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Evaluation of Resilience Parameters of Soybean Oil-Modified and Unmodified Warm-Mix Asphalts—A Way Forward towards Sustainable Pavements

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Abstract: The sustainable design and construction of highways is indispensable for the economic growth and progress of any region. Highway pavements are one of the core transportation infrastructures that require energy efficient materials with durability and an optimized lifecycle. Recent research has proven that warm-mix asphalt pavements prepared with renewable bio-binders are less susceptible to distresses. This study aims to investigate the resilience characteristics (load time, deformation time) of soybean oil modified and unmodified warm-mix asphalts. Aggregates, asphalt binders and asphalt mixes were characterized in accordance with the Superpave Mix Design Criteria. The resilient modulus tests were performed as per ASTM D7369. The test results indicated that the soybean-modified warm asphalt mix samples showed a 20% to 32% reduction in load-carrying capacity than unmodified warm asphalt mixes. The values of the horizontal and vertical recoverable deformations observed in the soybean-modified mixes were found to be 3% to 7% more than in the unmodified mixes. A slight variability (up to 7%) was also observed in the time-response spectra, i.e., peak load, unload and rest periods, in the soybean-modified mixes compared with the unmodified mixes. The Pearson correlation coefficient showed a significant trend between the resilient modulus test parameters for the soybean-modified warm asphalt mixes, i.e., load deformation, load time and deformation time. Soybean oil showed sustainable behavior as a bio-binder, particularly in the deformation-time response for the warm asphalt mixes. However, the effect of soybean in terms of the reduction of the load-carrying capacity from a sustainability perspective needs to be investigated.

Keywords: transportation infrastructures; sustainable pavements; durable pavements; warm-mix asphalts; bio-binders; lifecycle

1. Introduction

Highway infrastructures have a significant influence on the socioeconomic development of countries [1]; therefore, the investment in these infrastructures provides opportunities for the economic growth [2,3] and development of a region [4,5]. The lack of transport infrastructure in developing countries is one of the major hinderances to accessing international markets [6], which highlights the global significance of transport infrastructure [7]. Non-conventional and environmentally friendly materials are beneficial for sustainable construction in the highway industry [8]. The use of these materials enhances the quality of environmental control measures and the development of durable transport infrastructures [9,10]. The sustainable construction of highways is indispensable for the transportation of people and goods [11]. Researchers have taken the motivation of using renewable resource-derived materials and utilized it in the modification of asphalt binders. The asphalt mixes produced using these modified binders exhibit merits over unmodified binders, such as emerging cost, environmental issues and the short supply of materials based on nonrenewable resources [12,13]. The properties of asphalt binders have a considerable effect on the performance of asphalt mixes [14]; therefore, to cope with the evolving issues related to pavement distresses, the modification of asphalt binders is indispensable. The utilization of bio-oils in asphalt binders reduces the stiffness of asphalt mixes, and thereby lessens the cracks that develop in the pavements [15–17]. Soybean-derived oil-based asphalt modification improves the mechanical properties of the asphalt binders [18–22].

The asphalt mixes (wearing and base) used in pavement surfacing primarily comprise asphalt binder and aggregates [23–28]. These asphalt mixes, termed as warm asphalt mixes, are generally prepared between temperatures of 140 °C and 160 °C [18]. The key objective of the warm asphalt mix design is to obtain the optimum combination of different constituents of the mix [29]. The asphalt mixes exhibit viscoelastic, viscoplastic, and time- and stress-dependent behavior when subjected to repeated loadings [23,30–34]. Therefore, pavement surface courses face different distresses during their service life, such as rutting, fatigue and thermal cracking. For the assessment of the viscoelastic behavior of asphalt mixes, the resilient modulus test can be performed [35,36].

This study aims to evaluate the effects of soybean as a bio-binder on the resilient modulus of warm asphalt mixes. The objectives of this research were: (1) to determine the effects of soybean oil on the load time and deformation time behavior of warm-mix asphalt during resilient modulus tests, (2) to compare the resilient modulus of soybean-modified and unmodified warm asphalt mixes, and (3) to assess the correlation dependency trends of different parameters (on each other) obtained in soybean-modified warm-mix asphalts' resilient modulus tests and compare these with unmodified warm-mix asphalt trends.

2. Materials and Methods

Commercially available soybean was processed to extract the soybean oil used in this study. The unmodified and soybean oil-based asphalt binders were selected in accordance with the details reported by Tarar et al. [37]. Two unmodified asphalt binders, PG 64-16 and PG 64-22, were labeled as A and B, whereas the two soybean oil (5% by weight of binder)-modified asphalt binders, PG 52-22 and PG 52-28, were categorized as A_o and B_o, respectively. The binders' characteristics such as high and low temperatures, performance grade, viscosity, mass change, penetration, softening point, ductility, flash and fire point were evaluated in laboratory based on respective American Association of State Highway and Transportation Officials (AASHTO)/American Society for Testing and Materials (ASTM) standards.

Two crushed aggregate sources, i.e., Sargodha (S) and Margalla (M), were used. The properties of the aggregates such as soundness, water absorption, Los Angeles abrasion (C131), elongation and flakiness index, fractured faces, uncompacted voids and sand equivalent were determined in the laboratory as per prevailing ASTM standards.

The Superpave (Sup-1 and Sup-2) and National Highway Authority (NH-A and NH-B) gradations were used. The wearing and base course mixes were designated as W1 to W24 and B1 to B8, respectively. The test matrix of the mixes is summarized in Table 1.

Table 1. Summary of the test matrix of warm asphalt mixes.

Mix ID	Asphalt Binders		Aggregates		Gradations
	A	**Ao**	**S**	**M**	
W1	√	-	√	-	SUP-1
W2	√	-	-	√	
W3	-	√	√	-	
W4	-	√	-	√	
W5	√	-	√	-	NH-A
W6	√	-	-	√	
W7	-	√	√	-	
W8	-	√	-	√	
	B	**Bo**	**S**	**M**	
W9	√	-	√	-	SUP-1
W10	√	-	-	√	
W11	-	√	√	-	
W12	-	√	-	√	
W13	√	-	√	-	NH-A
W14	√	-	-	√	
W15	-	√	√	-	
W16	-	√	-	√	
	B	**Bo**	**S**	**M**	
B1	√	-	-	√	SUP-2
B2	-	√	-	√	
B3	√	-	-	√	NH-A
B4	-	√	-	-	

Note: W = wearing course, B = base course, S = Sargodha aggregate, M = Margalla aggregate, Sup = Superpave, NH = National Highway Authority.

To determine the optimum binder contents (OBC), the mixes were tested according to the Marshall Mix test (ASTM D6926). The mixing and compaction temperatures of the binders were determined using a rotational viscometer (RV) test at 135 °C to 165 °C before the mix preparation. The binders were mixed with aggregate in a controlled mechanical mixer at 145 °C. The Superpave gyratory compactor (SGC) was used to compact the samples while keeping the air voids at 7 ± 0.5%. The indirect tensile strength and modulus of resilience test specimens were fabricated at 101.6 mm (4 inches) in diameter and 63.5 mm (2.5 inches) in thickness.

Modulus of resilience (M_R) describes the mechanical properties of asphalt mixes subjected to dynamic (traffic) loading. The asphalt mixes were tested according to ASTM D6931 for indirect tensile strength determination before M_R testing. The M_R tests were performed according to ASTM D7369 using an environmentally controlled universal testing machine: Cooper Research Technology HYD25 II.

The test temperature was set at 25 °C. The load was applied in the form of a haversine shape, i.e., $(1 - \cos\ \theta)/2$, as shown in Figure 1.

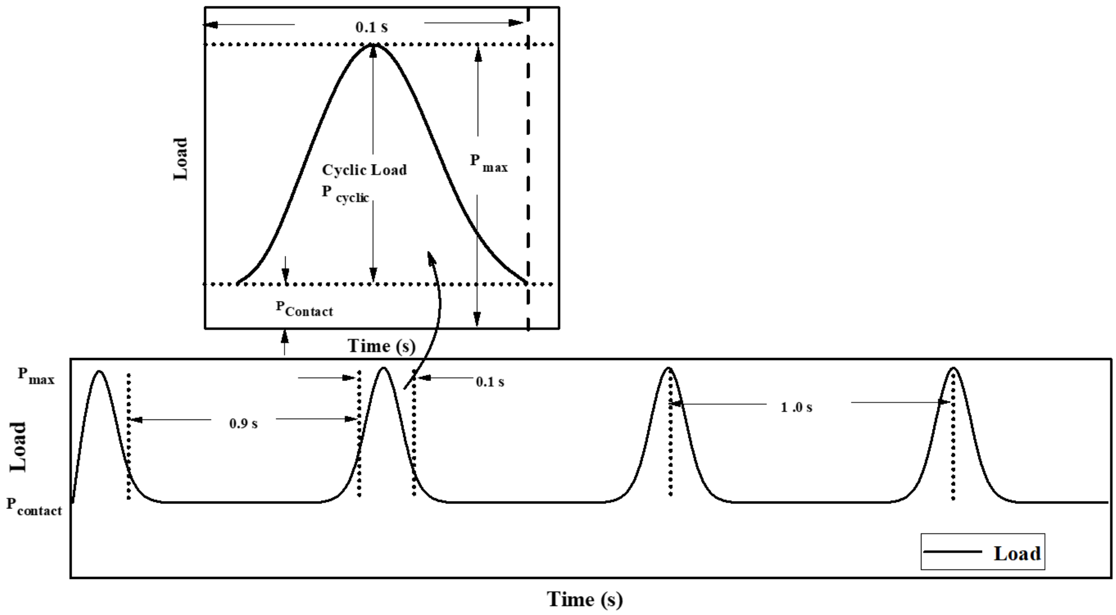

Figure 1. Typical load-time cycles with rest periods during M_R tests.

The instantaneous deformation, total deformation, Poisson's ratio and M_R were calculated according to the equations below.

$$Y = a + bx, \tag{1}$$

where Y is deformation value, x is time and a and b are regression constants.

$$Y = a + \frac{b}{x} \tag{2}$$

where Y is deformation value, x is time and a and b are regression constants.

$$\mu = \frac{I_4 - I_1 \times \left(\frac{\delta_v}{\delta_h}\right)}{I_3 - I_2 \times \left(\frac{\delta_v}{\delta_h}\right)}, \tag{3}$$

where μ is Poisson's ratio, I_1, I_2 I_3 and I_4 are constants and δ_v and δ_h are vertical and horizontal recoverable deformations, respectively.

$$M_R = \frac{P_{Cyclic}}{\delta_h t}(I_1 - I_2\delta), \tag{4}$$

where M_R is resilient modulus, P_{Cyclic} is the cyclic load applied to the specimen and t is the thickness of the specimen.

3. Results and Discussion

The physical properties of the soybean oil are summarized in Table 2a. The properties of the asphalt binders are shown in Table 2b.

Table 2. (**a**) Soybean oil physical properties [22]. (**b**) Summary of unmodified and soybean oil-modified asphalt binders' properties [22].

(a)

Description	Soybean Oil
Flash point (°C), ASTM D93	320
Fire point (°C), ASTM D93	354
Carbon residue (%), ASTM D189	0.37
Dynamic viscosity @ 25 °C(Pa.S), AASHTO T-316	0.062
Cloud point (°C), ASTM D5551	−9
Melting point (°C), ASTM D5440	0.5

(b)

Test Description	Type of Asphalt Binder			
	A	Ao	B	Bo
Original asphalt binder (high temperature °C)AASHTO T315	68.9	54.1	65.3	53.6
BBR (low temperature), AASHTO T313	−17	−24	−23	−29
Performance grades (PG), AASHTO M320	64–16	52–22	64–22	52–28
Viscosity (Pa.s) at 135 °C, AASHTO T316	0.462	0.250	0.445	0.242
Viscosity (Pa.s) at 165 °C, AASHTO T316	0.116	0.125	0.110	0.115
VTS	−3.557	−1.890	−3.381	−2.053
Mass change (%), AASHTO T240	0.078	0.083	0.056	0.068
Penetration (1/10th mm), ASTM D5	43	49	65	68
Softening point (°C), ASTM D36	54	47.1	48	45.6
Ductility (cm), ASTM D113	100+	100+	100+	100+
Flash and fire point (°C), ASTM D113	300	317	307	315

By the addition of soybean oil in binders A and B, few properties showed a decrease, i.e., high and low temperatures, viscosity at 135 °C and softening point, while others showed an increase, i.e., viscosity at 165 °C, mass change, penetration, flash and fire point, viscosity temperature susceptibility (VTS). The performance grade after the addition of soybean oil altered from 64–16 to 52–22 in one sample and 64–22 to 52–28 in another. However, overall, the penetration grade of the asphalt binder remained unchanged with the addition of the soybean oil to the asphalt binders. Soybean oil blended into the asphalt binder proved to have significant potential as a bio-binder.

The physical properties of the aggregates are summarized in Table 3.

Table 3. Summary of aggregate physical properties [11].

Description	Type of Aggregate		Standards
	S	M	
Water absorption (%)	0.95	0.93	ASTM C 127
Soundness (fine) (%)	3.8	4.5	ASTM C 88
Soundness (coarse) (%)	4.65	6.98	ASTM C 88
Los Angeles aberration (%)	23	24.5	ASTM C 131
Elongation index (%)	7	3	ASTM D 4791
Flakiness index (%)	9	5	ASTM D 4791
Fractured faces (%)	100	100	ASTM D 5821
Uncompacted voids (fine) (%)	45	44	ASTM C 1252
Sand equivalent (%)	71	74	ASTM D 2419

Note: S = Sargodha aggregate, M = Margalla aggregate.

The aggregates S and M have water absorption values of 0.95% and 0.93% respectively. The water content in the aggregates affects the performance of the asphalt mixes [38–41]. The optimum binder content is affected by the higher water absorption of the aggregates [42]. The soundness values of S and M are 3.8 and 4.5, respectively. The soundness value signifies the resistance of the aggregates against weathering. The Los Angeles abrasion values of S and M are 23 and 24.5, respectively, which specifies that the M aggregate source has higher abrasive resistance than S. The long-term performance of the pavement exposed to traffic loadings depends upon the abrasion resistance of the aggregates [43–45]. The elongation indices values of S and M are 7 and 3. The flakiness index values of S and M are 9 and 5. Researchers have reported that higher values of elongated and flaky particles reduce the strength of asphalt mixes [42,46,47]. The morphological properties of the aggregates affect the performance of asphalt mixes [48–51]. The aggregate gradation can also affect the modulus of resilience [52]. The uncompacted voids of S and M are 45 and 44, and the sand equivalents are 71 and 74, respectively. The engineering properties of both M and S aggregates qualify the acceptable limits for possible use in warm asphalt mixes. The consistency in the engineering properties of the aggregates is desirable, as it influences the resilient modulus of sustainable pavement structures [53,54]. The resilient modulus value affects the service life of the material and its resistance against pavement damage [55,56]. The energy absorption of soybean-modified mixes can be calculated based on the hysteresis loop response of samples under repeated loads [57]. This can be used as a potential advantage of soybean-modified mixes by researchers in the future.

The results in Table 4 show a summary of the different parameters obtained in the resilient modulus test, as illustrated in Figures 1 and 2.

Table 4. Summary of load, deformation and their corresponding time parameters obtained during the resilient modulus tests.

Mix ID	Load (kN)	T_m (s)	T_1 (s)	T_2 (s)	T_c (s)	T_{55} (s)	T_D (s)	T_e (s)	T_f (s)	δ_h (mm)	δ_v (mm)	δ_{total} (mm)
W1	1198.29	0.11000	0.09900	0.09240	0.06600	0.05280	0.02310	0.02750	0.01870	0.00140	0.08550	0.08690
W2	1165.23	0.11100	0.09980	0.09310	0.06650	0.05320	0.02330	0.02770	0.01880	0.00141	0.08620	0.08760
W3	939.72	0.11900	0.10700	0.09970	0.07120	0.05700	0.02490	0.02970	0.02020	0.00145	0.09230	0.09380
W4	907.75	0.11900	0.10700	0.10000	0.07160	0.05730	0.02510	0.02980	0.02030	0.00146	0.09280	0.09430
W5	1222.13	0.11100	0.09980	0.09310	0.06650	0.05320	0.02330	0.02770	0.01880	0.00139	0.08620	0.08760
W6	1210.35	0.11100	0.09990	0.09320	0.06660	0.05330	0.02330	0.02770	0.01890	0.00140	0.08630	0.08770
W7	954.65	0.11200	0.10100	0.09420	0.06730	0.05390	0.02360	0.02810	0.01910	0.00144	0.08720	0.08860
W8	923.15	0.11600	0.10400	0.09700	0.06930	0.05540	0.02430	0.02890	0.01960	0.00145	0.08980	0.09120
W9	1096.39	0.11600	0.10400	0.09710	0.06940	0.05550	0.02430	0.02890	0.01970	0.00143	0.08990	0.09130
W10	1067.33	0.11600	0.10500	0.09790	0.06990	0.05590	0.02450	0.02910	0.01980	0.00144	0.09060	0.09200
W11	913.52	0.11900	0.10700	0.09980	0.07130	0.05700	0.02490	0.02970	0.02020	0.00147	0.09240	0.09390
W12	889.45	0.11900	0.10700	0.10000	0.07140	0.05710	0.02500	0.02980	0.02020	0.00148	0.09250	0.09400
W13	1132.23	0.11100	0.09990	0.09320	0.06660	0.05330	0.02330	0.02770	0.01890	0.00140	0.08630	0.08770
W14	1109.35	0.11700	0.10500	0.09790	0.07000	0.05600	0.02450	0.02920	0.01980	0.00141	0.09070	0.09210
W15	852.65	0.11600	0.10400	0.09700	0.06930	0.05540	0.02430	0.02890	0.01960	0.00144	0.08980	0.09120
W16	823.15	0.11700	0.10500	0.09790	0.07000	0.05600	0.02450	0.02920	0.01980	0.00145	0.09070	0.09210
B1	584.45	0.11600	0.10400	0.09700	0.06930	0.05540	0.02430	0.02890	0.01960	0.00146	0.09060	0.09200
B2	494.87	0.11900	0.10700	0.09980	0.07130	0.05700	0.02490	0.02970	0.02020	0.00149	0.09250	0.09400
B3	623.25	0.11700	0.10500	0.09790	0.07000	0.05600	0.02450	0.02920	0.01980	0.00147	0.08720	0.08860
B4	514.34	0.11700	0.10500	0.09790	0.07000	0.05600	0.02450	0.02920	0.01980	0.00151	0.08610	0.08760

Note: peak load time (T_m), straight portion of unloading path between points T_1 and T_2, 40% rest period (T_c), 55% rest period (T_{55}), 90% rest period (T_d), time for 85% rest period (T_e), time for 95% rest period (T_f) in measurement units of second (s).

It is evident that the soybean-modified mixes took lesser loads (20% to 32%) than unmodified mixes in both wearing and base-course samples. In addition, the peak load time (T_m) was observed to be higher (2% to 7%) in the soybean-modified mixes than in the unmodified mixes. The straight portion of the unloading path T_1 and T_2 values were lower (2% to 7%) in the unmodified samples than in the soybean-modified samples. The time spectra of the rest periods (T_c, T_{55}, T_d, T_e and T_f) were also noted to be higher (2% to 7%) in the soybean-modified samples than in the unmodified mixes. The soybean-modified mixes exhibited improved horizontal (3% to 6%) and vertical (6% to 7%) recoverable deformations in comparison to the unmodified mixes.

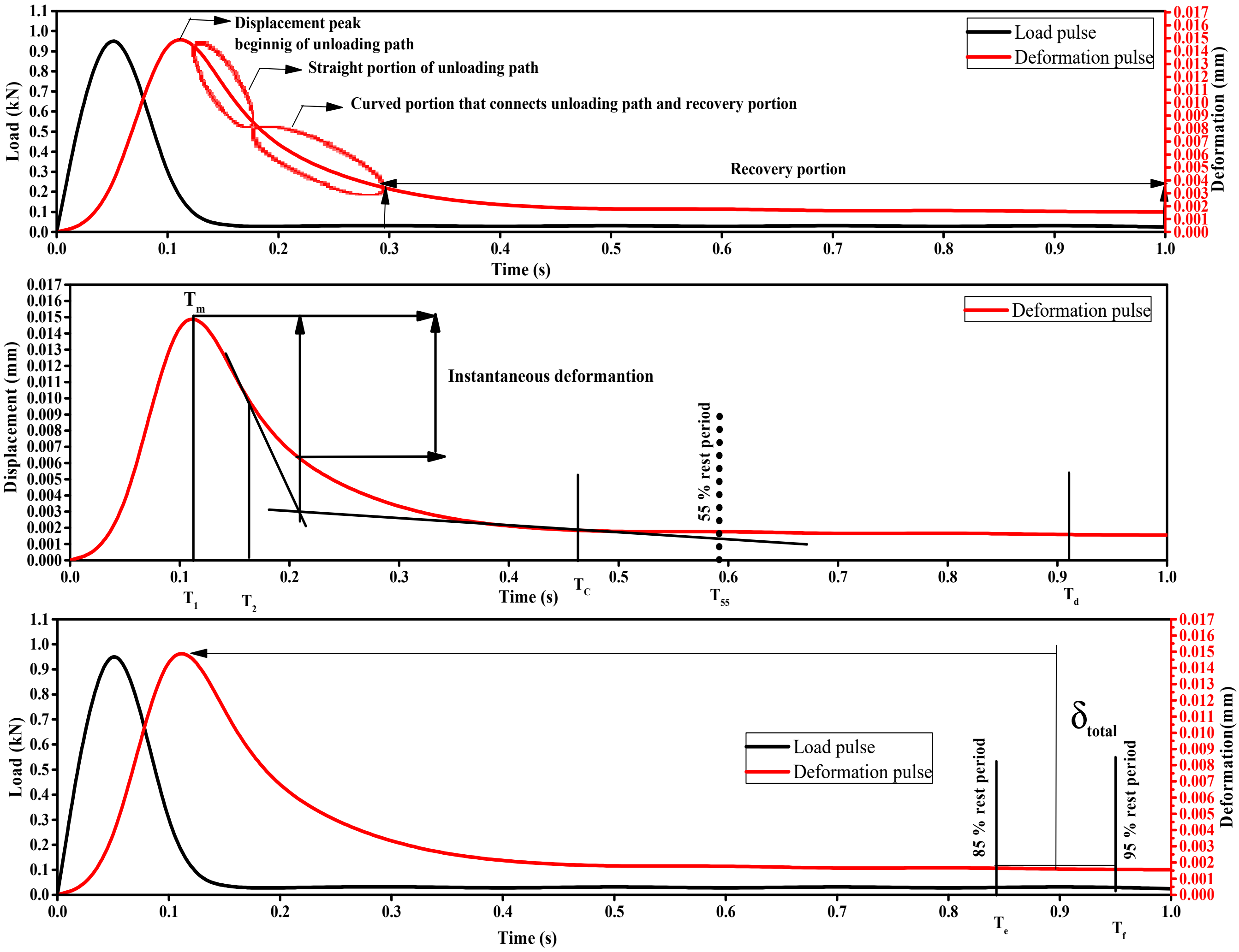

Figure 2. Typical load-time and deformation-time plots for a single cycle with time parameter explanation during M_R tests, as per ASTM D7369.

The M_R values for all wearing and base-course mixes were determined using Equation (4), as shown in Figures 3–5.

The M_R value of S for the Superpave and NH gradations was higher than for M. Figure 3 shows that the M_R values of S and M for the Superpave gradation and asphalt binder A were 7049 MPa and 6802 MPa, respectively, while the soybean oil-modified asphalt binders with Superpave gradations showed M_R values of 5063 MPa and 4751 MPa, respectively. The NH gradation exhibited an M_R value for the asphalt binder A and S and M of 7350–7224 MPa. On the other hand, the M_R values for the A_o and NH gradation were 5086–4850 MPa.

Figure 4 indicates that the M_R values of S and M for the Superpave gradation and B asphalt binder were 6344 and 6129 MPa, respectively, while the B_o asphalt binders with Superpave gradations showed M_R values of 4823 and 4665 MPa, respectively. The NH gradation exhibited M_R values for the B asphalt binder and S and M of 6708 and 6512 MPa, respectively. On the other hand, the M_R values for the B_o asphalt binders and NH gradation were 4538 and 4349 MPa, respectively.

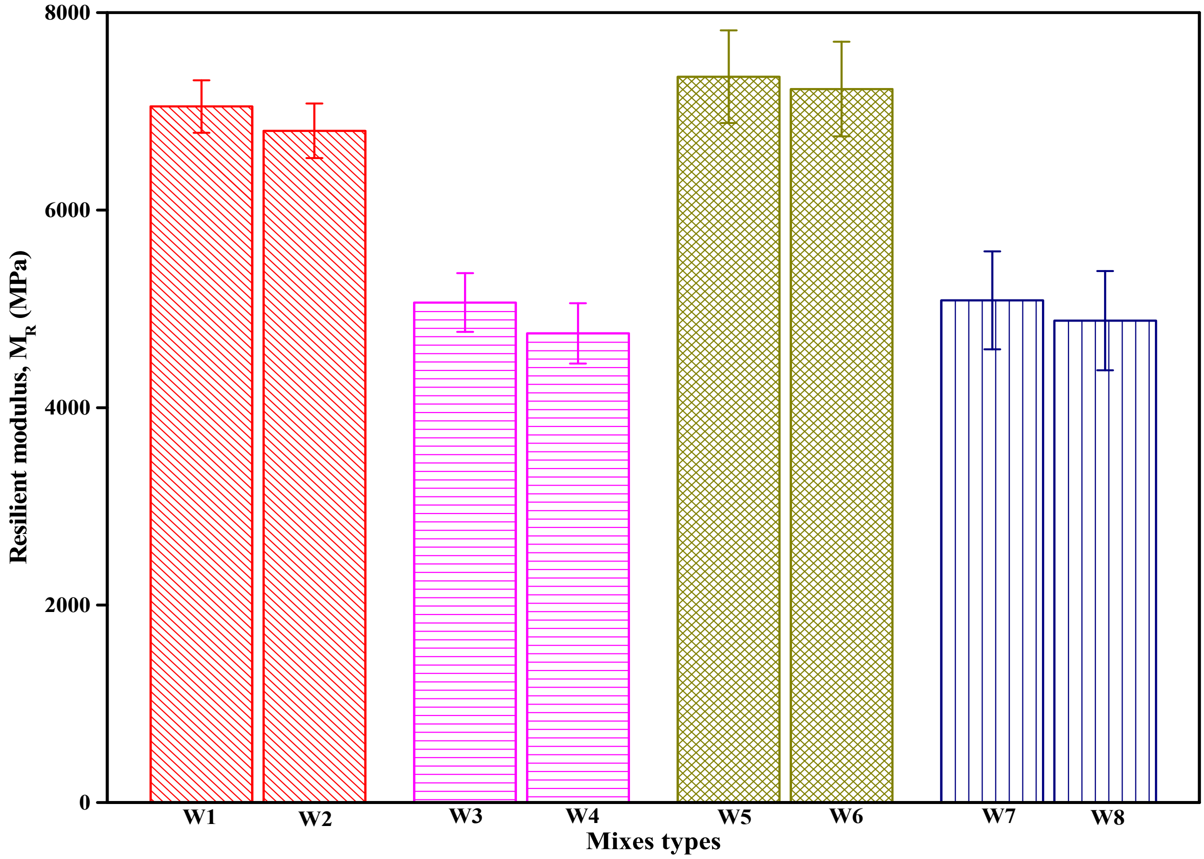

Figure 3. Resilient modulus of modified and unmodified asphalt mixes (W1–W8).

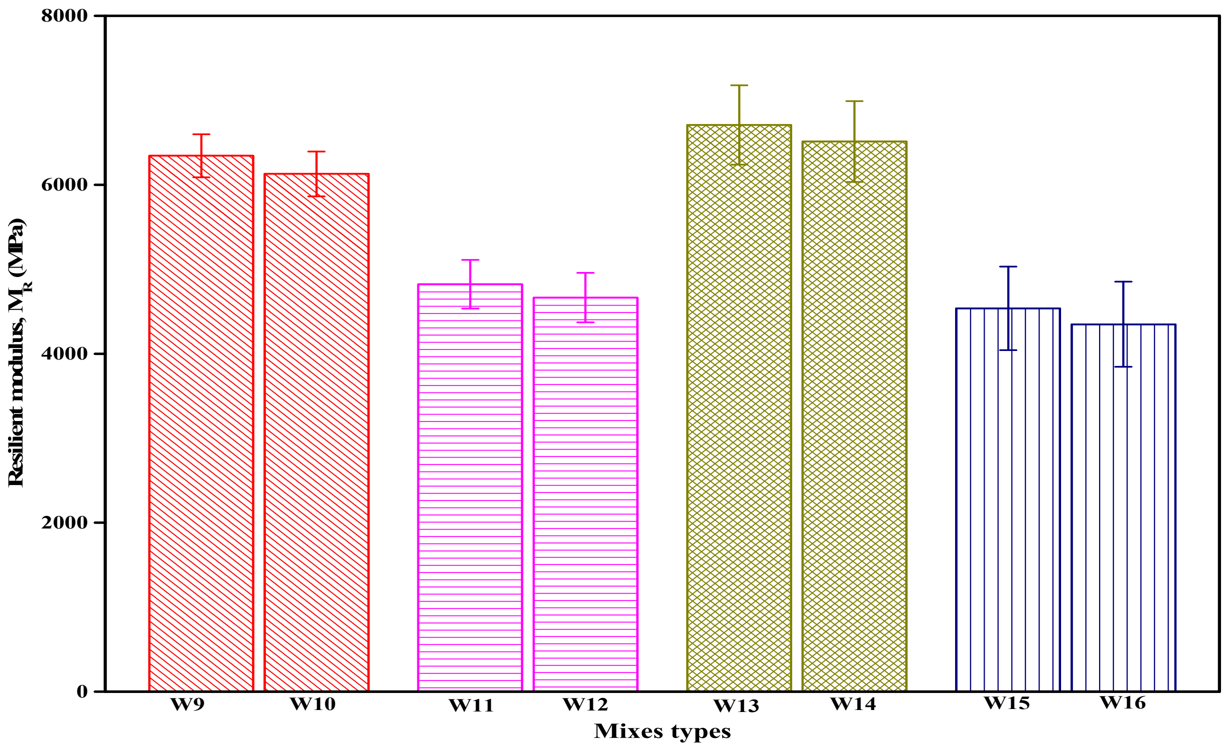

Figure 4. Resilient modulus of modified and unmodified asphalt mixes (W9–W16).

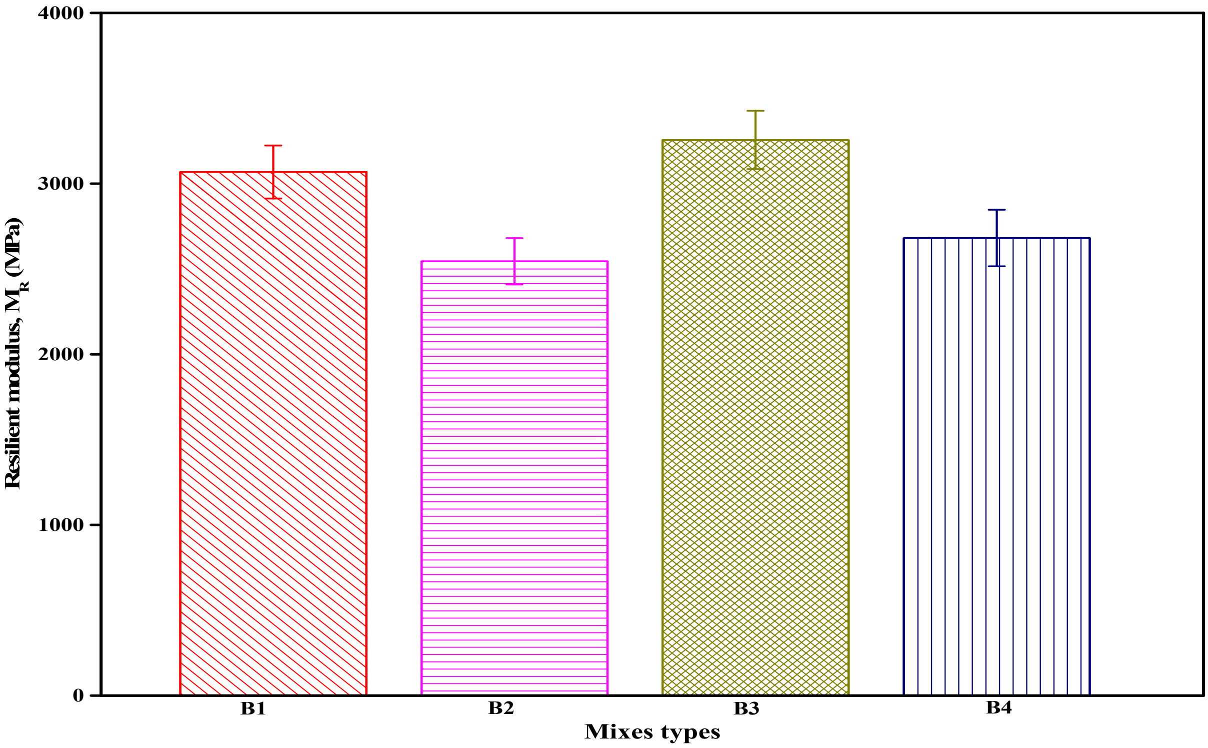

Figure 5. Resilient modulus of modified and unmodified asphalt mixes (B1–B4).

Figure 5 shows that the M_R values of M for the Superpave gradation and B asphalt binder were in the range of 3068 MPa, while the soybean oil-modified asphalt binders with Superpave gradations exhibited M_R values in the range of 2545 MPa. The NH gradation exhibited an M_R value for the asphalt binder B and M of 2911 MPa. On the other hand, the M_R value of the B_o asphalt binder with NH gradation was shown to be 2619 MPa.

Figures 3–5 show that the addition of soybean oil decreased the M_R values of both the wearing and base-course asphalt mixes.

Table 5 shows a summary of the statistical analysis carried out using the Origin software from OriginLab®. The different parameters (load, T_m, T_1, T_2, . . .) obtained in the M_R tests were correlated with each other to assess the trend and possible dependency. The Pearson correlation and the respective significance values are summarized in Table 5. The values of the Pearson correlation indicate the strength of the relationship (linear) between the different variables. A positive Pearson correlation value indicates that two parameters have a direct relationship—if one parameter increases, then the other increases, and vice versa, while a negative Pearson correlation value indicates that both of the parameters have an inverse relationship—if one parameter increases, then other decreases, and vice versa. It can be seen from Table 5 that the load deformation, load time and deformation time showed reasonable significance (shaded regions) for both the modified and unmodified mixes, in line with typical trends, as shown in Figures 1 and 2.

Soybean oil showed sustainable behavior as bio-binder, particularly in the deformation-time response for warm asphalt mixes. However, the effect of soybean in the reduction of the load-carrying capacity from a sustainability perspective needs to be investigated. The minimal requirement of M_R for asphalt mixes was reported in ASTM 7369. An M_R obtained with the 5% addition of soybean as an asphalt binder falls well within the optimal acceptable stiffness range, especially for pavements subjected to light to medium traffic loading.

Table 5. Summary of the statistical analysis on M_R test parameters using Origin software from OriginLab®.

		Load (kN)	T_m **(s)**	T_1 **(s)**	T_2 **(s)**	T_c **(s)**	T_{55} **(s)**	T_D **(s)**	T_e **(s)**	T_f **(s)**	δ_h **(mm)**	δ_v **(mm)**	δ_{tota} **(mm)**
Load(kN)	Pearson Corr.	1	−0.37007	−0.35666	−0.35665	−0.35684	−0.35421	−0.36084	−0.36444	−0.34458	−0.88334	−0.34865	−0.35739
	Sig.	–	0.02631	0.03274	0.03275	0.03265	0.03405	0.03062	0.02887	0.03959	9.88321×10^{-13}	0.03716	0.03236
T_m (s)	Pearson Corr.	−0.37007	1	0.99595	0.99612	0.99626	0.9957	0.99507	*0.99679*	0.99267	0.55234	0.9961	0.99579
	Sig.	0.02631	–	0	0	0	0	0	0	0	4.78096×10^{-4}	0	0
T_1 (s)	Pearson Corr.	−0.35666	0.99595	1	*0.9994*	0.99893	0.99854	0.99748	0.99876	0.99733	0.54857	0.99885	0.99881
	Sig.	0.03274	0	–	0	0	0	0	0	0	5.32052×10^{-4}	0	0
T_2 (s)	Pearson Corr.	−0.35665	0.99612	0.9994	1	*0.9997*	0.99944	0.99876	0.9992	0.9982	0.55396	*0.99967*	*0.99966*
	Sig.	0.03275	0	0	–	0	0	0	0	0	4.5638×10^{-4}	0	0
T_c (s)	Pearson Corr.	−0.35684	0.99626	0.99893	0.9997	1	*0.99982*	0.99922	0.99932	0.99856	0.55177	*0.99987*	*0.99987*
	Sig.	0.03265	0	0	0	–	0	0	0	0	4.85904×10^{-4}	0	0
T_{55} (s)	Pearson Corr.	−0.35421	0.9957	0.99854	0.99944	*0.99982*	1	0.99907	0.99919	0.99895	0.54864	*0.99978*	*0.99978*
	Sig.	0.03405	0	0	0	0	–	0	0	0	5.3103×10^{-4}	0	0
T_D (s)	Pearson Corr.	−0.36084	0.99507	0.99748	0.99876	*0.99922*	0.99907	1	0.99882	0.99728	0.55504	*0.99916*	0.99893
	Sig.	0.03062	0	0	0	0	0	–	0	0	4.42388×10^{-4}	0	0
T_e (s)	Pearson Corr.	−0.36444	0.99679	0.99876	0.9992	*0.99932*	0.99919	0.99882	1	0.99725	0.55563	0.99908	0.99898
	Sig.	0.02887	0	0	0	0	0	0	–	0	4.34876×10^{-4}	0	0
T_f (s)	Pearson Corr.	−0.34458	0.99267	0.99733	0.9982	*0.99856*	*0.99895*	0.99728	0.99725	1	0.54036	*0.99856*	*0.9986*
	Sig.	0.03959	0	0	0	0	0	0	0	–	6.69006×10^{-4}	0	0
δ_h (mm)	Pearson Corr.	*−0.88334*	0.55234	0.54857	0.55396	0.55177	0.54864	0.55504	*0.55563*	0.54036	1	0.54437	0.55288
	Sig.	9.88321×10^{-13}	4.78096×10^{-4}	5.32052×10^{-4}	4.5638×10^{-4}	4.85904×10^{-4}	5.3103×10^{-4}	4.42388×10^{-4}	4.34876×10^{-4}	6.69006×10^{-4}	–	5.98648×10^{-4}	4.70652×10^{-4}
δ_v (mm)	Pearson Corr.	−0.34865	0.9961	0.99885	0.99967	*0.99987*	0.99978	0.99916	0.99908	0.99856	0.54437	1	0.99982
	Sig.	0.03716	0	0	0	0	0	0	0	0	5.98648×10^{-4}	–	0

4. Conclusions

In this study, the effect of soybean oil on the resilient modulus of asphalt mixes was evaluated using the ASTM D7369 procedure. The statistical analysis was performed to check the correlations between the different parameters obtained in the M_R tests. The following conclusions can be drawn from the above findings:

1. The soybean-modified warm asphalt mixes showed a 20% to 32% reduction in load-carrying capacity, i.e., for the resilient modulus than the unmodified warm asphalt mixes.
2. The values of the horizontal and vertical recoverable deformations remained comparable (3% to 7%) in both the soybean-modified and unmodified warm asphalt mixes.
3. A slight variability (2% to 7%) was observed in the time-response spectra, i.e., peak, unload, rest periods of loads and deformations during the resilient modulus tests performed on the soybean-modified and unmodified warm asphalt mixes.
4. Each parameter obtained in the soybean-modified warm-mix asphalt resilient modulus test showed a reasonable correlation trend with the others, as depicted by the Pearson coefficient. Hence, the trends of the soybean-modified and unmodified warm-mix asphalt in resilient modulus tests are comparable.
5. Soybean oil showed sustainable behavior as bio-binder, particularly in the deformation-time response for warm asphalt mixes. However, the effect of soybean in the reduction of the load-carrying capacity from a sustainability perspective needs to be investigated.

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