanate functionalities (contain -NCO functional groups) can easily react with various compounds containing functional groups such as hydroxyl groups or amino groups. Due to the wide presence of free radicals (such as –OH, –NH, -NH2) in asphalt, the use of PUM was proved as a chemical modification for asphalt. PUM also presents good compatibility with asphalt (Li et al., 2021), which can significantly improve the high-temperature performance and fatigue resistance of asphalt. Since PUM commonly used for asphalt modification is a liquid modifier, there is no need to use a colloid mill to grind the modifier when preparing the modified asphalt binder. Compared with other solid modifiers, the production process is simpler. At the same time, due to the good fluidity of PUM, the mixing temperature for producing modified asphalt can also be reduced from the conventional 180°C to about 140°C (Li *et al.* 2021). Therefore, the use of PUM to prepare modified asphalt not only reduces the production cost, but also decreases the GHG emissions in the production process.

Although the properties and performance of asphalt binder modified by PUM have been reported in some previous studies, the preparation processes and performance of such PUM modified asphalt mixtures (PUAM) have not been comprehensively characterized yet. Therefore, to further verify the applicability of PUM in pavement

materials, the engineering performances of PUAM should be thoroughly studied. In addition, a suitable production process for PUAM needs to be determined, and a better understanding on the chemo-mechanical interactions between PUM, asphalt and aggregates should be obtained.

To fill these gaps, this study aims to characterize the engineering performance and reveal the modification mechanism of PUAM. To achieve this objective, a PUM was selected to produce PU modified binder (PUMB) and PUAM of two different PU contents (10% and 30%). Various laboratory tests, including rotational viscosity tests of binder, and Marshall test, indirect tensile strength (ITS) test, Hamburg wheel-tracking test, moisture susceptibility, and indirect tensile fatigue (ITF) test of mixture, were performed. Fourier transform infrared spectroscopy test was carried out to investigate the adhesive mechanism between binder and aggregate. The outcome of this study is expected to lay the foundation for the further application of PUAM in larger scales.

2 Materials and methodology

2.1 Materials

2.1.1 Polyurethane prepolymer

The PU prepolymer selected in this study is a solvent-free, unfilled and transparent 1k aliphatic polyurethane. It is a moisture curing adhesive. The basic physical properties of the PU prepolymer are shown in **Table 1**.

2.1.2 Base binder and aggregate

The penetration 60/70 binder (Pen 60/70), commonly used in Hong Kong, was selected as the base binder. Its basic properties are shown in **Table 2**. The aggregate and filler used in this research are both granites. The bulk densities of coarse aggregate, fine aggregate and mineral filler are 2.663, 2.649, 2.661 g/cm^3.

2.2 Preparation of polyurethane (PU) modified bitumen

The base bitumen was first heated to approximately 160 °C in an oven to achieve good fluidity. The PU prepolymer in target amount was then mixed with the fluid bitumen. To ensure homogeneity of the PU modified bitumen, high shear mixer was used to mix the blend at 150 °C at a speed of 3000 rpm for 30 min. PU was added to the bitumen at two different dosages, i.e., PU prepolymer: bitumen = 10:90, and 30:70, which are denoted as PUMB-10 and PUMB-30, respectively. The base binder Pen 60/70 was used as control.

In order to study the reaction mechanism of the PU modified asphalt mixture, the PU modified bitumen mastic was prepared by mixing the PU modified bitumen with dried mineral filler at a mass ratio of 1:1.5, which is close to their mass ratio in the asphalt mixture. The mastic was sealed in a closed centrifuge tube, which was then conditioned in an oven at 60 °C for up to 48 h (Si et al., 2018). The infrared spectra of the mastic during the conditioning were measured after 0 h, 12 h, 24 h, and 48 h conditioning.

2.3 Mix design of PU asphalt mixture

The typical gradation for the 20mm maximum aggregate size wearing course mixture (WC 20) used in Hong Kong was selected in this study to prepare the asphalt mixtures, as illustrated in **Figure 1**.

2.4 Mixture specimen preparation

Two types of PU asphalt mixture (PUAM) with different PU contents were prepared in this study: PUAM-10 and PUAM-30, which correspond to the mass ratios of PU prepolymer to virgin binder of 10:90 and 30:70, respectively. The hot mix asphalt (HMA) mixture prepared with Pen 60/70 binder was also produced as a reference mixture to investigate the improvement of the mechanical properties of PUAM.

For PUAM, the warm mix method was adopted to prepare the mixtures, and the mixing and compacting temperatures were reduced to 160°C and 140°C respectively.

The mixture specimens were prepared in accordance with ASTM D6926-10. From the Marshall test results and various volumetric parameters, the optimum asphalt contents for HMA, PUAM-10, and PUAM-30 were determined to be 5.2%, 5.3%, and 5.3%, respectively.

Since PU is a reactive modifier, similar to the epoxy resin (Apostolidis et al., 2018, Yang et al., 2022), it needs curing to develop its strength after the sample preparation. Therefore, after demolding, the PUAM specimens were cured in a 60°C oven for 4 days according to the curing method of epoxy asphalt mixtures (Yin *et al.* 2015, Cong *et al.* 2019).

2.5 Laboratory tests

2.5.1 Rotational viscosity

The rotational viscosity of the binders was measured in accordance with ASTM D4402 at 150 °C at a constant rotational speed of 20 rpm using the #27 cylindrical spindle (spindle diameter=11.76 mm, side length=33.02 mm, effective length=39.29 mm) (Wang et al., 2021). It was reported that potential chemical reaction between the PU prepolymer and base bitumen will lead to dramatic viscosity change of the binder (Li et al., 2022). To further evaluate whether there is any chemical reaction occurs, the viscosity of PU modified binders was continuously monitored at 150 °C for up to 120 min.

2.5.2 Fourier transform infrared (FTIR) spectroscopy

Attenuated total reflection ATR-FTIR (Spectrum Two, PerkinElmer) was used to analyse the FTIR spectra of the PU modified bitumen and mastics with a 4 cm^{-1} resolution between 400 and 4,000 cm^{-1}. Each spectrum represents the accumulation of 32 scans. Two measurements were performed for each specimen.

2.5.3 Marshall test

Marshall test was conducted to measure the Marshall stability and flow values of asphalt mixture according to ASTM-D6927. The optimum asphalt content was also determined by this test. Specimens were first immersed in a 60°C water bath for 30-40 min. Then a loading with a constant displacement rate of 50.8 mm/min was applied to the specimens. Three replicates were prepared for each group and the maximum load and flow values were recorded.

2.5.4 Indirect tensile strength test

The indirect tensile strength (ITS) of the asphalt mixture was measured according to AASHTO T322. The testing temperature was 25°C, and a vertical compressive load with a 50±5 mm/min displacement rate was applied to the testing samples until the maximum load was reached. The ITS values of the specimens in MPa were calculated by Eq. (1):

$$ITS = \frac{2000P}{1000 \cdot \pi \cdot D \cdot t} \quad (1)$$

where P is the maximum load applied to the specimens (N), and t and D are the thickness and diameter of the specimens (mm), respectively.

2.5.5 Hamburg wheel-tracking test

Hamburg wheel-tracking test was conducted to evaluate the rutting resistance of asphalt mixture according to AASHTO T 324-11. The cylindrical specimens with 150 mm diameter, 60±1 mm height, and 7±1 % air voids content were prepared by a Superpave Gyratory Compactor (SGC). The test was conducted in a 60°C water bath and a repeated load of 705±4.5 N generated by the reciprocating steel wheel was applied to the specimens. The rut depth and the number of passes to specimen failure were recorded. The test stopped when the number of passes reached 20000 or the specified rutting depth was reached.

2.5.6 Moisture susceptibility

The freeze-thaw splitting test was adopted to estimate the moisture susceptibility of the asphalt mixture. Six cylindrical specimens with 7±1% air voids content were prepared for testing. Following the procedure recommended by ASTM D4867, three conditioned specimens were partially saturated with water and placed in a -18°C freezer for 16 h, and then immersed in a 60°C water bath for another 24 h. This process aims to simulate the damage caused by the water in the asphalt mixture after a freeze-thaw cycle. After freeze-thaw conditioning, the ITS test was performed on two subsets of specimens at 25°C to obtain the indirect tensile strength values. Tensile stress ratio (TSR), defined as the ratio of ITS of conditioned specimens to unconditioned specimens, as shown in Eq. (2), was used to evaluate the moisture susceptibility of asphalt mixtures.

$$\text{TSR} = \frac{ITS_{con}}{ITS_{uncon}} \cdot 100 \quad (2)$$

where ITS_{con} is the average tensile strength of the moisture conditioned subset, and ITS_{uncon} is the average tensile strength of the unconditioned subset.

2.5.7 Indirect tensile fatigue (ITF) test

The fatigue life of the asphalt mixture was determined by the indirect tensile fatigue (ITF) test. The testing temperature was 20 ^{o}C and the tests were conducted in a stress-controlled mode. A haversine load was applied on the specimen repeatedly with 0.1s loading time and 0.4s rest time. As recommended by BS EN 12697-24, five initial resilient strain levels were selected from the range of 70με to 400με for fatigue testing. However, because the strength of PUAM-30 is very high, it requires more than 2000kPa stress to make the initial strain within the recommended range, which is quite different from the actual load applied on road in a real situation. The pressure between the tire of a standard vehicle and the pavement is 700 kPa. Based on this value, this study selected three stress levels of 800kPa, 600kPa, and 400kPa for the ITF test. Three replicates were prepared for each stress level

to ensure the consistency of the results. The fatigue life is the number of load applications corresponding to the maximum energy ratio, and the energy ratio is calculated by Eq. (3):

$$w_n = \frac{n}{\varepsilon_{R,n}} \cdot 10^6 \quad (3)$$

where w_n is the energy ratio; n is the number of load applications, and $\varepsilon_{R,n}$is the resilient strain amplitude during cyclic loading (μm/m).

3 Results and discussions

3.1 Rotational viscosity

The rotational viscosity of the base bitumen and PU modified bitumen was tested after sample preparation. The viscosity was recorded after shearing for around 20 min, until the value became stable. It can be seen from **Table 3** that the viscosity decreased with the incorporation of PU prepolymer, as the PU prepolymer has lower viscosity compared with that of the base bitumen.

Figure 2 shows the shear viscosities of both PUMB-10 and PUMB-30 as a function of time at 150 ºC for up to 120 min. The viscosity of the PUMB was relatively stable during the monitoring duration. It was reported that potential chemical reaction between the PU prepolymer and base bitumen will lead to dramatic viscosity change of the binder (Li et al., 2022). The result indicates that the chemical reaction between PU prepolymer and bitumen is insignificant.

3.2 Marshall and volumetric properties

The Marshall stability test results are presented in **Figure 3**. It can be observed that the stability of PUAM is higher than that of the HMA mixture and it increases with the increase of PU content. PUAM-10 has a stability of 22.8 kN, a 50% increase over 15.7kN of the HMA mixture. For PUAM-30, its stability is higher than 50kN (limited by the machine measuring range), which is more than three times that of the HMA mixture. The

improvement of PUAM stability suggests that the high-temperature deformation resistance of the asphalt mixture has been greatly strengthened after PU modification.

The volumetric parameters of the mixtures are shown in **Table 4**. The air void content of PUAM is larger than that of the HMA mixture. With the increase of PU content, the air void of PUAM also increased. The possible reason is that PU is an active reactive modifier, which is easy to react with those substances containing active hydrogen groups, such as mineral aggregates, asphalt binder and moisture in the air, during the preparation process. This reaction (curing) makes the loose mixture stick together, gradually reduces the workability of the mixture, resulting in decreased compaction degree. However, it can be seen that, although the air void content of PUAM-30 is larger than those of the other two mixtures, its mechanical strength is still the highest, revealing the PU prepolymer can significantly enhance the strength of asphalt mixture.

3.3 Indirect tensile strength

Figure 4 compares the indirect tensile strength of the HMA mixture and PUAM. The ITS of PUAM is higher than that of the HMA, and its value increases with the increase of PU content. It can be noticed from **Figure 4** that the ITS of PUAM-30 is almost twice of that of the control HMA. This denotes that the PU prepolymer contributes to the higher tensile strength. It is believed that the PU prepolymer enhances the adhesion between the asphalt binder and the aggregates, thus improving the tensile properties of the asphalt mixture. Based on this result, the PUAM is expected to have better cracking resistance than the HMA.

3.4 Rutting resistance

Figure 5 shows the rutting depth evolutions of different asphalt mixture samples with the increasing number of loading passes. It can be found that the rutting depth of the control asphalt mixture sample increases dramatically with the increase of loading passes. On the

other hand, with the incorporation of PU prepolymer, the rutting depth decreased remarkably. The rutting depth of the control asphalt mixture reached 20 mm at the end of the test, while it was less than 2 mm and 1 mm for PUAM-10 and PUAM-30, respectively. **Figure 6** shows the pictures of the test samples after the wheel-tracking tests, which clearly illustrate the improvement of rutting resistance of PUMA.

3.5 Moisture susceptibility

The results of the moisture susceptibility tests are plotted in **Figure 7**. It can be seen that PUAM-30 has the highest TSR value, indicating PUAM-30 has the best moisture susceptibility resistance among these three mixtures. The strength of the unconditioned HMA mixture, PUAM-10, and PUAM-30 are 13.1kN, 16.2kN, and 21.1kN, respectively. After freeze-thaw cycling, the strength of HMA dropped to 7kN, and its tensile stress ratio is only 53%, which is far from the required value of 80%. Concerning PUAM, there is only a slight decrease in strength after conditioning, especially for PUAM-30. The strength of conditioned PUAM-10 and PUAM-30 are 14.4kN and 20kN, and their corresponding TSR values are 90% and 95%. This result indicates that PU prepolymer can effectively improve the resistance of moisture damage of asphalt mixture.

3.6 Fatigue performance

Figure 8 illustrates the fatigue test results of the PUAM and HMA under three stress levels, which show that the fatigue performance of PUAM was significantly better than that of the HMA, and the degree of the improvement is proportional to the PU dosage. At 800kPa stress level, the fatigue life of the PUAM-10 is 12284 cycles, while the HMA is only 422 cycles. As the applied stress decreases, the advantage of the fatigue performance of PUAM-10 becomes more obvious. This result demonstrates that the PUAM-10 exhibits much better fatigue performance than the HMA. For PUAM-30, due to its high mechanical property, even under 800kPa stress, the modulus did not change after 100000

loading cycles, meaning that the fatigue load caused nearly no damage to it. For this reason, the ITF tests of PUAM-30 under the three loading stress levels were manually stopped after 100000 loading cycles.

To more specifically display the relationship between modulus and loading cycles for PUAM and HMA, **Figure 9** depicts the profiles of modulus change with loading cycles. Regardless of the stress levels, the modulus of PUAM-30 almost did not decrease with the increase of loading cycles, indicating that the specimen hardly suffered fatigue damage during the loading process. For PUAM-10, it can be seen that under a stress level of 400kPa, its modulus was also very stable with the increase of loading cycles. However, under the stress level of 600kPa and 800kPa, its modulus decreased apparently with the increase of loading cycles, indicating damage accumulated in the samples. However, the decreasing rate is significantly smaller than the control HMA mixture. From the above results, it can be concluded that the fatigue performance of the HMA can be significantly enhanced by PU prepolymer, especially for PUAM-30.

3.7 PU modification mechanism

Figure 10 presents the FT-IR spectra of the base bitumen Pen 60/70 and PU modified bitumen binders (PUMB-10 and PUMB-30). The commonly seen bands in PU modified bitumen binders are summarized in **Table 5**. The distinct peak at 2270 cm^{-1} corresponding to the stretching of the isocyanate group (-NCO) increased significantly with larger concentration of PU prepolymer. The peaks at 1725 cm^{-1} and 1529 cm^{-1} are attributed to the absorption of the carbonyl group (C=O stretching) and the imino group (N-H bending), respectively, indicating the presence of amide group in PU prepolymer. In addition, the peak at 1113 cm^{-1} is ascribed to the stretching vibration of ether group (C-O-C). These characteristic peaks all increased with the increase of PU prepolymer concentration.

Figure 11(a) and **Figure 11(b)** show the infrared spectra of mineral filler and PU asphalt mastic. The peak at 3500 cm^{-1} in **Figure 11(a)** corresponds to hydroxyl groups (-OH). The mineral filler had been heated in oven at 150 ^{o}C for 4 hours to remove moisture. Thus, the hydroxyl groups should come from the mineral filler. In fact, it was reported that the surface atoms of mineral aggregate are attached with hydroxyl groups (-OH) (Gao et al., 2019, Zaidi et al., 2020). The hydroxyl groups can react with the isocyanate group (-NCO) in PU prepolymer. To confirm the hypothesis, PUMB-10 was mixed with the dried mineral filler to prepare the PU asphalt mastic and kept in an oven at 60 ^{o}C for up to 48 h. The infrared spectra of the mastic during the conditioning were evaluated at 0 h, 12 h, 24 h, and 48 h, as demonstrated in **Figure 11(b)**. It can be seen that the distinct peak at 2270 cm^{-1} ascribed to the isocyanate group of PU prepolymer decreased continuously in this process, while the peak at around 3300 cm^{-1} corresponding to amino group increased. The NCO peak intensity dropped significantly during the first 12 h, and then decreased slowly. The results indicated that the chemical reaction between PU prepolymer with the surface hydroxyl groups proceeded rapidly during the first 12 h, which then slowed down due to the decreasing concentration of PU prepolymer and the hydroxyl group on mineral filler. It is thus inferred that the PU prepolymer reacts majorly with the surface hydroxyl group on aggregate surface.

Figure 12 shows the schematic representation of the chemical reaction between PU prepolymer and aggregate. The isocyanate group of the PU prepolymer reacts with the surface hydroxyl group of aggregate, which forms the urethane group (-NHCOO-). Thus, the peak for isocyanate group decreased while the peak for amino group increased during this process as shown in **Figure 11(b)**. With the curing reaction between the PU prepolymer and the surface hydroxyl group of aggregate, the three-dimensional PU polymer network will be formed in the asphalt mixture as shown in **Figure 13**, which

leads to the improvement of the overall mechanical performance of the PU modified asphalt mixture.

6 Conclusions and recommendations

This study investigated the performance of asphalt mixture modified by one-component PU (PU prepolymer), and explored the PU modification mechanism, through various laboratory tests. The following points summarize the main conclusions of this study:

- PU prepolymer can decrease the viscosity of base bitumen, and the chemical reaction between PU prepolymer and bitumen is negligible.
- The overall performances of asphalt mixture were increased significantly by PU prepolymer, including increased Marshall stability, ITS, and resistance to moisture damage, rutting and fatigue damage.
- PU prepolymer can react with the hydroxyl groups on aggregate surface, which contributes to the improved performances of asphalt mixture.

For the future studies, life cycle cost analysis (LCCA) will be performed and the environmental impacts of PUMA will be systematically investigated to justify the applications of PUMA in different scenarios.

Declarations of interest: none.

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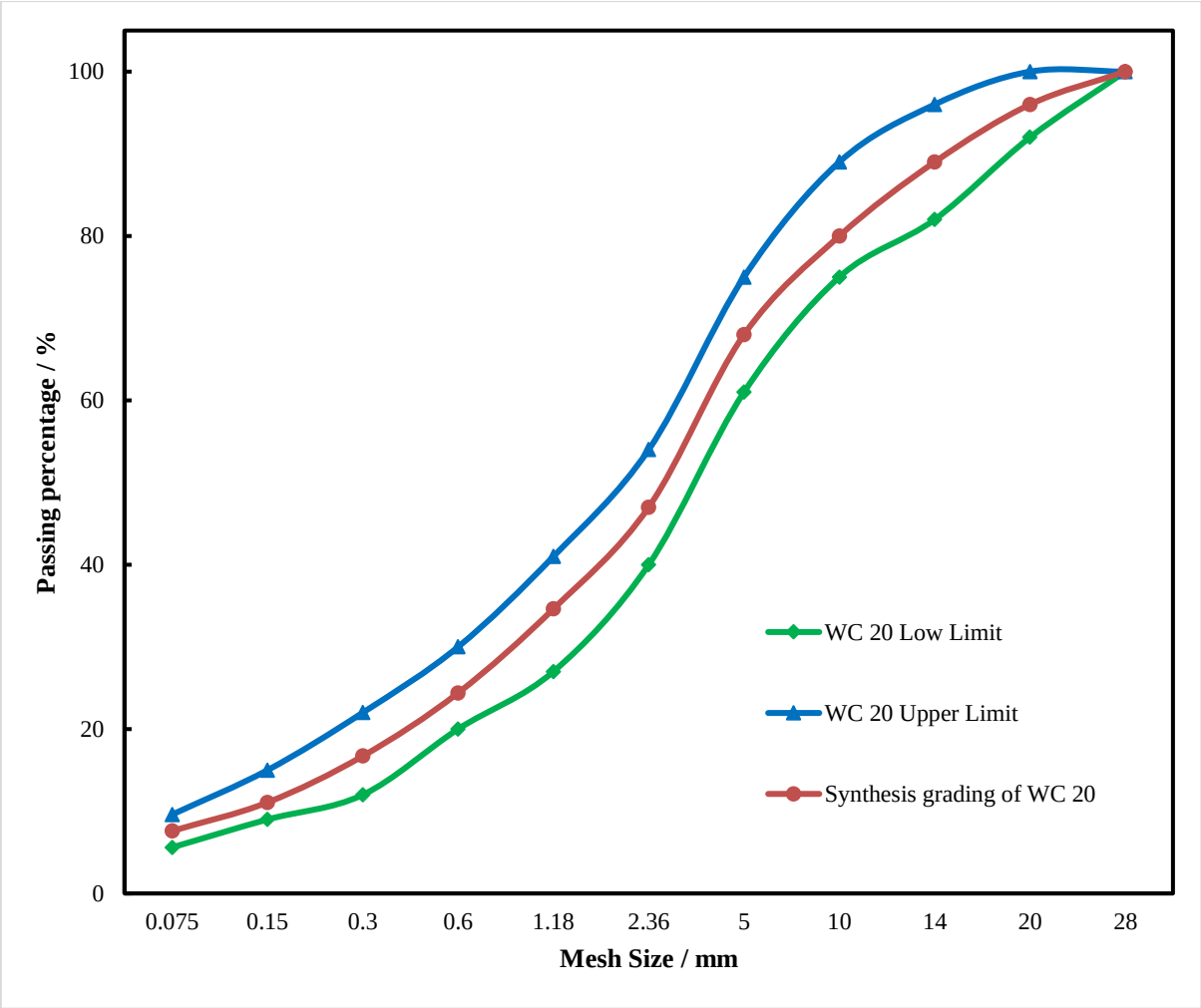

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437 **Fig. 1 Grain size distribution of WC 20**
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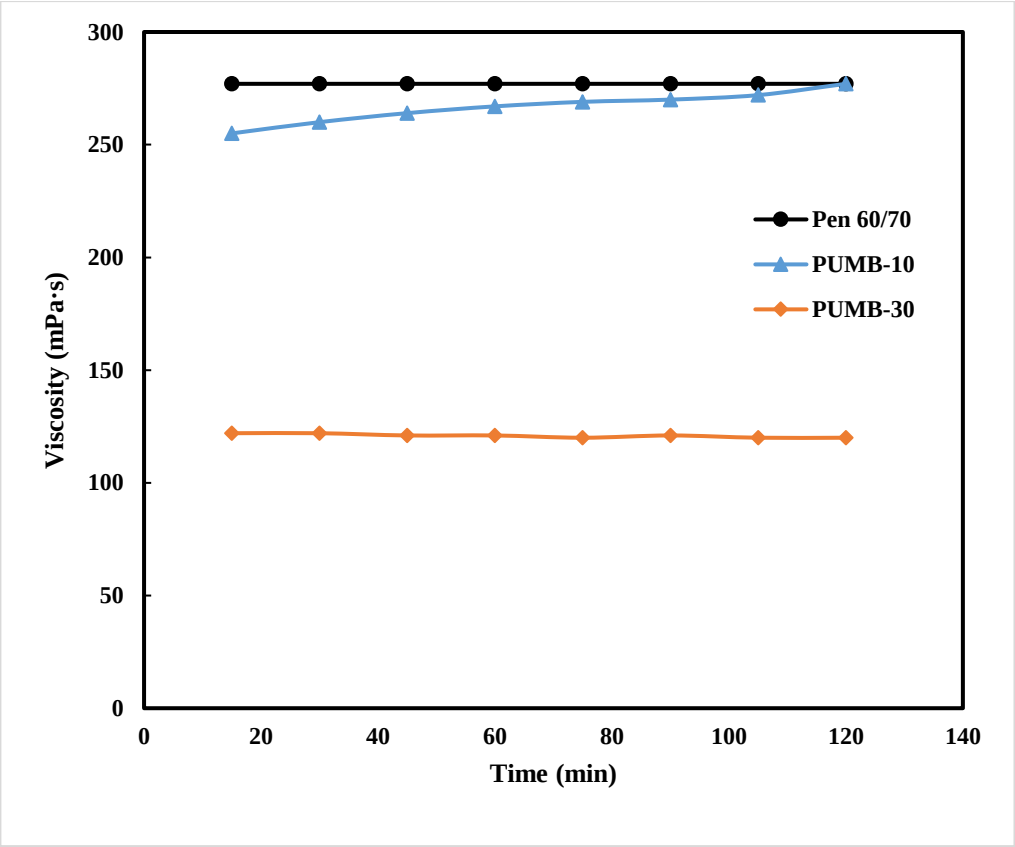

Fig. 2 Rotational viscosity of PU modified bitumen with time

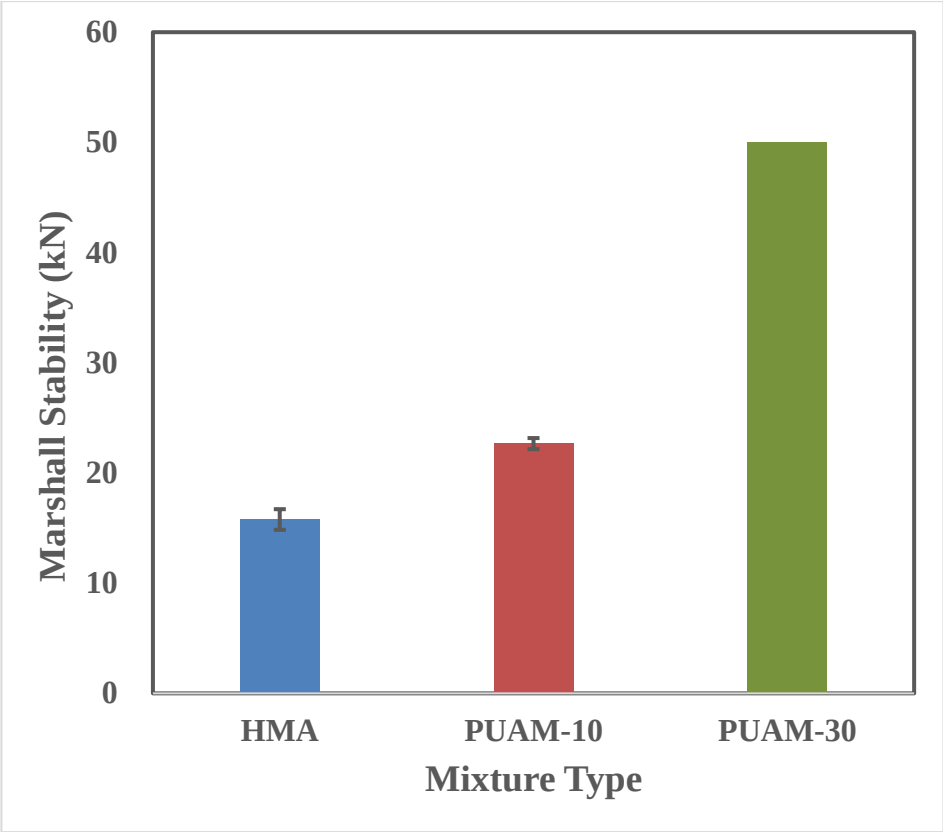

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Fig. 3. Marshall tests results of PUMA and HMA
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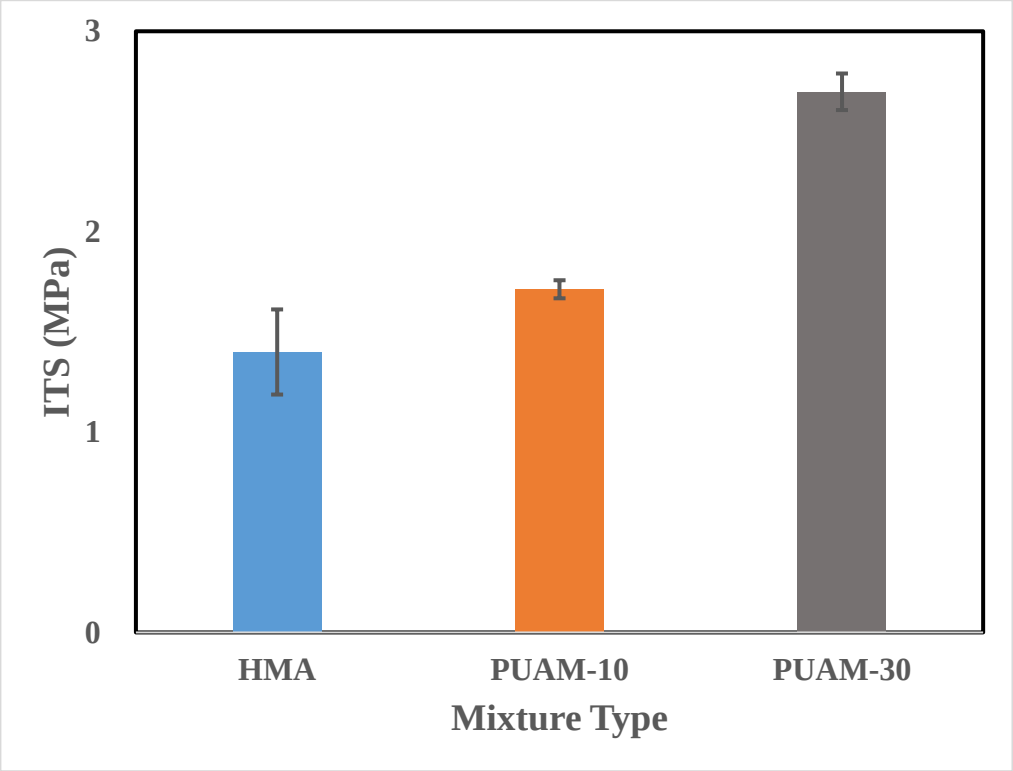

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Fig. 4. ITS results of PUAM and HMA
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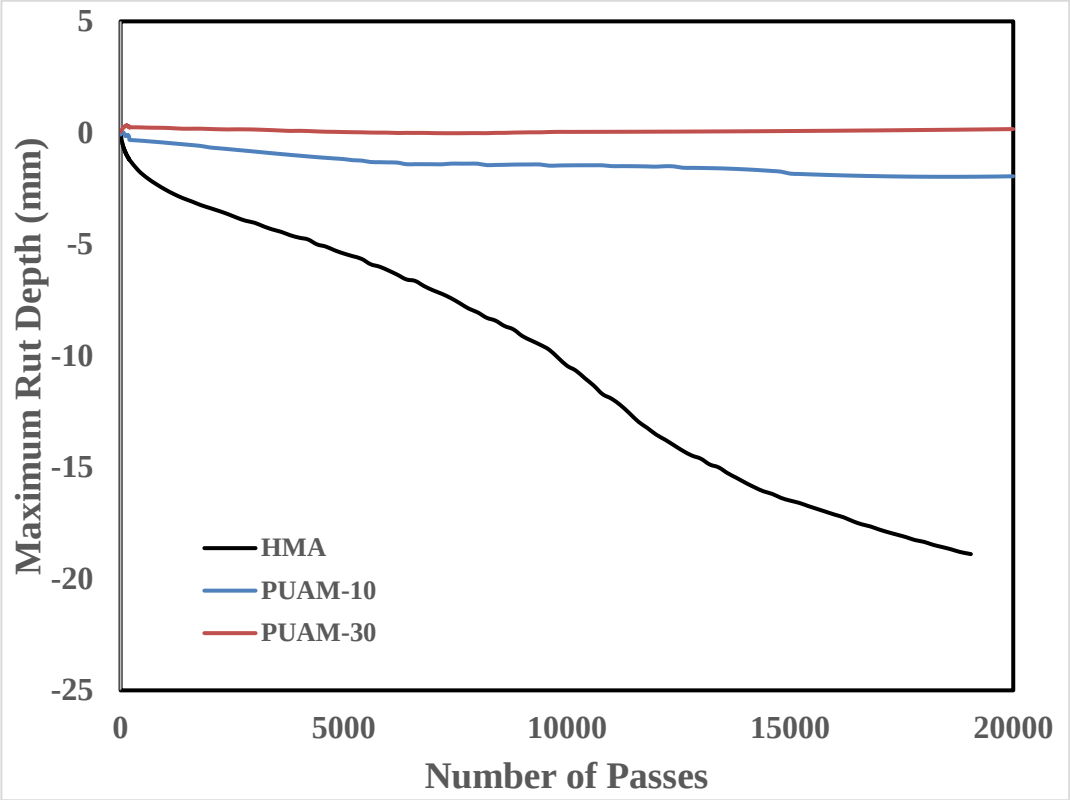


Fig. 5. Rut depths of different asphalt mixtures during wheel-tracking tests

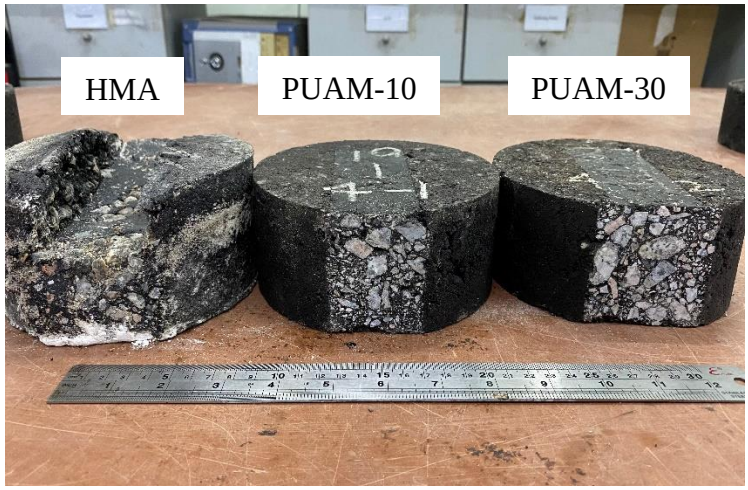


Fig. 6. Test samples after the wheel-tracking test

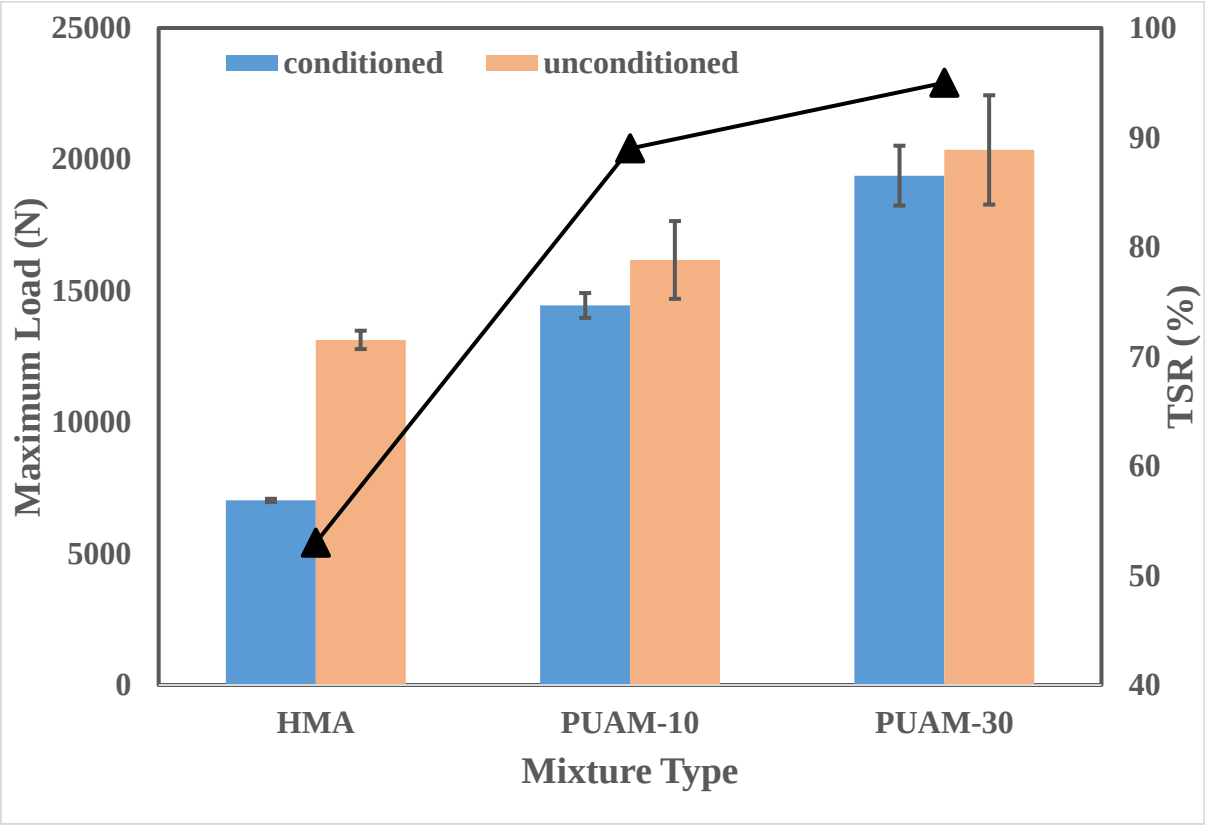


Fig. 7. Moisture susceptibility results

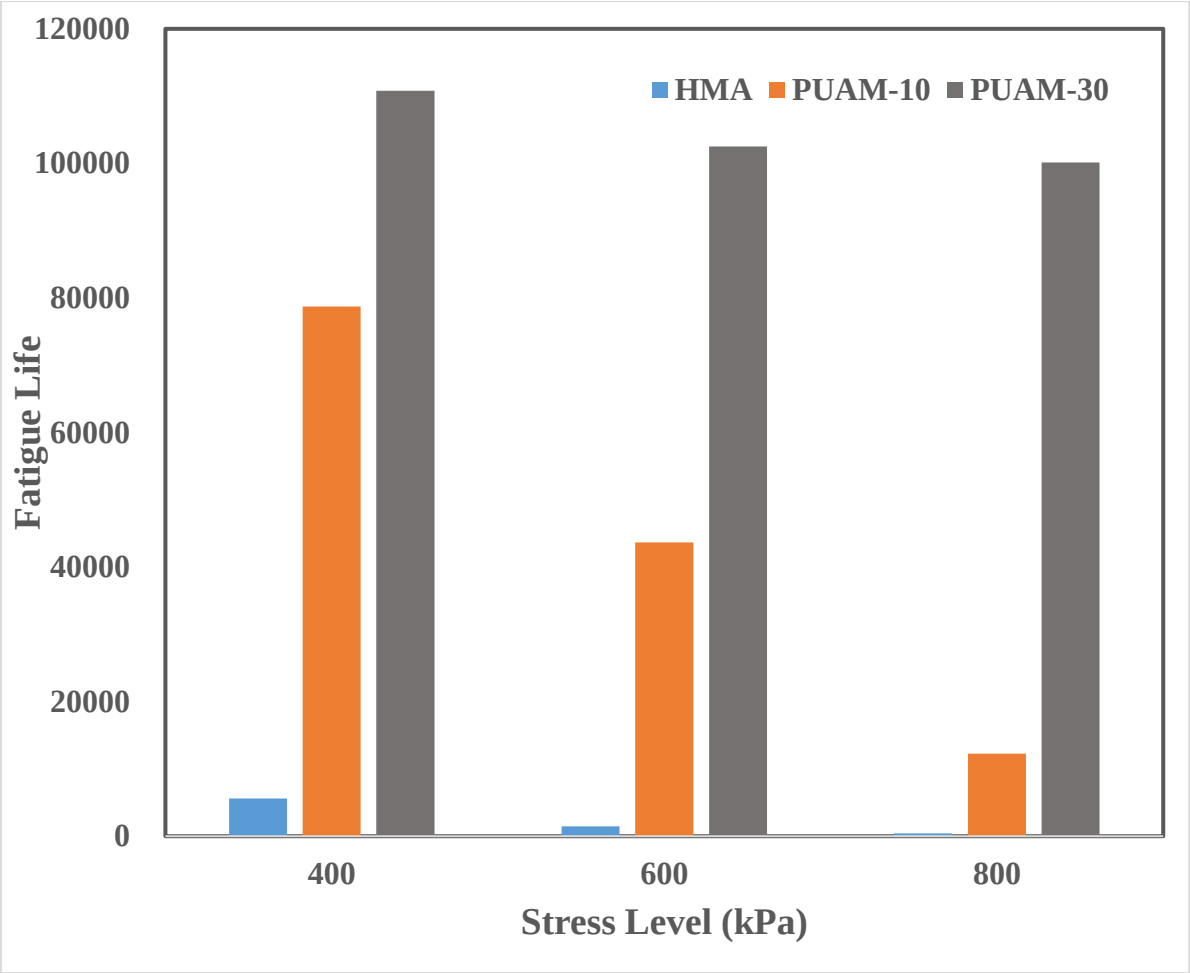
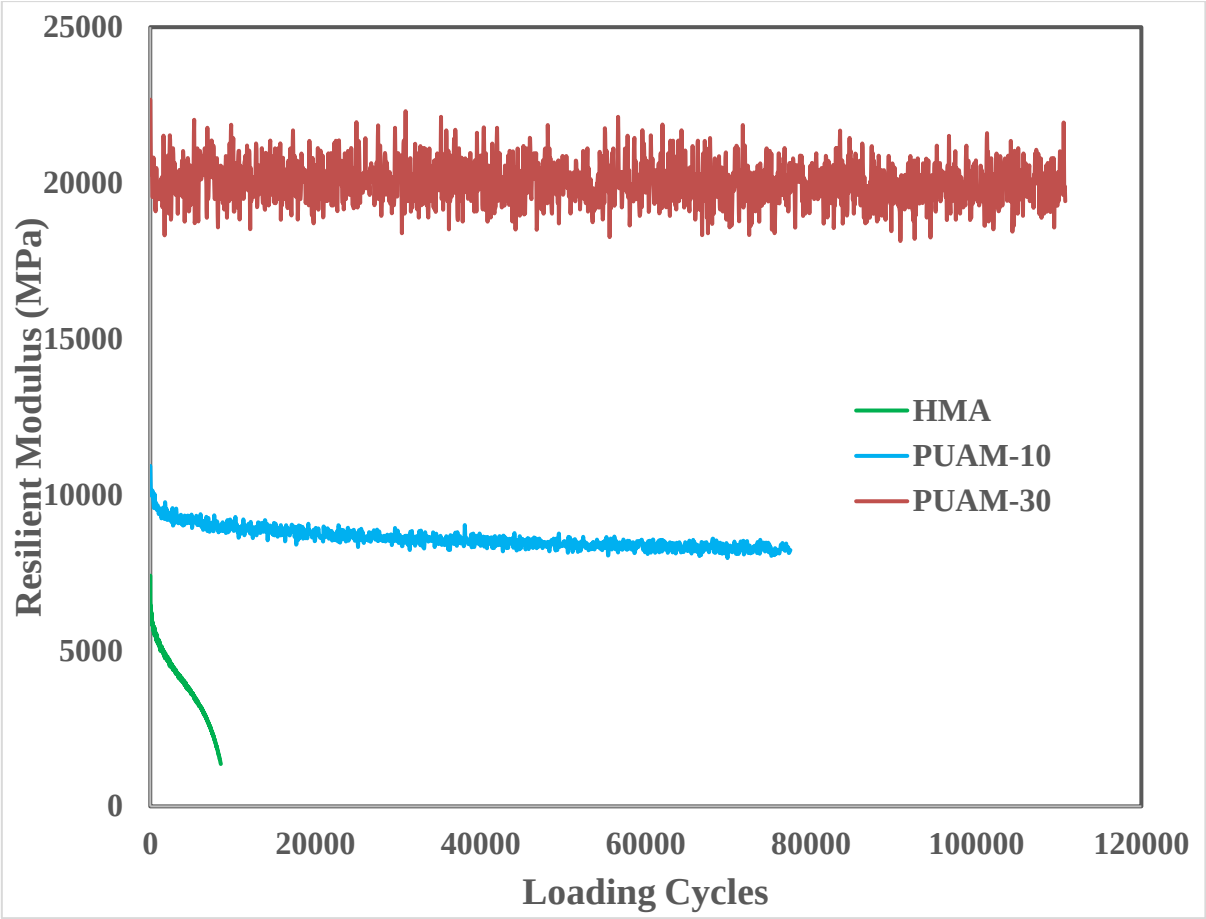


Fig. 8. Fatigue lives of PUMA and HMA under different stress levels



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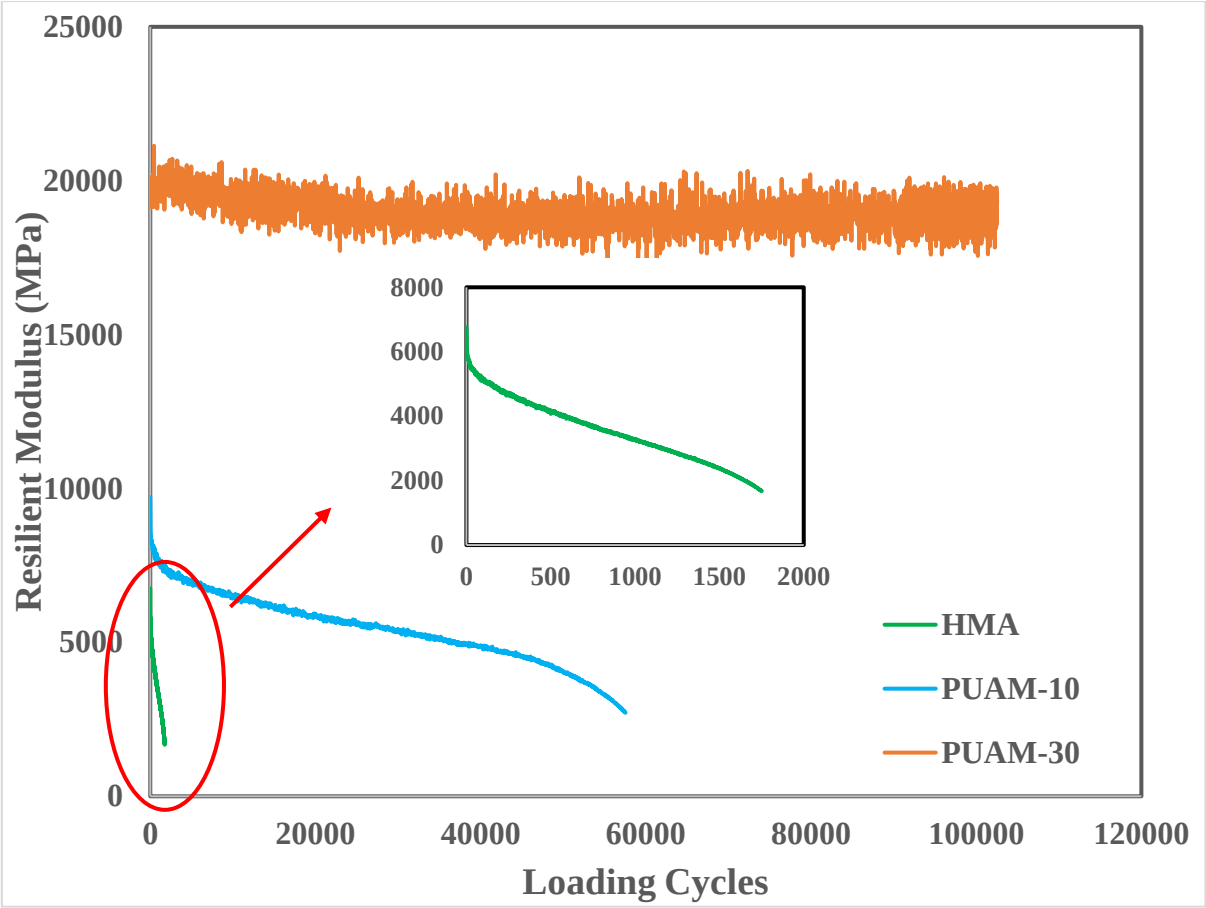
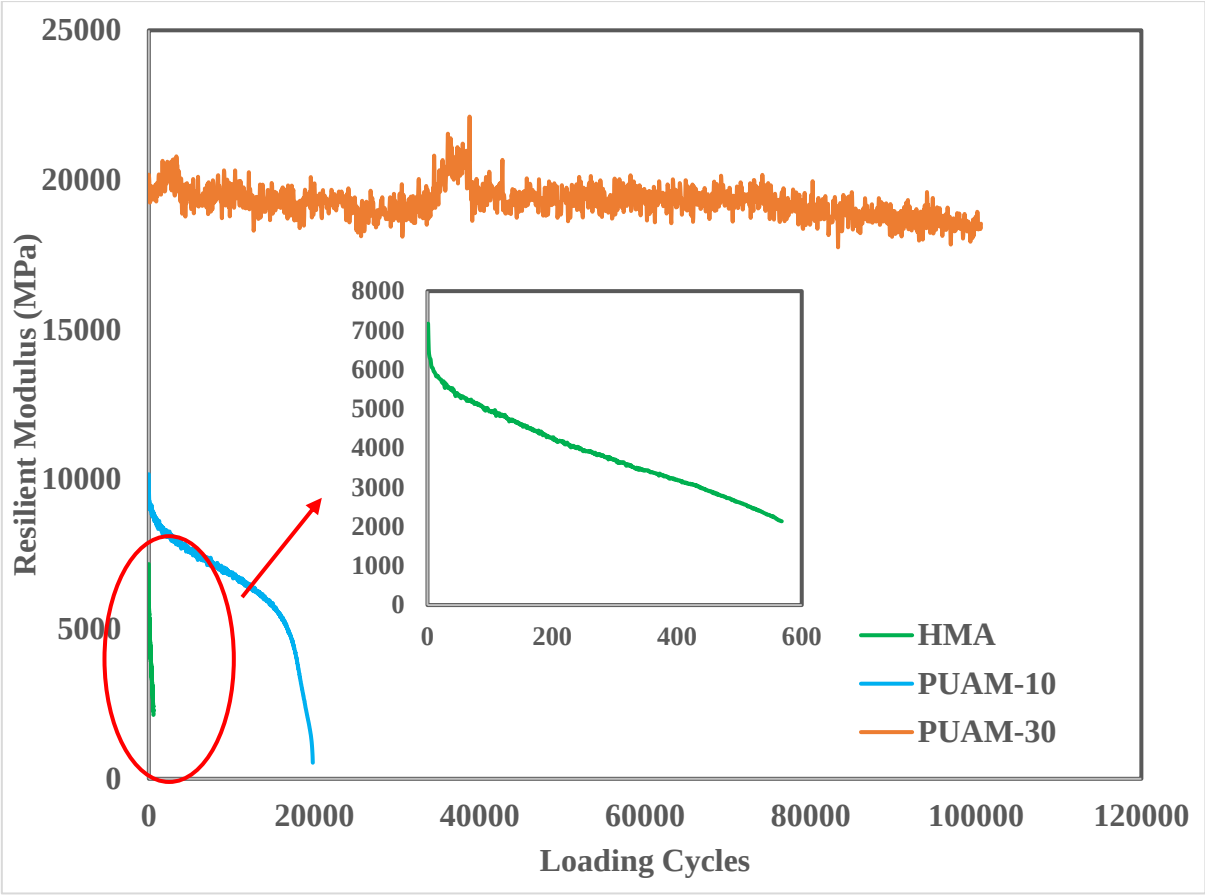
(a) 400kPa

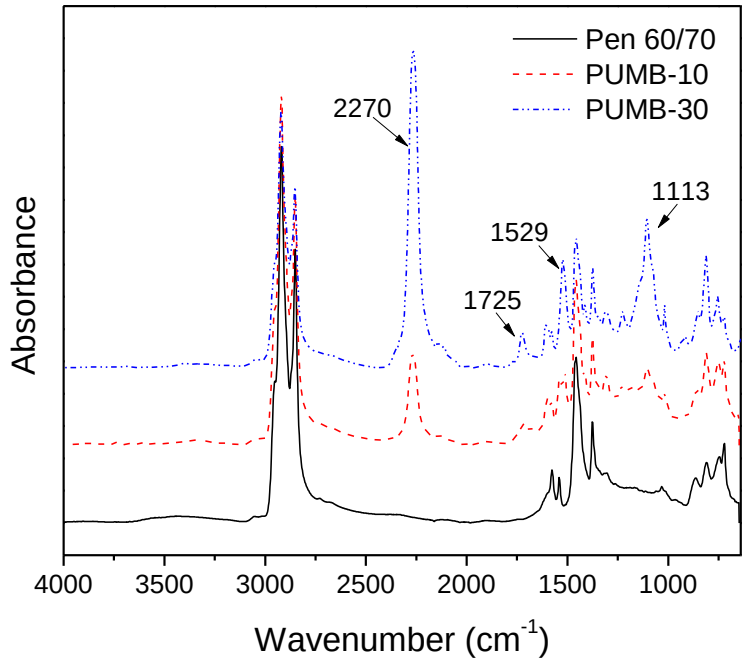

25000
20000
15000
10000
5000
0
Resilient Modulus (MPa)
0
20000
40000
60000
80000
100000
120000
Loading Cycles
8000
6000
4000
2000
0
0
500
1000
1500
2000
HMA
PUAM-10
PUAM-30

(b) 600kPa



(c) 800kPa

Fig. 9. Resilient modulus vs. loading cycles under each stress level (a) 400kPa (b) 600kPa (c) 800kPa



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502 **Fig. 10 FT-IR spectra of Pen 60/70 and PU modified bitumen binders**
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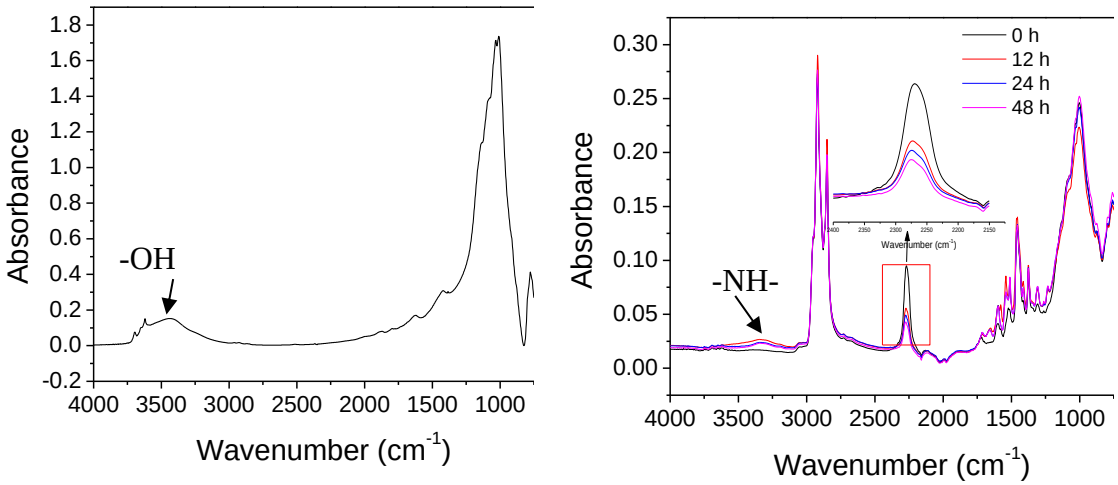

(a) **(b)**

506 **Fig. 11 Infrared spectra of (a) mineral filler, and (b) PU asphalt mastic**
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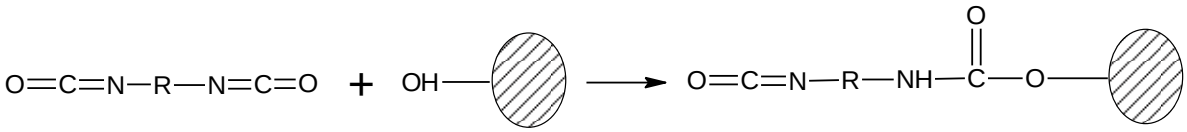

PU prepolymer **aggregate**

Fig. 12 Schematic representation of the chemical reaction between PU prepolymer and mineral aggregate

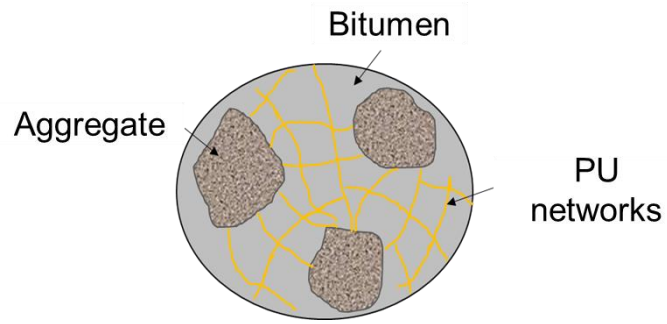

Fig. 13 Schematic illustration of the PU polymer network formed between bitumen and aggregate.

Table 1 Properties of PU prepolymer

Characteristics	Unit	Value	Method
Density (25°C)	kg/m^3	1120	G 133-08
Viscosity	mPa·s	4200	G 133-07
NCO content	%	15.5	G 133-06
Shelf-life	month	6	-

Table 2 Basic properties of Pen 60/70 binder

Properties		Value	Specification
Penetration (25°C, 0.1mm)		64.5	ASTM D5
Softening Point (°C)		48.5	ASTM D36
Viscosity at 135°C (mPa·s)		477.5	ASTM 4402
Ductility at 25°C (cm)		78.5	ASTM D113
SARA fraction	Saturate	17.58 wt %	ASTM 4124
	Aromatic	46.85 wt %	
	Resin	26.20 wt %	
	Asphaltene	9.37 wt %	

Table 3 Rotational viscosity of binders at 150 ºC

Sample-ID	Shear viscosity (mPa·s)
Pen 60/70	264
PUMB-10	260
PUMB-30	120

Table 4 Marshall and volumetric results of PUAM and HMA.

Test items	Mixture Type		
	HMA	PUAM-10	PUAM-30
Bulk density (g/cm^3)	2.33	2.31	2.30
Marshall Stability (KN)	15.8	22.7	>50
Flow Value (0.1mm)	2.12	1.83	NA
VA (%)	3.47	4.40	5.03
VMA (%)	16.4	17.0	17.7
VFA (%)	79.0	76.6	71.8

Table 5 Band assignment PU modified bitumen binders

Wavenumber (cm^{-1})	Band assignment
1113	C-O-C stretching
1529	N-H bending (amide)
1725	C=O stretching (amide)
2270	N=C=O stretching
2873	C-H stretching (CH2)
2927	C-H stretching (CH3)