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Construction Technology and Pavement Performance of Dry-Mix Polyurethane Modified Asphalt Mixtures: A Case Study

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Abstract: Polyurethane Modified Asphalt Mixture (PUAM) has been confirmed to possess good engineering properties and is a potential replacement material for pavement construction. This study aimed to provide guidance for the promotion and application of PUAM in pavement engineering by exploring the construction technology and verifying the practicality. Dry-mix PUAM (DPAM), wet-mix PUAM (WPAM), and SBS-modified asphalt mixture (SBSAM) were prepared. After systematically investigating the construction process of the three mixtures, their pavement performance was comparatively evaluated. Subsequently, the DPAM was utilized to construct the trial pavement, and the completed pavement was tested and evaluated. Furthermore, the costs of the DPAM and SBSAM were analyzed. The results reveal that the construction technology had a significant effect on the mechanical properties of the mixtures. Compared with SBSAM, the optimum mixing temperature and time of the DPAM and WPAM were reduced. The mixing temperature, mixing time, and hitting number were recommended to be 160 °C, 60 s, and 75 times for the DPAM. Fourier Transform Infrared Spectroscopy tests confirmed that the PU reacted sufficiently in the binder. The DPAM exhibited good overall pavement performance, and its low-temperature cracking and fatigue resistance were significantly better than that of SBSAM. Meanwhile, all the pavement indexes constructed with DPAM met specifications, and the performance and service condition of the test road after the operation will be paid attention to continuously. Additionally, the cost of DPAM was close to that of SBSAM, and the more straightforward construction process and better pavement performance of DPAM could reduce the construction energy consumption and maintenance frequency, which was meaningful for promoting the scale application of DPAM and the sustainable development of transportation infrastructure.

Keywords: polyurethane; dry-mix; asphalt mixture; construction technology; trial pavement; cost analysis

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1. Introduction

As an essential part of transportation infrastructure, asphalt pavement plays a vital role in ensuring smooth logistics and driving safety [1,2]. However, the rapid development of the economy and the continuous improvement of living standards have contributed to the booming development of the transportation industry. The dramatic growth in traffic volume and the continuous increase in traffic loads have led to frequent occurrences of rutting, cracking, potholes, and other diseases on asphalt pavements during service life [3,4]. This not only reduces the service life of the pavement but also challenges the safety and comfort of driving. As a result, polymer modifiers, represented by styrene-butadiene-styrene (SBS), styrene-butadiene rubber (SBR), and polyethylene (PE), have been utilized to improve the deficiencies of the insufficient performance of traditional asphalt binders [5–7].

Although these modifiers positively improve the performance of the asphalt binder to a certain extent, the physically modified asphalt binder still needs to be further upgraded in terms of water and storage stability [8–10]. In recent years, reactive polymer modifiers, represented by polyurethane (PU), have been gradually favored by researchers.

PU is a polymer material containing a carbamate group (-NHCOO-) in the molecular structure, which is generated by the reaction between isocyanate and polyol [11,12]. PU not only has good mechanical properties, elasticity, and chemical stability but also has the characteristic that the formula can be flexibly adapted and is abundant in variety. Hence, PU has been widely used in adhesive, elastomer, civil engineering construction, and petrochemical industries [10,13,14]. Many scholars have studied the feasibility of PU as an asphalt modifier and achieved satisfactory results. Li et al. prepared modified asphalt binders using PU synthesized via in situ polymerization and explored their micromolecular structure and macroscopic properties. The results demonstrated that PU with a content of more than 4 wt% could form a crosslinked structure in the binder, and the increase in PU content could simultaneously improve the high- and low-temperature performance and outperform the SBS-modified asphalt (SBSA) binder [15]. Jin et al. utilized PU and rock asphalt (RA) to prepare a composite-modified asphalt and focused on its rheological properties and microscopic characteristics. The results indicated that the addition of PU and RA significantly improved the physical properties of the asphalt and displayed superior compatibility. Moreover, the chemical reactions within the system played an essential role in enhancing the properties [16]. Huang et al. systematically investigated the effects of preparation temperature as well as PU content on the compatibility of the two by combining laboratory tests and molecular dynamics simulations. They found that the compatibility between PU and asphalt was optimal at 135 °C, and the addition of PU could improve the sealing of the asphalt molecular structure. It is worth affirming that the simulation results correlated well with the results of the segregation and fluorescence microscopy tests [17].

PU-modified asphalt (PUA) has been confirmed to have significantly improved overall performance and has the potential to be applied in pavement engineering on a large scale. However, it is worth noting that the pavement performance of asphalt mixtures determines their applicability in practical projects. For this reason, researchers have conducted numerous studies on the performance of PU-modified asphalt mixtures (PUAM). Jia et al. conducted a detailed study on the pavement performance of PUAM and compared it with currently used asphalt mixtures. The results showed that the mechanical strength, rutting, cracking, fatigue, and corrosion resistance of PUAM were superior to those of SBS-modified asphalt mixtures (SBSAM) [18]. Shirzad et al. prepared modified asphalt and mixtures using a qualified photoactivated PU pre-polymerization system. They analyzed its self-healing ability and mechanical properties using indoor tests and microscopic means. The results revealed that PU could significantly improve the high temperature and fatigue resistance of asphalt mixtures, and the self-healing ability of cracks was also significantly enhanced [19]. Sun et al. developed a PUAM with a skeleton interlocking structure and thoroughly evaluated its pavement performance. They found that the increase in temperature reduced the workability of the PUAM, which could be better addressed by utilizing diluents. The high temperature resistance, cracking resistance, fatigue resistance, and water stability of the PUAM were all enhanced [20]. It can be seen that the incorporation of PU significantly enhances the pavement performance of asphalt mixtures and is superior to the current commonly used pavement materials, which have a high promotion and application potential. However, there are few studies on the construction technology and field application of PUAM. Additionally, it is worth noting that all of the above studies on the mixture performance adopted the wet-mix method; that is, the PUA binder was prepared first, and then the PUAM was prepared. Compared to the wet-mix method, the dry-mix method is significantly different. Specifically, the dry-mix method involves mixing the aggregates with modifiers/additives prior to mixing with the binder. Obviously, the dry-mix method has the remarkable advantages of reducing the construction steps,

diminishing the energy consumption, avoiding modifier segregation, and facilitating the construction organization [21,22].

Based on this, this study aims to investigate the construction technology and pavement performance of dry-mix PUAM (DPAM) and through the construction of the trial pavement and cost analysis, to clarify the applicability of DPAM in pavement engineering. The research results contribute to guiding the field construction of DPAM as well as promoting its scale application in pavement engineering. First, DPAM and wet-mix PUAM (WPAM) were prepared separately, and their construction technology and pavement performance were systematically investigated and compared with the SBS-modified asphalt mixture (SBSAM), which is commonly used in current pavement projects. Then, the indoor research results of the DPAM were applied to the construction of the trial pavement, and the completed pavement was tested. Finally, the costs of the DPAM and SBSAM were calculated and compared.

2. Background of the Trail Pavement

The trial pavement constructed in this study belongs to the highway of Pingli to Zhenping, which is a part of Chinese national highway G6911. The project is located in Ankang, Shaanxi Province, which has a subtropical humid monsoon climate. The average temperature throughout the year is 10–15 °C, with an extreme minimum temperature of −14.5 °C and an extreme maximum temperature of 39.8 °C. In addition, the annual precipitation in this area is 450–1200 mm. The new pavement of this project adopts the structure of SBSAM (4 cm, AC-13) + SBSAM (6 cm, AC-20) + base asphalt mixture (8 cm, ATB-30), with the base layer of water-stabilized crushed stone (36 cm) and the sub-base layer of water-stabilized crushed stone (18 cm). On this basis, a trial pavement with a length of 150 m was constructed, and the top layer of SBSAM was replaced with PUAM, as shown in Figure 1.

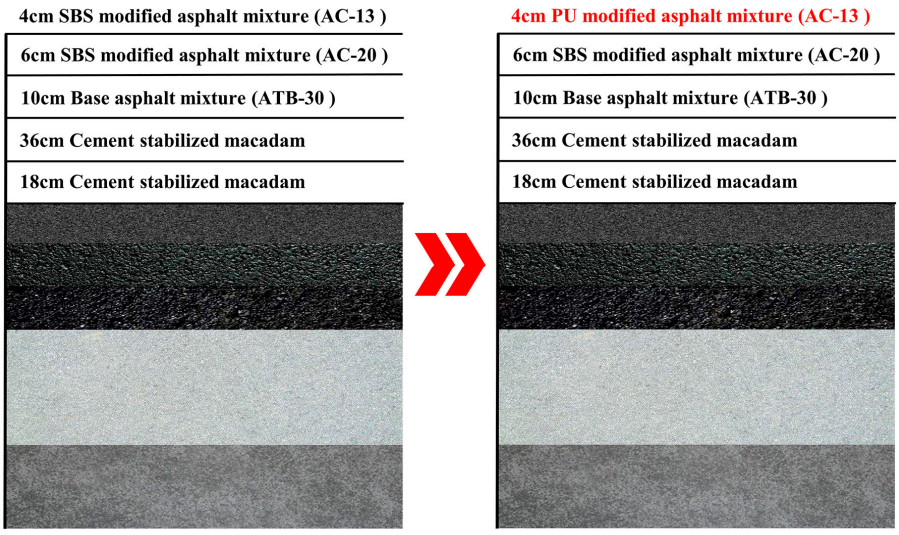

Figure 1. Structure of the trial pavement.

3. Materials and Methods

3.1. Raw Materials

The raw materials used in this study consisted of 80–100 pen-grade base binder, PU system (PU prepolymer, chain extender, and diluent), SBS I-C modified asphalt binder, and aggregates. The base binder was produced by China Petroleum & Chemical Corporation Qilu Branch (Zibo, China); the PU prepolymer was synthesized by using polypropylene glycol (PPG) and toluene diisocyanate (TDI), provided by Zibo Huatian Rubber & Plastic Technology Co., Ltd. (Zibo, China). The chain extender and diluent were selected as p-di-octachloroaniline methane (MOCA) and reactive diluent PU-10, respectively, which

were produced by Jining Huakai Resin Co. Ltd. (Jining, China). The purpose of adding the appropriate amount of diluent is to regulate the viscosity of the PUA binder and to ensure it has satisfactory flowability; the coarse and fine aggregates were basalt, which was produced in Shiyan, Hubei Province; the mineral powder was manufactured in Ankang, Shaanxi Province, which was milled by using limestone crushed stone. Additionally, the SBS I-C-modified asphalt binder used for the performance comparison was from the same manufacturer as the base binder, with a linear SBS content of 4.5 wt%. The molecular structures of PPG, TDI, and MOCA are shown in Figure 2. The technical properties of each raw material are shown in Tables 1–4, and according to the specification, "Technical Specification for Highway Asphalt Pavement Construction" (JTG F40-2004) [23].

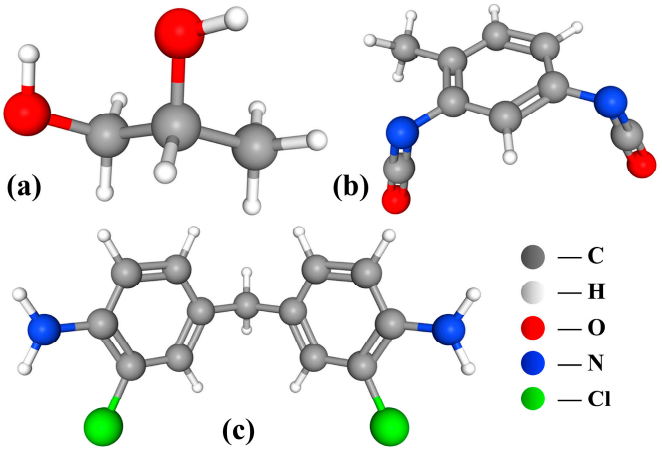

Figure 2. Molecular structure of raw materials: (**a**) PPG, (**b**) TDI, and (**c**) MOCA.

Table 1. Basic properties of asphalt binders.

Test Item		Base Binder		SBS-Modified Asphalt Binder	
		Result	Specification	Result	Specification
Penetration (25 °C,100 g, 5 s)/(0.1 mm)		81	80–100	68	60–80
Ductility (10 °C for base binder and 5 °C for SBS binder, 5 cm/min)/cm		92	≥20	37.2	≥30
Softening point/°C		48.0	≥45	83.5	≥55
Dynamic viscosity (60 °C)/Pa·s		204.8	≥245	-	—
Kinetic viscosity (135 °C)/Pa·s		-	-	2.4	≤3
Density (25 °C)/(g/cm^3)		1.022	-	1.026	-
After RTFOT	Mass loss/%	−0.242	≤±0.8	−0.246	≤±1.0
	Penetration ratio (25 °C)/%	73.1	≥57	76.5	≥60
	Ductility (10 °C for base binder and 5 °C for SBS binder)/cm	10	≥8	24	≥20

Table 2. Basic properties of the PU prepolymer, chain extender, and diluent.

Material Type	Technical Specification
PU prepolymer	Viscosity (85 °C): 230 mPa·s; -NCO ratio: 4.3 ± 0.2%; Density (25 °C): 1.08 g/cm^3
Chain extender	Melting point: 98–102 °C; moisture content: <0.3%; amine value: 7.4–7.6 mmol/g; free phenylamine: <1.00%; acetone insoluble matter: <0.04%; density (25 °C): 1.44 g/mol
Diluent	Exterior: colorless transparent liquid; moisture content: <0.05%; acetone insoluble matter: <0.04%; flash point: >120 °C; density (25 °C):1.17 g/mL

Table 3. Basic properties of coarse aggregates.

Aggregate Type		Technical Performance					
		Apparent Density/(g/cm^3)	Hygroscopic Rate/%	Soundness/%	Abrasion Value/%	Crush Value/%	Adhesion Grade
Result	9.5–13.2 mm	3.036	0.8	4.7	15.8	12.5	5
	4.75–9.5 mm	3.018	0.8				
	2.36–4.75 mm	3.031	0.9				
Specification		≥2.6	≤2.0	≤12	≤26	≤28	≥4

Table 4. Basic properties of the fine aggregate and mineral powder.

Aggregate Type	Technical Performance		
	Test Item	Result	Specification
Fine aggregate	Apparent density/(g/cm^3)	2.753	≥2.5
	Methylene blue value/(g/kg)	1.4	≤2.5
	Soundness/%	6.0	≤12
	Angularity/s	42	≥30
	Sand equivalent/%	72	≥60
Mineral powder	Apparent density/(g/cm^3)	2.708	≥2.5
	Hydrophilic coefficient	0.6	<1.0
	Plasticity index/%	2	<4
	Hygroscopic rate/%	0.3	≤1.0

3.2. Mixing Parameters

This study prepared three mixtures: DPAM, WPAM, and SBSAM. Previous studies have shown that the modifier content in the PUA binder should have an appropriate range. Specifically, suppose the modifier content is too low. In that case, it tends to result in a limited improvement in the properties of the binder, while too high results in a decline in the storage stability as well as an increase in the cost of the material [24]. For this reason, with reference to previous research results as well as indoor tests, the contents of PU and diluent in PUA binder were determined to be 6 and 5 wt% of the modified asphalt binder, respectively. The theoretical consumption of MOCA for the chain-expansion reaction is shown in Equation (1). Ultimately, the amount of MOCA was determined to be 0.8 wt% of modified asphalt binder.

$$C_{MOCA} = \frac{C_{PU} \times C_{\text{-NCO}} \times 3.18 \times f}{100} \quad (1)$$

where C_{MOCA} represents the amount of MOCA, wt%; C_{PU} represents the amount of PU prepolymer, wt%; $C_{\text{-NCO}}$ represents the content of -NCO in the PU prepolymer; and f represents the chain expansion coefficient, which is set at 0.95.

3.3. Proportion Design of the Mixture

According to the project requirements, AC-13 was selected for mixture gradation design in this study. The results are shown in Figure 3. The predicted optimum asphalt-to-aggregate ratio was 5.0%. Five different asphalt-to-aggregate ratios, 4.0%, 4.5%, 5.0%, 5.5%, and 6.0%, were selected to prepare the Marshall specimens by varying the ratio at ±0.5% intervals. According to the Chinese specification (JTG F40-2004) [23], the optimum asphalt-to-aggregate ratios were determined to be 4.8%, 4.9%, and 4.8% for DPAM, WPAM, and SBSAM, respectively. It can be seen that the optimum asphalt-to-aggregate ratios of the three mixtures are fairly similar. Consequently, the asphalt-to-aggregate ratio of 4.8% was used for all the mixtures to ensure the reasonableness of the performance comparisons.

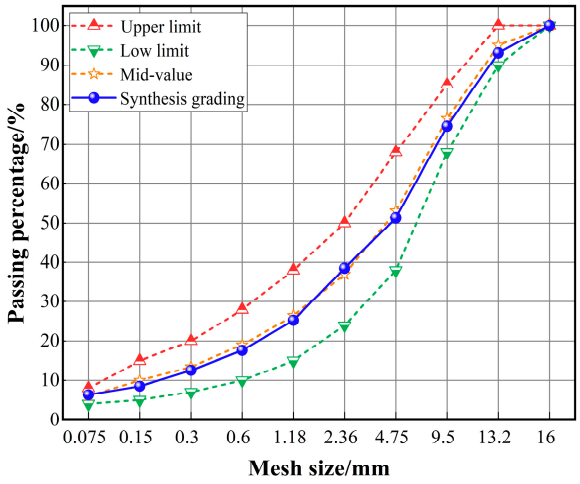

Figure 3. Mixture gradation design results.

3.4. Construction of the Trial Pavement

As shown in Figure 4, the field trial pavement was paved with DPAM with the following steps: (i) The aggregate preheated to 170 °C in advance was added to the mixing plant with a preheating duration of 2 h. Subsequently, the base binder preheated to 150 °C was pumped into the mixing plant, and the preheating duration was 1 h. Simultaneously, PU, MOCA, and diluent preheated to 100 °C were added with a preheating duration of 1 h. The DPAM was obtained after mixing by a mixing temperature of 160 °C and a mixing duration of 60 s; (ii) the transportation of the mixture was carried out by employing material trucks with thermal insulation; the inner walls and bottom plates of the transportation tanks should be coated with a layer of oil-water blend to facilitate on-site unloading; (iii) a CU DT2000 paver was used to spread the mixture, the paving width was 11.25 m, the paving speed was 2.0~2.5 m/min, and the loose paving coefficient was 1.18; (iv) oscillatory compactor has the advantages of good compaction effect, it is not easy to crush pavement materials, and little disturbance to the environment [25]. Hence, the oscillatory compactor was used for mixture compaction, and the specific frequency and amplitude were determined according to the actual construction situation. The finalized paved DPAM pavement is shown in Figure 4c.

Figure 4. Construction of the field trial pavement: (**a**) paving, (**b**) compacting, and (**c**) finished trial pavement.

4. Test Methods

According to the Chinese specifications, "Standard test methods of bitumen and bituminous mixtures for highway engineering." (JTG E20-2011) and "Field Test Methods of Highway Subgrade and Pavement" (JTG 3450-2019) [26,27], the strength, high-temperature stability, low-temperature cracking resistance, water stability, and fatigue resistance of DPAM, WPAM, and SBSAM was evaluated through a series of indoor tests. Additionally, the performance of the completed constructed trial pavement was tested. Notably, three parallel tests were conducted for the same mixture.

4.1. Laboratory Test of Pavement Performance

The mechanical strength of the specimens was tested using the SYD-0709 Marshall Stability Meter manufactured by Shanghai Changji Geological Instrument Co., Ltd. (Shanghai, China). The prepared Marshall specimens were placed in a thermostatic water bath at 60 °C for 45 min. The dimensions of the specimens were Φ101.6 × 63.5 mm, and the loading rate was 50 ± 5 mm/min.

The rutting test was carried out using the HYCZ-1 rutting tester of Shanghai Shenrui Test Equipment Manufacturing Co., Ltd. (Shanghai, China). The molded plate specimens were placed in an oven at 60 °C for 4 h. The specimen size was 300 × 300 × 50 mm. The test temperature was 60 °C, and the wheel pressure was 0.7 MPa.

The plate specimens from the rutting tests were cut into beams with dimensions of 250 × 30 × 35 mm and tested using the UTM-25 multifunctional materials testing system manufactured by IPC Global (Melbourne, Australia). The test temperature was −10 °C, and the loading rate was 50 mm/min.

Unlike the Marshall test, the immersion Marshall test divided the Marshall specimens into two groups; one group was placed in a thermostatic water bath at 60 °C for 48 h, and the other group was placed in for 45 min. Similarly, in the freeze–thaw splitting test, the Marshall specimens were separated into two groups, one of which was placed at room temperature, and the other group of which had to be vacuum saturated with water, frozen (−18 °C/16 h), and held in a thermostatic water bath (60 °C/24 h). Subsequently, the two groups of specimens were placed in a thermostatic water bath under the condition of 25 °C/2 h. The splitting test was carried out on the specimens at a loading rate of 50 mm/min.

Three-point bending and four-point bending fatigue tests are often used to evaluate the fatigue resistance of asphalt mixtures. Compared to three-point bending, four-point bending fatigue tests provide a more uniform bending moment distribution and more accurate test results [28]. Consequently, four-point bending fatigue tests were performed on the mixture using the UTM-25 multifunctional materials testing system manufactured by IPC Global (Melbourne, Australia), as shown in Figure 5. The fatigue resistance of the mixture was evaluated in terms of the loading times when the strength modulus (S) of the specimen reached 50% of the initial modulus. The maximum tensile stress (σ_t), maximum tensile strain (ε_t), and S of the specimens were calculated as shown in Equations (2)–(4).

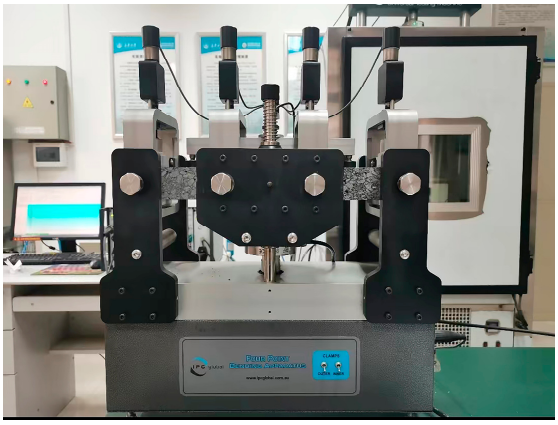

Figure 5. Four-point bending fatigue test instrument.

$$\sigma_t = \frac{L \times P}{W \times h^2} \tag{2}$$

$$\varepsilon_t = \frac{12 \times \delta \times h}{3L^2 - 4a^2} \tag{3}$$

$$S = \frac{\sigma_t}{\varepsilon_t} \tag{4}$$

where L is the length of the outer scale distance, 355.5 mm; P is the peak force, kN; W is the width of the beam, mm; h is the length of the beam, mm; δ is the maximum strain at the center of the beam; a is the length of the inner scale distance, 118.5 mm.

4.2. Fourier Transform Infrared Spectroscopy (FTIR) Test

A Nicolet 6700 Fourier Transform Infrared Spectrometer manufactured by Thermo Fisher Scientific (Waltham, MA, USA) was used to test the different materials. The attenuated total reflectance (ATR) method was utilized. The resolution for the tests was 4 cm^{-1}, and the scanning range was 4000–600 cm^{-1}.

4.3. Field Test of Pavement Performance

After the trial pavement was completed, the field performance of the pavement was tested according to the specification (JTG 3450-2019) [27]. According to T0924-2008, the AL-20 pavement corer produced by Shandong Aolian Machinery Co., Ltd. (Jining, China) was used to obtain samples of the pavement and test the compactness of the specimens using an electronic balance and a thermostatic water bath; the manual sanding method was used, and T0964-2008 was adopted as a guideline to test the texture depth of the test pavement surface to evaluate the skid resistance; according to T0932-2008, an LXBP-8 continuous eight-wheel flatness tester of Cangzhou Qiuzhen Instrument and Equipment Co., Ltd.(Cangzhou, China) was used to test the International Roughness Index (IRI) of the pavement; an HDSS-II pavement seepage tester produced by Hebei Huaxi Experimental Instrument Co., Ltd. (Cangzhou, China) was used to test the pavement permeability, according to T0972-2008.

5. Results and Discussion

5.1. Optimization of the Construction Technology

As a novel pavement material, the construction process of DPAM needs to be thoroughly explored before it is used in pavement construction to ensure that it has satisfactory service performance. This study focused on the mixing temperature (M_{TE}), mixing time (M_{TI}), and the hitting number (H_N) of DPAM and compared it with WPAM and SBSAM. Notably, the other process parameters were kept the same when a particular mixture preparation process was investigated.

5.1.1. Mixing Temperature

The Chinese specification (JTG F40-2004) requires the preparation temperature of modified asphalt mixtures to be 160–185 °C. Meanwhile, considering the poor heat-resistant properties of PU, an excessively high M_{TE} will lead to the destruction of its molecular structure as well as the degradation of properties [29,30]. Therefore, the M_{TE}s of the asphalt mixture were set to 150 °C, 160 °C, 170 °C, and 180 °C, and the M_{TI} and H_N were standardized to 75 s and 75 times. The resulting Marshall specimens were prepared, and Marshall tests were conducted. The test results are shown in Figure 6.

It can be seen that the Marshall Stability (MS) of the two PUAMs, that is, the DPAM and WPAM, exhibited a tendency first to increase and then decrease as the M_{TE} increased. When the M_{TE} was 160 °C, the MS of the two mixtures was at maximum, which was 15.85 and 16.58 kN, respectively. However, when the M_{TE} increased to 180 °C, the MS of the two declined significantly, by 23.2% and 21.7%, respectively, compared to that at 160 °C. In contrast, the MS of SBSAM increased gradually with increasing temperature, from 11.63 to 15.26 kN. The main reason for this is that SBS is a thermoplastic elastomer, and when SBS was added to the base binder, the modifier adsorbed the light components of the asphalt at high temperatures, which resulted in solubilization and cross-linking, thus increasing the viscosity of the binder [31]. As a result, the SBSA binder displayed high viscosity characteristics, while the increase in temperature contributed to a reduction in the viscosity of the binder, increasing the flowability and improving the adhesion to the aggregate. Notably, the optimum M_{TE} for DPAM and WPAM was 10–20 °C lower than that of SBSAM. On the one hand, the continuously elevated temperature accelerated the

decomposition of PU, the molecular structure was damaged, and the reaction between PU and MOCA was adversely affected [30]; on the other hand, an appropriate amount of diluent had been added to the PUA binder to ensure satisfactory flowability of the PUA binder. In this case, continuing to raise the temperature caused a further decrease in the viscosity of the binder, which in turn led to downward accumulation under the effect of gravity and the occurrence of segregation [32]. As a result, the *MS* of the DPAM and WPAM decreased significantly. Furthermore, the *MS* of PUAM was higher than that of SBSAM at all M_{TE}s except 180 °C. The results indicate that the utilization of PU as a modifier could reduce the M_{TE} of the mixture, while the chemical reaction between the isocyanate and hydroxyl group, as well as between the isocyanate and amine group, was more effective in improving the mechanical properties of the mixture. Eventually, the optimal M_{TE} for DPAM and WPAM was 160 °C, and the optimal M_{TE} for SBSAM was 170 °C.

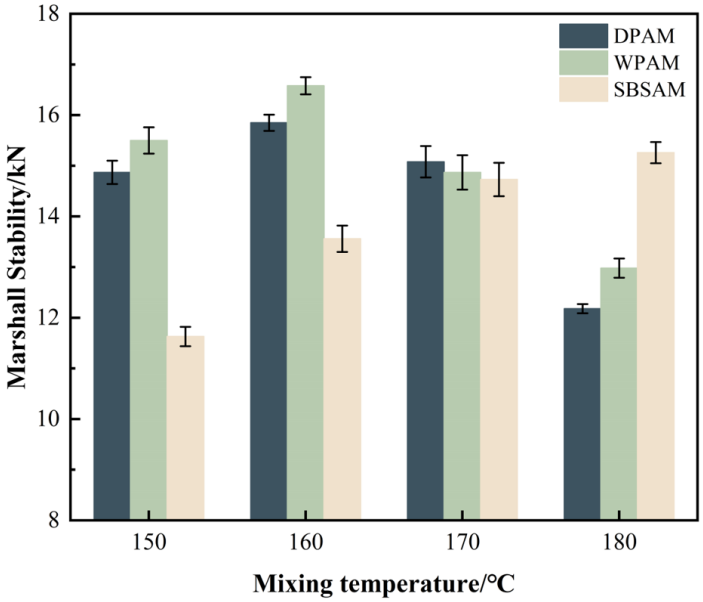

Figure 6. Marshall test results of asphalt mixtures prepared with different M_{TE}.

5.1.2. Mixing Time

The prolongation of the M_{TI} of the mixture could help to enhance the connection between the binder and the aggregate and improve the adhesion [33,34]. The specification (JTG F40-2004) requires that the M_{TI} should be ≥45 s and that the M_{TI} of the modified asphalt binder should be extended appropriately [23]. Thus, this study selected 45, 60, 75, and 90 s as the M_{TI}, H_N was fixed 75 times, and the M_{TE} was 160 °C for DPAM and WPAM and 170 °C for SBSAM. The results are shown in Figure 7.

As seen in Figure 7, the *MS* of all the mixtures gradually increased with the increase of M_{TI}. The difference was that the growth rate in *MS* of the DPAM and WPAM obviously slowed down when their M_{TI} was higher than the 60 s. In contrast, this phenomenon was observed for SBSAM at higher than 75 s. The reason is that the increase in M_{TI} enabled the binder to contact the aggregate fully, and the adhesion was improved [34], but mindlessly increasing the M_{TI} could not consistently improve the mechanical properties of the mixture. Importantly, the DPAM and WPAM exhibited excellent mechanical properties at the M_{TI} of 60 s, whereas the higher viscosity SBSA binder required 75 s for optimal performance. Additionally, it can be seen that at the same M_{TI}, the *MS* of the DPAM was always slightly lower than that of WPAM, which may be attributed to the fact that WPAM used a PUA binder prepared in advance. The PU was uniformly dispersed in the asphalt, whereas the dry-mix method tended to result in the non-uniform distribution of PU. In summary, the optimal M_{TI} for DPAM and WPAM was 60 s, and the optimal M_{TI} for SBSAM was 75 s.

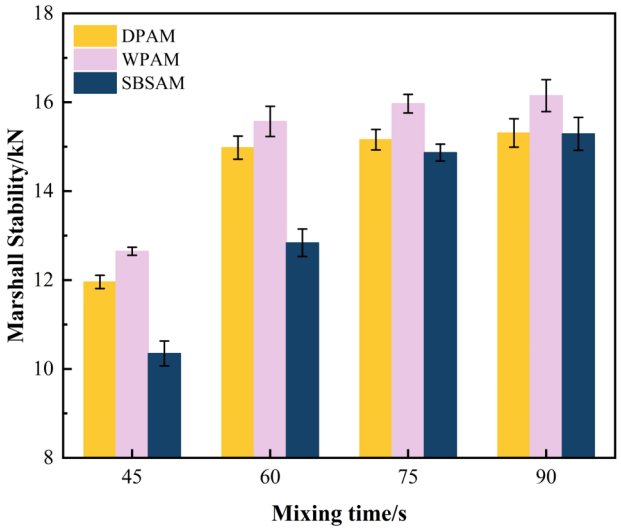

Figure 7. Marshall test results of asphalt mixtures prepared with different M_{TI}.

5.1.3. Hitting Number

An appropriate H_N is necessary for adequate compaction and excellent service performance of the mixture. The Chinese specification, JTG F40-2004, requires an H_N of 75 times for high-grade highways and 50 times for general highways [23]. Based on this, three different H_Ns, 50, 75, and 100 times, were selected. Conditions of 160 °C and 60 s were used for M_{TE} and M_{TI} for DPAM and WPAM, respectively, and 170 °C and 75 s for M_{TE} and M_{TI} for SBSAM.

Figure 8 demonstrates the Marshall test results of the three asphalt mixtures at different H_Ns. There is no doubt that the *MS* of the mixture all increased with the increase in H_N. This is due to the fact that the increase in H_N caused the internal porosity of the mixture to decline and the densification to increase [35]. The rise of H_N from 50 to 75 times enhanced the *MS* of the DPAM, WPAM, and SBSAM by 39.5%, 35.0%, and 41.5%, respectively. Nevertheless, the H_N was further increased, and the improvement in *MS* of the three mixtures reduced by 3.7%, 8.6%, and 9.2%, respectively. The results indicated that a reasonable compaction power existed for asphalt mixtures. A too-high compaction power could easily lead to the crushing of aggregates and the destruction of the mixture skeleton. Although this could further enhance the mechanical strength of the mixture, the excessively low porosity tended to lead to cracks and pothole defects in the pavement [36]. Consequently, the optimum H_N for the three mixtures was determined to be 75 times.

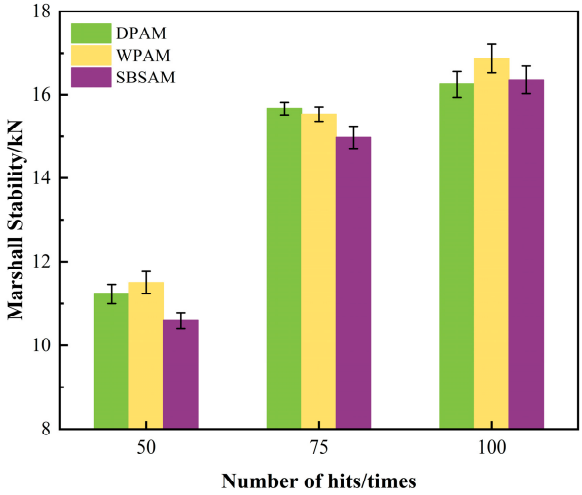

Figure 8. Marshall test results of asphalt mixtures prepared with different H_N.

5.2. Chemical Reactions in PUA Systems

It can be seen in the construction technology study that the DPAM possessed mechanical properties close to those of WPAM. In order to verify whether the PU underwent sufficient chemical reaction in the DPAM, this study utilized trichloroethylene to extract the asphalt binder from the DPAM and WPAM, and named them DPA and WPA binders, respectively. The FTIR test was performed on PU, base, DPA, and WPA binders, and the test results are shown in Figure 9.

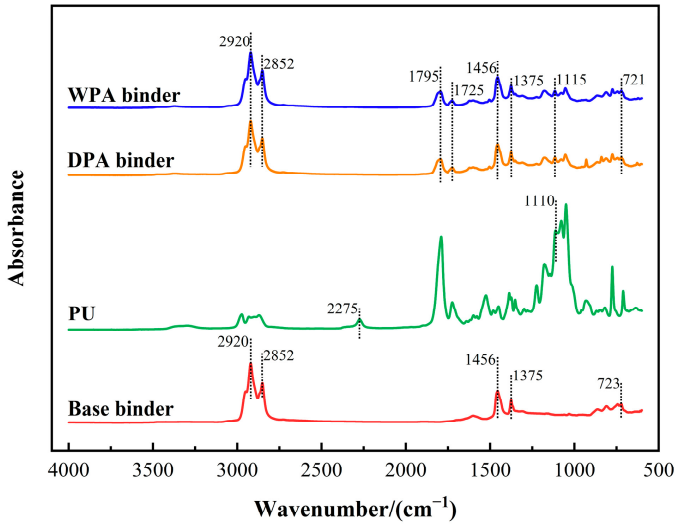

Figure 9. FTIR test results of different materials.

Typical absorption peaks appeared in the infrared spectrum of the PU, such as the -NCO characteristic absorption peak at 2275 cm^{-1} and the ether bond C-O-C characteristic absorption peak at 1110 cm^{-1}. Typical characteristic peaks in the base binder appeared in the DPA and WPA binders, including the -CH_2 stretching vibrational absorption peaks at 2920 and 2852 cm^{-1}, the -CH_3 variable-angle vibrational absorption peaks at 1456 and 1375 cm^{-1}, and the C-H vibrational absorption peaks formed by the in-plane swinging of the benzene ring at 721 cm^{-1} [3]. Notably, the DPA binder had a similar infrared spectrum to the WPA binder. Specifically, the -NCO characteristic absorption peak at 2275 cm^{-1} in the PU disappeared. The reason is that, as shown in Equations (5) and (6), -NCO reacted with -NH_2 in MOCA and -OH in asphalt to produce isocyanurate and carbamate, and their characteristic absorption peaks were located at 1795 and 1725 cm^{-1}, respectively, which were essential for improving the high-temperature performance of the asphalt binder and mixture [9,37]. Meanwhile, the ether bond, C-O-C, in PU was injected into the DPA and WPA binders, which was at 1115 cm^{-1}. The ether bond was characterized by low cohesive energy and easy rotation, which contributed to the improvement of the flexibility of the binder and mixture [3,9,37]. The results suggested that PU could fully react chemically during the preparation of DPAM, and it was feasible to prepare PU asphalt mixtures using the dry-mix method.

$$\text{R-NCO} + \text{R}_1\text{-NH}_2 \rightarrow \text{R-NHCONHR}_1 \quad (5)$$

$$\text{R-NCO} + \text{R}_1\text{-OH} \rightarrow \text{RNHCOOR}_1 \quad (6)$$

5.3. Laboratory Mixture Pavement Performance

To ensure that DPAM has good pavement performance, it is necessary to evaluate its high- and low-temperature performance, water stability, and fatigue resistance and compare it with WPAM and SBSAM.

5.3.1. High- and Low-Temperature Performance

Figure 10a illustrates the rutting test results. It can be seen that WPAM had the lowest rutting depth (*RD*) of 2.214 mm, and DPAM had a slightly higher *RD* than WPAM. Meanwhile, SBSAM possessed the highest RD of 2.841 mm. From the results of dynamic stability (*DS*), it can be seen that the *DS* of all the mixtures met the requirement of ≥2800 times/mm in the specification, JTG F40-2004 [23], which indicated that they had satisfactory high-temperature performance. Among them, the *DS* of both DPAM and WPAM exceeded 7000 times/mm, reaching 7241.4 and 7590.4 times/mm, which were 18.1% and 24.1% higher compared to SBSAM, respectively. The results demonstrate that, owing to the chemical reaction that occurred in the system, PU formed a crosslinked structure in the binder [17], which resulted in better high-temperature resistance to permanent deformation than the SBSA binder. Moreover, the high-temperature stability of DPAM was slightly worse than that of WPAM, which may be attributed to the fact that PU was more uniformly dispersed and formed a more stable crosslinked structure in the modified asphalt binder prepared using the shear equipment.

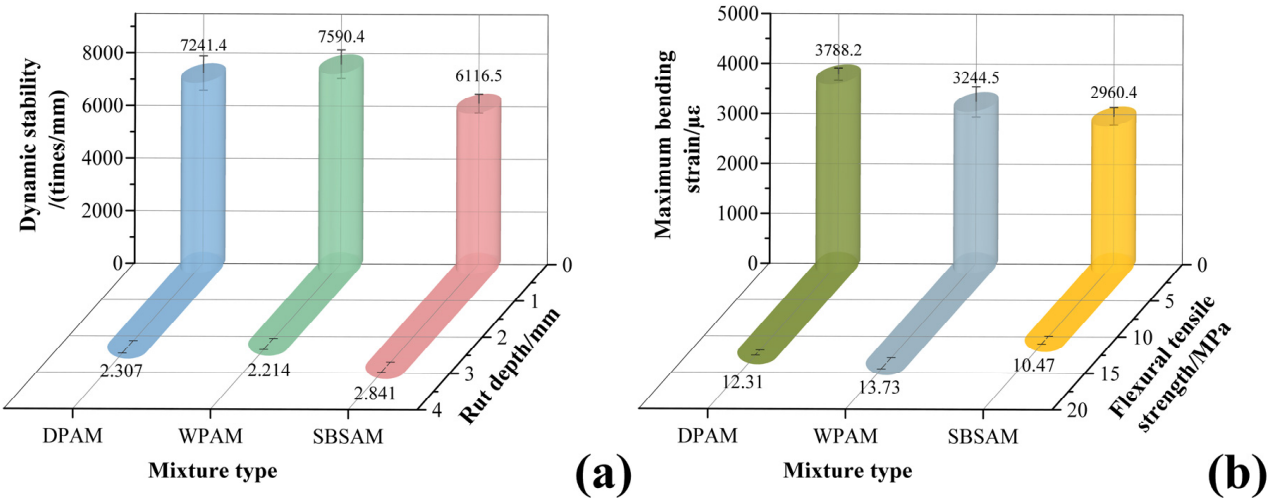

Figure 10. High- and low-temperature performance test results of mixtures: (**a**) rutting test and (**b**) bending beam test.

The results of the bending beam test are shown in Figure 10b. For the flexural tensile strength (R_B), the relationship between the magnitudes of R_B of the three mixtures was WPAM > DPAM > SBSAM, which was similar to the Marshall and rutting test results. The specification, JTG F40-2004, requires that the maximum bending strain (ε_B) should be ≥2500 με [23]. Observing the results of ε_B, it can be seen that all the mixtures exhibited good low-temperature flexibility. Among them, DPAM had the highest ε_B of 3788.2 με, which was 16.8% and 28.0% higher than WPAM and SBSAM, respectively. The results reveal that DPAM had the best low-temperature flexibility. As mentioned in the FTIR test, the ether bond, C-O-C, in PU injected into the asphalt binder positively improved its flexibility [3,9,37]. Notably, the flexibility of WPAM was inferior to that of DPAM. The reason is that, on the one hand, the preparation of WPAM required the preparation of the WPA binder first, and the increasing time of the binder at high temperatures exacerbated the aging of the asphalt binder, making it hard and brittle; on the other hand, the WPA binder prepared in advance may segregate during storage. This may lead to a deterioration in the stability of the performance of the mixture, and the increase in the error bars of its test results supported the view.

5.3.2. Water Stability

The pavement is affected by environmental factors such as precipitation and weather during service, which cause irreversible damage to the performance of the pavement. Hence, the water stability of asphalt mixtures was evaluated, and the test results are shown in Figure 11.

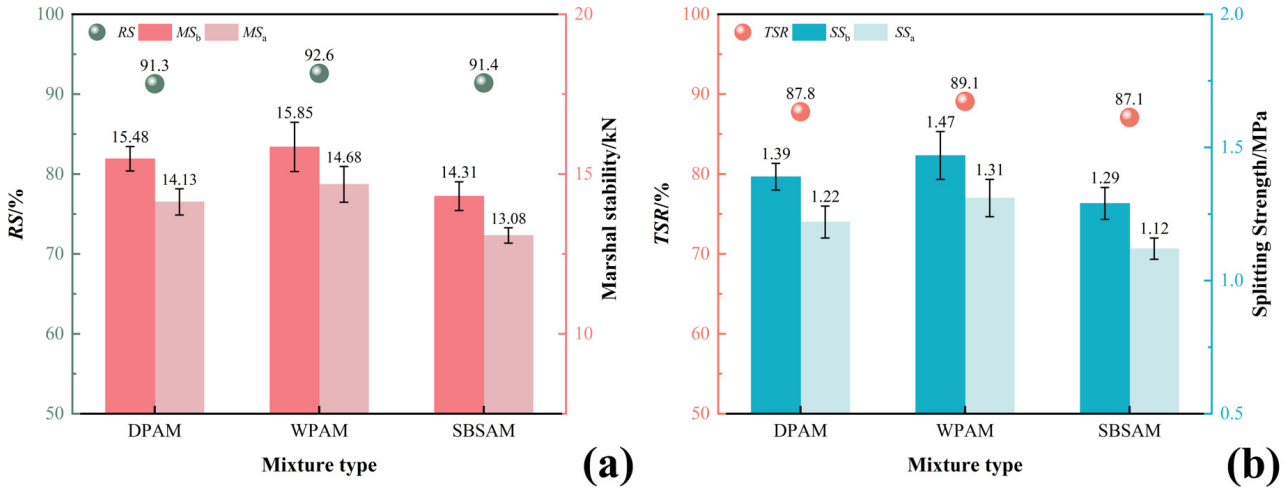

Figure 11. Water stability test results of mixes: (**a**) immersion Marshall test and (**b**) freeze–thaw splitting test.

Figure 11a demonstrates the water immersion Marshall test results. It can be found that after 48 h of immersion, the *MS* of the mixture all decreased, indicating that the high temperature and moisture damaged the internal structure of the specimen [38,39]. The residual stability (*RS*) was utilized to evaluate the water stability of the mixture, and the specification, JTG F40-2004, requires that the *RS* should be ≥85% [23]. The results show that the *RS* of all the mixtures was above 90%, which satisfies the specification requirements. The *RS* of WPAM was the highest, while the *RS* of DPAM and SBSAM were quite close to each other, which were 91.3% and 91.4%, respectively. Compared to WPAM, the *RS* of DPAM decreased. This is because PU was directly put into the mixing device during the mixture production process, which may lead to non-uniform dispersion of PU in the binder. In this case, the asphalt film on the surface of partial aggregates was peeled off and damaged under the action of moisture.

The results of the freeze–thaw splitting test are shown in Figure 11b. Similarly, the specimens were adversely affected by moisture and freeze–thaw and exhibited a deterioration in performance. It is worth noting that the freeze–thaw splitting tensile strength ratios (*TSR*) of the specimens were all lower than *RS*, and the adverse effect of the coupling of moisture and temperature on the water stability of the mixture was more significant. The specification, JTG F40-2004, requires that the *TSR* of the mixture should be ≥80% [23], and it can be seen that their *TSR*s all met the specification requirements and displayed satisfactory water stability. Similar to the pattern exhibited by *RS*, the *TSR* of DPAM was lower than that of WPAM, which was correlated with the uneven distribution of modifiers mentioned above. Additionally, the *TSR*s of DPAM and WPAM were higher than those of SBSAM, indicating that the chemically modified PUA binder contributed to the improvement of the water stability.

5.3.3. Fatigue Resistance

The fatigue performance of asphalt mixtures is also worthy of attention. The fatigue performance of the mixture was evaluated using the four-point bending fatigue test, and the test results are shown in Figure 12.

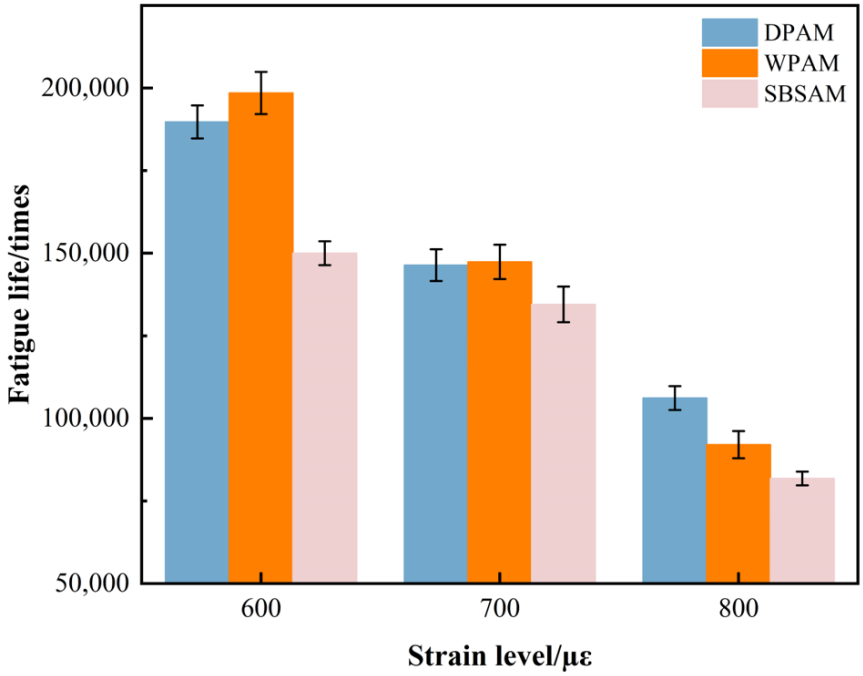

Figure 12. Fatigue test results of the mixture.

As shown in Figure 12, the fatigue life (*FL*) of all three mixtures gradually declined as the strain level increased. In other words, the higher the vehicle loads subjected to during service, the more prone the pavement is subject to damage. Under the same strain level, the *FL* of DPAM and WPAM were consistently higher than those of SBSAM, demonstrating the superior performance of the mixtures prepared using PUA binders, which could not only prolong the service life of the pavement but also contribute to the reduction of the maintenance frequency of the pavement after operation. Interestingly, the relationship between the *FL* of DPAM and WPAM gradually shifted as the stress level increased. Specifically, at a stress level of 600 με, the *FL* of WPAM was higher than that of DPAM; at a stress level of 700 με, the *FL* of the two were close; and at a stress level of 800 με, the *FL* of DPAM was higher than that of WPAM. This phenomenon may be because, as demonstrated in other tests, DPAM possessed lower mechanical strength but better flexibility than WPAM. As the stress level gradually increased, WPAM was more prone to cracking defects, which in turn caused damage to the specimens. Thus, DPAM may be more suitable than WPAM for pavements with high traffic loads.

5.4. Trail Pavement Performance

From the above tests and analysis, it can be seen that DPAM had satisfactory comprehensive pavement performance and met the application requirements of the practical project. After the trial pavement was completed, the thickness, compactness, texture Depth, IRI, and pavement permeability coefficient of the surface layer were tested, and the test results are shown in Table 5.

Table 5. Performance test results of the trial pavement.

Test Item	Test Result	Specification
Thickness/cm	4.1	4.0
Martensian compactness/%	98.8	≥98
Theoretical compactness/%	94.8	≥94
Texture Depth/mm	1.0	≥0.6
International Roughness Index IRI/(m/km)	0.62	≤2.0
Pavement permeability coefficient/(ml/min)	57	≤100

It can be seen that the thickness of the upper layer of the completed pavement was 4.1 cm, which was close to the 4.0 cm required by the project. The Martensian compactness and theoretical compactness were 98.8% and 94.8%, which satisfy the requirements of ≥98% and ≥94%, respectively, in the "Specification for Quality Acceptance of Highway Construction" (JTG (2016) 24-2016) [40]. The texture depth of the upper layer was 1.0 mm, which exceeded the requirement of being not less than 0.6 mm in the specification, JTG (2016) 24-2016 [40]. The IRI of the upper layer was 0.62 m/km, which is much lower than the requirement of ≤2.0 m/km in the specification. Moreover, the permeability coefficient of the pavement was 57 mL/min, which could meet the requirement of ≤100 mL/min in the specification. The results show that all the indexes of the pavement constructed with DPAM reached the application requirements, and its service quality could be fully guaranteed. The pavement performance and service condition after the operation of the trial pavement will be continuously paid attention to and tested in the future.

5.5. Construction Cost Analysis

Since the same asphalt-to-aggregate ratio was used for all the asphalt mixtures in this study, only the binder cost was calculated. DPAM negated the step of preparing the modified asphalt binder in advance, so only the cost of each raw material was considered in the DPA binder. The cost of different materials is shown in Figure 13.

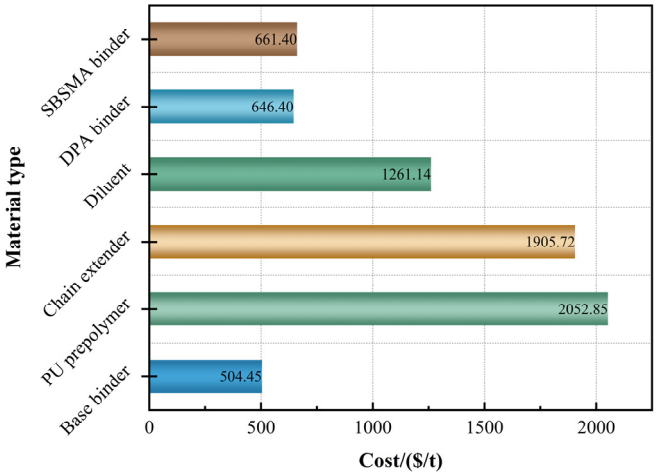

Figure 13. Cost of different materials.

In the DPA binder, the mass ratio of each raw material was PU: MOCA: diluent: base binder = 6.0:0.8:5.0:88.2. As seen in Figure 13, the cost of PU, MOCA, diluent, and base binder were USD 2052.85, USD 1905.72, USD 1261.14, and USD 504.45/t, respectively. After calculation, the cost of the DPA binder was USD 646.40/t. After the market research, the cost of most of the large-scale applications SBSMA binder ranged from $USD 630.57 to USD 672.61/t, and the cost of the SBSMA binder used in this study was USD 661.40/t. It can be noticed that the cost of the DPA binder was close to that of the SBSMA binder, but the cost of DPAM may be further reduced if it can be applied on a large scale. Meanwhile, the performance of DPAM is apparently superior. Additionally, it should not be neglected that the utilization of the dry-mix method for the preparation of asphalt mixtures had evident advantages. First, the dry-mix method negated the production of finished product-modified asphalt binder, thus reducing the energy consumption and pollutant emissions in the production process; second, it avoided the segregation and degradation of performance indicators of the binder in the process of storage and transportation; third, the dry-mix method was convenient for the on-site construction organization, and the modifiers had a relatively long storage time so that they could be arranged for production at any time, in accordance with the actual situation. To summarize, DPAM has excellent potential for promotion and application.

6. Conclusions

DPAM was first prepared in this study, and its construction technology and pavement performance were explored and compared. Subsequently, the research results were applied to the practical project and tested on the completed trial pavement. Additionally, the costs of DPAM and SBSAM were analyzed. The main conclusions can be summarized as follows:

(a) The construction technology could significantly affect the mechanical properties of DPAM, and the recommended optimal M_{TE}, M_{TI}, and H_N were 160 °C, 60 s, and 75 times, respectively. Compared with SBSAM, the MTE and MTI of DPAM decreased, which contributed to the reduction in energy consumption and cost.

(b) The FTIR results suggested a sufficient chemical reaction of the PU in DPAM. DPAM had satisfactory overall pavement performance; although slightly inferior to WPAM in terms of high-temperature performance and water stability, it was significantly better than SBSAM, especially in terms of low-temperature cracking resistance and fatigue performance.

(c) The trial road paved with DPAM met the relevant requirements for construction quality. The cost of DPAM was comparable to that of SBSAM. Still, its simplified construction process and better pavement performance can positively reduce energy consumption, prolong service life, and promote the large-scale application of PUAM in pavement engineering.

(d) The pavement performance and service conditions of the trial road after the operation will continue to be monitored and tested, and the investigation on the performance optimization and micro-mechanism of DPAM will be conducted in the future. Additionally, the Hertzian stresses developed when the DPAM pavement was subjected to distributed loads and the simulation analysis will be carried out in future work.

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