RESEARCH ARTICLE-CIVIL ENGINEERING

Comparative Evaluation of Waste Cooking Oil and Waste Engine Oil Rejuvenated Asphalt Concrete Mixtures

Abdullah Al Mamun[1] · H. I. Al-Abdul Wahhab[2] · M. A. Dalhat[3]

Abstract

In road construction, different types of waste oil have been recommended to overcome the stiffening effect of reclaimed asphalt pavement content. However, the selection of an effective rejuvenator based on a comparative study can lead to using the resources more efficiently. In this study, waste cooking oil and waste engine oil are used to rejuvenate three different percentages (30%, 40%, and 50%) of reclaimed asphalt pavement following the current maximum industrial adaptability. The waste oil rejuvenated mixtures are compared to the fresh mixture, and mixtures rejuvenated with commercial rejuvenator. The moisture sensitivity, indirect tensile strength, and resilient modulus of the various asphalt mixtures are analyzed. Based on the statistical analyses and overall ranking, it is concluded that 7% of waste engine oil performs better till 40% of reclaimed asphalt pavement, whereas 13% of waste cooking oil can be used till 50% of reclaimed asphalt pavement.

Keywords Asphalt binder · Reclaimed asphalt pavement · Rejuvenator · Waste cooking oil · Waste engine oil

1 Introduction

It has been established that the use of reclaimed asphalt pavement (RAP) in asphalt pavement construction leads to saving in material expenses, lower carbon emission, lower required energy consumption, lesser water utilization, etc. [1–3]. However, the use of a higher percentage of RAP ingredient (usually more than 20%) in asphalt pavement becomes challenging due to its increased stiffness. The stiffness of RAP due to aging is the consequence of altered constituent, i.e., asphaltenes-to-maltenes ratio in the asphalt binder [4]. The uncontrolled use of RAP can lead to a stiffer mixture and subsequently ended up in a premature failure [5]. Therefore, the use of RAP in new asphalt pavement requires the rejuvenation of the lost properties. The traditional process of regaining the lost properties is carried out by adding a chem-

ical recycling agent that counteracts the altered constituent of aged asphalt [6]. Chemical additives that blended into the asphalt mixture as rejuvenators are known as recycling agents. The recycling agent in a RAP-incorporated mixture restores the chemical composition of asphalt and provides consistency. Restoration of the lost properties of asphalt by countering the RAP-hardening effect may be achieved using different types of commercial rejuvenators (CRs) [7]. In addition to different CRs, the use of waste materials with similar characteristics was also reported [8].

There are many potential recycling agents that can rejuvenate the RAP, and one of the highly recommended agents is waste oil. Waste oils can be categorized differently according to their constituents and source. Among different types of waste oil, the potential of waste engine oil (WEO) and waste cooking oil (WCO) have been explored by many researchers [9–18]. These studies concluded that WCO and WEO can significantly affect different characteristics of asphalt mixture [19–21]. Other previous studies concluded that a better rejuvenating effect can be attained by providing a significant amount of aromatic fractions or resin [22], and recommended WEO and WCO base on different properties. However, most of these previous studies on WEO and WCO are independent and did not analyze the WEO and WCO comparatively. The only studies that attempted comparative analysis, either conducted their analysis based on self-predetermined reju-

✉ Abdullah Al Mamun
amamun@qu.edu.qa

1 Department of Civil and Architectural Engineering, Qatar University, Doha, Qatar

2 Department of Civil and Environmental Engineering, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

3 Department of Transportation and Traffic Engineering, College of Engineering, Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia
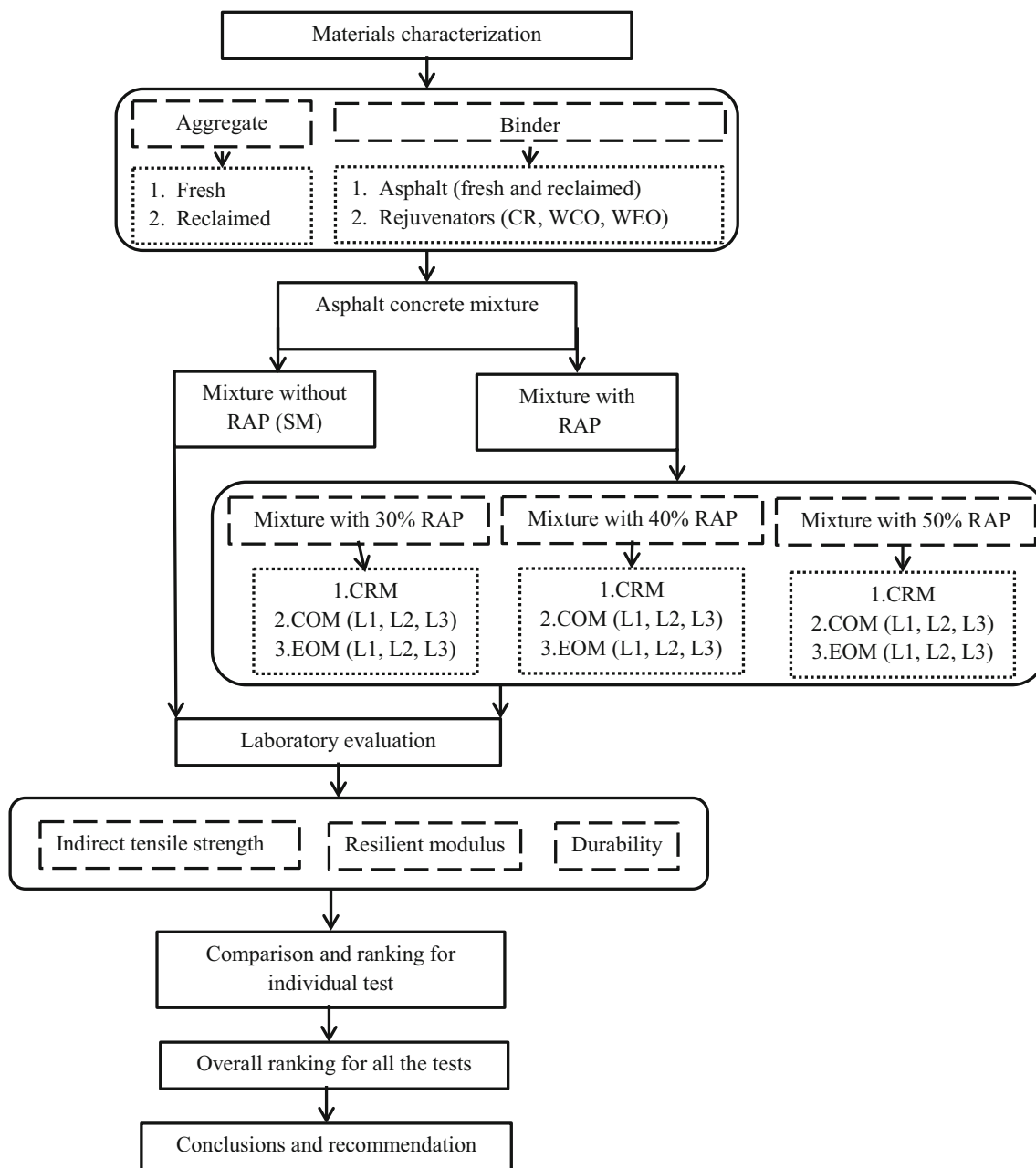
Fig. 1 Experimental design flowchart

venator content instead of the optimum [23], or conducted the analysis of the results independently, with little attention to relative comparison [24].

The selection of effective waste oil as a rejuvenator can lead to efficient use of resources and help towards a more sustainable pavement construction. However, the selection of a waste oil among these oils requires a comparative study of their performance for different properties. Therefore, the main objective of the study is to evaluate and compare different properties of the WCO and WEO rejuvenated asphalt concrete mixtures for high contents of RAP. To comparatively evaluate the effectiveness of RAP incorporated

mixtures, the indirect tensile strength, resilient modulus, and moisture sensitivity of the fresh mixture, and the mixtures rejuvenated by the desired rejuvenators are measured. Based on the comparison, for a certain percentage of RAP, an optimal amount of waste oil is recommended.

2 Experimental Program and Procedures

Some of the major steps followed in the study can be observed in Fig. 1.

The materials collected from different sources are evaluated according to their respective standard tests. This includes characterizations of binder (fresh and extracted asphalt, CR, WCO and WEO) and aggregate (fresh and reclaimed). The optimum binder content of all the mixtures with RAP rejuvenated by any of the rejuvenators (CR, WCO, and WEO) or without any RAP (denoted as SM) was estimated using the Marshall method of mixture design (ASTM-D1559). The RAP incorporated mixtures comprised of three distinct levels of RAP (30%, 40%, and 50%). Here, 50% percent of RAP is selected as a maximum considering industrial limit [25]. Mixture with a certain percentage of RAP comprises three different levels of each waste oil (L1, L2, and L3). Finally, the mixtures are evaluated in the laboratory for three different tests: Indirect Tensile Strength, Resilience Modulus, and Moisture Sensitivity as a function of Retained Strength Index. Based on these evaluated characteristics, the RAP incorporated mixtures were compared to the mixture without any RAP and ranked to find the most effective rejuvenator and its percentage. The details are discussed further in the following sections.

3 Material

All the materials used in the study were collected from the local asphalt plant in Dammam, Saudi Arabia. The RAP is evaluated by the ignition test (ASTM D6307) and is found to have an asphalt level of 5%. Different properties of the binders are presented in Table 1.

The blending chart and viscosity of the binder (asphalt, WCO, WEO, CR) dictate the required amount of the corresponding binder in the mixture. The desired viscosity of the final binder is the viscosity of the fresh asphalt, which is obtained by adding 7%, 13% and 20% of CR, WEO, and WCO, respectively. In addition to that, two other percentages of WCO (13% and 27%) and WEO (7% and 20%) are also introduced. All the applied percentages of WCO and WEO are by the weight of the total reclaimed binder. In Table 2, the obtained properties of aggregate from RAP are subsequent to the solvent extraction method (ASTM D2172).

Table 1 Properties of asphalt and rejuvenator

Property	Specific gravity (g/cc)	Viscosity @60 °C (poise)
Fresh asphalt	1.017	3980
Reclaimed asphalt	–	43,000
WCO	0.917	0.125
WEO	0.872	0.5
CR	0.860	0.3715

Table 2 Specific gravity of aggregate

Specific gravity type (g/cc)	Type of aggregate	Fresh aggregate	RAP
Bulk	Coarse	2.503	2.425
	Fine	2.53	2.575
Apparent	Coarse	2.678	–
	Fine	2.575	–

RAP is enriched in finer aggregate; therefore, previous studies suggested to use a higher amount of coarse portion of RAP for the final gradation of a mixture [26]. Table 3 indicates the final gradation for all the mixtures that follow the specification by the Ministry of Transport in Saudi Arabia. It was obtained by adding a constant gradation of RAP and different percentages of fresh aggregate. The same gradation was also adopted for the mixture without any RAP.

4 Preparation and Evaluation of Specimens

The study comprises four different types of mixtures. All the RAP-incorporated mixtures comprised the corresponding rejuvenator and required amount of binder, fresh aggregate following the percentage of RAP in the mixture. The study follows the Marshall mix design (ASTM-D1559) method in preparing the specimens, and the details are summarized below.

4.1 Mixture Fabrication

The study optimizes the mixture following the Marshall mix design method (ASTMD1559) that optimizes the mixture based on the Marshall criteria. Each of the RAP incorporated mixtures comprises a predefined percentage of the modifier, RAP, fresh asphalt and aggregate. To prepare the mixture, at first the fresh aggregate and asphalt, and the RAP was heated individually for 2 h at 146 °C. The heating period is considered as the standard procedure [27]. At the end of 2 h, the constituents were mixed properly by the mixer, and finally it was compacted by 75 blows on each side. The percentages of CM, WEO, and WCO used in the mixtures were 7%, 13%, and 20% respectively. The optimum asphalt level is subject to change depending on the type of rejuvenator. However, for a certain percentage of RAP in the mixture, the observed insignificant differences in optimum asphalt levels due to different rejuvenators were adjusted by keeping similar asphalt level. The optimum asphalt level for fresh mixture is 6.1%, whereas the value is 5.5%, 5.2%, and 5.0% for 30%, 40%, and 50% of RAP, respectively. All the mixtures followed the specification mentioned in Table 4.

Table 3 Asphalt concretes aggregate gradation

Sieve size	RAP aggregates	Virgin aggregate	Combined	Specification
No. 3/4	100.0	100.0	100.00	100.00
No. 1/2	15.0	72.22	85.83	76.00–92.00
No. 3/8	5.0	40.28	69.58	64.00–79.00
No. 4	0.0	12.50	50.00	41.00–56.00
No. 10	0.0	6.67	32.92	23.00–37.00
No. 40	0.0	4.44	18.33	7.00–20.00
No. 80	0.0	2.22	11.67	5.00–13.00
No. 200	0.0	0.50	6.50	3.00–8.00

Table 4 Specification for Marshall properties

Properties	Specification
Stability (kg)	800 (minimum)
Stability loss (%)	20 (maximum)
Void in mineral aggregate	14 (minimum)
Void filled with asphalt	70–80
Air void (%)	3.0–5.0
Flow (mm)	2.0–4.0

4.2 Laboratory Evaluation

Based on the optimum asphalt level obtained from the Marshall mix design, the specimens are prepared for different tests following the specification and standard. The tests carried out in the study are described below:

4.2.1 Indirect Tensile Strength

The tensile property is an important parameter that plays a significant role to identify the cracking behavior of asphalt pavement. Indirect tensile strength (ITS) is considered as one of the fundamental tests that indicate resistance to different failure types such as intermediate temperature fatigue cracking [28, 29], etc. So, identifying ITS will be an important parameter for waste oil rejuvenated mixtures. The ITS value is measured at a temperature of 25 °C following the ASTM D6931. At the experimental setup, the cylindrical sample (101-mm diameter) experiences uniform tensile stress (51 mm/min) across the diametrical axis tensile force until it fails. The tensile strength at failure point is calculated using the equation below:

$$\text{ITS} = P_{\max}\big/ 3.1416 \times H \times D \tag{1}$$

here, $P_{\max}$ is the maximum applicable load and H and D are the height and diameter of the sample, respectively.

4.2.2 Resilient Modulus

Resilient modulus (M_R) dictates the load-carrying ability and resistance to rutting of the asphalt pavement [30, 31]. Previous studies concluded the change in percentage of recycling agent and RAP in the mixture can regulate the M_R values [32]. So, the test is expected to dictate an important indication for the desired mixture. In this study, the test is conducted on the 25 °C temperature with 0.33 Hz loading frequency based on ASTM D-4123. The M_R of the mixture is measured by simulating the dynamics of the traffic by a computer-based waveform. The simulation is carried out by "Servo-Pneumatic Universal Testing Machine".

4.2.3 Durability

The durability of the asphalt pavement is measured by evaluating the resistance to the adverse effects of the environment [33]. One of the significant environmental factors that jeopardize the performance of the flexible pavement is moisture [34]. Of the numerous numbers of distress that an asphalt pavement experiences during its service life, moisture is regarded as one of the significant factors that subsequently results in the failure of asphalt pavement [35, 36]. The safe performance of a structure for the specified life expectancy depends on increasing durability against water-induced damage. The use of RAP in the mixtures reduces the moisture damage [37], whereas the inverse was also concluded by another study [38, 39]. In this study, the moisture susceptibility (durability) is assessed following the AASHTO T245 method. To analyze the results, the average wet and dry tensile strength of the specimens known as the tensile strength ratio (TSR) is considered.

$$\text{TSR} = \text{ITS}_{\text{wet}}/\text{ITS}_{\text{dry}} \tag{2}$$

Here, ITS_{wet} and ITS_{dry} are the ITS values of the wet and dry samples, respectively, and the recommended minimum value is 80%.

Fig. 2 ITS values of SM, CRM, EOM and COM for various combination of RAP **a** 30%, **b** 40%, and **c** 50%
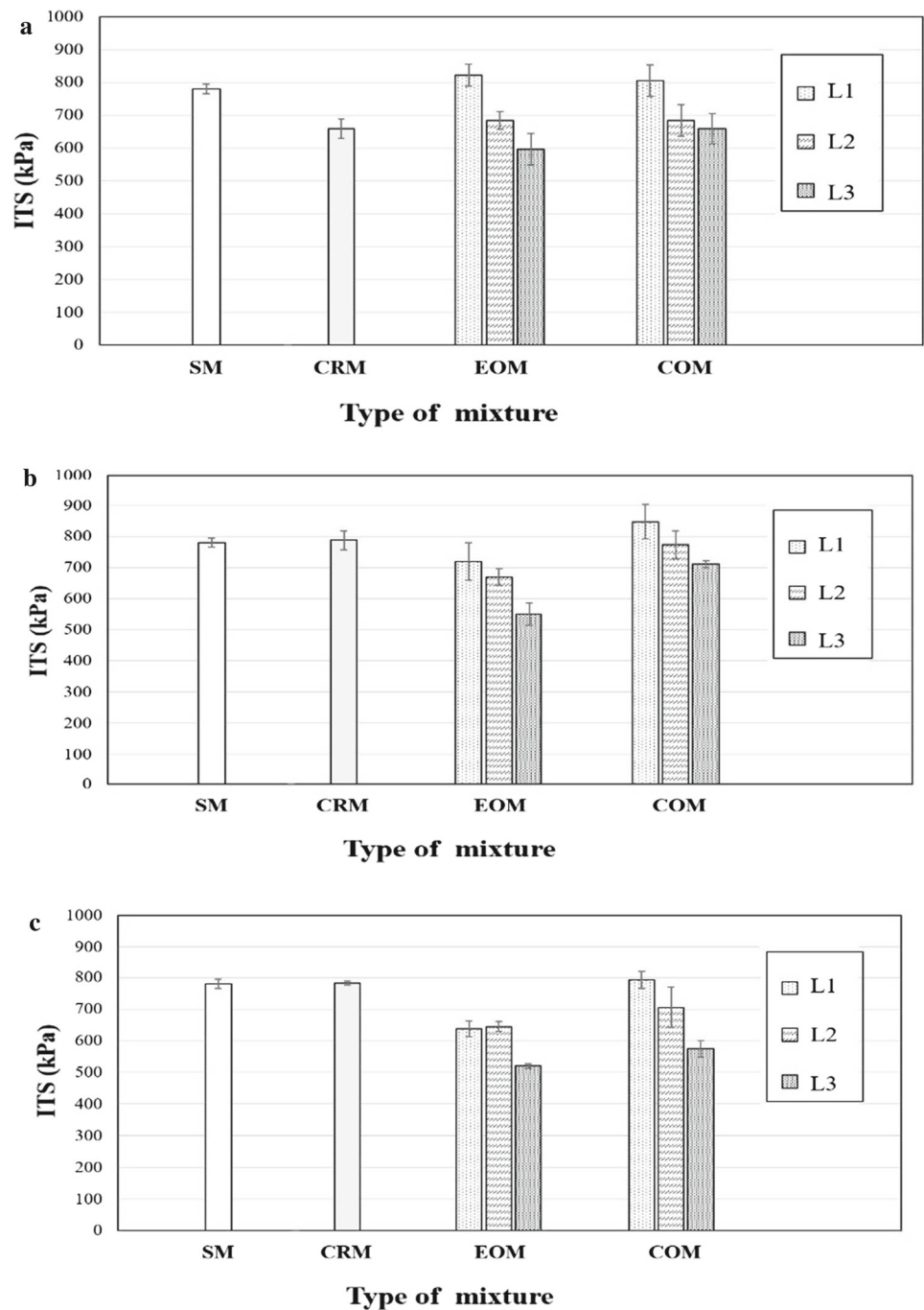

5 Results

The tests mentioned above are carried out to evaluate the effectiveness of different properties of CR, WEO and WCO rejuvenated mixtures and are compared to the mixtures without any RAP denoted as SM. The comparison is discussed in two different sections.

5.1 Graphical Analysis

The effect of percentage rejuvenators for different percentages of RAP is visualized. Here, the mixtures rejuvenated by CR, WEO and WCO are denoted as CRM, EOM, and COM respectively. Three different levels of rejuvenators are denoted as L1, L2, L3, where L1 represents the lowest percentage of the corresponding rejuvenator and L3 indicates the highest percentage of the rejuvenator.

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Fig. 3 M$_R$ values of SM, CRM, EOM, and COM for various combination of RAP **a** 30%, **b** 40%, and **c** 50%
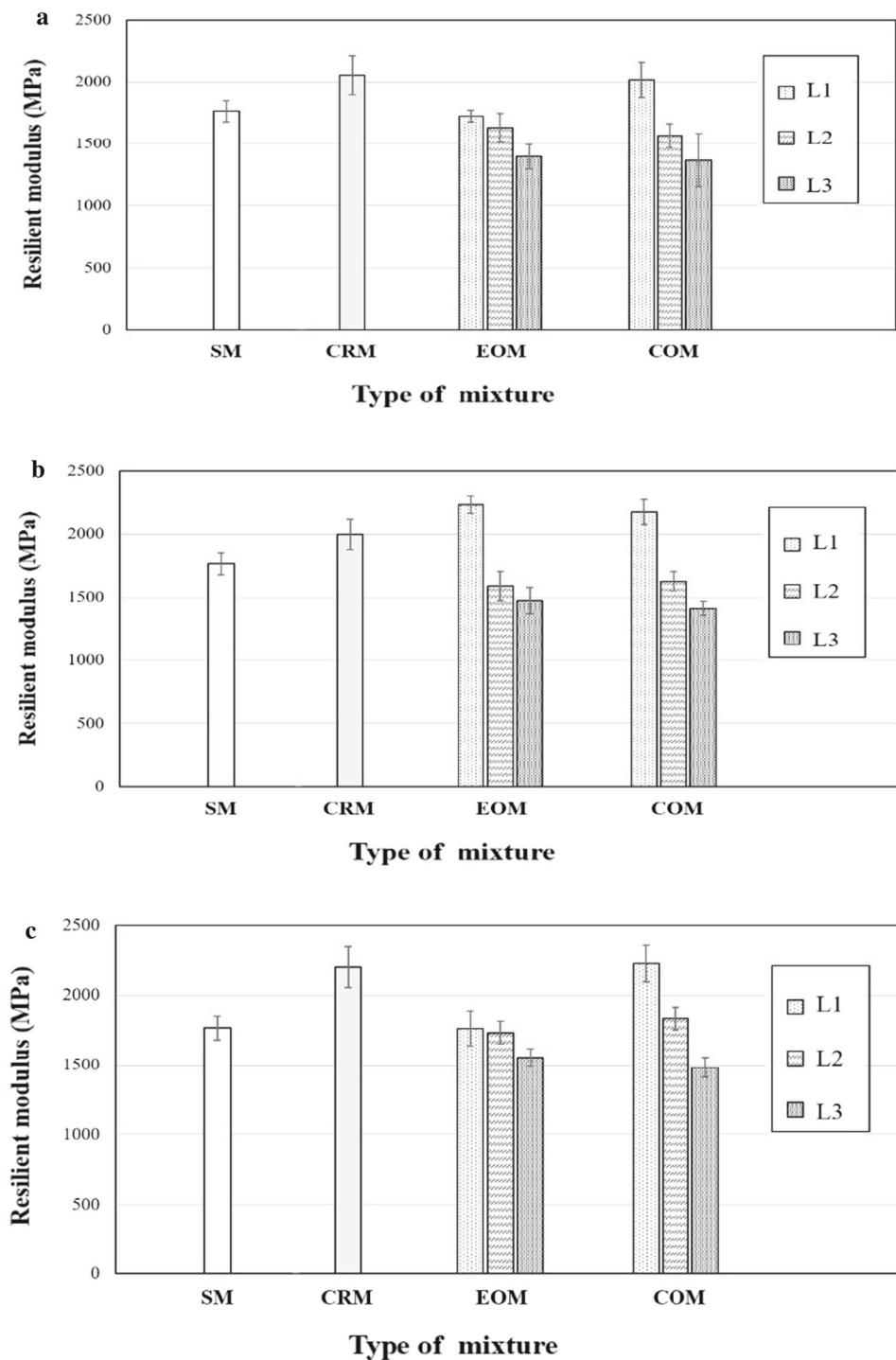

5.1.1 Effect of RAP and Rejuvenator on ITS

Figure 2 depicts the ITS values of EOM and COM mixtures at different rejuvenator levels and are compared to SM and CRM.

The figure shows that the percentage and type of rejuvenator and the percentage of RAP are significantly affecting the ITS values of the mixtures. The increase in the percentage of rejuvenator (L1–L3) for WCO and WEO results in a decrease in ITS value. This usual tendency of decreasing the ITS values is observed for both EOM and COM regardless of the

Fig. 4 TSR values of SM, CRM, EOM, and COM for various combinations of RAP **a** 30%, **b** 40%, and **c** 50%
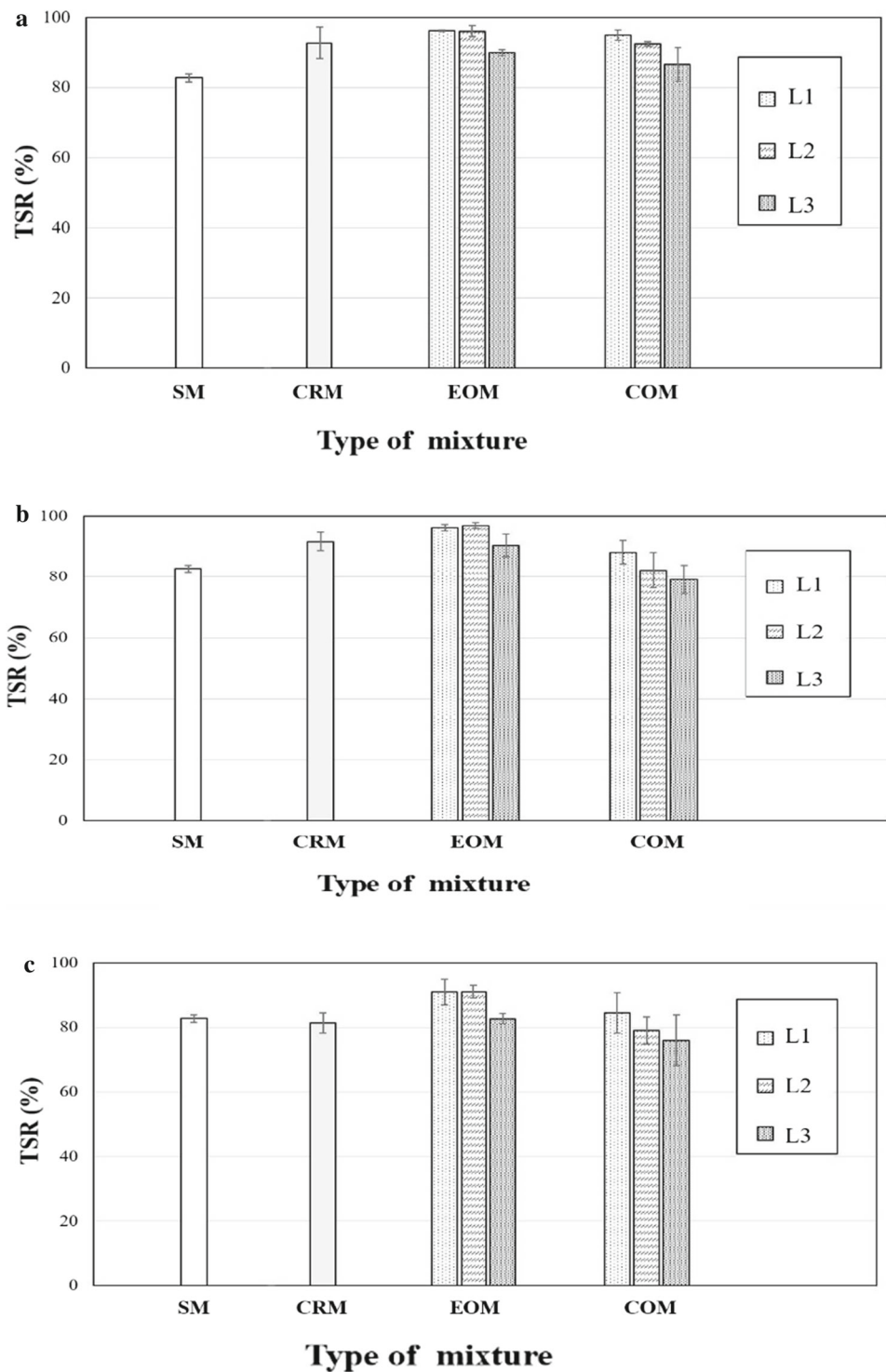
percentage of RAP in the mixtures. The increased percentage of rejuvenators results in a softer binder by decreasing the viscosity and results in a lower adhesion capacity which could lessen the ITS values. In addition to that, the increased percentage of RAP also reduces ITS values. However, the decreasing rate for EOM and COM is different. For any per-

centage of RAP and rejuvenator, COM shows higher ITS values than the corresponding EOM. Incoherent bonding with the fresh ingredients due to increased RAP could lead to a less homogeneous mixture and subsequently resulted in lower ITS.

5.1.2 Effect of RAP and Rejuvenator on M_R

In Fig. 3, the effect of percentages of RAP and rejuvenator on M_R for the CRM, EOM, and COM mixtures are depicted and compared to SM.

The mixture with 40% of RAP and rejuvenated by the L1 percentage of WEO is comparable to the SM and CRM. On the contrary, all the mixtures rejuvenated by L1 and L2 percentages of WCO are comparable to SM and CRM. For any percentage of RAP and rejuvenator, COM shows comparatively higher M_R values than the corresponding EOM. The shift in rejuvenator percentages from L1 to L3 decreases the M_R values. However, the rate of decrease is different for EOM and COM. The increased rejuvenators result in a soft mixture, and consequently, the softening effect of the rejuvenators is expected to decrease the M_R values. The higher percentages of RAP raised the M_R of the mixture due to the stiff nature of the aged RAP. The increased percentage of RAP could lead to a less homogeneous mixture and subsequently resulted in lower M_R values. Overall, the combined increment in rejuvenator and RAP show dual effects: the hardening effect of RAP and the softening effect of rejuvenators.

5.1.3 Effect of RAP and Rejuvenator on TSR

The TSR values of different mixtures can be observed in Fig. 4.

It is observed that the susceptibility to moisture damage increases due to the increased percentages of RAP and rejuvenators in mixtures. For both rejuvenators, the mixtures rejuvenated by L1 and L2 are comparable to those of SM and CRM. However, after 40% of RAP in the mixtures, the L3 level provides a TSR value very close to the permissible limit indicating lower durability due to the increased percentages of rejuvenators in the mixtures. It is expected that lower cohesion and adhesion due to the higher percentages of rejuvenators will increase moisture damage [40]. Similarly, the increased percentages of RAP also reduce TSR values, yet the mixtures passed the criterion of minimum TSR in most of the cases. Although the presence of RAP has increased the durability comparatively, its gradual increment negatively affects the mixtures due to less cohesion with the fresh ingredients and subsequently resulted in lower TSR values.

5.2 Numerical Analysis

The effect of the percentage of rejuvenators, RAP and rejuvenator type is evaluated statistically and is ranked in the subsequent section. COM and EOM are denoted based on their percentage of rejuvenator, i.e., COM-13 specifies the mixture rejuvenated by 13% of WCO.

Table 5 P values obtained by analysis of variances (ANOVA)

Percentage of RAP	ITS	M_R	TSR
Mixture type	0.000	0.081	0.000
Percentage of RAP (mixture type)	0.000	0.005	0.000
Percentage of Rejuvenator (mixture type)	0.000	0.000	0.000

5.2.1 Statistical Evaluation

The effect of the percentage of RAP and rejuvenator and the type of rejuvenator in different types of tests are evaluated using the analysis of variances (ANOVA). The evaluation is based on a marginal P value of .05, indicating that factors with a P value less than .05 are significant. Table 5 indicates that the percentage of RAP and rejuvenation affected all the desired properties significantly.

The type of rejuvenator (WCO/WEO) affects all properties except M_R. The results of ANOVA also show that the WCO and WEO have a different effect on the mixture; however, it cannot be inferred which of them should be prioritized according to their characteristics.

5.2.2 Ranking of EOM and COM

The discussion above indicates the effectiveness of WCO and WEO for different percentages of RAP. However, the rejuvenation capacity of these waste oils is subject to change following the percentages of RAP, rejuvenator percentage and type of test. Therefore, for a certain percentage of RAP, the most effective rejuvenator and corresponding percentage need to be addressed. Here, the mixtures are grouped based on the percentages of RAP (Table 6).

For a certain percentage of RAP, EOM and COM are compared to CRM and SM and ranked according to the obtained properties. The most effective mixture is ranked as 1, whereas the least effective mixture is ranked as 8. For example, for 30% RAP mixture, EOM-7 shows an average ITS value of 822 kPa and outperformed the other mixtures, and therefore it was ranked 1. However, for 30% RAP mixture, EOM-7 shows an average M_R value of 1726 MPa which is less than the observed M_R values of CRM, COM-13, and SM and therefore it was ranked 4. Similarly, the ranking of the mixtures was carried out for 40% and 50% of RAP mixtures. It is to be mentioned that Table 6 indicates the rounded values for the ITS and M_R and up to two digits for the TSR, however, the ranking was carried out based on the actual values. It is observed that the properties of any of the mixtures are subject to change following the test. Therefore, to evaluate the overall effectiveness of any of the mixtures, it needs to be ranked for the observed properties which can be observed in Table 7.

Table 6 Ranking of mixtures for different percentages of RAP

Percent of RAP	Mixture type	ITS (kPa)	Ranking	M_R (MPa)	Ranking	TSR (%)	Ranking
30	SM	780	3	1765	3	82.73	8
	CRM	658	7	2054	1	92.67	4
	EOM-7	822	1	1726	4	96.17	1
	EOM-13	683	4	1629	5	96.00	2
	EOM-20	596	8	1398	7	89.83	6
	COM-13	805	2	2017	2	94.83	3
	COM-20	683	5	1566	6	92.38	5
	COM-27	659	6	1366	8	86.52	7
40	SM	780	3	1765	4	82.73	6
	CRM	787	2	1998	3	91.67	3
	EOM-7	719	5	2231	1	96.83	1
	EOM-13	669	7	1591	6	96.17	2
	EOM-20	551	8	1476	7	90.33	4
	COM-13	848	1	2173	2	88.11	5
	COM-20	773	4	1627	5	82.13	7
	COM-27	710	6	1413	8	79.08	8
50	SM	780	3	1765	4	82.73	4
	CRM	781	2	2198	2	81.33	6
	EOM-7	645	5	1762	5	91.00	2
	EOM-13	638	6	1733	6	91.00	1
	EOM-20	520	8	1555	7	82.67	5
	COM-13	792	1	2227	1	84.46	3
	COM-20	705	4	1833	3	78.94	7
	COM-27	574	7	1482	8	75.97	8

Hence, the overall ranking of the mixtures was carried out by summing the observed ranking for each test. Finally, the mixture with the least summation value was ranked as 1. For example, for 30% RAP mixture, the summation of ranking for the EOM-7 is 6 and the overall ranking is 1. For a certain percentage of RAP, any of the waste oil rejuvenated mixtures ranked as less than SM is considered as an effective mixture. The table indicates that for 30% of RAP, EOM-7 outperforms all the mixtures and the mixtures with 13% of WCO and 13 to 20% of WEO provide better characteristics than SM. Similarly, for 40% of RAP, EOM-7 outperforms all the mixtures, whereas COM-13 provides better characteristics than SM and are comparable to CRM. However, COM-13 outperforms all the mixtures for 50% of RAP and for 50% RAP, the overall characteristics of EOM are less satisfactory than the SM and CRM.

6 Conclusions and Recommendation

The effectiveness of different percentages of RAP and waste oil (WCO and WEO) was evaluated for different types of tests and is compared to SM and CRM. Based on the analysis of observed results, the following conclusions are made:

1. The mixtures with 7% of WEO outperformed all the other mixtures for 30% of RAP mixtures. The mixtures rejuvenated by 13% of WEO and WCO provide better performance than SM and CRM.
2. The mixtures with 7% of WEO provide better performance than all the other mixtures for 40% of RAP. The mixtures rejuvenated by 13% of WCO provide better performance than SM and are comparable to the CR rejuvenated mixtures. The mixtures rejuvenated by 13% of WCO outperformed all the other mixtures for 50% of RAP mixtures.
3. Overall, 7% of WEO can be used until 40% of RAP, whereas 13% of WCO can be used until 50% of RAP. However, an extensive comparison based on advanced performance tests such as fatigue and rutting is also recommended.
4. The constituent of waste oil may affect the phase integrity, new bonding capacity, and crystalline structure of the fresh and aged asphalt. A nanoscale evaluation of

Table 7 Final ranking of the mixtures for different percentages of RAP

Percent of RAP	Mixture type	Summation of ranking	Overall ranking
30	SM	14	5
	CRM	12	4
	EOM-7	6	1
	EOM-13	11	3
	EOM-20	21	7–8
	COM-13	7	2
	COM-20	16	6
	COM-27	21	7–8
40	SM	13	4
	CRM	8	2–3
	EOM-7	7	1
	EOM-13	15	5
	EOM-20	19	7
	COM-13	8	2–3
	COM-20	16	6
	COM-27	22	8
50	SM	11	3
	CRM	10	2
	EOM-7	12	4
	EOM-13	13	5
	EOM-20	20	7
	COM-13	5	1
	COM-20	14	6
	COM-27	23	8

these factors can provide more insight into the waste oil rejuvenated asphalt binder. In addition to that, a thorough economic analysis is required before applying waste oil rejuvenated asphalt in the industry; therefore, a Life Cycle Cost Analysis (LCCA) of aged asphalt rejuvenated by WCO and WEO is recommended.

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