Balancing the Performance of Asphalt Binder Modified by Tire Rubber and Used Motor Oil

Eslam Deef-Allah, Magdy Abdelrahman

Abstract**:** ***The crumb rubber modifier (CRM) particles release polymeric fractions in the matrix of the asphalt binder, which increase the asphalt binder's fatigue and rutting resistance. The used motor oil (UMO) compensates the asphalt binder for the low-molecular-weight components lost during the aging processes. Moreover, UMO could increase the asphalt binder's fluidity and softness. Therefore, modification of the asphalt binder by CRM in combination with UMO could enhance the asphalt binder's performance. In this paper, the asphalt binder was modified by CRM. Then, the UMO was added to the crumb rubber modified asphalt (CRMA). The neat asphalt, CRMA, and UMO–CRMA binders' resistance to rutting and fatigue cracking was evaluated. Temperature sweep test was used to evaluate the neat and modified asphalt binders' resistance to rutting and fatigue cracking by measuring |G*|/sinδ and |G*|.sinδ parameters, respectively. Linear amplitude sweep (LAS) test was used to analyze the neat and modified asphalt binders' resistance to fatigue cracking by measuring the number of load repetitions to failure (N_f). It was found that using CRM and UMO enhanced the asphalt binder's resistance to rutting and fatigue cracking. Therefore, UMO succeeded as a rejuvenator to balance the CRMA binder's performance. This had occurred by creating a balance between the enhanced properties at high, intermediate, and low temperatures. Interaction temperature plays a dominant role in enhancing the asphalt binder's performance: the enhancement in rutting and fatigue cracking parameters reached the highest values for CRMA or UMO–CRMA samples interacted at 190°C interaction temperature. At 220°C interaction temperature, these enhancements had decreased due to the devulcanization and depolymerization processes of the polymeric components released in the asphalt binder's matrix.***

Keywords**:** ***LAS, CRM, UMO, fatigue and cracking resistance.***

I. INTRODUCTION

Crumb rubber modifier (CRM), used motor oil (UMO), or both could enhance the asphalt binders' performance and resistance to fatigue cracking [1, 2]. Abdelrahman et al. [3] recommended that the UMO percentage should be 3% or less combined with 10% or more CRM, by the weight of the neat asphalt binder. Ragab and Abdelrahman [2] found that using 3% UMO in combination with 10% CRM enhanced the resistance of asphalt binder to fatigue cracking by decreasing the fatigue cracking parameter (|G*|.sinδ). Deef-Allah et al. [1] showed that modified asphalt binders by both 2.5% UMO and 10% or 15% CRM had the highest resistance to fatigue cracking as compared to neat asphalt or crumb rubber modified asphalt (CRMA) binders. Using CRM and UMO gave the best enhancement in the fatigue cracking parameter as compared to neat asphalt, UMO, or CRM modified asphalt binders [2]. This occurred because CRM particles absorbed the low-molecular-weight fractions (resin and oils) in the UMO [1, 2]. Moreover, during the long-term aging process, the absorbed components would be released in the matrix of the asphalt binder that decreased the asphalt binder's stiffness and increased its resistance to fatigue cracking [2].

Fatigue cracking can result from the horizontal tensile strain at the bottom of the hot mix asphalt (HMA). Fatigue cracking does not initialize until a certain number of load repetitions. Then, it increases rapidly as the pavement weakens. Consequently, the number of load repetitions to failure (N_f) has a relation with the tensile strain at the bottom of the asphalt layer. This relation is presented in Equation 1. Fatigue cracking starts at the bottom of the asphaltic layer or stabilized base and propagate to the surface; the cracking connects and forms a pattern like an alligator skin [4].

$$N_f = f_1(\epsilon_t)^{-f_2} \tag{1}$$

where
N_f is the number of load repetitions to failure,
ϵ_t is the tensile strain,
f_1 is a fatigue constant, which is the value of N_f at $\epsilon_t = 1$, and
f_2 is the inverse slope of a straight line; this line reflects the relationship between log N_f and log ϵ_t.

The linear amplitude sweep (LAS) test is more suitable to evaluate the modified asphalt binders' damage resistance [5]. This test was developed on the same concept presented in Equation 1. The resistance to fatigue damage resistance can be calculated using the results of the LAS test at 2.5 and 5% strain percentages. The 2.5% strain percentage represents strong pavement (asphalt layer thickness > 4 inches). On the other hand, the 5% strain percentage represents weak pavement (asphalt layer thickness < 4 inches) [6].

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***** Correspondence Author
Eslam Deef-Allah *, Ph.D. Student; Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science & Technology; emddkc@mst.edu
Magdy Abdelrahman, Missouri Asphalt Pavement Association (MAPA) Endowed Professor; Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science & Technology; m.abdelrahman@mst.edu

It was found that the CRM particles released polymeric fractions in the matrix of the asphalt binder. These components increased the asphalt binder's fatigue and rutting resistance. Furthermore, UMO could increase asphalt binder's fluidity and softness by compensating it with the low-molecular-weight components lost during the aging processes.

Finally, UMO is recommended to be used as a rejuvenator to balance the performance of the CRMA binders.

II. MATERIAL AND EXPERIMENTAL PROGRAM

A. Material

One asphalt binder's type was used in this study with a performance grade PG64-22. It purchased from Philips 66 (Granite, IL, USA). The CRM, obtained from EnTire Recycling, Inc. (Rock Port, Mo, USA), was a cryogenically processed crumb rubber. CRM (30-40), retained on sieve #40 and passed from sieve #30, was used to modify the asphalt binder. Used motor oil is mixed with CRMA binders. This UMO has a viscosity of 5.5 centipoise (cP), measured at 135°C. The UMO obtained from an automotive repair shop. Based on the recommendations of Abdelrahman et al. [3], the optimum UMO percentage should be 3% or less by the weight of asphalt binder and to be combined with at least 10% CRM to enhance the performance of the asphalt binder. Moreover, this UMO percentage is suitable to balance the enhanced rheological properties of the modified asphalt binders and environmental concerns [1]. Accordingly, 2.5% UMO and 10% CRM percentages by the weight of the neat asphalt binder were selected to enhance the asphalt binder's performance.

B. Modified Asphalt Binders' Interactions

The asphalt binder was heated in an oven to the interaction temperature (160, 190, or 220°C) and moved to a Glas-Col heating mantle purchased from Cole-Parmer Co. (Vernon Hills, IL, USA) under a fume hood. The temperature was controlled using a DIGI-SENSE probe-type J connected to a temperature controller DIGI-SENSE TC 9100, which in turn controlled the heating mantle's temperature. After that, 10% CRM of the asphalt binder's weight was added. The asphalt binder was mixed with CRM at low or high speeds (10 or 50 Hz) using an LCI-t high shear mixer obtained from Charles Ross & Son Company (Hauppauge, NY, USA) for 60 minutes interaction time. For samples modified with CRM and UMO, UMO was added immediately after introducing CRM to the asphalt binder. The percentage of the UMO was 2.5%, which was calculated as a percentage from the neat asphalt binder weight. At the end of the mixing process, the modified asphalt binder was stored in the refrigerator to prevent binder aging and excess dissolution process of the CRM particles.

Table I illustrates the interaction matrix used in this article. Three interaction temperatures were used (160, 190, and 220°C), two interaction speeds were used (10 and 50 Hz), and one interaction time was used (60 minutes). For the CRMA and UMO–CRMA binder code column, the first number between the two parentheses is the interaction temperature, the second number is the interaction speed, and the last number is the interaction time.

Table- I: Interaction matrix for the modified asphalt binders.

Asphalt binder PG	UMO (%)	CRM (%)	Interaction temperature (°C)	Interaction speed (Hz)	Interaction time (minutes)	CRMA and UMO–CRMA binder code
64-22	0	10	160	10	60	CRMA (160–10–60)
				50		CRMA (160–50–60)
			190	10		CRMA (190–10–60)
				50		CRMA (190–50–60)
			220	10		CRMA (220–10–60)
				50		CRMA (220–50–60)
	2.5		160	10		UMO–CRMA (160–10–60)
				50		UMO–CRMA (160–50–60)
			190	10		UMO–CRMA (190–10–60)
				50		UMO–CRMA (190–50–60)
			220	10		UMO–CRMA (220–10–60)
				50		UMO–CRMA (220–50–60)

C. Experimental Program

The resistance of neat and modified asphalt binders to rutting and fatigue cracking was evaluated using temperature sweep test for samples aged by rolling thin film oven (RTFO) and pressure aging vessel (PAV), respectively. Temperature sweep test was conducted on RTFO and PAV neat asphalt, CRMA, and UMO–CRMA binders. The fatigue damage resistance of the neat asphalt, CRMA, and UMO–CRMA binders was evaluated using the LAS test. This test was implemented for neat and modified binder samples aged using both RTFO and PAV. Fig. 1 illustrates the stages of the experimental program.

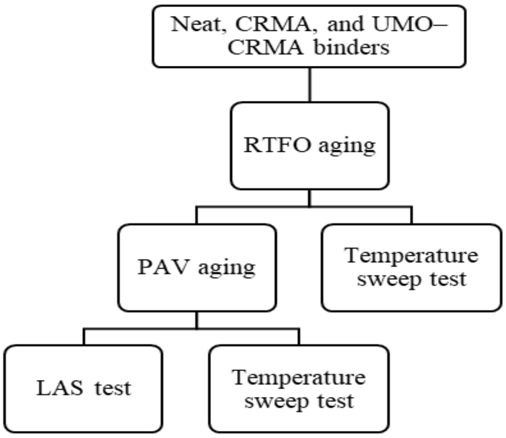

Fig. 1. Experimental program.

1. RTFO Aging

The RTFO aging represents short-term aging. Testing followed the ASTM D2872 [7]. It was executed using a CS325-B RTFO model purchased from James Cox & Sons INC, (Colfax, CA, USA).

2. PAV Aging

The PAV aging simulates long-term aging. Testing was applied according to ASTM D6521 [8]. It was carried out using a PAV 9300 machine purchased from Prentex Alloy Fabrication, INC, (Dallas, TX, USA).

3. Temperature Sweep Test

A Dynamic Shear Rheometer (DSR) was used to make a viscoelastic analysis for RTFO and PAV neat asphalt, CRMA, and UMO–CRMA binders. This DSR is Anton Paar Modular Compact Rheometer (MCR) 302. The test was carried out at a temperature range (10–76°C) with 6°C increments. For temperatures above 45°C, plates with a 25 mm diameter and a 1 mm gap size were used. The temperature range between 46 and 76°C was selected to evaluate the rutting resistance of RTFO samples by measuring the rutting parameter (|G*|/sinδ). On the other hand, for temperatures below 45°C, plates with an 8 mm diameter and a 2 mm thickness were used. The range of temperatures between 10 and 40°C was chosen to analyze the samples' resistance to fatigue cracking by measuring the fatigue cracking parameter (|G*|.sinδ).

4. LAS Test

The LAS test was implemented on the DSR according to AASHTO TP 101-14 [9]; it was conducted using PAV binders at 25°C as a reference temperature. Samples with an 8 mm diameter and a 2 mm thickness were used. The test was conducted by applying two stages. The first stage was a frequency sweep test, while the second one was an amplitude sweep test. The frequency sweep test was used to evaluate the damage analysis by applying a 0.1% strain load over a frequency range (0.2–30 Hz). The amplitude sweep test was conducted at a constant frequency of 10 Hz in a strain-control mode. A linearly increased load was applied from zero to 30% over 3100 loading cycles with 10 cycles per second. The number of load repetitions to failure (N_f) for binders was calculated based on the measurements of the LAS test. The N_f represents the fatigue damage's resistance: a higher N_f value reflects a higher resistance to fatigue damage. The N_f was calculated for strong and weak pavements at 2.5 and 5% strain, respectively.

III. RESULTS AND ANALYSIS

A. Temperature Sweep Test Results

Table II presents the rutting parameter for the neat asphalt, CRMA, and UMO–CRMA binders measured at a temperature range from 46 to 76°C. The modified asphalt binders mixed at (160, 190, or 220°C) interaction temperature, (10 or 50 Hz) interaction speed, and 60 minutes interaction time. For CRMA binders, the rutting parameter significantly increased due to the CRM particles' elastic nature and their polymeric components released in the asphalt binder's matrix. Adding UMO to the CRMA binders decreased the rutting parameter due to the lubricating effect between the CRM particles. Additionally, the UMO could compensate the asphalt binder for the low-molecular-weight fractions lost due to CRM particles' absorption and the aging processes. At 220°C interaction temperature, the rutting parameter slightly decreased as compared to the other CRMA binders. This had occurred due to the devulcanization and depolymerization processes during this interaction temperature, which decreased the resistance to rutting.

Table- II: Rutting parameter measured for the neat and modified asphalt binders mixed at (160, 190, or 220°C) interaction temperature, (10 or 50 Hz) interaction speed, and 60 minutes interaction time.

Asphalt binder	Interaction parameters	|G*|/sinδ measured at a temperature range 46–76°C (KPa)					
		46°C	52°C	58°C	64°C	70°C	76°C
Neat	--	41.022	17.127	7.371	3.304	1.548	0.757
CRMA	(160–10–60)	113.468	57.854	28.748	14.038	6.871	3.455
	(160–50–60)	102.677	52.123	25.966	12.680	6.230	3.138
	(190–10–60)	108.958	55.286	28.175	14.274	7.230	3.721
	(190–50–60)	91.813	49.229	25.938	13.417	6.908	3.613
	(220–10–60)	72.246	38.196	20.135	10.659	5.703	3.086
	(220–50–60)	80.180	41.464	21.618	11.333	5.972	3.176
UMO–CRMA	(160–10–60)	76.713	37.620	18.504	9.001	4.416	2.230
	(160–50–60)	79.985	40.058	19.883	9.745	4.815	2.449
	(190–10–60)	73.426	37.610	19.212	9.701	4.913	2.542
	(190–50–60)	70.673	36.025	18.417	9.305	4.719	2.446
	(220–10–60)	54.537	27.930	14.521	7.610	4.017	2.166
	(220–50–60)	58.507	28.983	14.599	7.435	3.844	2.021

Table III shows the fatigue cracking parameter for the neat asphalt, CRMA, and UMO–CRMA binders measured at a temperature range from 10 to 40°C. The modified asphalt binders mixed at (160, 190, or 220°C) interaction temperature, (10 or 50 Hz) interaction speed, and 60 minutes interaction time. In a temperature range between 10 and 28°C, the fatigue cracking parameter decreased for the CRMA binders, which illustrates more resistance to fatigue cracking. This occurred due to the CRM particles' polymeric components released in the asphalt binder's matrix. Using UMO increased the asphalt binders' resistance to fatigue cracking by showing lower (|G*|·sinδ) values as compared to the neat asphalt and the CRMA binders. This happened since UMO compensated the asphalt binder for the low-molecular-weight fractions lost during the aging processes. Moreover, UMO could increase the asphalt binder's fluidity and softness.

Table- III: Fatigue cracking parameter measured for the neat and modified asphalt binders mixed at (160, 190, or 220°C) interaction temperature, (10 or 50 Hz) interaction speed, and 60 minutes interaction time.

Asphalt binder	Interaction parameters	|G*|·sinδ measured at a temperature range 10–40°C (KPa)					
		10°C	16°C	22°C	28°C	34°C	40°C
Neat	--	16065	9623	5223	2616	1234	557
CRMA	(160–10–60)	11631	6599	3716	2038	1073	563
	(160–50–60)	13146	8098	4654	2493	1270	627
	(190–10–60)	13068	7941	4545	2431	1238	610
	(190–50–60)	11887	7203	4090	2172	1100	540
	(220–10–60)	11185	6795	3811	2004	1007	491
	(220–50–60)	11533	6883	3892	2066	1049	517
UMO–CRMA	(160–10–60)	9851	6061	3464	1857	957	479
	(160–50–60)	9924	6103	3479	1863	956	478
	(190–10–60)	9067	5635	3192	1702	872	435
	(190–50–60)	9305	5717	3240	1735	891	446
	(220–10–60)	9380	5676	3192	1696	864	428
	(220–50–60)	9589	5931	3440	1843	940	467

Some samples present the best enhancement to rutting resistance like samples mixed at the low (160°C) and the intermediate (190°C) interaction temperatures. This happened due to the CRM particles' elastic nature and their polymeric components released into the asphalt binder's matrix. However, for samples mixed at high (220°C) interaction temperature, more resistance to fatigue cracking was observed due to the CRM excess dissolution. Therefore, asphalt binder samples modified by CRM have the highest rutting resistance; however, samples modified by both CRM and UMO show the highest resistance to fatigue cracking. Consequently, comparing the best enhancement in rutting and fatigue cracking resistance for modified asphalt binders is a complicated process. Hence, a new factor is presented in Equation 2. This factor combines the effect of rutting and fatigue parameters. The pass/fail high and intermediate temperatures for the neat asphalt binder were calculated at the critical values of the rutting (2.2 KPa) and fatigue (5000 KPa) parameters, respectively. The pass/fail high and intermediate temperatures for the neat asphalt binder were found to be 67.58 and 21.42°C, respectively. Consequently, the $F_{Rutting\text{-}Fatigue}$ has a value of one for the neat asphalt binder. Moreover, this value is expected to increase (greater than one value) for modified asphalt binders by increasing the rutting resistance, higher numerator, increasing the fatigue cracking resistance, lower denominator, or both.

$$F_{Rutting-Fatigue} = \frac{|G^*|/\sin\delta}{|G^*|.\sin\delta} \times \frac{10^4}{4.4} \tag{2}$$

where

|G*|/sinδ is the rutting parameter measured at 67.58°C (KPa), and

|G*|.sinδ is the fatigue parameter measured at 21.42°C (KPa).

The $F_{Rutting\text{-}Fatigue}$ values are shown in Fig. 2. For CRMA binders, the highest value of $F_{Rutting\text{-}Fatigue}$ was obtained for samples mixed at (160–10–60) and (190–50–60) interaction parameters. For (160–10–60) interaction parameters, the CRM particles' dissolution was not enough to release the polymeric components in the asphalt binder's matrix. This reflects that no internal polymeric network structures exist at this temperature. However, the enhancement in this factor during (160–10–60) interaction parameters was due to the elastic nature of the CRM particles, which enhanced the resistance to rutting and fatigue cracking. For samples modified by both CRM and UMO, the highest $F_{Rutting\text{-}Fatigue}$ value was obtained for samples mixed at 190°C interaction temperature. Hence, the (190–50–60) interaction parameters are the best interaction variables that can dissolve CRM particles, release CRM polymeric components in the asphalt binder's matrix, and form the internal polymeric network structures.

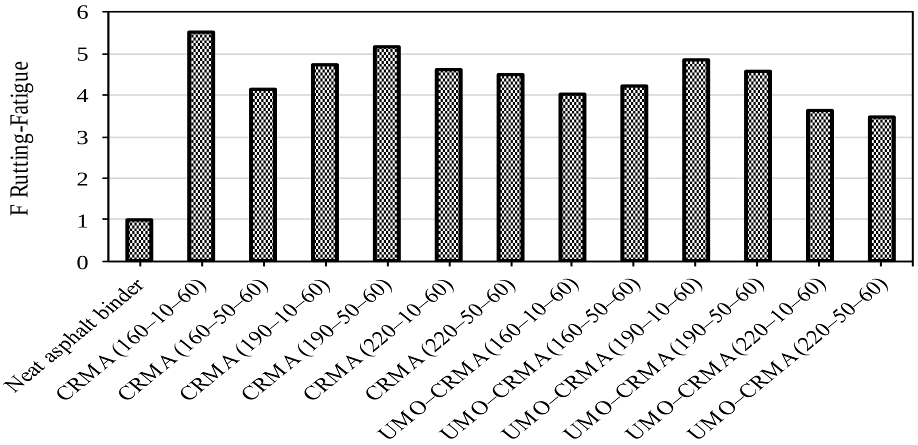

Fig. 2. Rutting-fatigue factor for the neat and modified asphalt binders mixed at (160, 190, or 220°C) interaction temperature, (10 or 50 Hz) interaction speed, and 60 minutes interaction time

B. LAS Test Results

Fig. 3 shows the N_f for the neat asphalt, CRMA, and UMO–CRMA binders mixed at (160, 190, or 220°C) interaction temperature, (10 or 50 Hz) interaction speed, and 60 minutes interaction time. Fig. 3-a presents the values of N_f calculated at 2.5% strain. Replicated tests were implemented to ensure the repeatability of this test; the coefficient of variation (COV) between the results was found ranging from 0.2 to 37%. It can be observed that the neat asphalt binder had the lowest resistance to fatigue cracking since it had the lowest N_f value. Adding CRM to the asphalt binder increased the resistance to fatigue cracking by showing higher N_f values. This occurred due to the ability of CRM particles to partially dissolve in the matrix of the asphalt binder and release their polymeric components. These components enhanced fatigue cracking resistance. At 220°C interaction temperature, the resistance to fatigue cracking decreased due to the depolymerization and devulcanization processes for the polymeric components released in the asphalt binder's matrix. Adding 2.5% UMO to the crumb rubber modified asphalt (CRMA) binders increased the resistance to fatigue cracking significantly. The UMO acted as a rejuvenator since it compensated the asphalt binder for the low-molecular-weight components that were lost during the aging processes. Therefore, restoring these components would increase the asphalt binder's resistance to fatigue cracking. The highest resistance to fatigue cracking happened at (190-50-60) interaction parameters. These interaction parameters can form internal polymeric network structures [10]; this was approved by the highest N_f value and the lowest COV value.

Fig. 3-b presents the values of N_f calculated at 5% strain. Replicated tests were implemented to ensure the repeatability of this test; the coefficient of variation (COV) between the results was found ranging from 0.18 to 36%. It can be observed that the N_f values decreased at a 5% strain (weak pavement) as compared to the values at a 2.5% strain (strong pavement). However, the same trend of results in Fig. 2(a) can be shown in Fig. 2(b): adding CRM with or without UMO to the neat asphalt binder increased the asphalt binder's fatigue resistance. Moreover, the highest resistance to fatigue cracking happened at (190-50-60) interaction parameters.

Table IV presents the percentage increase in the N_f values for the modified asphalt binders mixed at (160, 190, or 220°C) interaction temperature, (10 or 50 Hz) interaction speed, and 60 minutes interaction time as compared to the neat asphalt binder. It is notably seen that the N_f values increased significantly as compared to the value of the neat asphalt binder. For the CRMA binder, the percentage increase in the N_f values ranges from 50 to 470%. For the UMO–CRMA binders, the percentage increase in the N_f values ranges from 430 to 786%. This illustrates that the CRM particles' polymeric components released in the matrix of the asphalt binder and the low-molecular-weight fractions in the UMO enhanced the asphalt binder's resistance to fatigue cracking. Additionally, the highest percentage increase in the N_f values obtained for modified asphalt binders mixed at (190-50-60) interaction parameters. These interaction parameters have the ability to form polymeric network structures that enhanced the asphalt binder's resistance to fatigue cracking.

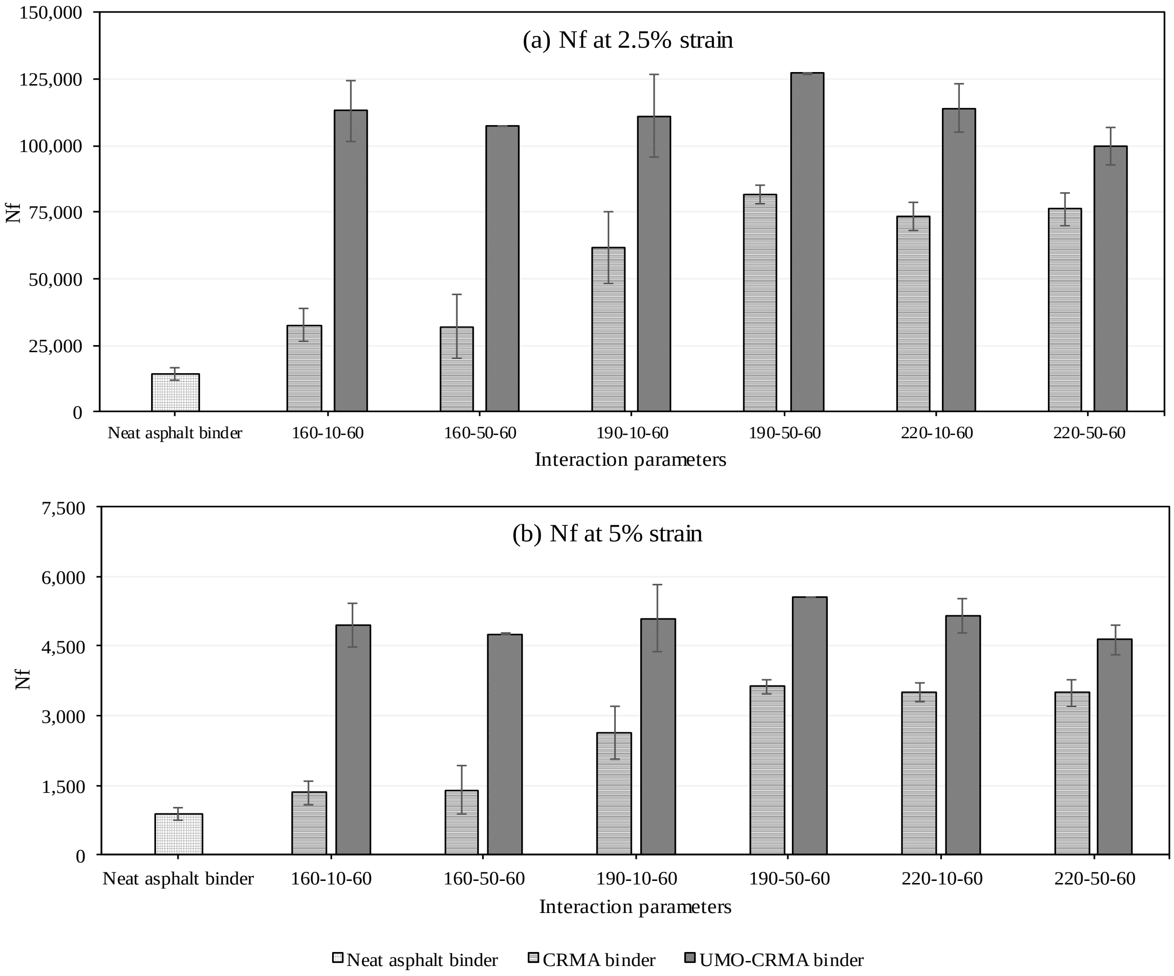

Fig. 3. LAS test results measured at 25°C for neat and modified asphalt binders mixed at (160, 190, or 220°C) interaction temperature, (10 or 50 Hz) interaction speed, and 60 minutes interaction time.

Table- IV: Percentage increase in N_f values for the modified asphalt binders.

	Percentage increase in N_f			
	CRMA		UMO-CRMA	
Interaction parameters	2.5% strain	5% strain	2.5% strain	5% strain
(160–10–60)	125.92	49.48	688.21	456.64
(160–50–60)	123	56.77	648.37	433.64
(190–10–60)	328.87	195.2	674.51	471.42
(190–50–60)	469.62	308	785.59	523.53
(220–10–60)	411.16	293.58	694.5	479.41
(220–50–60)	430.59	291.46	594.44	420.43

C. The Role of UMO to Balance the CRMA Binders' Performance at High and Low PG Temperatures

Deef-Allah et al. [1] investigated the effect of CRM and UMO on resisting the rutting and thermal cracking. This had been occurred using different methods. In this section, one of these methods is discussed. Fig. 4 shows the high and low PG temperatures for the neat PG64-22 asphalt binder modified by 10% CRM with or without 2.5% UMO. Adding CRM to the asphalt binder changed its high PG temperature from 64 to 76°C. This happened due to the release of the CRM particles' polymeric components in the asphalt binder's matrix, which increased the asphalt binder's stiffness and elasticity. The UMO decreased the high PG temperature for the CRMA binder from 76 to 70°C since UMO acts as a lubricant between the CRM particles. This reflects more resistance to rutting for modified asphalt binders as compared to the neat asphalt binder. However, the low PG temperature did not change [1].

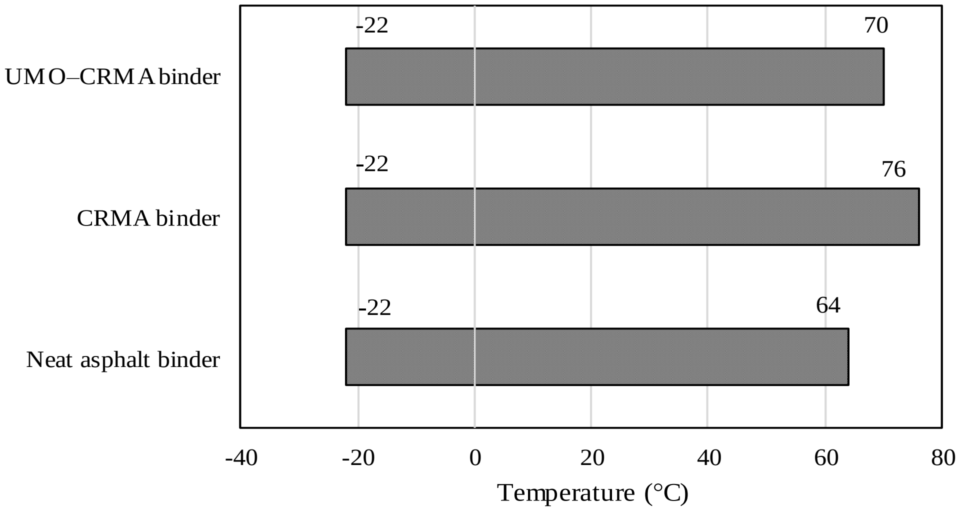

Fig. 4. High and low PG temperatures for the neat PG64-22 asphalt binder modified by 10% CRM with or without 2.5% UMO, mixed at 190°C interaction temperature, 50 Hz interaction speed, and 62 minutes interaction time [1].

Fig. 5 shows high and low PG temperatures for the neat PG52-28 asphalt binder modified by 15% CRM with or without 2.5% UMO. Adding CRM to this type of asphalt binder shifted its high PG temperature from 52 to 70°C, which presented more resistance to rutting. Furthermore, introducing UMO to the CRMA changed its high PG temperature from 70 to 64°C. On the other hand, UMO succeeded to change the CRMA binder's low PG temperature from -28 to -34°C [1]. Therefore, not only the modifiers type and interaction conditions but also the asphalt binder's type has a significant effect on the performance of the modified binder. Due to the stiffness nature of the CRM particles, a deterioration in the performance of the modified binder at the low temperatures could happen. Hence, the role of UMO is to make a balance between the high and low PG temperatures for the CRMA binder.

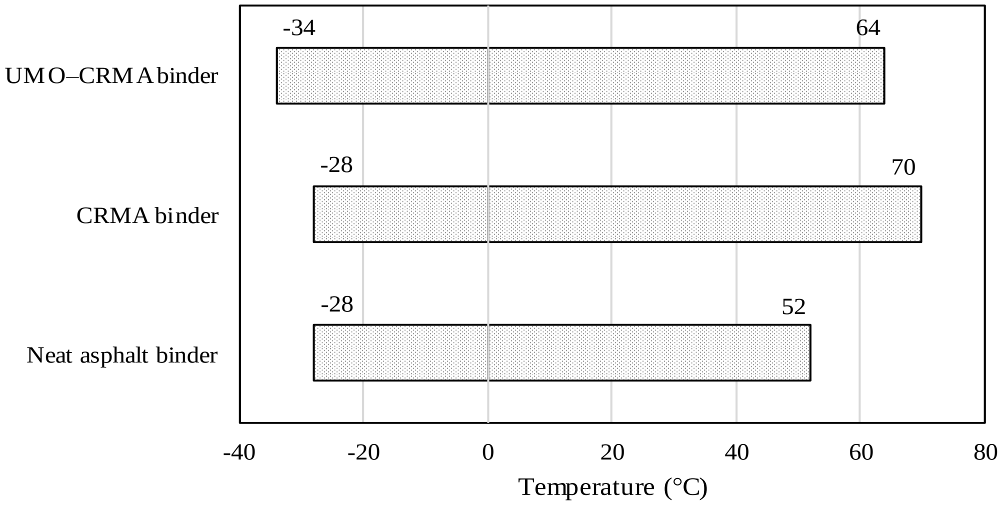

Fig. 5. High and low PG temperatures for the neat PG52-28 asphalt binder modified by 15% CRM with or without 2.5% UMO, mixed at 170°C interaction temperature, 50 Hz interaction speed, and 75 minutes interaction time [1].

IV. CONCLUSIONS

The modification of asphalt binder with crumb rubber modifier (CRM) and used motor oil (UMO) could enhance the asphalt binder's performance by presenting higher resistance to rutting and fatigue cracking. The used CRM and UMO percentages were 10% and 2.5% by the weight of the neat asphalt binder, respectively. Different interaction parameters were used. The interaction temperature was (160, 190, or 220°C), the interaction speed was (10 or 50 Hz), and the interaction time was 60 minutes. The following points were concluded:

- The rutting resistance enhanced for both crumb rubber modified asphalt (CRMA) and UMO–CRMA binders as compared to the neat asphalt binder.

The CRM polymeric components increased the stiffness and elasticity of the asphalt binder, which increased asphalt binder's rutting resistance. Furthermore, UMO regulated the CRMA binder's stiffness by balancing its performance at the high and low PG temperatures.

- It was found that CRM increased the asphalt binder's resistance to fatigue cracking by increasing the N_f values at 2.5 and 5% strains and decreasing the fatigue cracking parameter ($|G^*|.\sin\delta$). This occurred due to the CRM particles' polymeric components released in the matrix of the asphalt binder.
- Adding 2.5% UMO by the weight of the neat asphalt binder to the CRMA binders increased the fatigue cracking resistance. The UMO increased the asphalt binder's fluidity by compensating it for the low-molecular-weight fractions lost during the short- and long-term aging processes.
- The newly developed rutting-fatigue factor ($F_{\text{Rutting-Fatigue}}$) showed that (190–50–60) interaction parameters can form internal polymeric network structures, which enhanced the resistance to rutting and fatigue cracking.
- The highest resistance to rutting and fatigue cracking was observed for binders mixed at (190–50–60) interaction parameters. Additionally, CRMA or UMO–CRMA binder interacted at (190–50–60) had the lowest coefficient of variation (COV). These interaction parameters form internal polymeric network structures, which increased the asphalt binder's resistance to rutting and fatigue cracking.
- At 220°C interaction temperature, the resistance to rutting and fatigue cracking resistance slightly decreased as compared to samples mixed at 190°C. The high interaction temperature (220°C) may cause devulcanization and depolymerization processes for the CRM particles' polymeric components, which caused a decrease in the rutting and fatigue cracking resistance.
- To summarize, UMO compensated the asphalt binder for the low-molecular-weight fractions lost during the aging processes. Furthermore, UMO could increase the CRMA binder's softness and fluidity. Therefore, UMO succeeded as a rejuvenator to regulate the CRMA binder's performance.

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AUTHORS PROFILE

Eslam Deef-Allah, Ph.D. student. His research interests are focused on asphalt modifications, pavement materials, and highway engineering. He has published 3 publications.

Prof. Magdy Abdelrahman, Ph.D. Missouri Asphalt Pavement Association (MAPA) Endowed Professor. Research, industry and teaching experiences are in the area of infrastructure sustainability with applications in pavement design, materials, and performance. Focus is on the interdisciplinarity aspects of infrastructure sustainability; making civil engineering more fundamental and more scientific. Integrating research into educational programs. National and international recognition. Service in national committees on construction/pavement areas. An expert in asphalt modifications including the use of recycled modifiers in civil/construction applications. He has published more than 100 publications in reputable international journals and conference proceedings