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Evaluation and Comparison of Mechanical Properties of Polymer-Modified Asphalt Mixtures

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Abstract: Polymer modification is extensively used in the Kingdom of Saudi Arabia (KSA) because the available asphalt cement does not satisfy the high-temperature requirements. It was widely used in KSA for more than two decades, and there is little information regarding the differences in the performance of different polymers approved for binder modification. Pavement engineers require performance comparisons among various polymers to select the best polymer for modification rather than make their selection based on satisfying binder specifications. Furthermore, the mechanical properties can help select polymer type, producing mixes of better resistance to specific pavement distresses. The study objective was to compare the mechanical properties of the various polymer-modified asphalt (PMA) mixtures that are widely used in the Riyadh region. Control mix and five other mixes with different polymers (Lucolast 7010, Anglomak 2144, Pavflex140, SBS KTR 401, and EE-2) were prepared. PMA mixtures were evaluated through different mechanical tests, including dynamic modulus, flow number, Hamburg wheel tracking, and indirect tensile strength. The results show an improvement in mechanical properties for all PMA mixtures relative to the control mixture. Based on the overall comparison, the asphalt mixture with polymer Anglomk2144 was ranked the best performing mixture, followed by Paveflex140 and EE-2.

Keywords: polymer-modified asphalt; mechanical properties; dynamic modulus; Hamburg wheel-tracking; indirect tensile strength

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1. Introduction

Saudi Arabia roadways had evolved highly through the previous decades. Flexible pavement is the dominant type used for these roads. The increase in heavy truck loads had led to premature rutting in the asphalt layer of roadway pavements. To control the asphalt pavement deformation, it was suggested to use stiffer asphalt binder to sustain the heavy truck loads. Implementation of SUPERPAVE specifications showed that the available asphalt binder was not hard enough at high service temperature. Asphalt binders can be made harder by modification. Different types of modifiers were tried worldwide to enhance the rheological properties of asphalt binder, such as polymers [1–6], crumb rubber [5,7–11], waste plastic [12–16], geopolymers [17], and nano-materials [18–21]. Polymers are commonly used to modify and improve the rheological properties of asphalt binders. Polymer modification of asphalt binders for pavement construction can increase its resistance to permanent deformation at high temperatures and its resistance to thermal cracking at low temperatures. These possible improvements can increase pavement life [22–26]. There are two main kinds of polymers—namely, elastomers and plastomers. The elastomers are usually used to extend the binder's low and high service temperatures. However, plastomers are notable as effective additives that can raise the high service temperature [12,27,28]. The polymer-modified asphalt (PMA) properties depend upon two parameters: the first one is the material properties such as polymer type, polymer content, asphalt binder grade, and asphalt source [29]; the second is the mixing process of asphalt binder and modifiers [5,30,31]. Several studies have explored the effect of using modifiers on asphalt binder and mixture properties. The results of these studies showed that polymer modification could alter binder properties by increasing the softening point [1–4,14,32–38], increasing the viscosity [3,37,39,40], decreasing the penetration [2,3,14,37,38], and improving the performance grade [2,4,6,37,41]. For asphalt mixture, the previous studies indicated that polymers could improve the mechanical properties of asphalt mixture, such as resilient modulus [14,42–46], fatigue cracking resistance [4,14,47–51], and rutting resistance [43,50,52–56].

The asphalt binder produced in the Kingdom of Saudi Arabia (KSA) is only one penetration grade, 60–70, which satisfies the performance grade (PG) specification PG64-22 [57]. Field measurement of pavement temperatures in KSA revealed that the asphalt pavement temperature ranges between 3 °C and 72 °C for coastal areas, and between 4 °C and 65 °C for inland areas [58,59]. Therefore, the recommended high-temperature grade of asphalt binder for Riyadh city is higher than 64 °C by one grade, as presented in Figure 1.

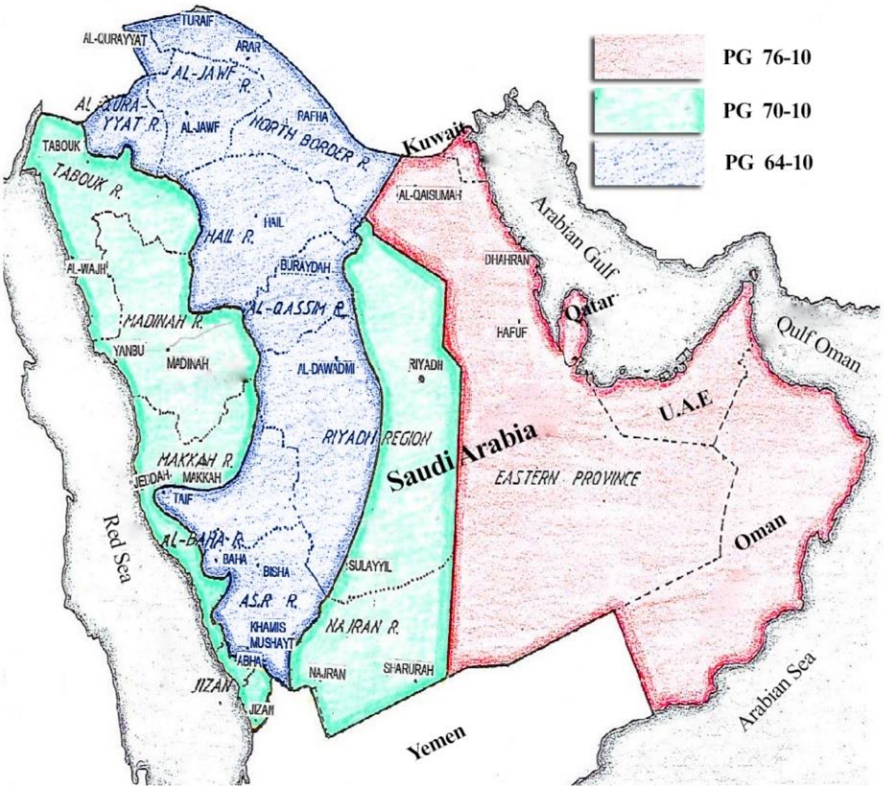


Figure 1. The temperature zoning for Gulf countries.

This available asphalt binder grade (PG64-22) is not satisfactory for Riyadh and other regions of KSA where high-temperature conditions prevail. It is not satisfactory for high-traffic roads and slow-speed and stationary conditions such as road intersections. Therefore, the asphalt binder needs to be modified to meet the requirements of local climate and traffic conditions. To overcome premature pavement distresses, the Ministry of Transportation (MOT) and Riyadh Municipality (RM) implemented SUPERPAVE™ mix design, which improved materials selection and mixed design procedures. Implementation of SUPERPAVE™ specification increased the demand for the utilization of polymer for asphalt modification. As a result, many asphalt plants produce modified asphalt binders to satisfy the performance grade specification. Many types of polymers were approved by the MOT for pavement construction. Although polymer-modified asphalt was widely used in KSA for more than two decades, there is little information regarding the differences in performance of different types of polymers approved by the MOT for binder modification. Pavement engineers require performance comparisons among the various polymers to select the best polymer for modification rather than making their selection based on satisfying binder specifications. Therefore, there is a need to investigate the properties of the various PMA produced by asphalt plants in the Riyadh region and to extend the evaluation to the mechanical properties of their asphalt mixtures. These properties can help select polymer types that produce mixes of better resistance to specific pavement distresses. The main objective of this study was to evaluate and compare the mechanical properties of various PMA mixtures which are widely used in the Riyadh region, as well as to compare the results with a range of mixtures containing the original binder (un-modified). Dynamic modulus, flow number, Hamburg wheel tracking, and indirect tensile strength tests were conducted on the control mix and five other mixes prepared with different PMA (Lucolast 7010, Anglomak 2144, Pavflex140, SBS KTR 401, and EE-2).

2. Materials

2.1. Asphalt Binder

Asphalt cement produced in KSA has a performance grade PG64-22 (60/70 penetration grade). Table 1 presents the properties of the asphalt binder.

Table 1. Properties of asphalt cement.

Properties	Unit	References	Values
High-temperature grade	°C	ASTM-D7175	64
Low-temperature grade	°C	ASTM-D6648	−22
$G^*/\sin\delta$ @ 64 °C	-	-	1.62
Penetration @ 25 °C	0.1 mm	ASTM-D0005	68
Softening Point	°C	ASTM-D0036	48
Flash Point	°C	ASTM-D1310	300
Penetration index	-	-	−0.99
Ductility	cm	ASTM-D0113	+100
Rotational viscosity @ 135 °C, cps	cp	ASTM-D4402	487
Rotational viscosity @ 165 °C, cps	cp	ASTM-D4402	150
Specific gravity	-	ASTM-D0070	1.025
Loss after RTFO	%	ASTM-D2872	0.07

2.2. Aggregate

In this study, the aggregate used was limestone procured from a hot mix plant located near Riyadh city in Saudi Arabia. In order to ensure precise gradation, the aggregate was sieved into several sizes and combined to get the specified gradation that would satisfy the maximum and minimum limits of aggregate percentage passing according to the Ministry of Transportation of KSA specification [60]. The aggregate gradation used in this study was dense-graded, as shown in Figure 2 and Table 2. The physical properties of limestone aggregate are presented in Table 3.

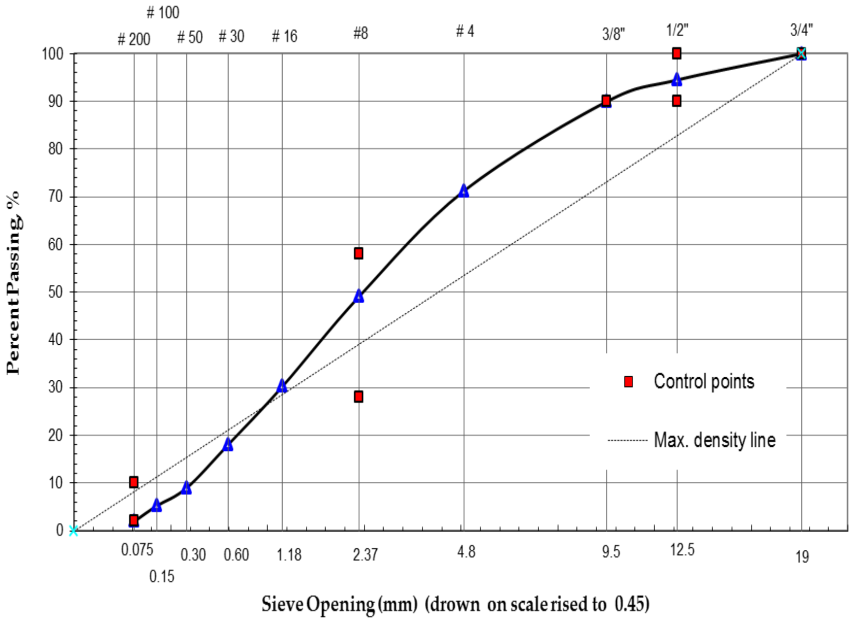


Figure 2. Aggregate gradation.

Table 2. Aggregate gradation and MOT specification.

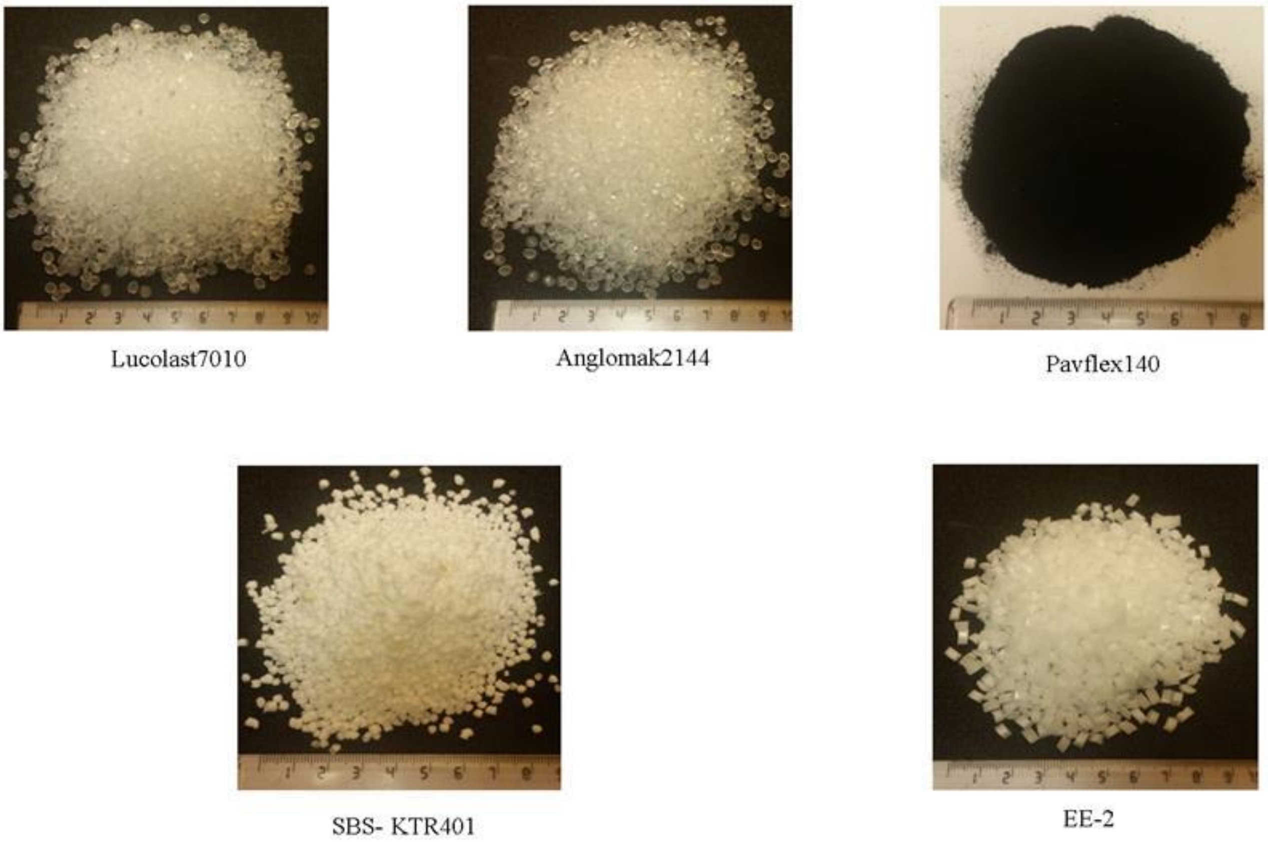
Sieve Opening (mm)	% Passing	Specification	
19.00	100.0		100
12.50	94.5	90	100
9.50	89.5		90
4.75	71.3		
2.36	49.1	28	58
1.18	30.3		
0.60	18.0		
0.30	9.0		
0.15	5.2		
0.075	3.2	2	10

Table 3. The limestone aggregate properties.

Property	Test Method	Value
Percentage loss by Los Angeles Abrasion Test, %	ASTM-C0131	21
Flat and Elongated Particles, %	ASTM-D4791	7
The Specific gravity of coarse aggregate	ASTM-C0127	2.585
Water absorption of coarse aggregate, %	ASTM-C0127	2.7
The Specific gravity of fine aggregate	ASTM-C0128	2.567
Water absorption of fine aggregate, %	ASTM0C0128	2.2

2.3. Polymer-Modified Asphalt

Five types of polymers were selected, which represent polymers widely used in the Riyadh region. These polymers were Lucolast 7010, Anglomak 2144, Pavflex 140, SBS KTR 401, and EE-2. All polymers used in this study were in pellet and powder form, as shown in Figure 3. The physical and chemical properties of those modifiers are tabulated in Table 4. The base asphalt binder was mixed with the specified polymer using an asphalt blender. The polymer content for each polymer was determined so that it reached the required PG 76-10 set by the KSA Ministry of Transportation, as shown in Table 5. As mentioned before, polymer modification needed to satisfy the high-temperature grade of 76 °C, which is required for the Riyadh region and other hot regions of KSA [61].



Lucolast7010 Anglomak2144 Pavflex140

SBS- KTR401 EE-2

Figure 3. Types of modifiers evaluated.

Table 4. Polymer's properties.

Modifiers	Physical Form	Density (g/cm^3)	Melting Point (°C)	Melt Flow Index (g/10 min)	Components
Lucolast7010	Pellet	0.924	95	3.9	Ethylene and Butyl Acrylate (EBA) with low crystallinity.
Anglomak2144	Pellet	0.930	96	3.5	Oxidized Polyethylene Homopolymer.
Paveflex140	Powder	-	212	-	Ethylene Vinyl Acetate Resins.
SBS KTR 401	Pellet	0.94	270	<1	Styrene Butadiene Styrene.
EE-2	Pellet	0.96	-	-	Medium-Density Oxidized Polyethylene.

Table 5. The rheological and physical properties of PMA.

Modifiers	Code	%	Penetration	Softening Point	G*/sinδ			m-Value			PG
					64 °C	70 °C	76 °C	−10 °C	−16 °C	−22 °C	
Lucolast7010	LU	3.6	36	59	5.69	2.68	1.37	0.366	0.315	0.285	76-16
Anglomak 2144	AM	3.2	34	60.8	7.51	3.39	1.68	0.312	0.279	-	76-10
Pavflex140	PF	5.0	34	59.2	6.25	2.99	1.49	0.320	0.290	-	76-10
SBS KTR 401	SBS	3.0	47	55	3.47	1.77	1.01	0.367	0.311	0.287	76-16
EE-2	EE	4.0	35	67	4.38	2.27	1.35	0.309	0.288	-	76-10

Note: G* = complex modulus; δ = phase angle; m-value = the tangent of the creep curve; PG = performance grade.

3. Mix Design and Experimental Program

HMA was prepared according to SUPERPAVE Volumetric Mixture design (AASHTO PP28-95) "Standard Practice for SUPERPAVE Volumetric Design for HMA" and KSA Ministry of Transportation specification for asphalt mixture design [60]. To optimize the binder content, three duplicate samples were prepared at four different contents of asphalt binder: 4.5, 5.0, 5.5, and 6.0% (by total weight of mixture). For each sample, the aggregate was merged with an asphalt binder at 155 °C then placed in the oven at 135 °C for 2 h to cure. Then the specimens were moved into another oven at 145 °C for half an hour and compacted by a SUPERPAVE gyratory compactor using a design number of gyration (Ndes) equal to 100 gyrations. Another set of specimens was also mixed and left loose to determine maximum theoretical specific gravity (AASHTO T209). The bulk specific gravity of each compacted specimen was measured according to AASHTO T166 test method and was used to calculate the volumetric parameters (AV, VMA, and VFA) according to AASHTO PP 19. The average volumetric properties for the control mix are summarized in Table 6.

Table 6. Volumetric properties for different asphalt binder content.

Property	Values				MOT Specification
Binder Content, %	4.5	5.0	5.5	6.0	-
%Gmm @ N_{ini}, %	83.1	85.5	87.4	88.4	≤89
%Gmm @ N_{des}, %	92.2	95.2	97.3	98.0	96
Air Voids, %	7.8	4.8	2.7	2.0	4
VMA, %	14.9	14.1	13.3	13.3	≥14
VFA, %	47.6	65.6	79.4	85.0	65–75
Effective Binder Content (P_{be})	3.1	4.0	4.6	4.9	-
Dust Proportion (DP ratio)	0.99	0.77	0.68	0.64	0.6–1.2

The optimum asphalt content was defined as the percentage that produced 4.0% air void. At 4.0% air void, an asphalt mixture will show less asphalt bleeding and better rut resistance [62]. The optimum asphalt content was found equal to 5.20% by the total mixture weight and satisfied all the mix requirements according to the specifications of the Ministry of Transportation [60]. For polymer-modified asphalt mixtures, it was decided to use the same aggregate structure and optimum binder content (5.2%) obtained for the control asphalt mixture. This was to make comparing the characteristics of mechanical asphalt mixtures easier without having to take into account other factors such as aggregate structure and binder content. However, the mixing and compaction temperatures were increased to 165 °C and 155 °C, respectively, to take into consideration the increase of binder viscosity due to modification. Table 7 summarizes the volumetric parameters for mixtures corresponding to 5.2% binder content.

Table 7. Volumetric properties for neat and PMA mixtures.

Property	Control	Anglomak	SBS	Lucolast	Pavflex	EE-2	Criteria
Gmm @ Nini, %	85.7	86.9	86.6	86.5	85.5	85.9	≤89
Gmm @ Ndes, %	95.8	96.6	96.1	96.2	95.4	96	96.0
Air Voids, %	4.2	3.4	3.9	3.8	4.6	4.0	3.0–5.0
VMA, %	13.7	13.0	13.2	13.1	13.8	13.9	14
VFA, %	68	73.3	70.4	70.8	66.7	71	65–75

4. Mechanical Properties Tests

The designed mixtures were subjected to different performance tests. They are described in the following sub-sections.

4.1. Dynamic Modulus (|E*|) Test

The test was used to obtain asphalt mix stiffness. It was performed according to AASHTO TP 62-07 using an asphalt mixture performance tester (AMPT). The test was performed according to AASHTO TP 62-07. The stress levels were varied with the frequency to keep the specimen response within linear viscoelastic limits (recoverable micro-strain below 150 microstrains). The test parameters, dynamic modulus, and phase angle (δ) were measured at four temperatures; −10, 4.4, 21.1, and 54.4 °C and frequencies: 25, 10, 5, 1, 0.5, and 0.1 Hz. The specimens were compacted with dimensions of 15 cm diameter and 17 cm tall using the SUPERPAVE gyratory compactor. First, the samples were compacted to target air voids of 7%. Consequently, the samples were cored from the center to 10 cm diameter and cut from the top and bottom to get the height of 15 cm as shown in Figure 4.


(**a**) (**b**) (**c**)

Figure 4. Preparation of test specimens (**a**) compacted specimens, (**b**) Cored specimens, (**c**) ends cut specimens.

4.2. Flow Number (Fn)

Permanent deformation characteristics of HMA mixtures under repeated loading can be determined by using the Fn test. Fn is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated load [63]. A high Fn value indicates better rutting resistance. The Fn test was conducted using the asphalt mixture performance tester (AMPT) according to the test method described in NCHRP Report 513 [64]. The cylindrical asphalt specimens were subjected to several thousand loading cycles, and the cumulative permanent deformations were recorded as a function of loading cycles. The load was a repetitive vertical axial stress of 600 kPa for 0.1 s, followed by a rest period of 0.9 s, as shown in Figure 5. The test was conducted at a temperature of 76 °C, equal to the pavement's high service temperature. The failure criterion of this test was either 10,000 cycles or 50,000 microstrains, either of which was first reached. There are three phases to the cumulative permanent strain curve: primary phase, secondary phase, and tertiary phase. The Fn specifies the starting point or cycle number at which the tertiary phase begins. Specimens for this test were prepared in the same way as those prepared for the dynamic modulus test.

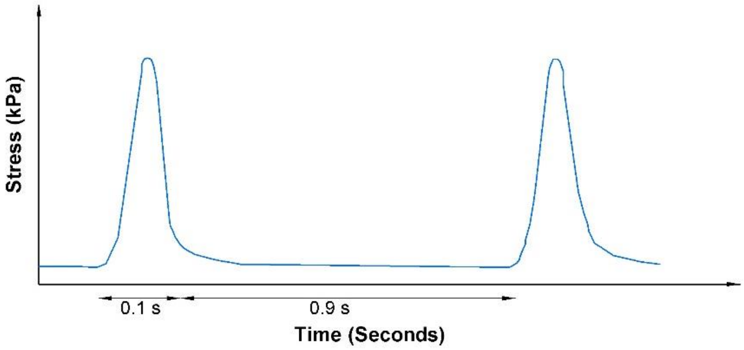


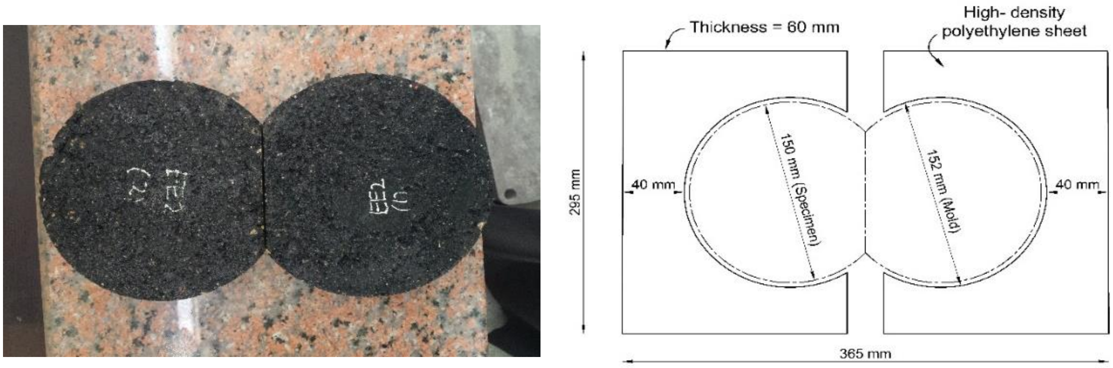
Figure 5. Loading form for Fn test.

4.3. Hamburg Wheel Tracking (HWT) Test

The test was performed according to AASHTO T 324 using a Hamburg wheel-tracker. The test was intended to determine how vulnerable HMA was to failure due to defects in the aggregate structure, a lack of binder coating, and poor binder–aggregate adhesion. As shown in Figure 6, the HWT tester is an electrically powered device-driven apparatus that has a rotating steel wheel with a diameter of 203.6 mm and a width of 47 mm. The wheel applies a force of 7054.5 N. The wheel reciprocates over the mid-span of the specimens at a rate of 52 ± 2 pass/min across the specimen.

Figure 6. The Hamburg wheel tracker.

The specimens of each mix design were formed with 150 mm diameter 62 ± 2 mm thickness gyratory compacted specimens. Specimens were cut vertically at the edge to be placed back-to-back in a high-density polyethene mold, as shown in Figure 7. The specimens were conditioned in water at a temperature of 50 ± 1 °C with 60 min of water temperature stabilization using a mechanical circulation system. The specimens' rut depth and the number of passes were recorded. The test ended when the rut depth reached 12.0 mm or 20,000 passes, whichever came first.



(**a**) (**b**)

Figure 7. (**a**) Cut edge samples, (**b**) high-density polyethene mold.

4.4. Indirect Tensile Strength (ITS)

An ITS test was conducted to determine the tensile strength of neat and polymer-modified asphalt mixtures according to AASHTO-T283 using an indirect tensile compression tester. The test was also conducted on wet conditioned samples to determine how sensitive the mixture was to moisture damage. Six specimens were fabricated for each mixture: three in dry condition and three in wet condition. The wet conditioning was performed by submerging samples in a water bath at a temperature of 60 ± 1 °C for 24 h and then at ambient temperature (25 ± 0.5 °C) for 2 h. Following that, a constant deformation rate of 50 mm/min is applied in the diametral direction of the specimen. To determine the tensile strength, the load at failure was recorded, as shown below. The load at failure was recorded and used to calculate the tensile strength as follows:

$$S_t = \frac{2P}{\pi \times T \times D} \tag{1}$$

where *St* is the tensile strength (MPa), *P* is the maximum load (N), *T* is the sample thickness (mm), *D* is the sample diameter (mm).

Finally, the tensile strength ratio (*TSR*) was determined using the following equation:

$$TSR = 100 * \frac{\text{Tensile strength of wet condition}}{\text{Tensile strength of dry condition}} \tag{2}$$

A higher *TSR* value indicates that the asphalt mix will have better resistance to moisture damage. The *TSR* must be greater than 80% as recommended by AASHTO T 283 and the Ministry of Transportation.

4.5. Comparison and Overall Ranking of PMA Mixture Performance

4.5.1. Pair Comparison

To compare the different mixtures pair, the "effect size method" was implemented in this research instead of statistical tests for significance (*t*-test and ANOVA), which were not applicable due to the limited number of data points for the experimental results. Therefore, the results of the statistical test might be misleading [65]. However, based on the difference in the means of the two groups and the standard deviation, the effect size value (*d*) can be determined by the following equation:

$$d = \frac{\left|\overline{x_t} - \overline{x_r}\right|}{\sqrt{\frac{(n_t-1)s_{t}2+(n_r-1)s_{r}2}{(n_t+n_r)}}} \tag{3}$$

where $\overline{x_t}$ is the mean of treatment group, $\overline{x_r}$ is the mean of the reference group, n_t is the number of samples in the treatment group, n_r is the number of samples in the reference group, s_t is the standard deviation of the treatment group, s_r is the standard deviation of the reference group.

4.5.2. Overall Ranking

In order to decide which mix design had better performance, all different mixes were ranked based on a 6-point scale. This could help select the best mix design by each of the asphalt mixture performances, where the mixture with the best performance would be ranked 1 and the mixture with the least (worst) performance would have the highest number. Based on the asphalt mixture performances for the selected asphalt mixtures analyzed in this study, the relative significance of each mix design's overall rank can be determined using the Relative Importance Index (*RII*) method. The *RII* is computed as:

$$RII = \sum \frac{1 + A - W}{A * N} \tag{4}$$

where A is the highest weight = 6; W is the weight given to each performance test and ranges from 1 to 6; and N the total number of performance tests.

5. Results and Discussions

5.1. Dynamic Modulus Result

The experimental data of dynamic modulus (|E*|) and phase angle (δ) versus frequency at different temperatures for different modified asphalt mixtures are presented in Figures 8 and 9, respectively.

Generally, the dynamic moduli values of all modified asphalt mixtures increased by decreasing the temperature, and they were increased by increasing the frequency. While phase angle increased by increasing the temperature, it was decreased by increasing the frequency. This is because as the temperature increases or decreases, the viscosity of the asphalt binder changes, which in turn causes a change in the elasticity of asphalt mixtures. In addition, it is also found that all asphalt mixtures showed similar trends regardless of modifier types. According to many studies [27,42,43,46,66–70], polymer modification resulted in a higher modulus for the modified asphalt mixture as compared with the control asphalt mixture. In this study, similar behavior was found by using different polymers, where the dynamic modulus of asphalt mixtures improved due to polymer addition.

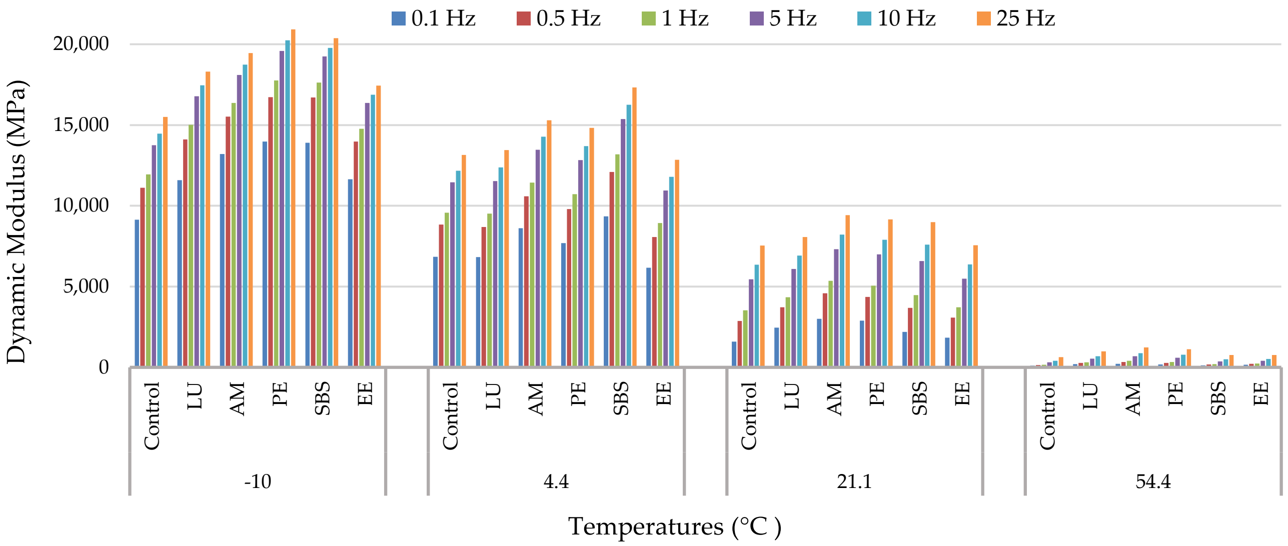


Figure 8. Dynamic modulus versus frequencies at different temperature.

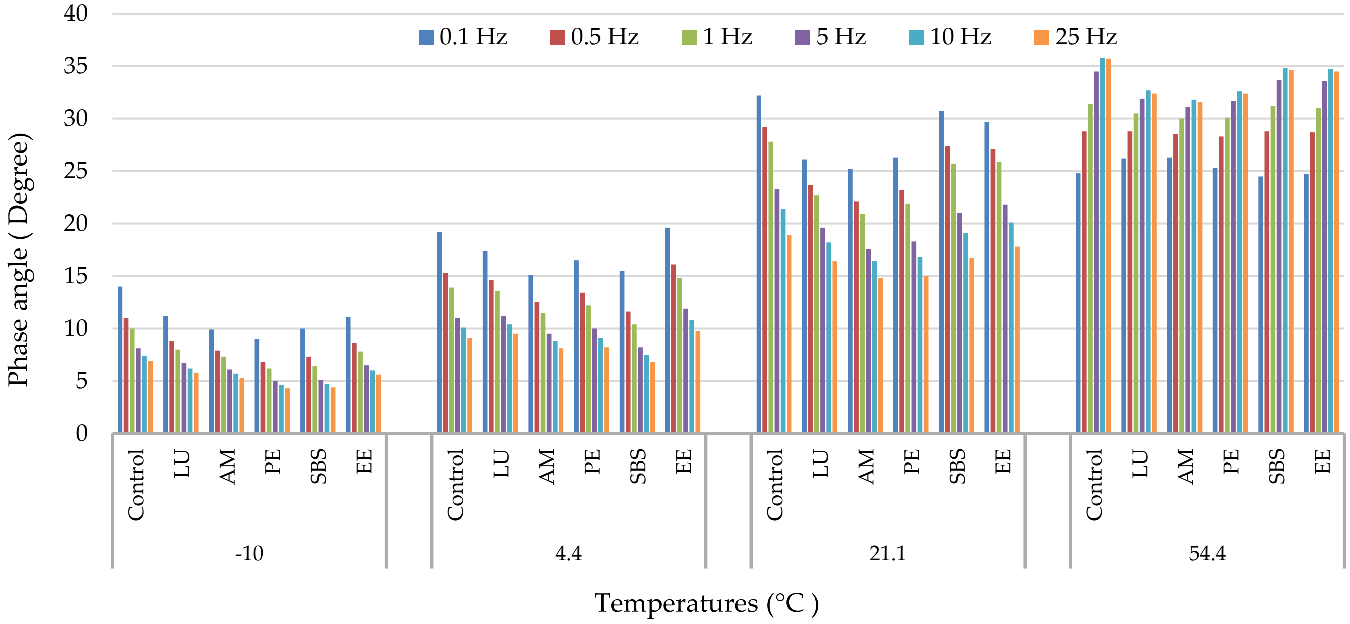


Figure 9. Phase angle versus frequencies at different temperatures.

Based on the difference in the means of the two groups and the standard deviation, the effect size values (d) were calculated for different asphalt mixture performance tests, as shown in Tables 8–11. Based on the literature, an effect size of 1.6 was used in this study to determine the effect of differences in dynamic modulus values of asphalt mixtures on the performance properties [65]. Effect sizes with values less than 1.6 indicate no difference in dynamic modulus values of the two asphalt mixtures. Table 8 presents the effect size values at the temperature of −10 °C; the results show that the Lucolast mixture had statistically no difference (0.26) in dynamic modulus compared with the EE-2 mixture. Additionally, the Paveflex mixture had statistically no difference (0.57) compared with the SBS mixture.

Table 8. Effect sizes dynamic modulus at the temperature of −10 °C.

	NEAT	**LU**	**AM**	**PF**	**SBS**	**EE**
NEAT	-	4.96	6.04	9.01	9.52	2.66
LU	4.96	-	2.81	8.15	9.48	0.26
AM	6.04	2.81	-	2.66	3.15	1.62
PF	9.01	8.15	2.66	-	0.57	3.21
SBS	9.52	9.48	3.15	0.57	-	3.47
EE	2.66	0.26	1.62	3.21	3.47	-

Table 9. Effect sizes dynamic modulus at the temperature of 4.4 °C.

	NEAT	**LU**	**AM**	**PF**	**SBS**	**EE**
NEAT	-	1.11	7.09	3.59	99.74	2.16
LU	1.11	-	7.21	3.74	63.32	1.93
AM	7.09	7.21	-	1.75	6.47	6.30
PF	3.59	3.74	1.75	-	7.61	4.10
SBS	99.74	63.32	6.47	7.61	-	13.95
EE	2.16	1.93	6.30	4.10	13.95	-

Table 10. Effect sizes dynamic modulus at the temperature of 21.1 °C.

	NEAT	LU	AM	PF	SBS	EE
NEAT	-	5.00	7.64	10.38	5.75	0.83
LU	5.00	-	5.17	11.48	1.01	3.92
AM	7.64	5.17	-	1.62	4.95	6.92
PF	10.38	11.48	1.62	-	16.62	9.20
SBS	5.75	1.01	4.95	16.62	-	4.62
EE	0.83	3.92	6.92	9.20	4.62	-

Table 11. Effect sizes dynamic modulus at the temperature of 54.4 °C.

	NEAT	LU	AM	PF	SBS	EE
NEAT	-	6.58	11.80	8.83	2.76	4.09
LU	6.58	-	3.03	0.42	5.45	2.84
AM	11.80	3.03	-	2.96	10.43	6.55
PF	8.83	0.42	2.96	-	7.35	3.75
SBS	2.76	5.45	10.43	7.35	-	2.65
EE	4.09	2.84	6.55	3.75	2.65	-

Table 9 shows the effect sizes for the dynamic modulus of different mixtures at 4.4 °C. It shows that the differences are statistically significant between all asphalt mixtures since the effect size values obtained were greater than 1.6 except for the mixture with Lucolast corresponding to the control mixture.

For a temperature of 21 °C, the results of which are tabulated in Table 10, the control mixture had statistically no difference (0.85) in dynamic modulus compared with the EE-2 mixture. Additionally, the Lucolast mixture had statistically no difference (1.01) compared with the SBS mixture.

Table 11 provides the effect size values at temperature of 54.4 °C, where only the mixture with Lucolast had no difference in dynamic modulus compared with the Paveflex mixture since the effect size values obtained were less than 1.6.

5.2. Flow Number (Fn) Result

Based on the test findings, all asphalt mixtures reached the failure stage with a cumulative permanent strain of 50,000 microstrains. Figure 10 illustrates the cumulative permanent strain curves of different asphalt mixtures. A significant variance was noticed between control and all modified asphalt mixtures. Thus, all mixtures with PMA demonstrated lower permanent strain than the control mixture. This is attributed to the presence of polymer material in the asphalt binder, which can increase the adherence of mixture components, resulting in increased mixture strength.

The Fn and final load cycle of asphalt mixtures are presented in Table 12. Asphalt mixture modified with Lucolast7010 displayed a higher Fn value (182) and reached the failure stage after 432 cycles, followed by the mixture containing Anglomk2144, which showed Fn 120 and reached the failure stage after 336 cycles.

Table 13 provides the effect sizes for the Fn test of different mixtures. It shows that the differences in Fn values are statistically significant between all asphalt mixtures since the effect size values obtained are greater than 1.6.

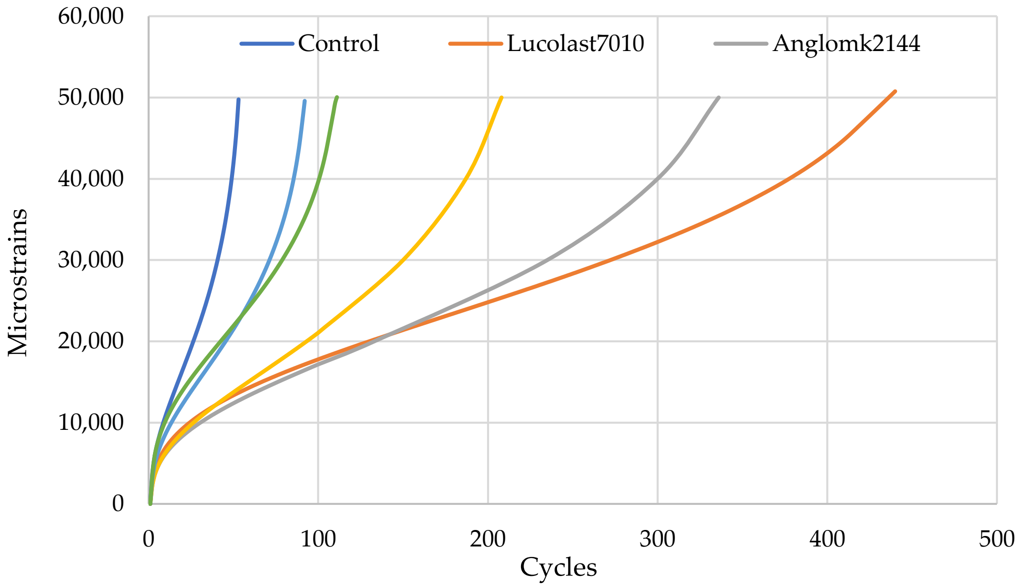


Figure 10. Cumulative permanent strain curves for different mixtures.

Table 12. Flow number test data for different mixtures.

Asphalt Mixture	**Fn**		**Failure**	
	Cycles	**Strain**	**Cycles**	**Strain**
Control	25	19,683	66	52,377
Lucolast7010	182	23,652	432	50,184
Anglomk2144	120	18,982	336	50,292
Paveflex140	93	20,209	244	50,058
SBS KTR401	33	16,811	93	52,246
EE-2	46	21,338	114	51,111

Table 13. Effect sizes of Fn.

	NEAT	**LU**	**AM**	**PF**	**SBS**	**EE**
NEAT	-	7.54	8.29	17.86	2.22	5.09
LU	7.54	-	2.65	4.33	7.26	6.60
AM	8.29	2.65	-	2.49	7.97	6.67
PF	17.86	4.33	2.49	-	37.95	18.43
SBS	2.22	7.26	7.97	37.95	-	5.81
EE	5.09	6.60	6.67	18.43	5.81	-

5.3. Hamburg Wheel Tracking Result

The test was used to evaluate rutting and to determine the failure susceptibility because of weak adhesion between the binder and aggregates. Before testing, the specimens were submerged underwater for 60 min at a temperature of 50 °C. All specimens were tested at 52 pass/minute. The specimen's rut depth and the number of passes were recorded. Testing ended when the rut depth reached 12.0 mm or 20,000 passes, whichever came first. Figure 11 presents the average rut depth recorded with the number of passes for all the mixtures. It is observed that the PMA mixtures had lower moisture sustainability than the neat asphalt mixture. From the figure, the asphalt mix modified with EE-2 ranked as the best mixture, followed by Anglomak2144, Paveflax140, Lucolast7010, and SBS KTR401.

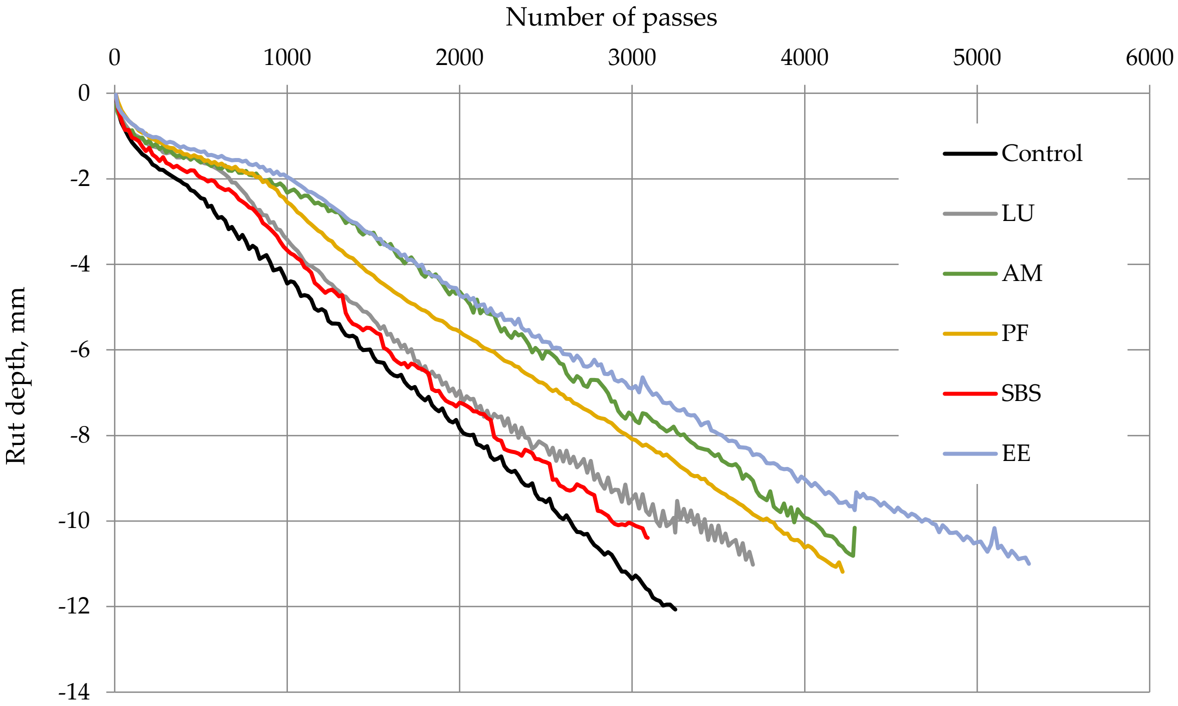


Figure 11. Rut depth versus the number of passes for different mixtures.

5.4. Indirect Tensile Strength Result

This test was conducted to determine the tensile strength and water susceptibility of neat and PMA mixtures using indirect tensile strength tests. The indirect tensile strength values for three specimens in dry and wet conditions of neat and PMA mixes are presented in Table 14. Asphalt mixture modified by SBS KTR401 showed the highest dry strength, while the mixture modified by polymer EE-2 showed the lowest strength compared with other PMA mixtures. The ratio of tensile strength of wet sample to dry sample was determined using Equation 2 and is presented in Figure 12. The results indicate that there were improvements in water susceptibility of polymer-modified mixtures over that of the neat mixture. It is worth mentioning that the tensile strength ratio (*TSR*) values of neat and PMA mixtures were higher than the recommended minimum limit based on SUPERPAVE specification (80%).

Table 14. Indirect tensile strength for different mixtures.

Asphalt Mixture	**Tensile Strength, kPa**	
	Dry Condition	**Wet Condition**
Control	1027.5	843.6
Lucolast7010	990.8	859.3
Anglomk2144	1029.7	917.5
Paveflex140	1086.9	940.20
SBS KTR401	1139.6	1033.7
EE-2	957.8	861.6

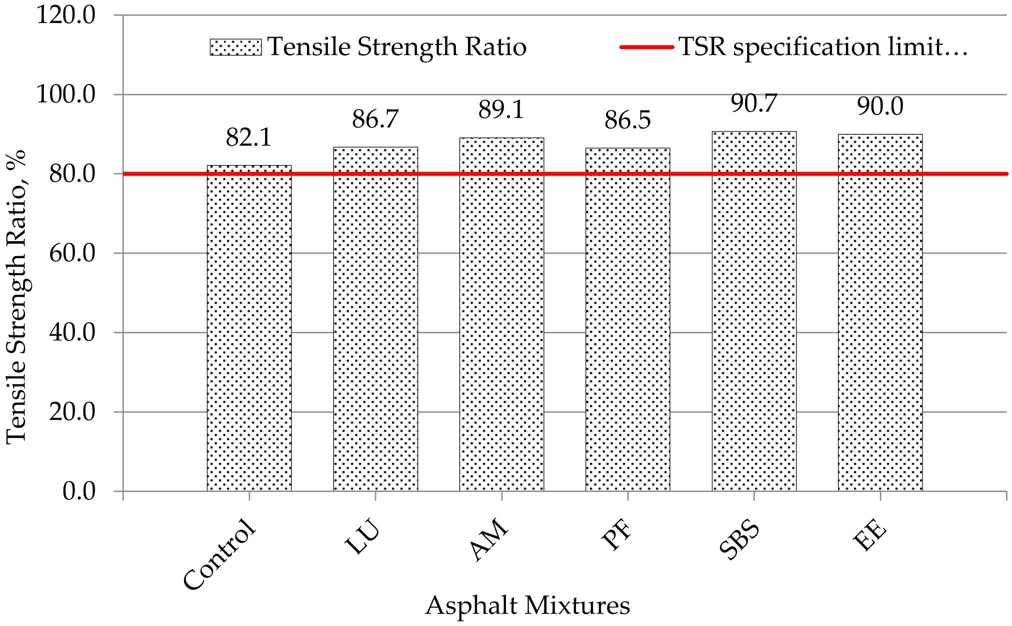


Figure 12. Tensile strength ratio for different mixtures.

Table 15 shows the effect sizes for the *TSR* of different mixtures. It shows that the differences in Fn values were not statistically significant between some asphalt mixtures since the effect size values obtained were less than 1.6. For example, the Lucolast mixture had statistically no difference in *TSR* compared with the Paveflex140 mixture since the effect size value was 0.12.

Table 15. Effect sizes for *TSR*.

	NEAT	**LU**	**AM**	**PF**	**SBS**	**EE**
NEAT	-	1.09	3.28	1.97	2.95	3.42
LU	1.09	-	0.50	0.12	0.81	0.70
AM	3.28	0.50	-	1.83	0.71	0.60
PF	1.97	0.12	1.83	-	1.72	2.09
SBS	2.95	0.81	0.71	1.72	-	0.31
EE	3.42	0.70	0.60	2.09	0.31	-

5.5. Overall Ranking of PMA Mixture Performance

The mixes were ranked based on a 6-point scale, where the mixture with the best performance would be ranked as 1 and the mixture with the worst performance would have the highest number, so the worst performance would be ranked as 6, as shown in Table 16. The Relative Importance Index (*RII*) (Equation 4) was used to calculate the mix design's relative significance for different performance tests. Based on the *RII* values, the overall ranking of asphalt mixture performance was determined. The findings show that asphalt mixture modified by Anglomk2144 was ranked as the best performance mixture (*RII* = 0.722), followed by asphalt mixtures modified by Paveflex140, EE-2, Lucolast7010, and SBS KTR40 (*RII* = 0.630, 0.630, 0.593, and 0.574, respectively).

Table 16. Asphalt mixture ranking.

Property	Mix Design					
	Control	**Lucolast7010**	**Anglomk2144**	**Paveflex140**	**SBS KTR401**	**EE-2**
ITS-Dry	4	5	3	2	1	6
ITS-Wet	6	5	3	2	1	4
TSR	6	4	3	5	1	2
Fn	6	1	2	3	5	4
E* at −10	1	3	4	6	5	2
E* at 4.4	3	2	5	4	6	1
E* at 21.1	6	4	1	2	3	5
E* at 54.4	6	3	1	2	5	4
HWT	6	4	2	3	5	1
Sum	44	31	24	29	32	29
Relative index	0.352	0.593	0.722	0.630	0.574	0.630
Overall Ranking	6	4	1	2	5	3

6. Conclusions

In this study, the aim was to evaluate and compare the mechanical properties of the various polymer-modified asphalt (PMA) mixtures. Based on the results and analysis, the following conclusions are offered:

- The dynamic moduli values of all modified asphalt mixtures increased by decreasing the temperature and increased by increasing the frequency. Polymer-modified asphalt mixtures showed higher dynamic modulus values than neat asphalt mixture values for different frequencies and temperatures.
- Modified mixtures showed significant improvement in flow number compared with neat asphalt mixture. Asphalt modified with Anglomak2144, Pavflex140, and Lucolast polymers ranked as the best mixtures to rut resistance.
- Hamburg wheel tracking test results showed that asphalt mixture modified with polymers has better adhesion between the binder and aggregates compared with the neat asphalt mixture. The asphalt mixture modified with EE-2 ranked as the best, followed by Anglomak2144, Paveflax140, Lucolast7010, and SBS KTR401.
- The mixture modified by SBS KTR401 showed the highest indirect tensile strength, while the mixture modified by polymer EE-2 showed the lowest strength compared with other PMA mixtures for dry conditions. For wet conditions, the highest wsa SBS KTR401 and the lowest was Lucolast7010. Moreover, there was an improvement in water susceptibility of PMA mixtures over that of neat asphalt mixture. The tensile strength ratios (*TSR*s) of neat and PMA mixtures were all higher than the recommended minimum value (80%).
- Based on the overall ranking of mechanical properties, the asphalt mixture with polymer Anglomk2144 was ranked as the best performing mixture, followed by the asphalt mixtures with Paveflex140 and EE-2 polymers.

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