KPU International Journal of Engineering & Technology
Volume 3, Issue1, Sep. 2023
e-ISSN:2790-0819, p-ISSN:2790-0800
Date Received: 2023-04-16
Date Accepted: 2023-09-02
Date Published: 2023-09-15

Evaluation of Asphalt Mixtures Containing Rejuvenated Reclaimed Asphalt Pavement

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Abstract

Reclaimed asphalt pavement (RAP), which is produced from the milling of old asphalt pavement, is one of the most widely recycled materials in the world. The use of reclaimed asphalt pavement (RAP) in freshly hot mixed asphalt (HMA) can save on material costs, preserve energy, and protect the environment. Asphalt mixtures that contain a lower amount of RAP can result in a similar performance to conventional mixtures. However, the use of a high percentage of RAP in hot mix asphalt (HMA) mixtures is limited due to the effect that it has on fatigue and low temperature properties of the mixture. To overcome the adverse effect of the RAP, it is sometimes necessary to rejuvenate the aged binder. This study has the objective of exploring the effect of two commercially available asphalt rejuvenators on the mechanical properties of RAP modified HMA mixture. Six different types of asphalt mixtures, including control mixture, RAP-modified mixture, and rejuvenated RAP mixtures were prepared. The mechanical properties of the mixtures were determined by the Marshall tests. The results of the study indicated that the properties of RAP mixtures were mainly affected by the rejuvenator percentage while the type of rejuvenator statistically has no significant effect. The Marshall test results also indicated that, the addition of 6% soybean and 3% sunflower to the 40% RAP mixture has similar properties values as the control mixture. According to the results of the indirect tensile strength test, it was found that the RAP mixtures with 3% rejuvenator has higher moisture resistance as compared to the 6% rejuvenator. In addition, the sunflower rejuvenator had more pronounced effect on the asphalt mixture properties than that of soybean rejuvenator.

Keywords: Reclaimed Asphalt Pavement, Asphalt binder rejuvenator, Vegetable-oils, Marshall tests.

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1. Introduction

1.1 Study Background

Over the past few decades, asphalt pavement has been widely used around the world due to its better performance, and comfortable driving conditions. As asphalt pavement is subjected to loads and environmental conditions, it loses its strength and deteriorates. It is common practice in asphalt pavement maintenance to mill part of the top layer and replace it with new one. Once these deteriorated parts of the pavements are milled, crushed and removed, they are called reclaimed asphalt pavement (RAP). It is reported that each year, millions of tons of asphalt pavement are milled globally from the road surfaces after being exposed to the long-term effects of climate change and increased traffic loads [1 – 4]. In Europe alone, more than 50 million tons of old asphalt pavement are milled annually [5]. In the USA, the Federal Highway Administration (FHWA) reported that 45 million tons of RAP are produced annually, most of which are dumped in landfills [6]. As a result of the excessive amount of old asphalt pavement being disposed in landfills, the need to increase the use of RAP in the hot mix asphalt (HMA) mixture has continued [7-8]. Besides diverting tons of waste asphalt pavement from landfills, it has been proven that the use of RAP saves on construction materials, and provides significant environmental benefits. Because of these substantial economic and environmental benefits, many countries started the use of RAP in the production of new asphalt mixtures [9-13]. In the United States, it was reported that 66.7 million tons of RAP were used in pavement construction in 2011[14]. Furthermore, according to the European Asphalt Pavement Association (EAPA), 47% of the produced RAP is used in asphalt applications in Europe each year [15].

1.2 The Use of RAP in Afghanistan

RAP is now recycled to a great extent in many countries as a component of HMA asphalt mixtures, however, it is still not frequently used in Afghanistan. After two decades of war when the Islamic Emirate of Afghanistan retook control of Afghanistan in 2021, the government focus more on the rebuilding the existing highways in this country. It is reported that millions of tons of old asphalt pavement are milled annually from the road surfaces in Afghanistan, most of which ends up in landfills. As a result, efforts have been made in this study to assess the feasibility of utilizing a high percentage of old asphalt materials in the production of new hot mix asphalt (HMA). This may result in increased raw material conservation as well as reduction of overburden pressure on landfills and aggregate quarries.

1.3 Problem Statement

It has been demonstrated from the previous researches that RAP collected from old road surfaces still contain valuable materials, including recycled aggregates and a recycled binder, which are materials that can be utilized to create fresh HMA mixtures. However, due to the significant impact that RAP material has on the stiffness of the mixture as a whole, the use of a high percentage of RAP in the production of fresh HMA is restricted

because of the increased stiffness, it is sometimes necessary to modify or rejuvenate the aged asphalt binder. Using a modifier to rejuvenate aged asphalt binder may be an option for incorporating high RAP into the fresh HMA mixture [16]. An aged binder rejuvenation is designed to provide a mix capable of resisting fatigue cracking while maintaining permanent deformation resistance [17-21]. Various manufacturers propose different types of rejuvenating agents to rejuvenate aged binder in asphalt mixtures. Among the many rejuvenators available, waste engines and cooking oils are the most commonly used rejuvenators. In contrast, waste oils have been reported with high viscosity and high moisture content, leading to decreased asphalt mixture moisture resistance [22-23]. On the other hand, bio-based vegetable oil is another potential source for rejuvenating aged binders [24]. According to [25-26] the use of a vegetable oil to rejuvenate RAP aged binders can reduce fatigue cracking susceptibilities. Rejuvenators can improve aged binder properties such as binder's brittleness; however, if not used in a proper amount, it can have an adverse effect on the mixture performance. Thus, it is important to emphasize that for a given amount of RAP, the rejuvenator rate should be selected in the optimum percentages to create a mix that is highly resistant to fatigue cracking while maintaining an adequate level of permanent deformation.

1.4 Study Objectives

In order to achieve a mixture with properties similar to those of new paving materials, the RAP recovered binder should be rejuvenated [10]. There have been several types of rejuvenators developed for the asphalt recycling industry so far, most of which have an oily base due to the issue that the RAP recovered binder lacks the oily components of the old asphalt pavement binder over the service life [27]. Rejuvenators can improve RAP recovered binder properties such as binder's binding and adhesion properties. However, if these rejuvenators are not used in a proper amount, they can have an adverse effect on the mixture properties. Thus, the primary objective of the study was to determine and compare the effect of two vegetable-based rejuvenators on the properties of HMA using the Marshall practice in asphalt pavement maintenance and rehabilitation.

2. Experimental Program

2.1 Materials

A brief overview of the materials used in this study is given in the following subsections.

2.1.1 Neat Binder

The 60/70 penetration graded asphalt cement was selected because it is the asphalt grade that is used in most temperature zoning of the country. The neat asphalt binder properties tests included specific gravity test as per [28], binder penetration test as per [29], softening point temperature test as per [30], and rotational viscosity test as per [31]. A summary of the neat asphalt binder physical properties that have been determined from laboratory testing is provided in Table1.

Table 1. Neat asphalt binder physical properties

Test	***Testing methods***	***Test results***
Specific gravity @ 25ºC	*ASTM D70*	1.030
Penetration value (0.1mm) @ 25ºC	*ASTM D5*	64
Softening point (ºC)	*ASTM D36*	45
Rotational viscosity unaged binder at (135ºC) mPa·s	*AASHTO T316*	494
Rotational viscosity unaged binder at (165ºC) mPa·s	*AASHTO T316*	123

2.1.2 Reclaimed Asphalt Pavement

Reclaimed asphalt pavement (RAP) was extracted by the recovering method using trichloroethylene following [32]. During the extraction process, a centrifuge extractor machine with a capacity of 1500 g was used on each representative RAP sample, and the recovered binder for each binder sample was separately stored. Then the recovered binder was subjected to typical standard laboratory tests to determine its physical properties. A summary of the recovered asphalt binder physical properties is shown in Table 2.

Table 2. Recovered RAP binder properties test results and the associated test methods

Test	***Testing method***	***Test results***
Specific gravity @ 25ºC	*ASTM D70*	1.054
Penetration value (0.1mm) @ 25ºC	*ASTM D5*	40.5
Softening point (ºC)	*ASTM D36*	58
Rotational viscosity of aged binder at (135ºC) mPa-s	*AASHTO T316*	1265
Rotational viscosity of aged binder at (165ºC) mPa-s	*AASHTO T316*	342

2.1.3 Rejuvenated Binders

Rejuvenating the recovered RAP binder is intended to restore its physical properties to those of an unaged binder. Two types of rejuvenator agents, namely soybean oil (SOY) and sunflower oil (SnF), were mixed with the RAP recovered binder. Table 3 presents the physical properties of the rejuvenators that are determined after conducting the laboratory tests. The percentage of rejuvenator that are used depends on the desired properties of the binder mix. The rejuvenators were then mixed with the recovered binder at proportions of 3 and 6% (by weight of recovered RAP binder) using a shear force mixer.

Table 3. SOY and SnF rejuvenator physical properties

Properties	***Rejuvenators***	
	SOY	*SnF*
Rotational viscosity @ 25ºC (Pa.S), AASHTO T-316	0.063	0.0608
Specific gravity @ 25ºC, ASTM D70	0.9798	0.9171
Flash point (ºC) ASTM D93	255	275

2.1.4 RAP Binder Content and Aggregate Gradation

First the binder content was determined from the RAP materials. Second aggregate gradation was determined. The residual aggregates were then washed, dried for sieve analysis. Sieve analysis following the [33] was conducted on the residual aggregates as shown in Table 4. The findings after the sieve analysis were tabulated and presented in Table 5.

Table 4. Extraction test results of RAP materials

Wt. of mix	*gm*	1862.0
Wt. Of filter before test	*gm*	20
Wt. Of filter after test	*gm*	21.3
Wt. Of aggregate after test	*gm*	1764.3
Total Wt. of aggregate	*gm*	1765.6
Loss of Wt.	*gm*	96.4
Asphalt % by Wt. of aggregate	*%*	5.46
Asphalt % by Wt. of mix	*%*	5.17

Table 5. Aggregate gradation for the collected RAP

Sieve No	***Retained (%)***	***Passing (%)***
3/4"	0.0	100.0
1/2"	12.2	87.8
3/8"	20.7	79.3
# 4	42.8	57.2
# 10	57.8	42.2
# 40	78.8	21.2
# 80	87.2	12.8

# 200	88.6	11.4

2.1.5 Virgin Aggregate Gradation

In this study, a typical aggregate gradation that is commonly used in producing HMA for the primary highways for asphaltic concrete wearing coarse is selected. To ensure that the aggregate gradation was the same for each mixture, the aggregate was separated into various sized fractions. Table 6 presents the aggregate gradation with the specification limits designated by Marshall method. The selected aggregate properties were then determined in the laboratory in accordance with the application of ASTM standards as shown in Table 7. These properties are used for calculating the mixture volumetric properties.

Table 6. Typical aggregate gradation for asphaltic concrete wearing course

Sieve size	***Retained (%)***	***Passing (%)***	***Specification Limits (Marshall)***
3/4"	0.0	100	100
1/2"	10.3	89.7	75-90
3/8"	22.9	77.1	64-79
# 4	45.2	54.8	41-56
# 10	67.1	32.9	23-37
# 40	81.67	18.33	7-20
# 80	88.2	11.8	5-13
# 200	94.8	5.2	3-8

Table 7. Physical properties of virgin aggregates for asphaltic concrete wearing course

Test	***Specification***	***Coarse Aggregate Results***	***Fine aggregate Results***	***Specifications Limits***
Los Angeles abrasion test (%)	*ASTM C131*	29.5%		*40%. Max*
Angularity (%)	*ASTM D5821*	96%		*90%.Min*
Flat and elongated particles ratio (%)	*ASTM D4791*	2.4%		*(5:1 ratio) 10%. Max*
Bulk specific gravity	*ASTM C127*	2.540		-
Apparent specific gravity		2.653		-

Sand equivalent (%)	*ASTM D2419*		62%	*40%.Min*
Bulk specific gravity	*ASTM C128*		2.52	-
Apparent specific gravity			2.61	-

As shown in Table 8, the combined gradations of asphalt mixture aggregates are presented. Since RAP aggregates are somewhat finer than the virgin aggregates, it is required to determine the proportion of each aggregate percentage to satisfy the desired aggregate gradation. Percentage of both virgin and RAP aggregate must be determined to meet the final gradation of the mixture and satisfy the specified volumetric properties. The combined aggregate gradation is shown in Figure 1.

Table 8. The combined aggregate gradation for asphaltic concrete wearing course

Sieve size	***RAP Aggregate Passing (40%)***	***Virgin Aggregate Passing (60%)***	***Combined Grading (%)***	***Specification Limits (Marshall) (%)***
3/4"	100.0	100	100.0	*100*
1/2"	87.8	89.7	88.9	*75-90*
3/8"	79.3	77.1	77.9	*64-79*
# 4	57.2	54.8	55.7	*41-56*
# 10	42.2	32.9	36.6	*23-37*
# 40	21.2	18.3	19.4	*7-20*
# 80	12.8	11.8	12.1	*5-13*
# 200	11.4	5.2	7.6	*3-8*

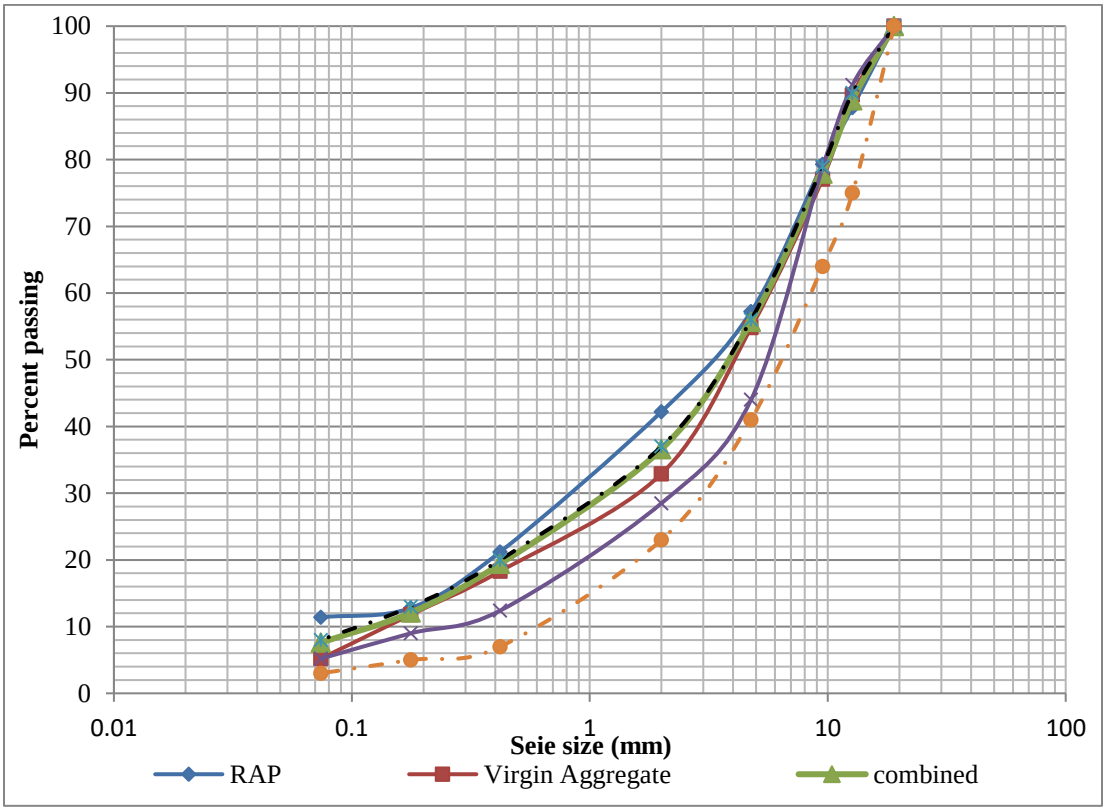


Figure 1. Aggregate gradation blending curves

2.2 Test Methods

In this study, the Marshall method of asphalt mix design accordance with the [34] was used to produce mixture specimens containing control, RAP and rejuvenated RAP mixtures. For the production of specimen, aggregates are heated for 16 hours at 170ºC and binder was heated for 1 hour at 150ºC. The heated aggregate was placed in a mixing bowl preheated to the same temperature as the aggregate; then the bowl was placed on a balance where the appropriate amount of binder was added. The binder was spread into the aggregate with a preheated spoon and then mixed with an electrical mixer. The binder and the aggregate were mixed for about three minutes to produce a mixture with a consistent binder distribution throughout. The mixtures were compacted using 75 impacts of the Marshall compactors, which is designed to handle heavy traffic.

2.2.1 Volumetric Properties

Measuring the volumetric properties of HMA mixture specimen is essential to make sure that the required criteria can be meet. Following [35 - 36], maximum and bulk theoretical densities of the HMA mixture specimens were determined. The air void content, the mineral aggregate voids, and voids in fine aggregates were calculated using the following equations.

$$V_a = \left\{\frac{G_{mm}-G_{mb}}{G_{mm}}\right\} * 100 \quad \text{(Eq. 1)}$$

$$VMA = 100 - \left\{\frac{G_{mb}*P_s}{G_{sb}}\right\} \quad \text{(Eq. 2)}$$

$$VFA = \frac{100\,(VMA-V_a)}{VMA} \quad \text{(Eq. 3)}$$

Where, V_a is the percentage of air voids (%), VMA is the void percentage in mineral aggregates (%) VFA is the void percentage in fine aggregates (%), P_s is the percentage of aggregates in the mixtures, G_{mm} is the maximum theoretical density, G_{mb} is the bulk density of the mixture, G_{sb} is the bulk density of the aggregates.

2.2.2 Marshall Stability and Flow

The Marshall testing apparatus was used to conduct the Marshall stability and flow tests, which were used as parameters for designing the asphalt mixture. As part of the Marshall stability test, the specimen is loaded to failure with a 50 mm/min speed. The required load to produce failure is defined as Marshall stability, while the specimen vertical deformation throughout the test till failure is defined as the Marshall flow. Besides the Marshall test, the asphalt mixture specimens were tested for Indirect Tensile Strength (ITS).

2.2.3 Indirect Tensile Strength (ITS)

The tensile strength test of HMA mixtures plays an important role in identifying the asphalt pavement cracking behavior. ITS is undertaken as a potential testing technique when evaluating the fatigue cracking resistance of asphalt mixtures [12]. The ITS test in this study was conducted at 25ºC as per [37]. Following the fabrication of the mixtures, cylindrical specimens were made with both rejuvenated RAP and non-rejuvenated RAP binder contents. Then, using the Marshall set up, the HMA mixture specimens were loaded along their diameter at a constant rate of deformation of 50 mm/min until they break. Using equation 4, the data achieved from the test can be used to determine the indirect tensile stresses.

$$S_t = \frac{2000P}{\pi tD} \quad \text{(Eq. 4)}$$

where, S_t = Indirect tensile strength (ITS), (kPa), P = The load required for breaking the specimen (in Newton), t = Thickness of the specimen (mm) and D = Diameter of specimen (mm)

2.2.4 Moisture Resistance

Moisture resistance to asphalt pavements is considered to be one of the most significant environmental factors influencing pavement failure [38]. Additionally, earlier researches have shown that adding RAP in the production of HMA mixture causes the mixture

specimen to become more susceptible to moisture resistance, whereas the addition of a small amount of a rejuvenator can enhance moisture resistance [39].
As part of this study, moisture susceptibility was assessed using the [40] method. The test as shown in Figure 2 was carried out on six cylindrical specimens having a diameter of 100 ± 2 mm with a thickness of 65 ± 1.5 mm. These specimens were split into dry and wet subsets. During the saturating process, it is necessary for the dry subsets to be saturated at 25°C in the oven for two hours. Subset of wet specimens are first vacuum saturated to 70-80% saturation, and then conditioned in a water bath for 24 hours. Once the specimens have been removed from the water bath, they are saturated at 25˚C for two hours before being tested for ITS. Finally, the ITS test was conducted at a temperature of 25ºC and a displacement rate that was kept as 50 mm per min.

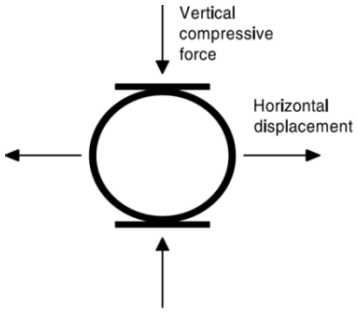


Figure 2. Indirect tensile strength test

Tensile strength ratio (TSR) of saturated (wet) and unsaturated (dry) specimens were then determined using Equation 5.

$$TSR = \frac{ITS_{wet}}{ITS_{Dry}} \quad \text{..... (Eq. 5)}$$

Where: TSR = Tensile strength ratio (%), ITS_{dry} = Indirect tensile strength of dry (unsaturated) samples, ITS_{wet} = Indirect tensile strength of wet (saturated) samples.

In general, it is recommended that the ratio of ITS_{wet}/ITS_{dry} must not fall below 80% [41].

2.2.5 Statistical Analysis

The statistical analysis consists of the effect rejuvenators on the properties of the RAP modified HMA mixture. In interpreting the data, it was assumed that the effect of the rejuvenators on the properties of rejuvenated RAP mixture would depend primarily on two variables namely rejuvenator type and rejuvenator percentage. It was also expected that in some cases these variables would strongly interact. For this reason, the experiment was statistically designed so that the data would be interpreted through analysis of the variance (ANOVA).
In ANOVA statistical terms, the null hypothesis (also known as H_0) is a statement that a population parameter's value is equal to a certain claim. A direct test is conducted on the null hypothesis. The hypothesis H_0 must either be rejected or not rejected. Contrary to the

null hypothesis, the alternative hypothesis indicates that a parameter differs in some way from that hypothesis. The null hypothesis is considered rejected if the P-value is very small and the alpha level is less than or equal to 0.05.

Independent Variables (Factors): In this analysis, the independent variables are rejuvenator type and rejuvenator percentage are considered.

Dependent Variables (Response Variables): The response variables evaluated were the Marshall stability, Marshall flow and indirect tensile strength.

3. Results and Discussion

The effect of rejuvenated RAP recovered binder was evaluated by examining the properties of HMA mixtures with rejuvenated RAP recovered binder. In order to determine the properties of HMA mixtures, Marshall mix design and Indirect Tensile Strength (ITS) tests were used. Asphaltic mixtures were tested to determine the optimum binder content that would achieve the required stability, density, and air voids.

3.1 Volumetric Properties

In asphalt mixtures, Va, VMA, VFA, and OBC are the significant factors affecting the performance of asphalt mixtures. Where, Va is the percentage of air voids, VMA is the void percentage in mineral aggregates, VFA is the void percentage in fine aggregates, and OBC is the optimum binder content. In order to meet these requirements, optimal binder content (OBC) is important. As can be shown in Table 9, adding RAP recovered binder increased the optimum binder level for the non-rejuvenated RAP mixture specimens. Possibly, this is due to the increase in the percentage of air voids that resulted from the decrease in workability caused by adding the RAP recovered binder, which has been resulted in the need for more binder to fill the air voids and meet the maximum air void content limit.

Table 9. Asphalt Mixture Properties

Samples	***Stability (kg)***	***flow (mm)***	***air void%***	***VMA %***	***VFA%***	***Optimum binder content %***	***Max. Unit weight (gm/cc)***
Specification Limits / *Mixture Samples*	*750 (min)*	*3.0 – 5.0*	*14 (min)*	*2.0 – 4.0*	*70 – 80*	-	-
Control Mix	1108	4.1	3.90	14.9	71	5.6	2.287
100RAP	1677	3.73	4.20	16.8	78	6.5	2.276
40RAP	1632	3.81	4.15	15.5	74	6	2.271
40RAP3SOY	1644	3.43	3.88	14.88	73.6	5.6	2.276
40RAP6SOY	1596	3.75	3.00	13.86	74.1	5.2	2.273
40RAP3SnF	1527	3.97	3.92	14.22	73.8	5.4	2.269
40RAP6SnF	1488	4.25	3.53	13.12	74.1	5	2.279

Note:

Sample Name	***Mixture type***
Control Mix	*Standard Asphalt Mix*
100RAP	*Mix with 100% RAP materials*
40RAP	*Mix with 40% RAP materials*
40RAP3SOY	*Mix with 40% RAP+3% Soybean oil*
40RAP6SOY	*Mix with 40% RAP+6% Soybean oil*
40RAP3SnF	*Mix with 40% RAP+3% sunflower oil*
40RAP6SnF	*Mix with 40% RAP+6% sunflower oil*

3.2 Marshall Test Results

The Marshall stability test results as shown in Figure 3 indicated that the asphalt mixture specimens comprising RAP asphalt materials have recorded higher stability values than the neat asphalt mixtures. For instance, the asphalt mixture with 40% RAP has a 32% higher Marshall stability rating than the control mixture. The findings given in Figure 3 also shown that the rejuvenated RAP mixtures achieve lesser stability values compared to the non-rejuvenated RAP asphalt mixtures. This is a sign that lubricant level is higher than what is necessary to counteract the hardening brought on by the RAP recovered binder, and as increasing the amount of rejuvenator caused the binder to soften excessively, which decrease its stability. In addition, the asphalt mixture having the SnF rejuvenator resulted in lower Marshall stability as compare to the asphalt mixtures rejuvenated with SOY, which indicating that the SnF rejuvenator has a more softening effect than the SOY rejuvenator.

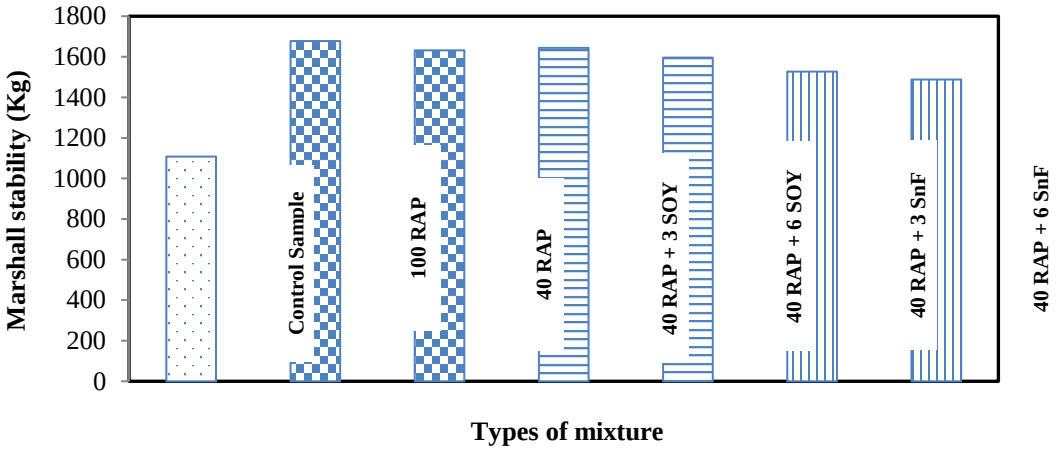


Figure 3. Marshall stability test results of the asphalt mixtures

As presented in Figure 4, the flow value of non-rejuvenated RAP asphalt mixtures increased more as compared to the control asphalt mixture. The increase flow rates were not expected. The reason for this result was that the RAP mixture contained more fines, which followed to the coarse particles. The increase in fines results in more softening and an increase in the flow value.

In addition, rejuvenated RAP mixtures exhibited flow rates within the limits specified by the specification standard. Furthermore, adding the SnF rejuvenator to RAP mixture has resulted in a slight decrease in the flow rate, and this improvement in the flow rate was because of the improved coating of recycled aggregates and the increased workability of the asphalt mixture.

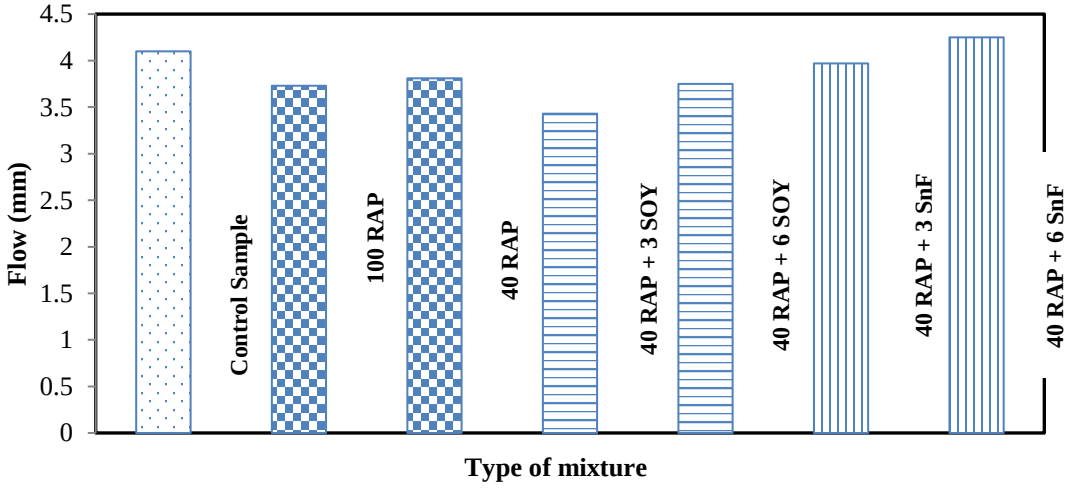


Figure 4. Marshall flow test results of the asphalt mixtures.

3.3 Indirect Tensile Strength Test Results

The observed values of indirect tensile strength (ITS) for control, RAP and rejuvenated RAP mixtures can be found in Figure 5. As shown, the control asphalt mixture exhibited higher ITS values that the RAP asphalt mixtures. For instance, the ITS value of the control mixture was 732 kPa, whereas, it was 535 kPa for 100RAP mixture and 641 for 40RAP mixture.

Furthermore, the rejuvenated RAP asphalt mixtures with 3% rejuvenator shown higher ITS values than the RAP asphalt mixtures, however, for higher rejuvenating content (i.e., 6%), the ITS value was somewhat lower than the asphalt mixture with 3% rejuvenator. This is because of the ITS values dropped as the rejuvenator content increased.

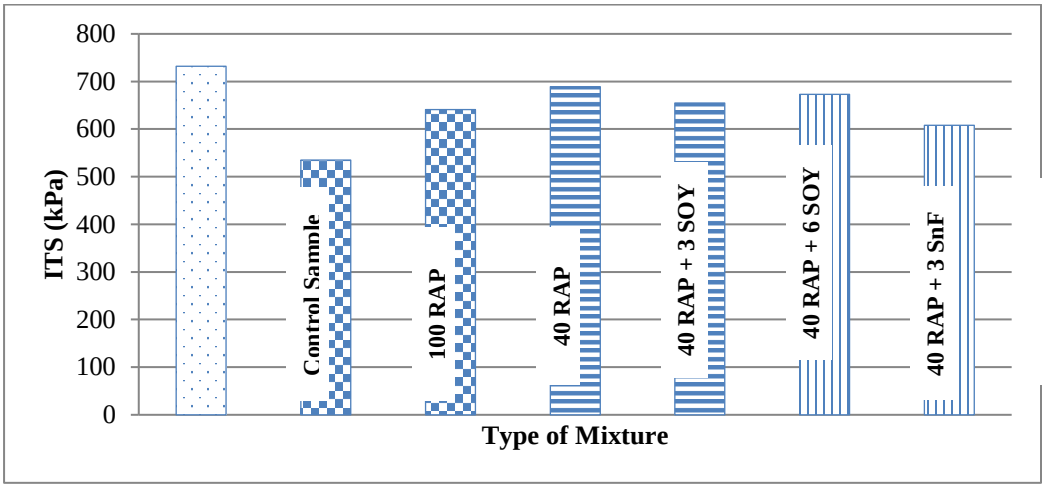


Figure 5. Indirect tensile strength test results of asphalt mixtures

3.4 Moisture Resistance Test Results

The moisture resistance test is performed using the tensile strength ratio (TSR) which is applied to evaluate the effect of rejuvenated RAP on the asphalt mixtures. It should be noted that the increased TSR values leads to better asphalt mixture moisture resistance. The result values of indirect tensile strength test for rejuvenated and non-rejuvenated RAP asphalt mixtures are presented in Figure 6. The indirect tensile strength values of both saturated and unsaturated mixtures increased with rejuvenated RAP asphalt mixtures as compared with non-rejuvenated RAP asphalt mixtures.

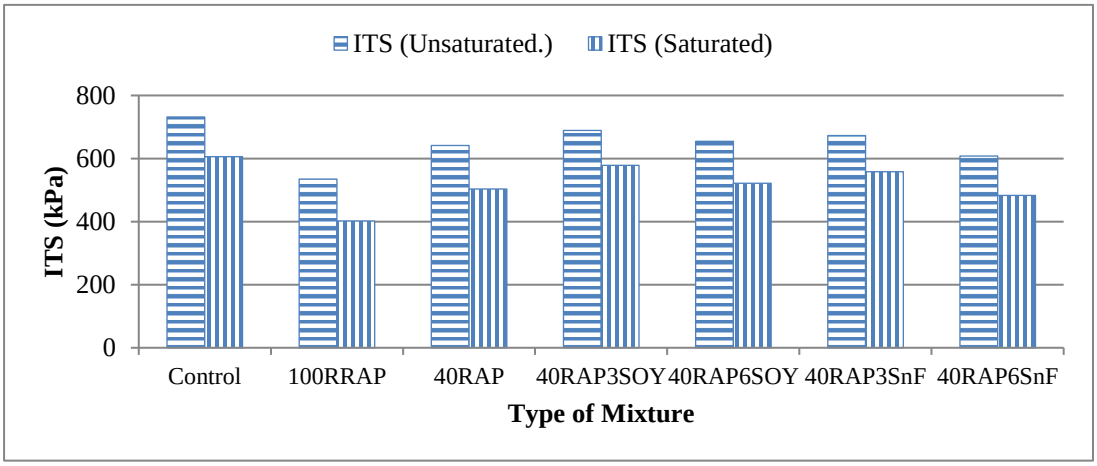


Figure 6. Indirect tensile strength test result of saturated and unsaturated asphalt mixtures

Furthermore, the observed TSR values of RAP mixtures significantly increased when the rejuvenator were added into the mixtures as shown in Figure 7. This indicated that the rejuvenators, improving the adhesion and cohesion bond and had a beneficial effect on tensile strength of asphalt mixtures. Among the different mixtures, highest TSR values were 84% and 83% for asphalt mix having 3% SOY and 3%SnF rejuvenators, respectively. In addition, with increasing rejuvenator percentages the TSR values of asphalt mixtures were reduced indicating lower moisture resistance of the mix with high percentage of rejuvenator.

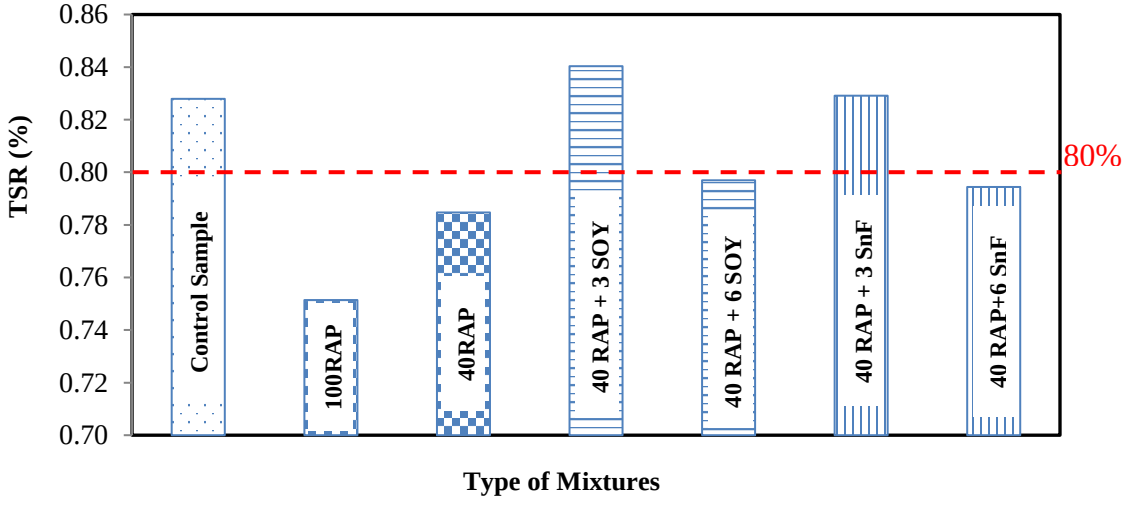


Figure 7. Tensile strength ratio (TSR) result for saturated and unsaturated asphalt mixtures

3.5 Statistical Analysis Results

The effect of rejuvenating agents on the asphalt mixture properties namely (Marshall stability, Marshall flow and indirect tensile strength), were evaluated. A marginal P value of 0.05 was used to base the evaluation, meaning that variables with a P value of less than

0.05 are significant. Based on the stated hypothesis, different observed properties of rejuvenated mixtures were evaluated, including the types and percentages of rejuvenating agents, and their interaction. ANOVA summary as shown in Tables 10, 11 and 12 illustrated that the rejuvenated percentage has statistically significant effect on the given asphalt mixture properties.

Based on the results given in Table 10, it was found that the rejuvenator percentage statistically have significant effect on the Marshall stability values of asphalt mixtures. Whereas, the rejuvenated type and the interaction of rejuvenator type with rejuvenator percentage statistically has no significant effects on the mixture stability value.

Table 10. Statistical analysis (ANOVA) on Marshall stability values of asphalt mixtures

Element	**P-value**	**Status**	**Decision**	**Effect**
Rejuvenator percentage	0.050	$P < 0.05$	Reject H_{01}	Significant
Rejuvenator type	0.14	$P > 0.05$	Do not Reject H_{02}	Insignificant
Percentage of rejuvenator with the type of rejuvenator	0.7	$P > 0.05$	Do not Reject H_{03}	Insignificant

Table 11 provides a summary of the statistical analysis of the asphalt mixtures Marshall flow values. It is shown that the rejuvenator percentage statistically has significant effect on the mixture Marshall flow, while, the rejuvenated type and the interaction of type and percentage of rejuvenator statistically have no significant effect on the mix Marshall flow values.

Table 11. Statistical analysis (ANOVA) on Marshall flow values of asphalt mixtures

Element	**P-value**	**Status**	**Decision**	**Effect**
Rejuvenator percentage	0.030	$P < 0.05$	Reject H_{01}	Significant
Rejuvenator type	0.06	$P > 0.05$	Do not Reject H_{02}	Insignificant
Percentage of rejuvenator with the type of rejuvenator	0.9	$P > 0.05$	Do not Reject H_{03}	Insignificant

The summary of the statistical analysis (ANOVA) of indirect tensile strength (ITS) values is shown in Table 12. The asphalt mixtures ITS values are statistically significantly

influenced by the percentage of rejuvenating agents, whereas, the type of rejuvenating agents and its interaction with the percentage of rejuvenating agents have statistically no significant effect on the ITS value.

Table 12. Statistical analysis (ANOVA) for the ITS values of asphalt mixtures

Element	**P-value**	**Status**	**Decision**	**Effect**
Rejuvenator percentage	0.030	$P < 0.05$	Reject H_{01}	Significant
Rejuvenator type	0.150	$P > 0.05$	Do not Reject H_{02}	Insignificant
Percentage of rejuvenator with the type of rejuvenator	0.4	$P > 0.05$	Do not Reject H_{03}	Insignificant

4. Conclusions

The main purpose of the study was to investigate the effects of rejuvenators on the properties of asphalt mixture containing high percentages of RAP, by using both binder conventional and Marshall mixture methods. Based on laboratory test results and statistical analysis conducted during this study, the general conclusions were reached that the properties of rejuvenated RAP mixtures vary and are mainly depended by the type and percentage of rejuvenators added.

As determined by the Marshall mixture test, it was found that by adding sufficient amounts of rejuvenator, the volumetric properties of RAP mixtures reached the desired level. In addition, the rejuvenator, due to its softening properties, has decreased RAP aged binder's stability. In general, Marshall mix test results shown that the rejuvenated RAP samples met the specification limits provided by the specification for the wearing and binder coarse mixtures.

Indirect tensile strength test showed that the TSR ratio (as indicate moisture susceptibility) increased with the addition of rejuvenator, while, with high percentage of rejuvenator it is reduced. It was also found that the 3% SnF and 6% SOY rejuvenated RAP mixture has nearly similar indirect tensile strength values to the control mixture. Furthermore. The SnF rejuvenator more effectively reduced the stability of the rejuvenated RAP mixture than SOY did.

5. Recommendations for future research

During this study, rejuvenators were tested on the properties of the rejuvenated RAP asphalt mixtures using the local paving mixture method. For further research, the author recommends the following:

- The asphalt mixture properties in this study were limited to the Marshall mix practice. Thus, further studies needed to investigate the effect of rejuvenator on using Superpave requirements for mixtures.

- Field testing should be used to validate the test results of this study.

6. Declare of Competing Interest

The author state that he has no competing financial interests that could have influenced the work reported in this paper.

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