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Comparison of Rubber Asphalt with Polymer Asphalt under Long-Term Aging Conditions in Michigan

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Abstract: The objective of this study is to compare the long-term aging performance of dry-processed rubber-modified asphalt mixture with styrene–butadiene–styrene polymer-modified asphalt mixture on heavy traffic volume roads in the wet-freeze environment of Michigan. The rutting performance was evaluated using the Hamburg wheel track device. The disc-shaped compact tension test was used to assess the fracture energy. The dynamic modulus experiment was used to estimate the load and displacement relationship. The asphalt binder properties were evaluated using multiple stress creep recovery and the linear amplitude sweep test. The pavement distresses were evaluated using the pavement mechanistic–empirical design. All three types of asphalt mixture show excellent rutting resistance after long-term aging conditions, while the fracture energy of the rubber mix is 17.1% to 30.5% higher than that of the control mix and 6.8% to 9.1% higher than that of the polymer mix. The rubber and polymer incorporated with the asphalt binder improved the resistance to permanent deformation and improved the fatigue life of the asphalt binder. In summary, the rubberized asphalt technology using the dry process shows better cracking resistance and fatigue life. Therefore, rubberized asphalt using the dry process will exhibit adequate performance when used for high-volume roads in the wet-freeze environment of Michigan.

Keywords: dry-processed rubber-modified asphalt mixture; disc-shaped compact tension test; hamburg wheel tracking device; dynamic modulus; multiple stress creep recovery test; linear amplitude sweep test; pavement M-E design

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1. Introduction

In the United States, automobiles produce millions of waste tires each year. It is a challenge to determine how to reduce that staggering amount to a manageable level. One possible solution is to pulverize the scrap tires into usable crumb rubber and then incorporate it into asphalt pavements. This will help protect the environment and save natural resources.

Numerous researchers have focused on the application of scrap tire rubber and its performance in asphalt mixtures. Scrap tire rubber-modified asphalt mixture has been proven to have outstanding low-temperature cracking and fatigue resistance in some experiments [1–3]. The low-temperature performance of scrap tire rubber-modified asphalt mixture improves as the scrap tire rubber content increases within a specific range. This is due to the consistent mixing of the scrap tire rubber and asphalt, which improves the ductility and integrity at low temperatures. Some researchers have studied the performance of scrap rubber-enhanced asphalt mixture at high temperatures. Due to the high in-service temperatures of pavements, bituminous mixtures must have excellent resistance to permanent deformation [4–6]. The scrap tire rubber incorporated with asphalt binder increased the viscosity of asphalt and improved the permanent deformation resistance. The most noticeable feature of the asphalt mixture made with scrap rubber-modified asphalt mixture is the improved fatigue cracking resistance. On this subject, many research investigations have been conducted. Venudharan et al. [7] and Miranda et al. [8] reported that scrap tire rubber incorporated with asphalt binder improves the binder content requirement in the mix design, and the cracking propagation also needs a longer time, which may improve the fatigue performance. The ability of scrap tire rubber-modified asphalt layers to contribute to noise reduction is an often-touted environmental benefit. Several studies have found that the noise reduction achieved by AR layers can range from two to ten dB [9]. Chen et al. [10] and Hernández-Olivares et al. [11] found that ground tire rubber used in gap gradation asphalt mixtures could enhance the deformation resistance compared with conventional gap gradation asphalt mixtures. Nguyen and Tran [12] reported that the rutting resistance of ground tire rubber- and polymer-modified asphalt mixtures is better than conventional asphalt mixtures. Lastra-González et al. [13] stated that compared with conventional asphalt mixtures, ground tire rubber could improve deformation resistance by 30%. Some researchers have analyzed the low-temperature performance of ground tire rubber-modified asphalt mixtures. Sangiorgi et al. [14] reported that by adding ground tire rubber, the stiffness could be reduced, and the cohesion between aggregate and asphalt binder could be increased. Yang et al. [15] proposed that rubber incorporated into asphalt could show better low-temperature properties than conventional asphalt mixtures. When Feiteira et al. [16] assessed permanent deformation resistance, the same level of resistance was observed between the wet and dry- treated ground tire rubber asphalt mixtures. Other researchers have also focused on the fatigue characteristics of ground tire rubber-modified asphalt mixtures. Silva et al. [17] stated that ground tire rubber-modified asphalt mixtures have a lifetime of 20 times longer compared with the conventional gap gradation mixtures. Picado-Santos et al. [18] noted that rubber incorporated into asphalt pavements shows good quality after a service life of eight years and would be satisfactory for eight more years. This suggests a good fatigue life performance.

In road construction, the use of polymeric waste to improve asphaltic mixture performance seems promising [19]. At both high and low temperatures, the polymer can impact the viscosity and ductility of the asphalt binder. Fang et al. [20] stated that polymer-modified asphalt improves stability at high temperatures and cracking performance at low temperatures. Romeo et al. [21] found that styrene–butadiene–styrene-modified asphalt improves the anti-cracking performance of asphalt mixtures. Xu et al. showed that treated polyethylene terephthalate improves the rutting and cracking performance of the asphalt binder. Some research has been done on the performance of polymer-modified asphalt pavements in the field. Greene et al. [22] used accelerated pavement testing to evaluate and implement a heavy polymer-modified asphalt binder, and both the rutting and cracking properties were improved. Zhu [23] studied the effect of thermal-oxidative aging on the rheological performance of modified asphalt binders and found the polymer-modified asphalt binder to have a lower susceptibility to aging. Blazejowski et al. [24] studied the properties of the high content of polymer-modified asphalt binder and reported that the polymer-modified asphalt binder shows better performance with regards to thermal cracking, fatigue cracking, and rutting.

Due to the lack of systematic study of the long-term aged pavement properties of the rubber mix, polymer mix, and control mix of asphalt mixtures on heavy traffic volume roads in the wet-freeze environment of Michigan, the objective of this study is to investigate the high-temperature rutting resistance, low-temperature cracking resistance, and fatigue resistance of rubber mix, control mix, and polymer mix before and after long-term aging conditioning and predict the pavement distress using pavement M-E. This study focused on three types of asphalt mixtures: rubber mix, polymer mix, and control mix. Samples were prepared by the SGC and then conditioned at 85 °C for five days to complete the long-term aging process. The Hamburg wheel track device (HWTD) was used to examine rutting and moisture susceptibility. The disc-shaped compact tension test (DCT) was used to estimate low-temperature cracking, and the dynamic modulus test was utilized to reveal the load and displacement relationship. The asphalt binder performance was evaluated using the asphalt binder extracted from a loose mixture, and the short-term aging and long-term aging asphalt binders were prepared using a rolling thin-film oven and pressure aging vessel. A dynamic shear rheometer (DSR) was used to estimate the high-temperature rheological characteristics and medium-temperature fatigue performance. Then, using the pavement M-E design approach, the road distresses were calculated.

2. Materials and Methods

2.1. Materials and Gradation

The project is located on Cascade Road in Kent County, Michigan. The loose mixtures (scrap tire rubber asphalt loose mixture using the dry process, conventional asphalt loose mixture, and polymer-modified asphalt mixture) were collected from the asphalt plant (2020 Chicago Drive, Wyoming, MI, USA, 49519). The aggregate gradation of the asphalt pavement is shown in detail in Table 1. The asphalt binders PG 58-28, PG 58-28 with 10% wt. of scrap tire rubber, and PG 70-28 were employed in the conventional asphalt mixture (control mix), rubber-modified asphalt mixture (rubber mix), and polymer-modified asphalt mixture (polymer mix), respectively. The asphalt binder content of the control mix, rubber mix, and polymer mix is 5.07%, 5.25%, and 5.07%, respectively. The polymer-modified asphalt (PG 70-28) was directly collected from the plant, and the styrene–butadiene–styrene modifier was incorporated with PG 58-28 asphalt binder to get the PG 70-28 polymer-modified asphalt. The basic qualities of the asphalt binder met all of the requirements of the specification. The dry process mix temperature of rubber mix and polymer mix asphalt pavement is 163 °C. The reclaimed asphalt pavement (RAP) content is 20% wt. of loose aggregate. The long-term aged conventional asphalt mixture, rubber-modified asphalt mixture, and polymer-modified asphalt mixture will be referred to as control mix (aged), rubber mix (aged), and polymer mix (aged), respectively.

Table 1. Aggregate gradation in Kent project.

Aggregate Gradation and Aggregate Proportion						
Aggregate Type	2NS	Slag Sand	3/32	Trap Sand	CS-2	RAP
Blend%	12%	19%	13%	22%	16%	18%
Sieve size	Percent Passing					
½ inch (12.5 mm)	100%	100%	100%	100%	100%	100%
3/8 inch (9.5 mm)	100%	100%	100%	100%	88.8%	97.1%
No. 4 (4.75 mm)	100%	96.6%	98%	93%	5.2%	78%
No. 8 (2.36 mm)	87.4%	74.5%	79.2%	58%	1.6%	58.5%
No. 16 (1.18 mm)	74.5%	52.4%	46.1%	33.9%	1.2%	40.9%
No. 30 (0.6 mm)	58.1%	35.1%	26.9%	20.4%	1.2%	28.6%
No. 50 (0.3 mm)	25.5%	21.1%	14.8%	11.9%	1%	16.5%
No. 100 (0.15 mm)	2.7%	11.5%	7%	7.3%	1%	8.2%
No. 200 (0.075 mm)	0.9%	6.4%	4.1%	4.9%	0.9%	5.5%

2.2. Scrap Tire Rubber by Dry Process in the Asphalt Plant

As shown in Figure 1, scrap tire rubber was applied in the project. A rubber feeding system was utilized to inject the scrap tire rubber with asphalt binder using the dry process.

2.3. Traffic Inputs, Pavement Structure, and Local Calibration Factors

An M-E investigation of a pavement can be utilized to figure out its execution over time. When employing pavement M-E design for flexible pavement design, the average annual daily truck traffic (AADTT) is a significant input. The high traffic level (AADT (average annual daily traffic): 16,500, AADTT: 1400) on Cascade Road was applied as the traffic input. The design life was 20 years. The pavement had two lanes with a speed limit of 105 km per h (65 miles per h). The compound growth rate of traffic was 2%. The pavement structure and thickness used in this study are shown in Table 2. The resilient moduli of the layers are also provided.

Figure 1. The rubber feeding system and scrap tire rubber utilized in the research. (**a**) Rubber feeding system; (**b**) Scrap tire rubber.

Table 2. Existing pavement information utilized in this research.

Layer Types	Thickness/cm	Structure-1	Structure-2	Structure-3
Surface asphalt layer	5	Control mix	Rubber mix	Polymer mix
Jointed plain concrete	25.4	Mr = 6894 MPa		
Open graded drainage Course	15.24	Mr = 227 MPa		
Sand subbase	25.4	Mr = 137 MPa		
Subgrade		Semi-infinite		

Note: Mr means resilient moduli.

2.4. Research Methodology

This section concentrates on the laboratory mixture tests for the three types of asphalt mixtures before and after long-term aging conditions, which comprise the dynamic modulus test, DCT test, and high-temperature HWTD test. The characteristics of the extracted asphalt binder were assessed using a dynamic shear rheometer. The pavement distress prediction was also documented. Figure 2 depicts the research flowchart, which includes the experimental programs and the pavement distress prediction effort.

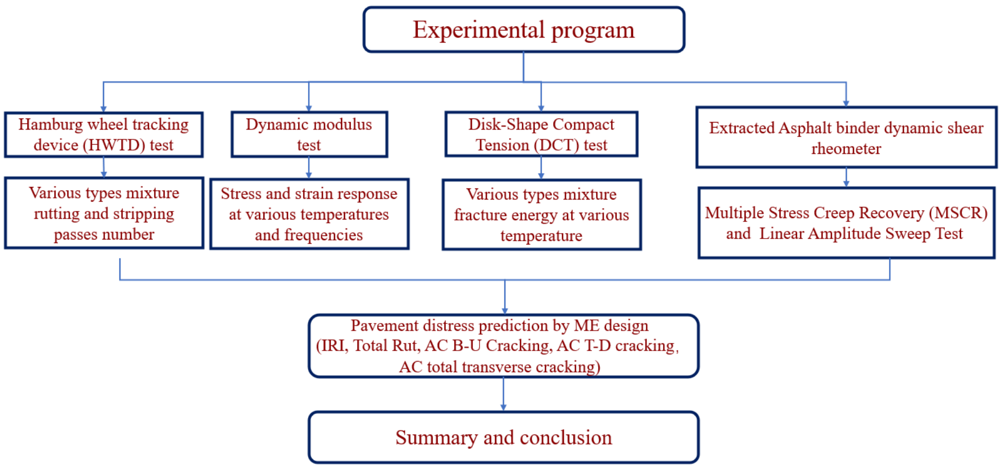


Figure 2. The experimental programs and the pavement distress prediction in the research flowchart.

2.4.1. Hamburg Wheel Tracking Device (HWTD) Test

Cascade Road is a high-traffic volume road with ~10,000,000 equivalent single axle loads (ESAL) during its service life. The rutting and moisture susceptibility are vital properties related to in-service performance. The HWTD test was applied to estimate the rutting and stripping potential of the control mix, rubber mix, and polymer mix in both aged and unaged conditions. The 47 mm wide loaded wheel (705 N) moved back and forth on the submerged asphalt mixture for 20,000 cycles, or up to 20 mm of rutting deformation. The rutting depth was measured with a series of LVDTs. The rutting test temperature was set at 50 °C.

2.4.2. Disc-Shaped Compact Tension (DCT) Test

The DCT test was utilized to evaluate the cracking resistance among the control mix, rubber mix, and polymer mix asphalt mixtures for both aged and unaged conditions. In accordance with ASTM D6373, a cylindrical sample with a thickness of 50 mm and a diameter of 150 mm was made. To reveal the effect of the test temperature on the property of the aged and unaged control mix, rubber mix, and polymer mix, the test temperature was set at −24 and −18 °C.

2.4.3. Dynamic Modulus Test

A UTM-100 with an environmental chamber was used to conduct the dynamic modulus test. The asphalt mixture was subjected to haversine axle compressive stresses at various frequencies and temperatures. The axle strain was collected during the test, and the stress–strain response was recorded. The dynamic modulus test was performed at five different temperatures and six distinct frequencies.

2.4.4. Dynamic Shear Rheometer

The viscoelastic properties of rubber-modified asphalt, conventional asphalt, and polymer-modified asphalt at high temperatures were characterized by a dynamic shear rheometer. The test temperatures for the rolling thin-film oven (RTFO)-aged multiple stress creep recovery test were 52, 58, 64, 70, and 76 °C. The linear amplitude sweep test temperature for the pressure aging vessel (PAV)-aged asphalt binder was 19 °C.

3. Results and Discussions

3.1. Hamburg Wheel Track Device (HWTD) Test Results

The HWTD rutting test was conducted to estimate the rutting and moisture susceptibility of the various types of asphalt mixtures [25]. The results are shown in Figure 3 and Table 3. If the deformation depth approached 20 mm, the program was stopped. The number of wheel passes for the control mix and rubber mix was 5620 and 18,590, respectively. The number of wheel passes for the polymer mix was more than 20,000. The number of wheel passes for the rubber mix is 330% higher than for the control mix, and the rutting depths of the rubber mix are 80.8% higher than those of the polymer mix. Therefore, without long-term aging conditions, the rubber mix has better rutting resistance than the control mix. However, the polymer mix has better rutting resistance than the rubber mix. This signifies that rutting performance was improved when rubber or polymer was added. The addition of rubber or polymer to the asphalt mixture enhanced the rigidity and stability of the mixture, boosting its rutting resistance. Meanwhile, the control mix and polymer mix have better rutting performance than the rubber mix after long-term aging. The average rutting depths of the control mix (aged), rubber mix (aged), and polymer mix (aged) after 20,000 wheel passes were 4.73 mm, 6.33 mm, and 4.96 mm. The creep slope is the inverse of the rutting slope after post-compaction consolidation, and it reflects the rutting potential of various types of asphalt mixture. The creep slopes for the control mix, rubber mix, polymer mix, control mix (aged), rubber mix (aged), and polymer mix (aged) were 0.003, 0.00267, 0.00253, 0.00083, 0.0009, and 0.00085, respectively. This means the rubber and polymer particles in asphalt mix enhance deformation resistance compared with the unaged control mix. After a long period of aging, all of the mixtures enhance the stiffness better than the unaged asphalt mixture, and the control mix has better rutting resistance than the rubber mix and polymer mix. The stripping slope and stripping point were utilized to estimate the moisture susceptibility potential of various types of asphalt mixture. The stripping point for the control mix, rubber mix, and polymer mix was 3188, 16,264, and 16,521, respectively. The stripping slope for the control mix, rubber mix, and polymer mix was 0.005, 0.0018, and 0.00109, respectively. This means that the rubber- and polymer-modified asphalt mixtures have better resistance to moisture damage than ordinary asphalt, while all of the mixtures have superior moisture damage resistance after long-term aging.

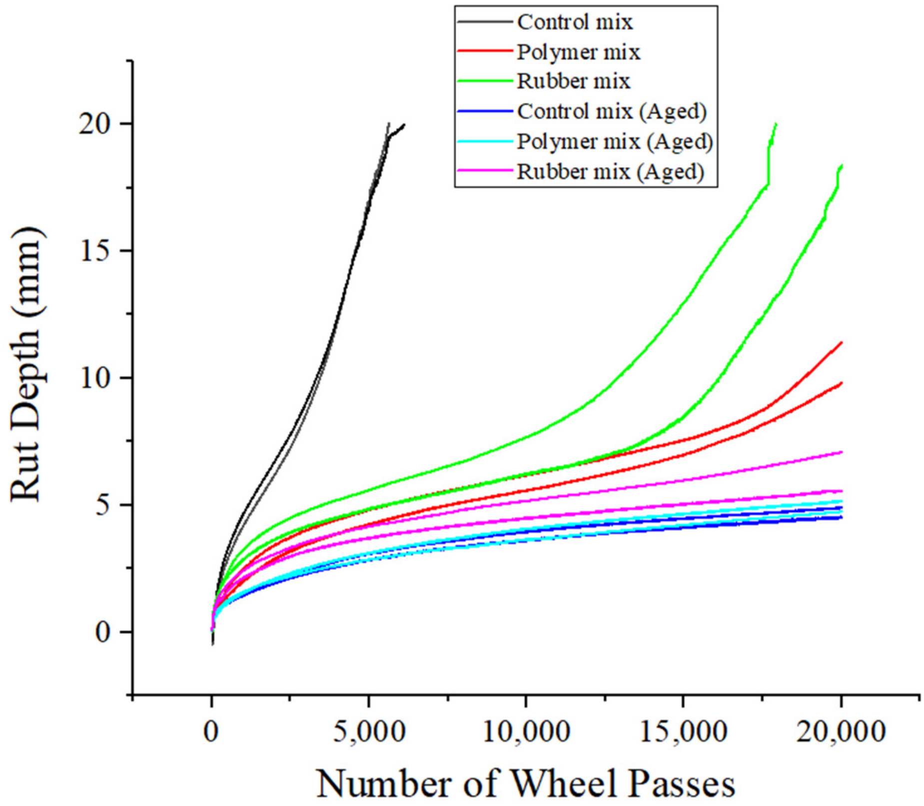


Figure 3. Hamburg wheel track device (HWTD) test results.

Table 3. The rutting test results of various mixture types.

Mixture Type		Creep Slope	Stripping Slope	Stripping Point Passing	Failure Point Passing
Unaged samples	Control mix	0.003	0.005	3188	5620
	Rubber mix	0.00267	0.0018	16,264	18,590
	Polymer mix	0.00253	0.00109	16,521	20,000 [1]
Long-term aging sample	Control mix (aged)	0.00083	NA	20,000 [1]	20,000 [1]
	Rubber mix (aged)	0.0009	NA	20,000 [1]	20,000 [1]
	Polymer mix (aged)	0.00085	NA	20,000 [1]	20,000 [1]

Note: NA means not available. [1]. The failure point and stripping point passing is higher than 20,000.

3.2. Disc-Shaped Compact Tension (DCT) Test Results

The DCT test was applied to reflect the cracking properties at low temperatures of various sorts of asphalt mixtures. Figure 4 depicts the fracture energy of various types of asphalt mixtures. The fracture energy levels at −18 °C for the control mix, rubber mix, polymer mix, control mix (aged), rubber mix (aged), and polymer mix (aged) were 572 J/m^2, 670 J/m^2, 614 J/m^2, 348 J/m^2, 483 J/m^2, and 452 J/m^2, respectively. This means the rubber- and polymer-modified asphalt mixtures have a higher level of crack resistance than traditional asphalt mixtures. While all of the mixtures have poorer cracking resistance during long-term aging than the unaged asphalt mixture, the rubber mix has the best cracking properties after long-term aging. The fracture energy levels at −24 °C for the control mix, rubber mix, polymer mix, control mix (aged), rubber mix (aged), and polymer mix (aged) were 361 J/m^2, 453 J/m^2, 387 J/m^2, 331 J/m^2, 432 J/m^2, and 382 J/m^2, respectively. The lower temperature has worse fracture energy for all of the asphalt mixtures, and the rubber- and polymer-modified asphalt mixtures have better cracking resistance than the conventional asphalt mixture. While all of the mixtures have lesser cracking resistance after long-term aging than the unaged asphalt mixture, the rubber mix has the best cracking properties after long-term aging. In summary, the rubber mix has better cracking performance than the control mix and polymer mix, as the fracture energy of the rubber mix is 17.1~30.5% higher than the control mix, and the fracture energy of the rubber mix is 6.8~9.1% higher than the polymer mix.

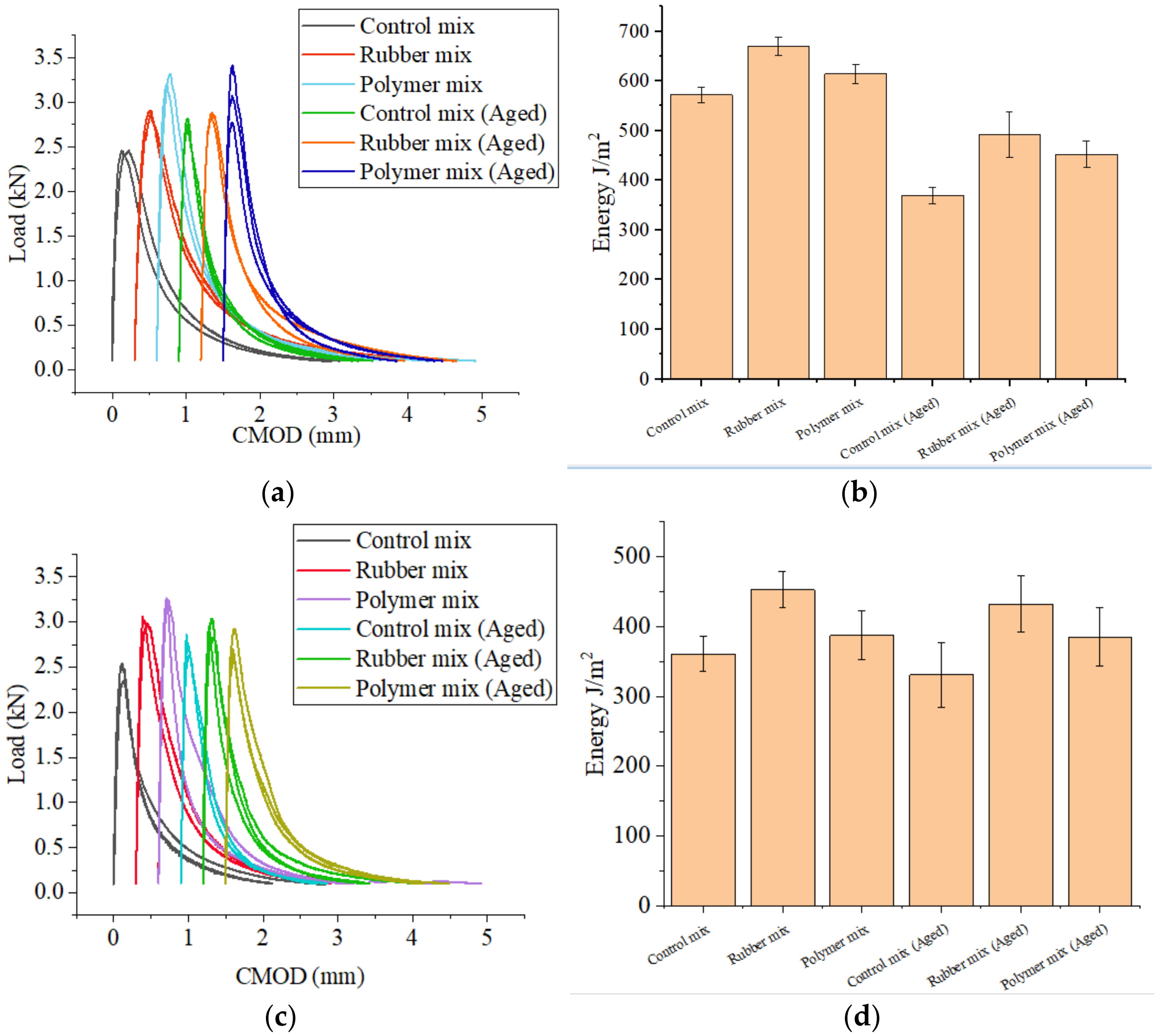


Figure 4. DCT test results of three kinds of asphalt mixtures. (**a**) Load vs. displacement results of asphalt mixture at −18 °C; (**b**) Fracture energy of three types of asphalt mixtures at −18 °C; (**c**) Load vs. displacement results of asphalt mixtures at −24 °C; (**d**) Fracture energy of three types of asphalt mixtures at −24 °C.

3.3. Dynamic Modulus Test

The dynamic modulus results of the three types of asphalt mixtures are illustrated in Figure 5. After PAV aging, all of the mixtures have a higher rutting resistance potential than the unaged asphalt mixtures, and the polymer mix has the best rutting resistance, while the rubber mix has the best rutting potential among the unaged asphalt mixtures. The dynamic modulus of the polymer mix is 13.8–24.6% higher than that of the control mix and 11.9–31% higher than that of the rubber mix. The dynamic modulus data were used as the M-E input for pavement M-E analysis.

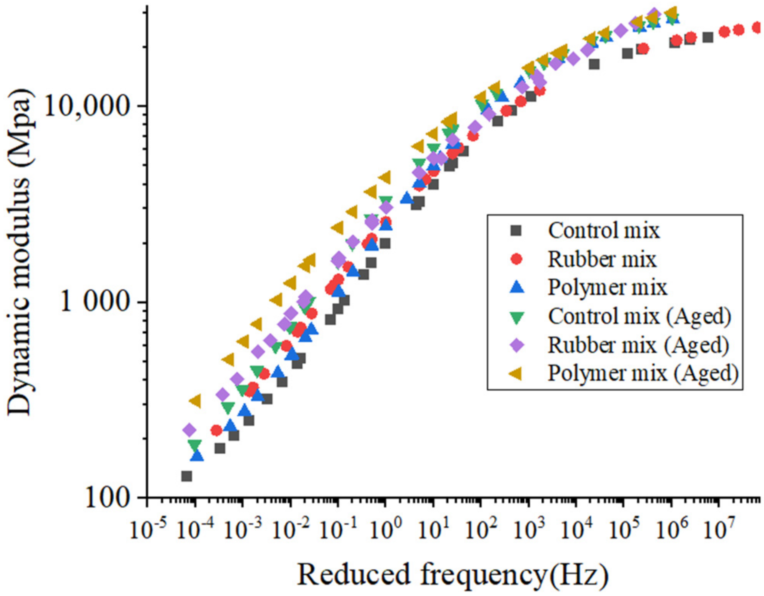


Figure 5. Dynamic modulus master curve of three types of asphalt mixtures.

3.4. Indirect Tensile Strength Test Results

The indirect tensile strength (IDT) results of the three sorts of asphalt mixtures are displayed in Figure 6. The indirect tensile strengths for the control mix, rubber mix, and polymer mix were 1.51 MPa, 1.83 MPa, and 1.97 MPa. This means the rubber and polymer particles enhance the strength between the asphalt and aggregate and hence improve the cohesiveness of the asphalt mixture.

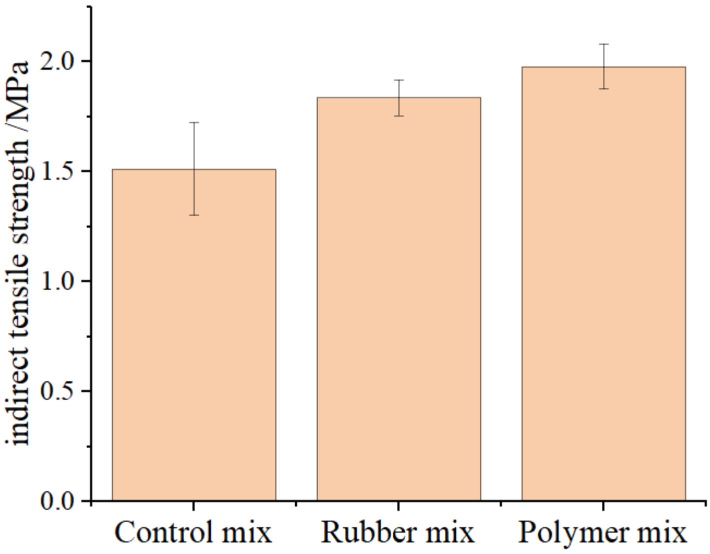
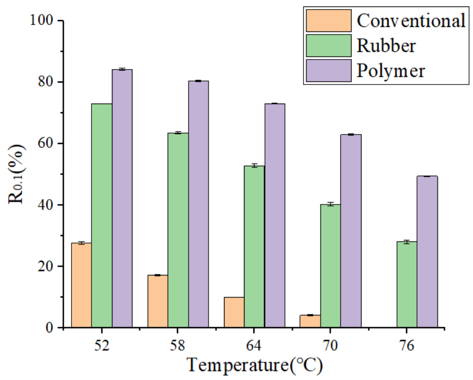


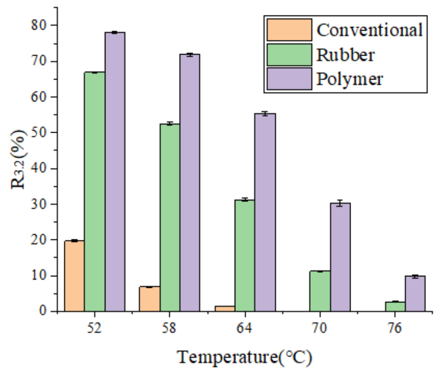
Figure 6. Indirect tensile strength results of three types of asphalt mixtures.

3.5. Multiple Stress Creep Recovery Test Results

The multiple stress creep recovery results of three sorts of asphalt are displayed in Figure 7. The average percent recovery (% recovery) of the three types of asphalt binders at various temperatures are shown in Figure 7a,b. With temperature increases, the % recovery declined. For example, when the temperature was elevated from 52 °C to 76 °C as shown in Figure 7a, the % recovery of conventional asphalt, rubber asphalt, and polymer asphalt decreased from 27.6% to 0%, 73% to 28.02%, and 84.2% to 49.37%, respectively. With increasing stress levels, the average % recovery dropped. When the temperature of the test was raised from 52 °C to 76 °C, the % recovery at 3.2 kPa of conventional asphalt, rubber asphalt, and polymer asphalt reduced from 19.67% to 0%, 66.9% to 2.69%, and 78.1% to 9.8%, respectively. This suggests that the traffic load level had an impact on the deformation of the asphalt road. A greater load results in more deformation.



(**a**)



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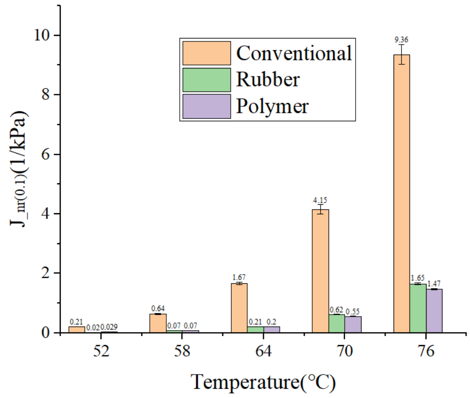

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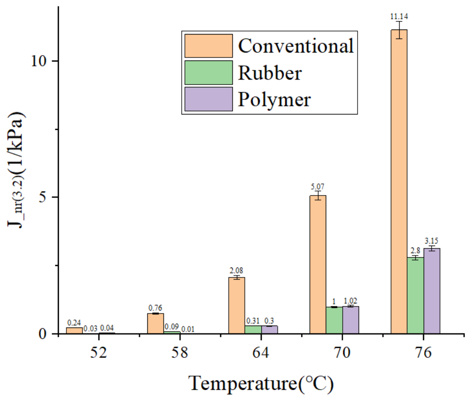

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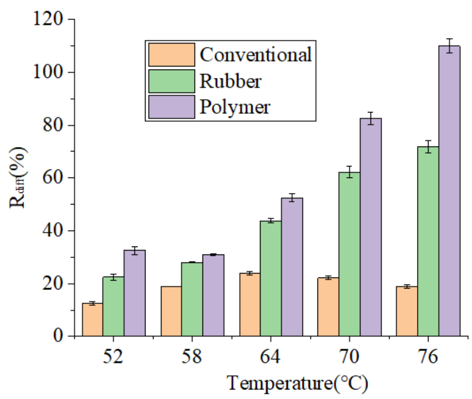

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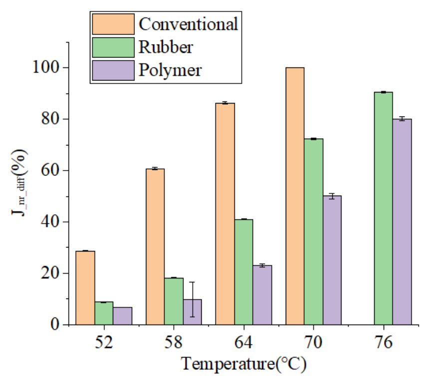
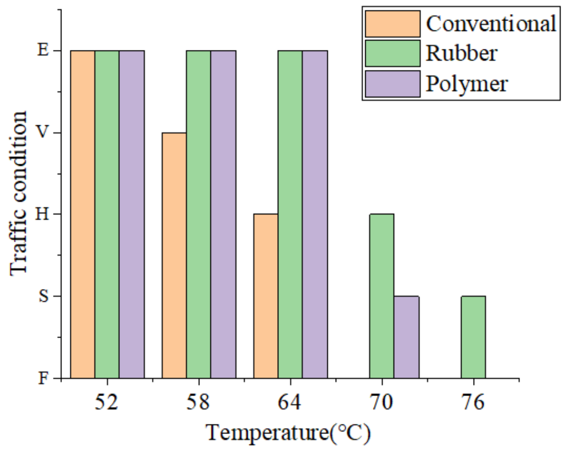


(**f**)

Figure 7. *Cont.*



(g)

Figure 7. Multiple stress creep recovery results. (**a**) Average percent recovery @ 0.1 kPa; (**b**) Average percent recovery @ 3.2 kPa; (**c**) Non-recoverable creep compliance @ 0.1 kPa; (**d**) Non-recoverable creep compliance @ 3.2 kPa; (**e**) Rdiff results; (**f**) Jnrdiff results; (**g**) Levels of traffic of different binders at various temperatures.

The average non-recovery creep compliance (J_{nr}) of the three types of asphalt at various temperatures are shown in Figure 7c,d. The rubber- and polymer-modified asphalt binder show higher deformation resistance under the load compared with the conventional asphalt binder. The increase in test temperature raised the non-recovery creep compliance at various stress levels. For instance, when the temperature climbed from 52 °C to 76 °C as shown in Figure 7c, the non-recovery creep compliance of conventional asphalt, rubber asphalt, and polymer asphalt decreased from 0.21 to 9.36, 0.02 to 1.65, and 0.029 to 1.47, respectively. This indicates that the rubber and polymer incorporated with asphalt have better rutting resistance. With an increase in stress level, the average non-recovery creep compliance increased. When the test temperature was raised from 52 °C to 76 °C, as illustrated in Figure 7d, the J_{nr} of conventional asphalt, rubber asphalt, and polymer asphalt reduced from 0.24 to 11.14, 0.03 to 2.8, and 0.04 to 3.15, respectively. This indicated that the large traffic load more easily created rutting in the road.

The R_{diff} and J_{nrdiff} results of the three types of asphalt binder at various temperatures are shown in Figure 7e,f. When the temperature of the test was raised from 52 °C to 76 °C, the R_{diff} of conventional asphalt, rubber asphalt, and polymer asphalt increased from 12.5% to 18.9%, 22.4% to 71.7%, and 32.5% to 109.8%, respectively. When the temperature of the test was raised from 52 °C to 76 °C, the J_{nrdiff} of conventional asphalt, rubber asphalt, and polymer asphalt increased from 28.7% to 100%, 8.7% to 90.4%, and 6.76% to 80.1%, respectively. This implies that stress sensitivity is influenced by temperature. A higher temperature causes a greater susceptibility to stress. The fundamental reason for this is that the asphalt binder after rubber or polymer modification is stiffer than the conventional asphalt binder, implying greater flexibility.

The traffic levels of different binders at various temperatures are shown in Figure 7g. The failure of the samples at the test temperature is indicated by the traffic condition "F", while the traffic conditions "S", "H", "V", and "E" denote standard, heavy, very heavy, and extremely heavy traffic. At 52 °C, conventional asphalt binder, rubber-modified asphalt binder, and polymer-modified asphalt binder are all in extremely heavy traffic conditions. When the temperature increased to 70 °C, the conventional asphalt failed, while the rubber-modified asphalt binder and polymer-modified asphalt binder were still in heavy traffic and standard traffic conditions, respectively. When the temperature increased to 76 °C, both the conventional asphalt binder and polymer-modified asphalt binder failed, while the rubber-modified asphalt was in the standard traffic condition. This indicates that the rubber-modified asphalt binder has better rutting potential than the polymer-modified asphalt and conventional asphalt. The rubberized asphalt extracted from the rubber mix ensured that the asphalt binder could withstand large traffic loads, which increased the permanent deformation resistance of the asphalt binder.

3.6. Linear Amplitude Sweep Test Results

The linear amplitude sweep results of the three types of rubber- and polymer-modified asphalt binders are shown in Figure 8. Cycle numbers at strain level (2.5% and 5%) were applied for this calculation. Higher strain results in fewer failure cycles. This explains why a large truckload results in shorter service life. Furthermore, for both 2.5% and 5% strain levels, the rubber-modified asphalt binder has a higher number of cycles than the polymer asphalt binder. For example, the failure number of the rubber-modified asphalt binder at a 2.5% strain level compared with the polymer-modified asphalt binder increased by 21.6%. The rubber particles help to enhance the fatigue life of the asphalt binder.

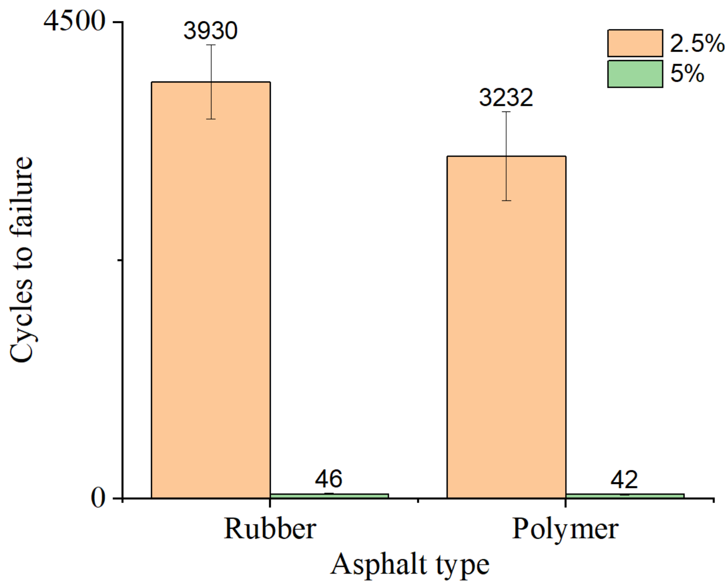


Figure 8. Linear amplitude sweep results of rubber- and polymer-modified asphalt binders.

3.7. Pavement M-E Design Results

Figure 9 shows the pavement distress prediction results for the rubber- and polymer-modified asphalt mixture and the traditional asphalt mixture. Tables 4–6 illustrate the M-E input for the rubber mix, the polymer mix, and the control mix in detail. As the solution still contains some rubber particles, the attributes of the rubber-modified asphalt may not be entirely reflected. The IRI, total rut, and AC total transverse cracking results for the three types of pavement structure components have significant differences. Total rut results show that the polymer mix and rubber mix have comparable performance with the rutting depth, and both the polymer mix and rubber mix are better than the control mix. The IRI results show that the rubber mix has better smoothness performance than the control mix and polymer mix. The control mix, polymer mix, and rubber mix show the same AC B-U and AC T-D cracking performance. The results shown above are based on the different asphalt overlay properties. All the left layers used the same M-E input, based on the MDOT recommendation. The pavement M-E results show the same trend as the high-temperature rutting test and low-temperature cracking test.

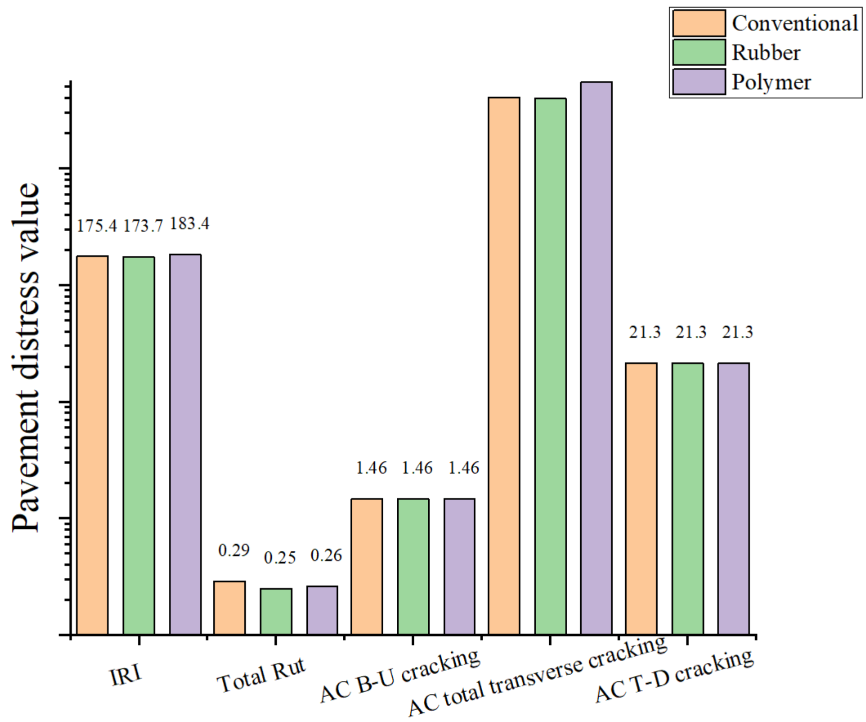


Figure 9. Pavement M-E design results of three types of asphalt mixtures (AADTT: 1400). Note: IRI (international roughness index) (in/mile or 0.016 m/km), Total rut (in or 0.0254 m), AC B-U (bottom-up) cracking (% lane area), AC T-D (top-down) cracking (% lane area).

Table 4. Pavement M-E inputs for the control mix.

|E*| (MPa) Average Value of Conventional Asphalt Mixture						
T (°C) \ F (Hz)	**0.1**	**0.5**	**1**	**5**	**10**	**25**
−10	14,774	18,339	19,300	21,961	23,137	23,913
10	3227	4943	5865	8317	9551	10,966
21	927	1566	1955	3378	4107	5167
37	316	392	436	765	999	1500
54	131	166	191	319	432	577

|G*| (MPa) Average Value		
Temperature (°C)	**Binder G* (Pa)**	**Phase angle (°)**
34	132,920	70.54
40	47,472	73.78
46	17,430	77.35
58	2918.8	83.25
82	163.79	88.97
(−10 °C) IDT strength: 1.51 MPa		

Creep compliance			
Time (s)	**Temperature (°C)**		
	−20	**−10**	**0**
1	2.89×10^{-7}	4.27×10^{-7}	8.11×10^{-7}
2	2.99×10^{-7}	4.57×10^{-7}	9.09×10^{-7}
5	3.15×10^{-7}	5.06×10^{-7}	1.09×10^{-6}
10	3.28×10^{-7}	5.54×10^{-7}	1.26×10^{-6}
20	3.45×10^{-7}	6.05×10^{-7}	1.45×10^{-6}
50	3.69×10^{-7}	6.91×10^{-7}	1.80×10^{-6}
100	3.91×10^{-7}	7.76×10^{-7}	2.15×10^{-6}

Table 5. Pavement M-E inputs for the rubber mix.

|E*| (MPa) Average Value of Rubber Modified Asphalt Mixture						
T (°C) \ F (Hz)	0.1	0.5	1	5	10	25
−10	18,004	21,320	22,197	24,537	25,296	25,612
10	4929	6964	7619	9760	10449	11,581
21	1307	2019	2499	3938	4386	5620
37	386	578	743	1333	1646	2292
54	225	307	365	631	899	1168

|G*| (MPa) Average Value			Creep compliance			
Temperature (°C)	Binder G* (Pa)	Phase angle (°)	Time (s)	Temperature (°C)		
34	170,890	68.32		−20	−10	0
40	106,750	66.59	1	2.55×10^{-7}	3.54×10^{-7}	6.32×10^{-7}
46	43,089	69.67	2	2.60×10^{-7}	3.71×10^{-7}	7.00×10^{-7}
58	7436.4	76.73	5	2.69×10^{-7}	3.99×10^{-7}	8.00×10^{-7}
82	375.82	86.44	10	2.76×10^{-7}	4.25×10^{-7}	8.92×10^{-7}
(−10 °C) IDT strength: 1.83 MPa			20	2.84×10^{-7}	4.53×10^{-7}	1.01×10^{-6}
			50	2.96×10^{-7}	4.97×10^{-7}	1.20×10^{-6}
			100	3.08×10^{-7}	5.40×10^{-7}	1.37×10^{-6}

Table 6. Pavement M-E inputs for the polymer mix.

|E*| (MPa) Average Value of Polymer Modified Asphalt Mixture						
T (°C) \ F (Hz)	0.1	0.5	1	5	10	25
−10	17,378	21,804	22,753	25,935	26,734	26,967
10	3546	5425	6470	9308	10,433	12,106
21	1146	1878	2433	4215	5090	6210
37	329	512	603	1117	1450	2192
54	212	246	272	433	541	754

|G*| (MPa) Average Value			Creep compliance			
Temperature (°C)	Binder G* (Pa)	Phase angle (°)	Time (s)	Temperature (°C)		
34	56,779	62.8		−20	−10	0
40	30,082	62.77	1	2.46×10^{-7}	3.85×10^{-7}	7.47×10^{-7}
46	15,493	63	2	2.58×10^{-7}	4.22×10^{-7}	8.57×10^{-7}
58	4470.2	65.3	5	2.78×10^{-7}	4.78×10^{-7}	1.04×10^{-6}
82	502.48	75.4	10	2.94×10^{-7}	5.27×10^{-7}	1.20×10^{-6}
(−10 °C) IDT strength: 1.97 MPa			20	3.14×10^{-7}	5.92×10^{-7}	1.42×10^{-6}
			50	3.47×10^{-7}	6.93×10^{-7}	1.79×10^{-6}
			100	3.73×10^{-7}	7.84×10^{-7}	2.13×10^{-6}

4. Summary and Conclusions

This study focused on evaluating the unaged and long-term aged control mix, dry-processed rubber mix, and polymer mix performance. The dynamic modulus test, DCT test, and high-temperature HWTD test for the asphalt mixtures were conducted, and the extracted asphalt binder properties and mechanistic–empirical (M-E) pavement analysis were used in the study. The performance of three types of asphalt mixtures under unaged and aged conditions are summarized in Table 7.

Table 7. Summary of the performance of three types of asphalt mixtures.

	Control Mix	Rubber Mix	Polymer Mix	Control Mix (Aged)	Rubber Mix (Aged)	Polymer Mix (Aged)
HWDT (wheel passes)	-	330%↑	355%↑	355%↑	355%↑	355%↑
DCT (−18 °C fracture energy)	-	17.1%↑	7.3%↑	36%↓	14%↓	21%↓
DCT (−24 °C fracture energy)	-	25.5%↑	7.2%↑	8.6%↓	19.6%↑	6.6%↑
Dynamic modulus	-	7~42%↑	12~62%↑	8~32%↑	14~62%↑	18~72%↑

Note: ↑ means increased, ↓ means decreased, **-** means reference value, where all the values compared with the reference value in this table.

Some conclusions can be summarized as follows:

(1) The DCT test shows the fracture energy notably decreased after long-term aging; the rubber mix has better cracking performance than the control mix and polymer mix, as the fracture energy of the rubber mix is 17.1~30.5% higher than that of the control mix, and the fracture energy of the rubber mix is 6.8~9.1% higher than that of the polymer mix. The rubber mix has the highest fracture energy among the asphalt mixtures that have not been aged and among those that have been aged for a long time.

(2) The HWTD results show that the polymer mix and rubber mix have better moisture damage and rutting resistance compared with the control mix. After long-term aging, the rutting and moisture susceptibility performance significantly improve, but the polymer mix and control mix have better moisture damage and rutting resistance compared with the rubber mix.

(3) The dynamic modulus test shows that the polymer mix and rubber mix have higher stiffness compared with the control mix; specifically, the dynamic modulus of the polymer mix is 13.8–24.6% higher than that of the control mix and 11.9–31% higher than that of the rubber mix. After long-term aging, the polymer mix and control mix have higher stiffness compared with the rubber mix.

(4) The MSCR and LAS results of the asphalt binders reveal that the rubberized asphalt binder showed better high-temperature deformation resistance and fatigue property compared with the polymer-modified asphalt. The failure number of the rubberized asphalt binder at a 2.5% strain level compared with polymer asphalt increased by 21.6%. The rubber and polymer incorporated with the asphalt binder improved the resistance of permanent deformation and the fatigue life.

(5) Pavement M-E analysis showed that rubber incorporated with asphalt reduced the AC rutting, IRI, and AC transverse cracking predictions under heavy traffic volume in comparison with the conventional asphalt pavement. The pavement M-E results show the same trend as the high-temperature rutting test and low-temperature cracking test.

In summary, the implementation of dry-processed rubber asphalt mixtures in pavement construction improved the permanent deformation, cracking resistance, and fatigue properties of pavements. Meanwhile, the mechanistic–empirical (M-E) pavement analysis showed the dry-processed, rubber-modified asphalt pavement and polymer-modified asphalt pavement have comparable performance. Therefore, the dry-processed rubber-modified asphalt pavement would provide adequate performance if applied to high-traffic volume roads in a wet-freeze environment.

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