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The tailored traits of reclaimed asphalt pavement incorporating maltene: performance analyses

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ABSTRACT

Environmental issues and fluctuations in the price of asphalt binders have increased the demand in usage of reclaimed asphalt pavement (RAP) material for asphalt mixtures. The RAP binder, nevertheless, is often highly aged and has several drawbacks, for instance, low cracking resistance, low workability, and low fatigue in the resulting mixtures. These issues can be resolved by using rejuvenators. As such, this research work assessed the engineering properties of reclaimed hot-mix asphalt (HMA) mixture rejuvenated by maltene-derived asphalt. The tests examined Marshall properties, moisture damage, resilient modulus (M_R), dynamic creep, Cantabro loss, and rutting resistance, including the stripping and coating tests. The results showed that maltene had been effective in mitigating the aging effect of RAP asphalt, while the rejuvenated mixture exhibited considerable enhancement, especially when compared to the virgin and RAP mixtures without maltene. A simple cost analysis revealed that maltene was cost-effective as it compensated for the adverse effects of RAP, hence can be used to raise the content of RAP in asphalt mixture.

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1. Introduction

Typically, building and conserving road infrastructures demand plenty of finite and natural resources, including aggregates and asphalts (Fernandes *et al*. 2018). Furthermore, asphalt plants cause high level of pollution by emitting greenhouse gases (Pérez-Martínez *et al*. 2014, Fernandes *et al*. 2018). Although aggregates and asphalt from old pavements are still valuable despite reaching the end of their lifecycle (Eskandarsefat *et al*. 2018), huge amounts are disposed into the environment annually (Xiao *et al*. 2010, Behroozikhah *et al*. 2017). Therefore, the mixture of RAP with asphalts has been gaining attention (Singh *et al*. 2017) for the sake of sustainability and reduction in infrastructure cost by reducing the production of new asphalt and aggregates (Zhao and Liu 2018). Besides, RAP used in asphalt pavement substantially decreases the consumption of aggregate and virgin asphalt (VA), thus offering environmental and economic advantages (Debbarma *et al*. 2020). For instance, more fuel can be saved due to lower extraction, processing, and transportation of raw materials, while recycled pavement reduces undesired emissions (Aurangzeb *et al*. 2014, Zaumanis *et al*. 2014, Antunes *et al*. 2019). More importantly, wastage of RAP and massive use of non-renewable resources can be hindered.

Although the use of RAP for new road paving dates back to 1915, its initial success was recorded in 1974 at Texas and Nevada (Adresi *et al*. 2019). Researchers worldwide have been working in this area to maximise the use of RAP to have sustainable and durable pavement structures (Mogawer *et al*. 2016, Singh *et al*. 2018, Daryaee *et al*. 2020). Previous studies reported that adding low percentages of RAP did not influence the attributes of the mixtures (Foroutan Mirhosseini *et al*. 2018, Mirhosseini *et al*. 2019), but increment in viscosity was noted when RAP content exceeded 20% (Roberts *et al*. 1991). To date, many countries allow the use of 15-40% of RAP for mixture designs (Song *et al*. 2018) as inclusion of RAP at a higher percentage may lead to several drawbacks, such as low temperature and fatigue cracking (Mogawer *et al*. 2016, Pasetto and Baldo 2017). The physical properties and the characteristic composition of aged asphalt in RAP differ from the VA, whereby mixtures with high RAP percentage may possess undesired properties, including higher creep stiffness and viscosity, as well as lower penetration and flexibility (Yan *et al*. 2020). Usually, cohesive properties of aged asphalt are lower than those of VA (Nosetti *et al*. 2018). This is due to the natural short and long ageing processes during its service life. Typically, the concentration of polar functional groups in asphalt increases as a results of oxidation and volatilisation processes, which decreases the free movement of the maltenes and increases agglomeration of the asphaltenes (Daryaee *et al*. 2020). The reason is associated with the transformations and changes in the structure of aged asphalt during the lifespan, where light elements alter to heavy elements. (Aromatics constituents → resin constituents, resin constituents → asphaltene constituents, asphaltene constituents → carbenes/carboids) (Speight 2015).

The use of rejuvenating agents or soft asphalt can be the best solution to resolve this issue, apart from rejuvenating the properties of aged asphalt (Moghaddam and Baaj 2016). As such, softer VA may be added into low RAP content, while rejuvenating agents can be incorporated when RAP exceeds 25% to address several issues due to use of soft asphalt (Copeland 2011, Al Saffar *et al*. 2020). Rejuvenating agents have the ability to increase mobility of molecules, balance maltenes and asphaltenes, enhance asphaltenes dispersion in maltenes matrix, and minimise the size of asphaltene clusters (Elkashef *et al*. 2018, Kaseer *et al*. 2019). All of which enhance low temperature performance of aged asphalt (Yan *et al*. 2020), increase ductility, as well as reduce stiffness and viscosity (Ali *et al*. 2016), thus enabling the inclusion of higher percentages of RAP in HMA, without degrading asphalt performance (Ali *et al*. 2016). Numerous studies have discovered a range of rejuvenating and softening agents to be used with RAP, including commercial agents, bio-oils, plant oils, water-derived oils, and refinery-based oils (Zaumanis *et al*. 2013, Zhu *et al*. 2017, Cavalli *et al*. 2018, Kaseer *et al*. 2018, Zhang *et al*. 2018). However, some researchers are reluctant to include rejuvenating agents due to potential rutting damage or ineffective blending between the components (Im *et al*. 2014, Ma *et al*. 2015, Arámbula-Mercado *et al*. 2018, Espinoza-Luque *et al*. 2018, Jahanbakhsh *et al*. 2020).

Based on the concepts aforesaid above, this study aims to use the maltene as a rejuvenator in asphalt mixture containing 40% of RAP. The maltene (composed of resin, aromatics and saturates) was selected due to its several notable characteristics, when compared to other rejuvenators. In addition, the use of maltene as a rejuvenator has not been investigated in great detail. The optimum dose of maltene for renovation of aged asphalt was optimised through the physical and rheological tests. Then, the mechanical performance tests were determined using diverse analytical tools.

2. Objectives

The objective of this study is to investigate the effect of using maltene as a rejuvenator on the performance of HMA containing 40% RAP. To attain this goal, blends containing 40% of VA with 60% of aged asphalt were mixed with an optimum dose of maltene. Next, the mechanical performance of rejuvenated mixtures was investigated and compared with the virgin and aged mixtures via several tests, namely Marshal properties, Indirect tensile strength (ITS) before and after long term ageing, moisture damage, resilient modulus (M_R), dynamic creep, cantabro loss and wheel tracking. Furthermore, water immersion and coating tests were also evaluated. Finally, the cost analysis was conducted to determine the cost of asphalt mixtures with and without maltene, compared with VA.

3. Materials

3.1. RAP materials

The RAP materials were obtained from a stockpile of pavement materials reclaimed at a milling located at the Yong Peng highway in the direction of Pagoh, Malaysia. As a result of cracks, potholes, and other distress, the said six years old pavement was discarded via milling. Next, in order to characterise the aged asphalt, it was separated from RAP sample by dissolving it in trichloroethylene. After discarding all aggregate particles from the binder solution via centrifuge extraction technique in accordance to ASTM D2172 (2017b), the asphalt was retrieved via distillation using a rotary evaporator in adherence to ASTM D5404 (2012).

Later, the recovered asphalt binder (aged asphalt) was characterised through penetration (ASTM D5 2013), softening point (ASTM D36 2014), ductility (ASTM D113 2017a), and viscosity (ASTM D4402 2015) tests. Hard asphalt was obtained with low ductility and penetration, along with high softening point and viscosity (see Table 1). Several laboratory tests were performed to evaluate the quality of RAP aggregates (see Table 2).

Table 1. The characteristics displayed by virgin and aged asphalts. (Table view)

Properties	Virgin asphalt	Aged asphalt	Standard method
Density (gm/cm^3)	1.02	1.03	ASTM D70
Penetration (dmm.) at °C	64	18.5	ASTM D5
Softening Point (°C)	51.5	73	ASTM D36
Ductility (cm)	116	9	ASTM D113
Viscosity @ 135°C (mPa.s)	650	3500	ASTM D4402
Viscosity @ 165°C (mPa.s)	200	700	ASTM D4402

Table 2. Aggregate properties. (Table view)

Aggregate testing	Virgin aggregate	RAP aggregate	Criteria	Standard
SG. coarse	2.863	2.7	-	ASTM C 128
SG. fine	2.781	2.61	-	ASTM C 127
Aggregate impact value (%)	13.37	14.9	< 30	BS EN 1097-2
Aggregate crushing value (%)	17.1	21.3	< 30	BS EN 1097-2
Los Angeles abrasion (%)	17.4	21.8	< 45	AASHTO T96
Flakiness (%)	18.4	17	< 25	BS EN 933-3
Elongation (%)	22.19	19.3	< 25	BS 812

3.2. Aggregate and virgin asphalt (VA)

Pen. 60-70 asphalt was chosen as the VA. It was provided by Kemaman Bitumen Company (KBC) Malaysia that supplies asphalt for roadworks in Malaysia. Table 1 lists the physical properties of the selected binder.

Aggregate was collected from stockpiles at Hanson Quarry in Johor Bahru, Malaysia. The primary consideration in designing the mix was the properties of the aggregate parameters due to their impact on the asphalt mixture performance.

The fundamental RAP and virgin aggregate properties tested in this study were sieve analysis, aggregate crushing value (ACV), specific gravity (SG), flakiness index (FI), water absorption (WA), elongation index (EI), and aggregate impact value (AIV). The aggregate test (see Table 2) fulfilled the requirements set by Jabatan Kerja Raya (JKR) standard (2008). Asphaltic concrete grade 14 (AC14) had been selected for mixture design. Table 3 lists the gradation of the aggregates used in the mixtures. All the designed mixtures were graded based on mid-curve.

Table 3. Gradation limits of the combined aggregates for AC14. (Table view)

Sieve size (mm)	Gradation (JKR, 2008)	Passing (%)	Retained (%)	Mass retained (gm)
20	100–100	100	0	0
14	100–90	95	5	60
10	86–76	81	14	168
5	62–50	56	25	300
3.35	54–40	47	9	108
1.18	34–18	26	21	252
0.425	24–12	18	8	96
0.15	14–6	10	8	96
0.075	8–4	6	4	48
Pan	-	0	6	72
Total				1200

3.3. Rejuvenator

The rejuvenator used in this study; maltene, had a viscosity value of 42.97 mPa.s @ 95°C and a density of 0.955 gm/cm^3. It was extracted from a fresh asphalt, (which provided by Kemaman Bitumen Company (KBC) Malaysia) using petroleum ether. Speight (2015) demonstrated that maltene could be extracted from asphalt by adding a non-polar solvent such as low-boiling petroleum naphtha, petroleum ether, *n*-pentane, *iso*-pentane, *n*-heptane and liquefied petroleum gases. The fractions of maltene (saturates, aromatics, and resins) were calculated based on ASTM 4124 (2009), and their percentages were 8.3%, 56.26%, and 35.1%, respectively. The importance of using rejuvenating agent containing these components is that the asphaltene molecules in petroleum are usually stabilised by resin molecules to hinder major agglomeration of asphaltenes, while aromatics are a good solvent for asphaltene molecules (Ashoori *et al*. 2017). Furthermore, aromatics attribute to the flexibility of asphalt and improve the cracking resistance of binder, while resins provide anti-rutting ability at high-temperature.

3.4. Optimum maltene content

Previous studies conducted by Pradyumna *et al*. (2013), Tran *et al*. (2017), Ziari *et al*. (2019a) have reported that the dose of rejuvenator to improve rheological and physical properties of aged asphalt to the extent required is the optimum rejuvenator content. In this study and based on the physical and rheological properties tests shown in Tables 4 and 5, the optimum percentage of maltene required to rejuvenate the mixture with 40% RAP was 12% by weight of the total asphalt binder. With this dosage, the properties of the rejuvenated asphalt were close to that of VA (Pen. 60-70).

Table 4. Physical properties of asphalt binders. (Table view)

Type of asphalt	Penetration (dmm)	Softening point (°C)	Ductility (cm)	Viscosity (mPa.s)	
				@135°C	@160°C
Virgin asphalt (VA)	64	51.5	116	650	200
Aged asphalt	18.5	73	9	3500	700
40% Aged asphalt	38.3	62	71	1550	350
40% Aged +4% maltene	45.6	58.25	88	1250	300
40% Aged +8% maltene	53.2	55.5	106	950	250

Type of asphalt	Penetration (dmm)	Softening point (°C)	Ductility (cm)	Viscosity (mPa.s) @135°C	Viscosity (mPa.s) @160°C
40% Aged +12% maltene	62.7	51.25	119	625	175
40% Aged +16% maltene	70.8	47	141	350	100

Table 5. Performance grade of selected binders. (Table view)

Type of asphalt	Performance grade at high-temperature (°C)	Performance grade at low-temperature (°C)
Virgin asphalt	72.5	−23.02
Aged asphalt	98.95	−1.28
40% Aged asphalt	84.26	−16.78
40% Aged +12% maltene	70.63	−21.39

4. Sample preparation and mix design

The RAP mixtures were produced by adhering to the following steps: RAP and virgin aggregate were heated at 125°C and 163°C for 2 h, respectively. Next, the optimum amount of maltene was mixed directly with RAP for 1 min, for maltene and RAP binder to interact sufficiently. Past studies (Zaumanis *et al*. 2018, Moniri *et al*. 2019, Saleh and Nguyen 2019, Zaumanis *et al*. 2019) reported that an ideal dose of rejuvenating agent could be directly mixed with RAP. Afterward, the RAP rejuvenated by maltene was mixed with virgin aggregates before adding VA to the mixture. Figure 1 presents the process of blending the rejuvenated asphalt mixture ingredients. Marshall test was conducted to identify the value of optimum amount of asphalt binder (OAC). The mix designs were composed of a reference mixture (VA) and three asphalt mixtures: 100% RAP (R100), 40% RAP (R40), and 40% RAP with 12% maltene (R40-12M).

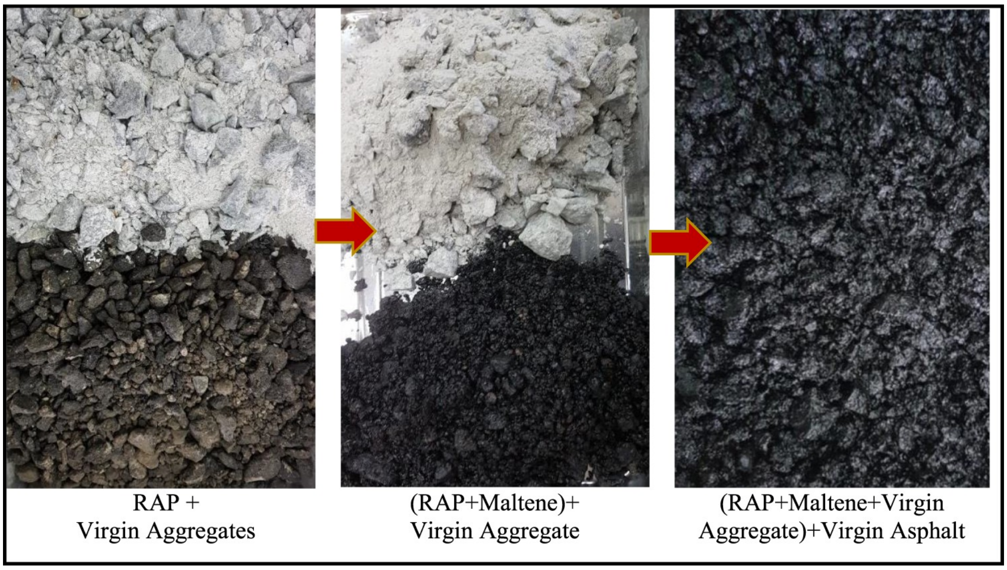

Figure 1. Procedure for blending asphalt mixture ingredients.

Adjustments were made to the mixtures based on the content of asphalt in VA for comparison purposes, except for R40-12M due to the percentage maltene added to the total asphalt binder is high (12%). The OAC was determined to identify volumetric properties and marshal stability. The asphalt contents in the samples ranged between 4.0% and 6.0% at 0.5% interval, which were later compacted with Marshal Compactor at 75 blows to each side of the sample. The OAC for the VA mixture was 4.97%, whereas the OAC for R40-12M was chosen to be 4.68% by weight of total virgin and RAP asphalt binders. For comparison purposes and to avoid the impact on the testing results, the RAP mixtures (R40 and R100) were fixed accordingly to the same asphalt content, mixing and compaction temperature as VA. This suggestion is in agreement with other studies conducted by Ziari *et al*. (2019c) and Xie *et al*. (2019). A decrease in the OAC of rejuvenated mixtures was due to two reasons: OAC decreased substantially with the addition of RAP material, and the contribution of RAP binder (aged asphalt) in the mixtures increased due to maltene. This result confirms with a research conducted by Moniri *et al*. (2019). Next, asphalt mixtures with OAC (exact %) were prepared for further testing.

5. Laboratory tests

5.1. Fourier transform infrared (FTIR) spectroscopy

The FTIR was employed to characterise the maltene fractions (aromatic and resin) as well as the chemical changes of the asphalt samples using an IRTracer-100 device displaying a 0.25 cm^{-1} resolution and fast 20 spectra/second scanning. The procedure involved an infrared beam penetrating the IR-transparent, high-refractive index, ATR crystal prism, to achieve complete reflection at the crystal-sample interface.

5.2. Marshal and flow test

Marshall stability and flow tests were performed on the asphalt mixture prior to fundamental engineering evaluation. The tests were performed based on ASTM D6927 (2015). A specimen (cylindrical) was submerged in a water bath for 40 min at 60 ˚C and was compressed on a lateral surface at 50.8 mm/min until maximum load (failure). Both maximum load resistance (stability) and flow values were recorded. Stiffness value was obtained from the correlation between stability and flow. Three samples for each combination were prepared and the average results are reported.

5.3. Moisture damage

The impact of moisture damage on the asphalt concrete paving mixtures was examined based on ASTM D4867 (2014b) before and after long-term ageing (LTA). A group of six samples for every type of mixture was prepared and compacted until obtaining 7% ± 0.5% air void (see Table 6). Then, the samples were segregated into two subgroups; one was dry, while the other was partially saturated with distilled water for several minutes at 25°C and 70 kPa pressure in a vacuum vessel. The saturation level was determined by dividing the volume of water absorbed (Vs) with the volume of voids (Vv), whereby the outcome is presented in %value. The ASTM standards stipulate that the saturation level must range from 55 to 80%. The wet subgroup was allowed to soak in a water bath for 24 h at 60°C, and later, placed in water bath for an hour at 25°C. The dry subset was soaked in water bath at 25°C for 20 min. After that, tensile splitting test was conducted with a loading rate of 50.8 mm/min. The maximum load at failure was applied to determine the ITS of the mixtures using Equation (1). The ratio of tensile strength of wet specimen to that of dry specimen (TSR) was determined by evaluating the sensitivity of asphalt mixes to moisture based on AASHTO T283 (2014a). LTA samples were prepared by keeping them in an oven at 85°C for 120 h (5 days) based on the recommendations of AASHTO R30 (2005).

$$\text{ITS} = 2000P/\pi dh \tag{1}$$

where ITS = Indirect tensile strength (kPa), P = maximum load (N), h = specimen height (mm), d = specimen diameter (mm), π = 3.14.

Table 6. Air voids percentages of the selected mixtures. (Table view)

Type of asphalt	Original samples	LTA

Type of asphalt	Original samples Air voids (%)		LTA Air voids (%)	
	ITS samples @ 25°C	ITS samples @ 60°C	ITS samples @ 25°C	ITS samples @ 60°C
	ITS samples @ 25°C	ITS samples @ 60°C	ITS samples @ 25°C	ITS samples @ 60°C
VA	6.6	6.8	6.8	7.0
	7.2	6.9	7.0	6.7
	7.3	7.2	6.6	6.9
R100	7.4	7.2	7.1	7.3
	6.5	6.8	6.9	7.0
	7.5	7.3	6.9	6.7
R40	7.3	7.0	6.5	6.8
	7.2	7.5	6.7	7.0
	6.9	7.3	6.9	7.0
R40-12M	7.0	6.7	7.2	6.9
	6.7	6.6	6.7	6.5
	7.3	7.5	6.8	7.0

5.4. Resilient modulus (M_R)

The elasticity behaviour of the asphalt mixture under repetitive loading was evaluated by conducting resilient modulus (M_R) test via Universal Testing Machine (UTM-5P) in accordance with ASTM D7369 (2011b) standard. It is a non-destructive test, and the results signify ability of materials to maintain under dynamic loads without plastic deformation, as well as the ability of the asphalt pavement mixture to revert to its initial condition after loading. For each mix design, three samples were prepared and pre-conditioned at the optimum temperature for at least 3 h. Tests were run at both 25°C and 40°C, respectively. The assumed Poisson's ratio values were 0.35 and 0.40 at 25°C and 40°C, respectively. The samples were subjected to compressive loads (stress) of 1000 N (minimum load) with a waveform defined by the haversine function. The M_R test instrument was set to apply a pulse repetition period up to 1 s. The applied load was diametrically vertical to the plane of the cylindrical specimen for 0.1 s duration and a rest period of 0.9 s. Each sample was subjected to 5 pulses. It is noteworthy to highlight that two tests were run for each conditioned sample in varied orientations (i.e. the test sample was rotated through 90° after the first test and before the second). Both load and deformation were automatically recorded by a computer connected to the test instrument, which subsequently calculated the M_R based on the assumed Poisson ratios (Equation (2)). The average reading was recorded for each sample.

$$M_R = F/Ht(0.27 + \mu) \tag{2}$$

where M_R = resilient modulus (MPa), F = applied force (N), t = sample thickness (m), H = horizontal displacement (m), μ = Poisson ratio.

5.5. Dynamic creep

Resistance to permanent deformation or rutting potential under repeatable axial loading stress was assessed via dynamic creep test using Universal Testing Machine (UTM-5P). It is a destructive test performed in adherence to BS EN 12697-25 (2016). Samples preparation was based on the steps comprised in Marshall design procedure and had been conditioned for 3 h at 40°C before the test. Next, the samples were preloaded for 30 s at 150 kPa and 0.5 Hz loading frequency as conditioning stress to ensure that the platen was loaded flat on the sample. The axial cycle loading stress and load cycles were fixed at 300 kPa and 3600 cycles, respectively. The linear variable differential transducer (LVDT) was employed to measure deformed samples. The total permanent strain and displacement of the samples were retrieved after completing 3600 cycles. The data obtained from a repeated load creep test, as presented in the form of creep stiffness modulus (CSM) and creep strain slope (CSS), were calculated using Equations (3) and (4)

$$E = \sigma/\varepsilon \quad (3)$$

$$\text{CSS} = (\text{Log}\varepsilon 3600 – \text{Log}\varepsilon 1200) – (\text{Log}3600 - \text{Log}1200) \quad (4)$$

where E = dynamic creep modulus (MPa), σ = applied stress (kPa), ϵ = Cumulative axial strain at 3600 cycles (mm), ε3600 = Strain at 3600 cycles, ε1200 = Strain at 1200 cycles, CSS = Creep strain slope.

5.6. Cantabro loss test

Cantabro test of abrasion loss allows the evaluation of mixture resistance to its disintegration by impact and abrasion caused by transport (Arrieta and Maquilón 2014). The test was conducted in accordance with (TxDOT Designation: Tex-245-F) by introducing the marshal specimen into the Los Angeles machine and rotating the drum for 300 revolutions at speed ranging between 30 and 33 revolutions/min without steel balls. The Cantabro loss (%loss of original specimen) was calculated based on the weight of sample before and after the test.

5.7. Rutting resistance

The wheel tracking test was performed to determine the susceptibility of asphalt mixtures to deform under load by measuring the rut depth formed by repeated passes of a loaded wheel at a fixed temperature. Asphalt mixtures were prepared (63.5 mm height and 150 mm diameter) based on the designed asphalt content and 6–8% air voids using Superpave gyratory compactor. Two samples were prepared for each mixture and were conditioned inside double wheel tracker (DWT) equipment, as portrayed in Figure 2, at 50°C for 5 h to be confirmed with EN 12697-22 standard (2013). Later, the samples were subjected to 10,000 cycles of 70 N wheel loading at a speed of 26.5 cycles/min. Raw data were recorded automatically on rut depth for each cycle. The criterion of rutting potential had been based on the cumulative rut depth.

Figure 2. Double wheel tracking equipment.

5.8. Water immersion test

The moisture sensitivity of different kinds of loose asphalt-coated aggregates was assessed via water immersion tests in accordance with AASHTO T182 (2002). It is involved immersing a 100-g asphalt-coated aggregate sample into a 500-ml glass bottle with distilled water for 16–18 h at 25°C. The glass bottle allowed sample visualisation to approximate the fraction of the overall visible aggregate with intact coating; higher or lower than 95%. Later, the total water immersion test, which is a more refined version of the static immersion test (Liu *et al*. 2014), was performed for determining the average proportion of asphalt coating. This test uses water at 40°C for 3 h instead of ambient temperature to gain better outcomes.

5.9. Coating test

A coating test was conducted according to AASHTO T 195 (2011a) to determine the percentage of coated particles after mixing. The test was performed on aggregates that had retained on 9.5 mm sieve. The sieving process was performed when the aggregates were still hot. As a result, 500 g of sample was gathered and was assessed under direct sunlight.

6. Results and discussion

6.1. FTIR analysis

6.1.1. Functional characteristics of maltene fractions

The impact of maltene on asphalt properties is highly related to aromatic and resin fractions. Therefore, the functional characteristics of aromatic and resin fractions were determined by using Fourier Transform Infrared (FTIR) spectroscopy. The infrared spectra at wavenumbers between 700 and 3000 cm^{-1} are illustrated in Figure 3. Variances were noted among peaks of aromatics and resins, such as those around 720 cm^{-1} $(CH_2)_n$, 744 cm^{-1} (–C = CH), 811 cm^{-1}(–C = CH), and 1030 cm^{-1} (S = O). Moreover, the band at 1454 cm^{-1} refers to the absorption peak of S = O stretching vibration. The band at 1597 cm^{-1} corresponds to the stretching vibration of C–C, which is related to the trace of aromatic hydrocarbons. The band at 1711 cm^{-1} is due to the stretching vibration of C = O. Besides, bands ranging at 2700–3000 cm^{-1} were due to the C–H stretching vibration peaks, which are related to the existence of short-chain alkanes, methane, aldehydes, alkenes, and aromatic hydrocarbons, respectively. The qualitative assessment of both aromatics and resins spectra showed no significant difference in peaks, but the intensity of the peaks did differ.

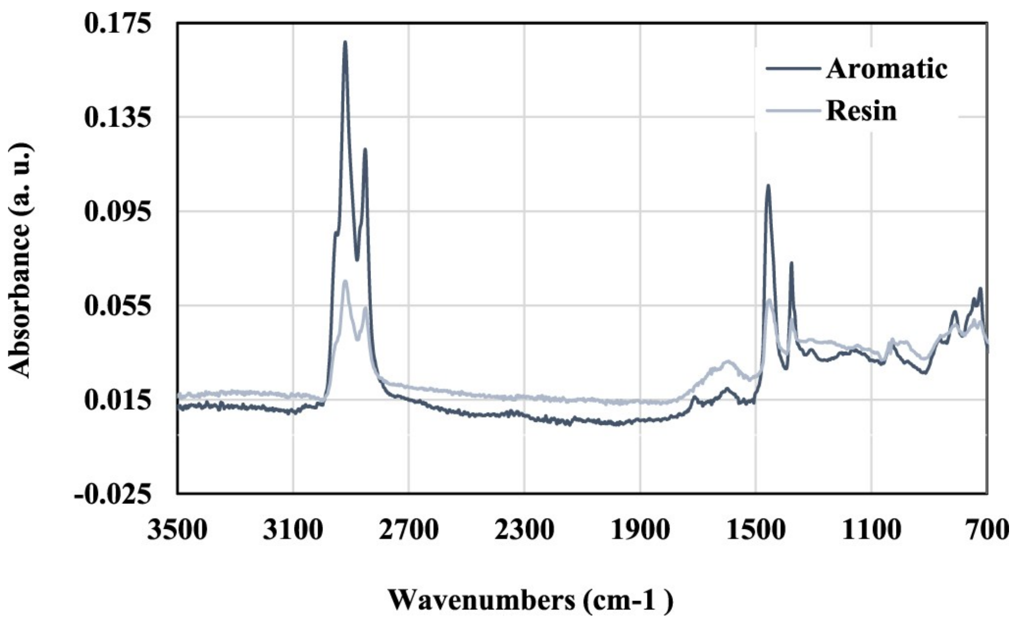

Figure 3. FTIR spectra for aromatic and resin.

6.1.2. FTIR analysis of asphalt binders

Figure 4 presents the Fourier transform infrared (FTIR) spectroscopy for different binders, namely VA, R100, R40 and R40-12M at the wavenumber between 600 cm^{-1} and 3000 cm^{-1}. The main chemical reaction takes place as a result of oxidative ageing, which can be assessed using the carbonyl (C = O) and sulfoxide (S = O) peaks (J. Claine Petersen 2011, Yan *et al*. 2016). In the present study, the increase in intensity of the band from the C = O at 1700cm−1 and S = O 1030 cm−1 for R100 associates with an increase in content of the most polar components in asphalt (asphaltenes). This increment in polarity induced by the functional groups affected the rheology of aged asphalt (Cavalli *et al*. 2018) which, in turn, leads to increase the stiffness (Mousavi *et al*. 2016). However, it was observed that the blending of aged asphalt with virgin asphalt and maltene decreased the oxygenated groups (C = O and S = O), reflecting the ability to rejuvenate the aged asphalt. In other words, a reduction in carbonyl and sulfoxide index means a reducing in the degree of oxidation in the rejuvenated asphalt binder, causing a reduce the brittleness property of aged asphalt. It is important to mention that the peaks linked to oxidation-induced binder ageing have not vanished, although maltene has been applied to the aged asphalt. This is a non-reversible form of ageing, as identified by Xiaohu and Isacsson (2002).

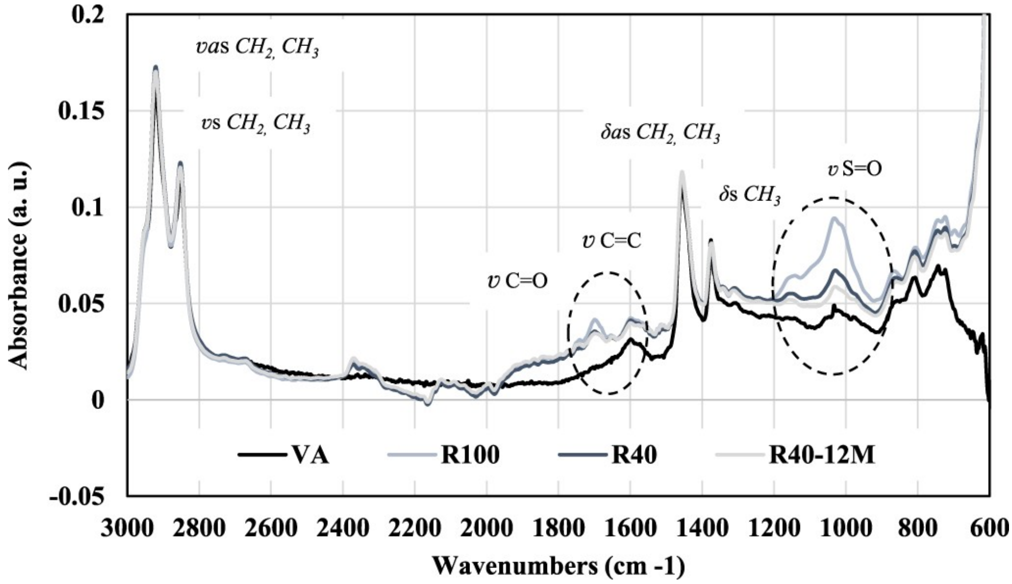

Figure 4. FTIR of asphalt binders.

6.2. Marshall properties

6.2.1. Stability, flow and stiffness

Table 7 tabulates the outcomes of Marshall stability, flow, and stiffness of the mixtures (mean value of three samples). Inclusion of RAP led to increase the Marshall stability, whereas the flow semi-deteriorated. Both loading capacity and rutting resistance increased as the mixture turned brittle. The specimen of asphalt appeared to be more prone to deterioration at low and intermediate temperatures with increased stiffness, whereby stiffness was determined based on the flow-stability correlation. A higher value of stability divided by a lower value of flow gave a stiffer mixture. In precise, the stability values of R100 recorded 1996 kN and R40 recorded 1768 kN comparing with VA, which showed a stability value of 1404 kN. Meanwhile, the flows of R100 and R40 were 1.8 and 2.23 mm, respectively. The low values in the flow and the high values in the stability of RAP mixtures were related to the ageing of asphalt binders during service life. This increased the viscosity of asphalt binder. Stability, which refers to the mass viscosity of aggregate–asphalt binder mixture, was substantially affected by asphalt binder viscosity at 60°C (Moghadas Nejad *et al*. 2014). Increment in asphalt binder viscosity led to the increase in Marshall stability.

Table 7. Marshall properties results. (Table view)

Type of asphalt	OAC total	Virgin asphalt content	Aged asphalt content	B_{SG}. (g/cm^3)	A_V (%)	VFA (%)	Stability (kN)	Flow (mm)	Stiffness (kN/mm)
VA	4.97	4.97	0	2.376	3.8	75.4	1404	3.05	460.30
R100	4.97	0	4.97	2.271	7.1	61.2	1996	1.80	1108.0
R40	4.97	2.98	1.99	2.370	4.2	73.2	1768	2.23	792.83
R40-12	4.68	2.8	1.87	2.382	4.0	75.3	1538	3.23	476.16

Inclusion of maltene decreased the stability and stiffness to be close to that of VA mixtures and achieved the minimum requirement for flow (2–4 mm). Since the addition of maltene increased the phases of saturates, aromatics, and resins in asphalt binder, the viscosity decreased as well in the asphalt mixture. In precise, R40-12M recorded a stability value of 1545 kN. This reduction in stability displayed by rejuvenated mixture is not remarkable, since more significant improvement was noted for R40-12M mixture when compared with RAP and VA mixtures. The results of Marshall stability, flow, and stiffness are in line with those reported by Moghadas Nejad *et al*. (2014) and Jahanbakhsh *et al*. (2020). To sum up, maltene increased the workability of the mixture by decreasing viscosity. This compensated for the stiffness of RAP mixtures. Thus, based on the Marshall Stability test, the performances displayed by maltene-added RAP and virgin mixtures were nearly similar.

6.2.2. Volumetric properties results

Table 7 also tabulates the results of volumetric properties for the tested mixtures. It can be seen that the VA mixture exhibited higher bulk specific gravity (B_{SG}.) than R40 and R100, while air voids (A_V) increased due to RAP. Particularly, B_{SG}. of VA recorded 2.376 g/cm^3, whereas R40 and R100 recorded 2.37 g/cm^3 and 2.271 g/cm^3, respectively. Furthermore, A_V of VA mixture was 3.8% and increased to 4.2% and 7.1% with the addition of 40% and 100% aged asphalt. The reason of increased A_V in the RAP mixtures is associated with high viscosity of aged asphalt (see Table 4), which hinder the ability of asphalt binder to fill the voids in the mixture. However, the inclusion of maltene to RAP mixtures enhanced the workability, which decreased A_V of R40-12M mixture to 4% and increased B_{SG} to 2.382 g/cm^3. This is in line with that reported in prior studies, such as Mogawer *et al*. (2013) and Jia *et al*. (2015), who found that rejuvenating agents can hinder the increment of A_V due to RAP inclusion. The results also showed that voids filled with asphalt (VFA) of R100 (61.2%) and R40 (73.2%) were lower than those of VA (75.4%) and R40-12M (75.3%). The lower VFA is ascribed to the high viscosity of aged asphalt in RAP mixtures. Therefore, V_A decreased and VFA increased when maltene was included in the RAP mixtures. This is because; maltene in the asphalt binder reduced the viscosity, thus easing compaction (Jia *et al*. 2015). It is known that the low value of A_V can cause rutting, while a high value of VFA may pose durability issues. Hence, adequate A_V and VFA values must be achieved to avoid those issues.

6.3. Moisture damage

Both durability and strength of asphalt mixtures can be adversely affected by moisture damage (Ayazi *et al*. 2017). As for this present study, TSR was employed to determine moisture susceptibility by comparing the ITS of asphalt mixtures after exposure to wet conditions with those of mixtures that were kept dry. Figure 5 presents the ITS values of the asphalt mixtures at 25°C and 60°C. As a result, mixtures with RAP (R40 and R100) displayed higher ITS values than VA and R40-12M mixtures in both conditioned and unconditioned samples. This is ascribed to the decreased stress and strain concentration in asphalt mixture with high RAP content stemming from the supplementary binder added in the mix and the stiff binder of RAP (Jahanbakhsh *et al*. 2020). The other reason is associated with the strong bonding between aged asphalt with the RAP aggregate, also known as black aggregate (Shu *et al*. 2012). Shu *et al*. (2012) had proven that black aggregates are less susceptible to moisture damage. Meanwhile, the ITS values of the wet samples were lower than those of the dry samples. This was expected since the decrease in ITS is ascribed to loss of cohesion in asphalt and loss of adhesion in mixture. The outcomes further revealed that the ITS values of VA samples at both 25°C and 60°C were 1105 and 957 kPa, respectively. Nonetheless, inclusion of 40% RAP increased the values of ITS to 1553.7 kPa at 25°C and 1505.3 kPa at 60°C, whereas the ITS values for R100 were 1590 kPa at 25°C and 1280 kpa at 60°C. This means; with increment in RAP, the ITS value at 25°C was dominated by RAP proportion, thus stronger and stiffer than fresh HMA (Jahanbakhsh *et al*. 2020).

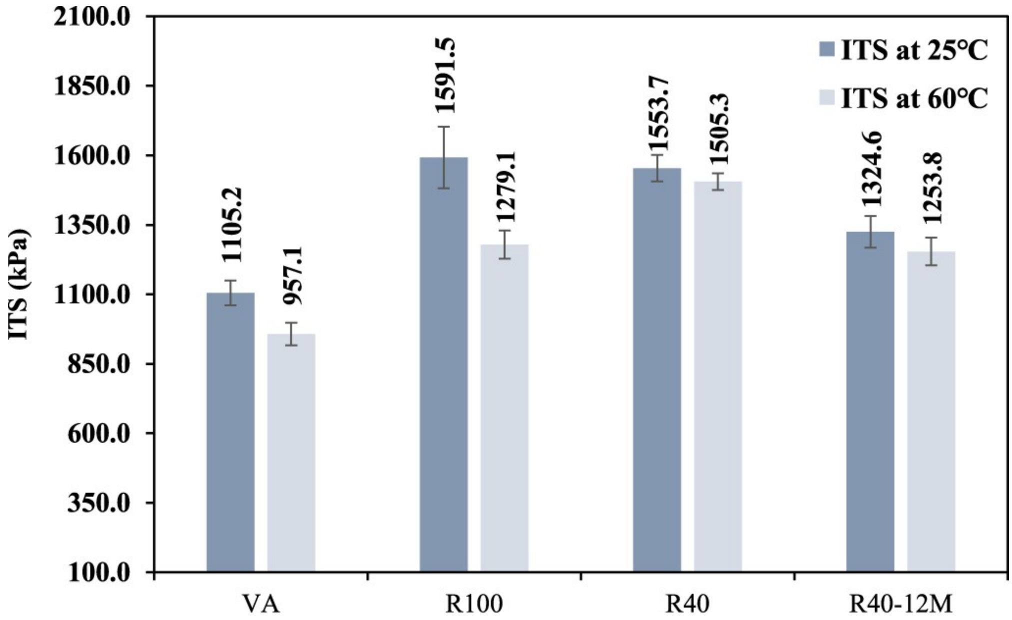

Figure 5. ITS results of obtained samples.

The addition of maltene, however, led to a decrease in the ITS at both 25°C and 60°C. This was expected as maltene reduced the stiffness of RAP binder, which decreased the ITS. However, the values were still higher than VA mixture. In precise, the ITS values of R40-12M at both 25°C and 60°C were 1324.7 kPa and 1253.8 kPa, respectively. These findings are in agreement with those reported by Ziari *et al*. (2019b).

Figure 6 presents the TSR values – a criterion for moisture susceptibility. Higher TSR value signifies better asphalt mixtures performance against moisture damage (Daryaee *et al*. 2020). It can be perceived that all the mixtures tested in this present study had passed the AASHTO TSR minimum threshold (>80%). The mixture with 40% RAP (R40) achieved the highest TSR value amongst all mixtures. This means; the presence of 40% RAP benefited the susceptibility of moisture in the mixture due to the strong bonding between aggregate particles in RAP and aged asphalt, when compared to that of VA that decreased the mixture susceptibility to damage due to moisture (Ayazi *et al*. 2017). Some fractions of the aged asphalt of RAP material had interacted during the re-mix process, while the remaining proportion of the aged asphalt formed a layer that coated the RAP aggregate particles (Moniri *et al*. 2019). The coated aggregates of RAP with hard binders decreased water penetration into the aggregate-binder bonding interface, which led to less destructive impact upon mechanical properties (Jahanbakhsh *et al*. 2020). On the contrary, the R100 exhibited the least value of TSR (80.35%). This trend shows that very high content of RAP can lead to poor mix due to potential moisture damage. Hence, one must be cautious while designing the mix with very high RAP percentage. The addition of maltene to the mixture led to a slight decrease in the TSR value, whereby the TSR value of R40-12M was 94.65%, which is slightly less than the value of R40 (96.8%). However, the TSR value of R40-12M was still higher than that of VA mixture. The presence of aromatic and saturates in the maltene reduced the stiffness of rejuvenated mixture, leading to decrease the ITS at both 25°C and 60°C. At the same time, the resin in maltene prevented any significant decreasing in ITS of mixture. The reason is that the resin functions as a 'glue' that binds asphalt pavement together, thus imparting adhesion properties. This result is completely different to other studies, such as a study carried out by Ziari *et al*. (2019b), who found that the TSR of RAP mixture samples significantly decreased with the addition of waste cooking oil, Cyclogen and Rapiol rejuvenators.

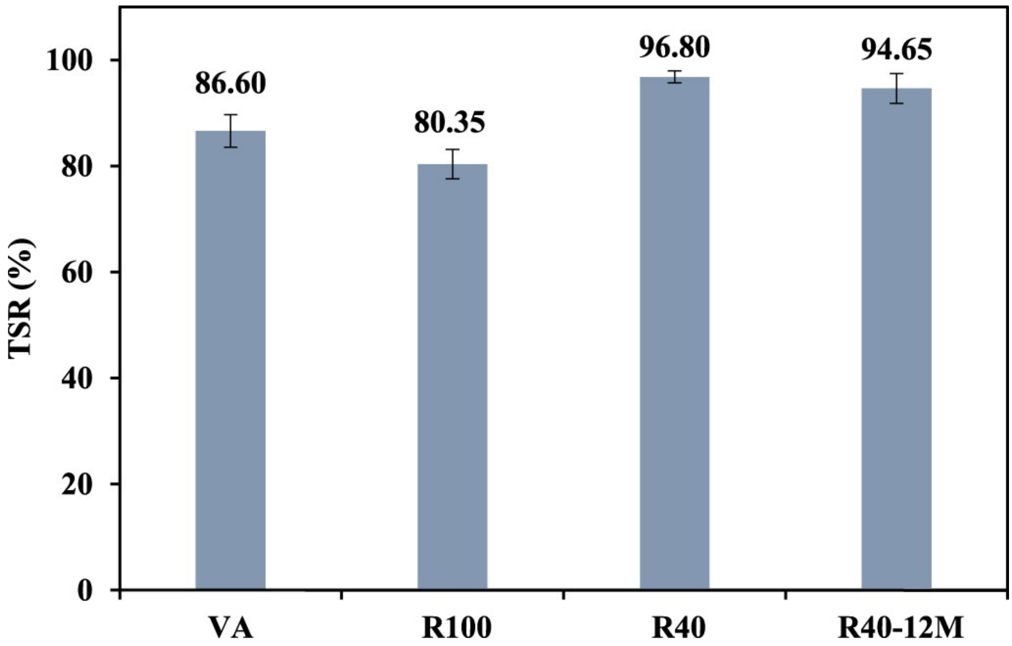

Figure 6. TSR results of collected samples.

The results of dry and wet ITS values conducted after LTA are presented in Figure 7. It can be inferred that the ITS of all mixtures increased by LTA. However, R100 and R40 at 25°C recorded higher values than VA and R40-12M mixtures, indicating high stiffness of RAP mixtures. Higher stiffness causes low-fatigue life. Meanwhile, the addition of maltene enhanced the stiffness of R40-12M to be slightly higher than that of VA. This means VA and R40-12 M have nearly comparable resistance to cracking (see Figure 8). On the other hand, compared with VA and R40-12M, ITS values for RAP mixtures at 60°C were substantially deteriorated. This denotes that the resistance of RAP mixtures against moisture damage negatively affected by LTA, while VA and R40-12M recorded a slight reduction in the values. More details can be clarified in Figure 9, which present the TSR of selected samples after LTA. It is showed that R40-12M recorded the highest TSR value, followed by VA mixture, whereas R100 and R40 recorded the lowest values. The improved performance of R40-12M is mainly due to the presence of resin in the maltene, which increased bonding between the rejuvenated asphalt and aggregate, and prevented the moisture to diffuse among the particles. Such a pattern of results may refer to the fact that the resistance to moisture damage increases with ageing of asphalt to some degree. Then, the asphalt binder 's' properties can then deteriorate and cause more severe damage, due to its brittleness property.

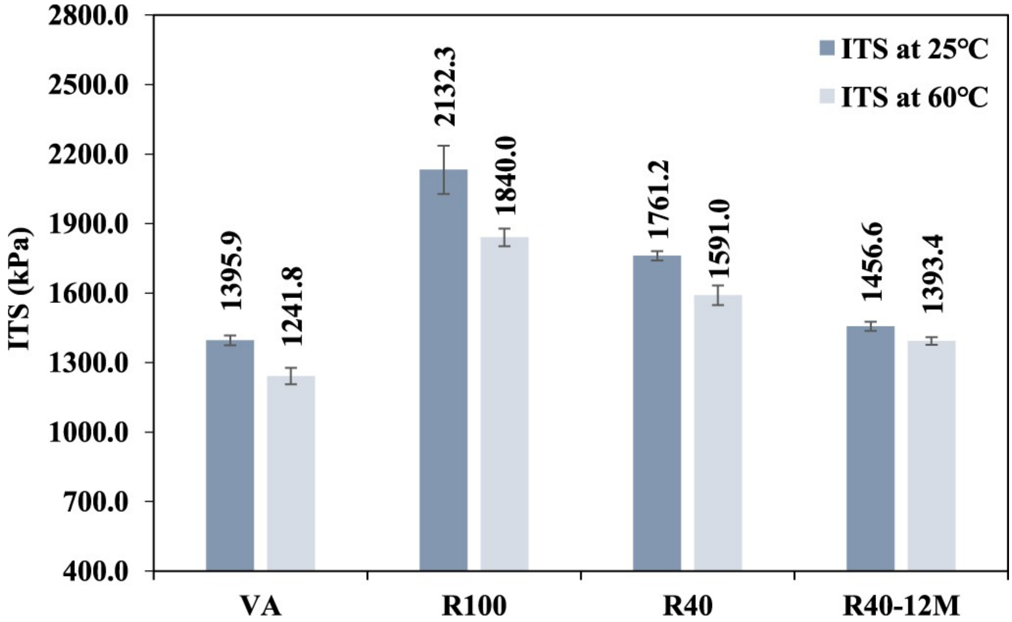

Figure 7. ITS results of collected samples after LTA.

Figure 8. Cracking shape of asphalt mixture samples after LTA.

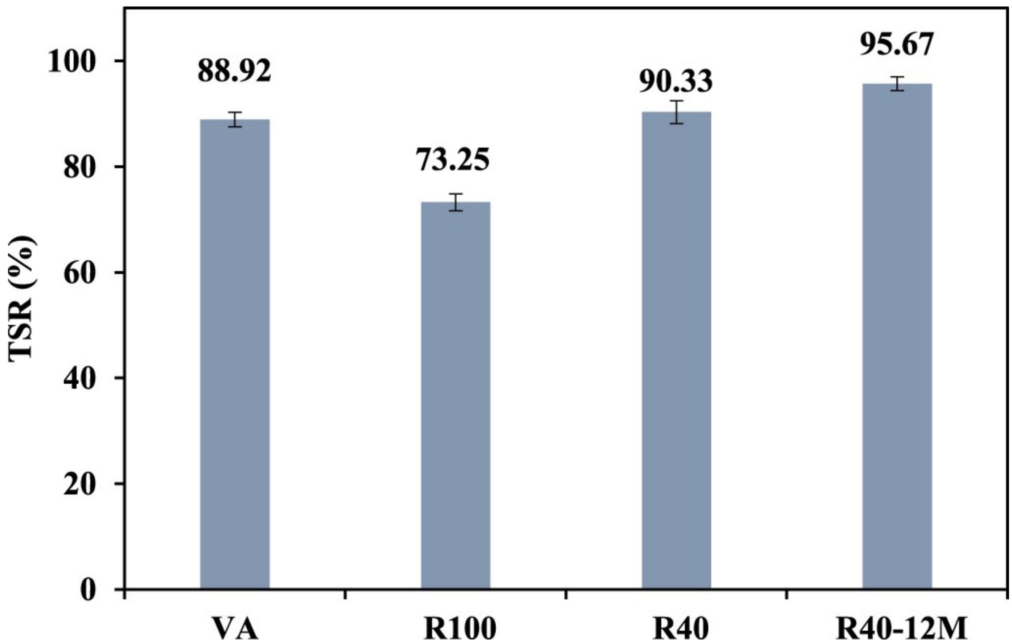

Figure 9. TSR results of collected samples after LTA.

6.4. Resilient modulus (MR)

Figure 10 presents the outcomes of M_R test at 25°C and 40°C for all mixtures. At 25°C, the M_R showed that the resistance of the mixture was fatigue, while the M_R at 40°C signified rutting resistance. From Figure 10, the inclusion of high amount of RAP into the mixture significantly increased the M_R. This outcome is ascribed to the impact of stiffening in aged asphalt on RAP (Behbahani *et al*. 2017). Upon increment in temperature, the variance in M_R turned more vivid, along with decrease in stiffness at 40°C. The VA mixture exhibited the lowest values of M_R (3059 MPa at 25°C and 1005 Mpa at 40°C), while R100 displayed the highest values (11,725MPa at 25°C and 5462 Mpa at 40°C), as well as R40 recorded (6312 MPa at 25°C and 1556 Mpa at 40°C). Nevertheless, inclusion of maltene to RAP mixtures had reduced the M_R values, signifying that maltene can alleviate the stiffness caused by aging, in which the M_R values of R40-12M were 4303 and 1192 Mpa at 25°C and 40°C, respectively. These results indicate that R40-12M was less susceptible to fatigue deformation in comparison with VA mixture at 25°C, while the findings at 40°C indicated that the R40-12M mixture was more resistant to rutting in comparison with the VA mixture. In summary, although the M_R of mixtures with RAP was alleviated by adding maltene, the values of the rejuvenated mixtures were still higher than VA. The M_R outcomes are in line with prior reporting, such as Kaseer *et al*. (2017) and Moniri *et al*. (2019), who had proven that the M_R of asphalt mixtures increased with increment in RAP material. On the contrary, the addition of rejuvenating agents reduced the M_R values regardless of temperature. Additionally, the results are also in agreement with the outcomes retrieved from FTIR results, which show that carbonyl (C = O) and sulfoxide (S = O) peaks of rejuvenated samples still higher than those in VA samples and lower than RAP mixtures. The increment in the oxygenated group is linked with an increase in asphaltene content, meaning that the stiffness of R40-12M sample is higher than that in VA mixture and lower than RAP samples.

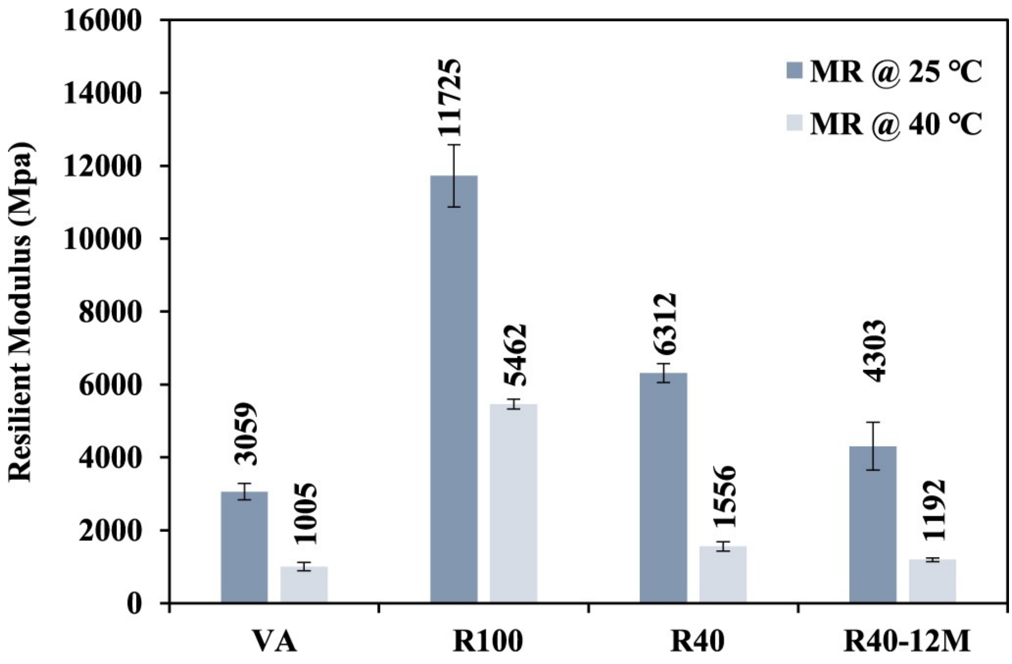

Figure 10. M_R values of asphalt mixture.

6.5. Dynamic creep

The resistance of asphalt mixtures to permanent deformation was determined based on creep stiffness modulus (CSM) and creep strain slope (CSS). Creep stiffness was found to be related to cumulative strain, which indicated resistance against rutting that decreased the tendency of the material to undergo permanent deformation. Figure 11 presents the cumulative permanent strains of all mixtures after 3600 cycles. As expected, the aged mixtures recorded the least permanent strain, while the VA mixture had the highest permanent strain. This is ascribed to the stiffening effect of ageing on the recycled asphalt, where maltene was low and asphaltene was high. In particular, the permanent strain values for R100 and R40 were 183 and 331 Mpa, respectively. However, when maltene was added to R40, the permanent strain of mixture substantially decreased, in which the R40-12M was 538 Mpa – a value that fell between R40 and VA mixtures. This is attributed to the reduction in stiffness for aged asphalt in the mixture when mixed with rejuvenator (Farooq *et al*. 2018) due to the presence of aromatic in the maltene. It was demonstrated that both saturates and aromatics imparted soft or plasticising properties, while resins and asphaltenes contributed to asphalt stiffness (Corbett 1969).

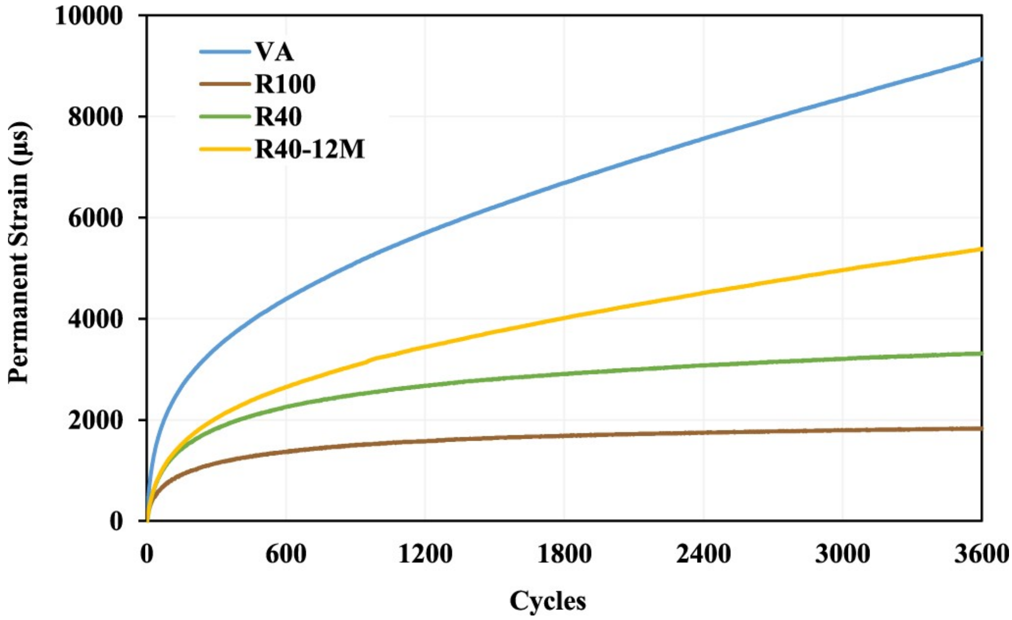

Figure 11. Cumulative strain result at 40°C.

Figures 12 and 13 illustrate the CSS and CSM of the mixtures. Many studies have employed CSS to determine the susceptibility of mixtures to permanent deformation with repeated loads (Oluwasola and Hainin 2016). As a result, a mixture displays more resistance to permanent deformation at low CSS. As expected, R100 recorded the lowest value (0.12), and followed by R40 (0.19). Upon adding maltene, the CSS value of R40-12M became 0.43, which was very close to that of VA mixture.

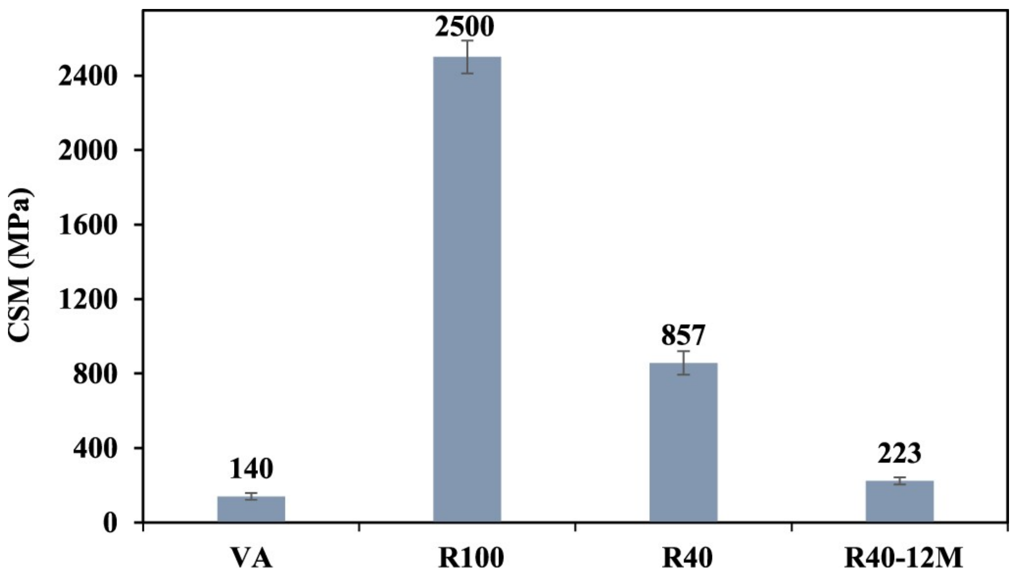

Figure 12. CSM results.

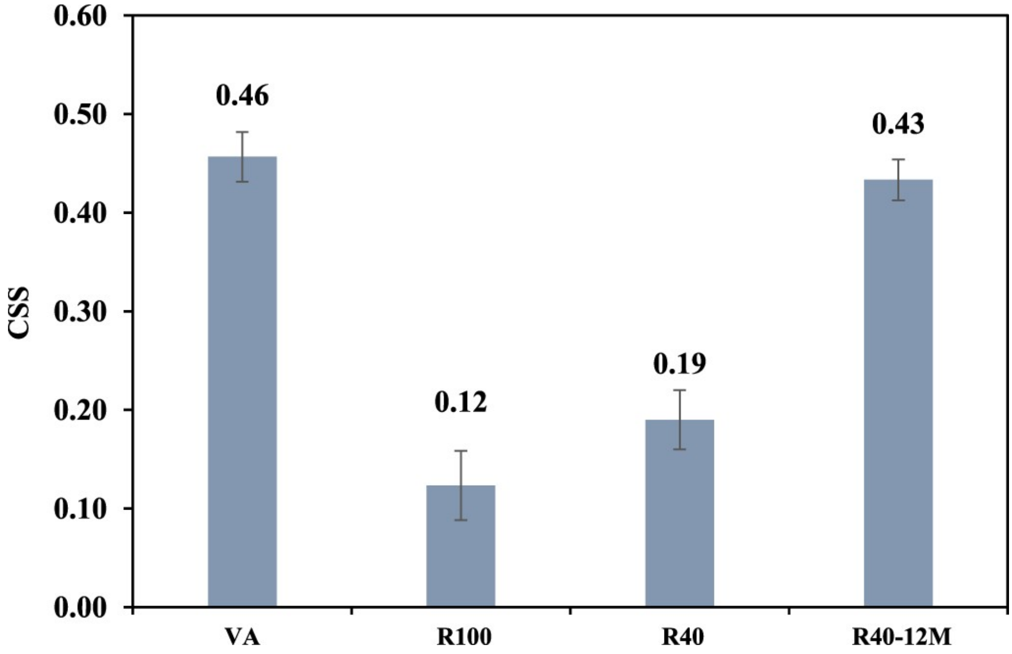

Figure 13. CSS results.

Meanwhile, R100 gave the highest value for CSM (2500 Mpa), and this was followed by R40 (857 Mpa), whereas VA displayed the lowest value (140 Mpa). Higher creep stiffness indicates high rutting resistance, thus reduced susceptibility to permanent deformation. This means; the impact of aging on CSS was similar to that of CSM values. Aging seemed to reduce CSS and increase CSM of all mixtures. As a result of ageing, the polar fraction (asphaltene) increased, thus enhancing the stiffness of asphalt. Conversely, the rejuvenated mixtures by maltene (R40-12M) exhibited a reduction in the CSM to 223 Mpa. The findings retrieved from the dynamic creep test are in agreement with marshall and M_R tests.

6.6. Cantabro loss

The Cantabro loss test was performed as an indirect measure of the potential ravelling and durability problems in asphalt mixtures. Figure 14 portrays the test results of mass loss for mixtures, whereby inclusion of RAP to the mixture had increased mass loss. Initially, the mass loss of VA mixture was 5.53%, but increased to 8.4% with the addition of 40% RAP, whereas R100 exhibited more than 13% mass loss. In this case, mass loss increased with ageing, and the mixture may become more prone to durability issues over time than VA mixture (Doyle and Howard 2016). Conversely, the addition of maltene recovered the original properties of mixtures containing RAP to some extent, where R40-12M exhibited 5.4% mass loss. This could be linked with the increase in the adhesion and cohesion properties upon inclusion of maltene, which contains a high quantity of aromatic and resin. The aromatic can soften the aged asphalt, while the resin can increase the adhesion between the asphalt and aggregate. It is noteworthy to highlight that Cantabro mass loss is positively correlated to air voids percentages in the specimen. Put simply, the addition of maltene decreased the viscosity of aged asphalt, thus decreasing the air voids percentage in the mixtures. This resulted in a decrease in mass loss.

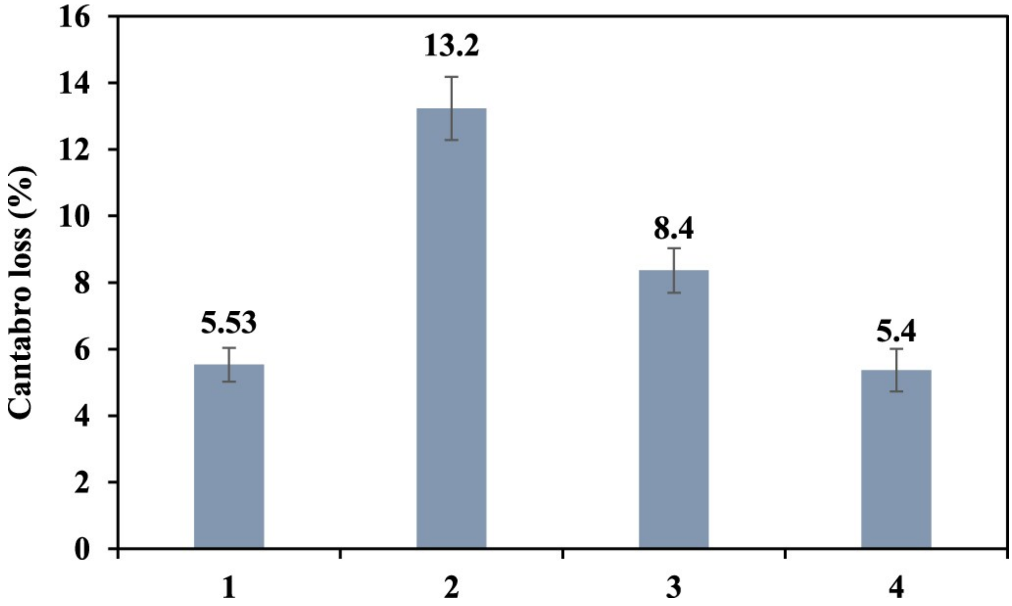

Figure 14. Cantabro loss of asphalt mixtures.

6.7. Rutting resistance

Figure 15 reveals the development of rut depths for VA, R100, R40, and R40-12M samples. It can be seen that the rut depth increased with increment in passes. The maximum rut depth for VA (0% RAP mix) was 1.97 mm after 10,000 cycle passes. Inclusion of RAP into mixtures of HMA enhanced rutting resistance, while maltene had compromised rutting resistance. This is because; the addition of maltene increased the flexibility of asphalt binder. In detail, the addition of 40% RAP had decreased the rutting depth, whereby R40 recorded 1.23 mm, while R100 mixture revealed the highest rut resistance after 10,000 passes among all the mixtures (0.59 mm). On the contrary, R40-12M exhibited 1.48 mm of rutting depth. These observations are ascribed to the effects of softening and stiffening as a result of including maltene and RAP. The rejuvenated mixture (R40-12M) displayed lower rutting depth than that for VA. The reason is associated with the presence of resin in maltene that provides anti-rutting performance and behaves as VA at high-temperature. The results verified the outcomes reported in Jia *et al*. (2015). Besides, the findings obtained from wheel track tests are in agreement with outcomes retrieved from M_R and dynamic creep tests, whereby RAP inclusion decreased the accumulated rut depth.

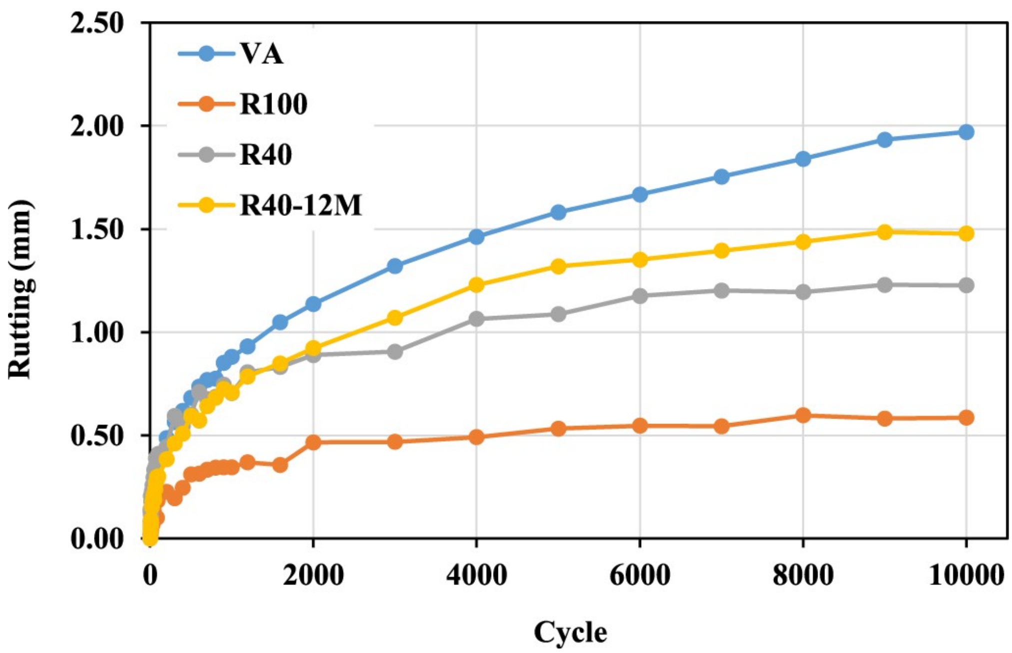

Figure 15. Rutting curve for asphalt mixtures samples.

6.8. Stripping test results

The moisture sensitivity of different kinds of loose asphalt-coated aggregates was assessed via water immersion tests. Figure 16 shows that all asphalt-coated aggregate types had >95% of coated aggregates properties after undergoing static and total immersion tests. The exception was aged asphalt that exhibited 95% aggregate-asphalt adhesion after undergoing the total water immersion test. In the case of VA, the aggregates retained their coating in a proportion of 97%. However, for R100, it retained coating in proportions of 96% and 95% after the static and total immersion tests, respectively. The aggregate retained its coating in the proportion of 98% after the static immersion test and the proportion of 97.5% after the total immersion test in for R40. Meanwhile, R40-12M showed 97% bonding coated at the end of the static and total immersion tests. These findings indicated that among the four asphalt binder types, the one with the poorest performance in terms of moisture susceptibility was R100. This trend signifies that the R100 mixture can lead to poor mix due to potential moisture damage. The reason is that the bonding strength between asphalt and aggregates, as well as the resistance to moisture, may be degraded when the asphalt binder is subjected to harsh weather condition over a long time.

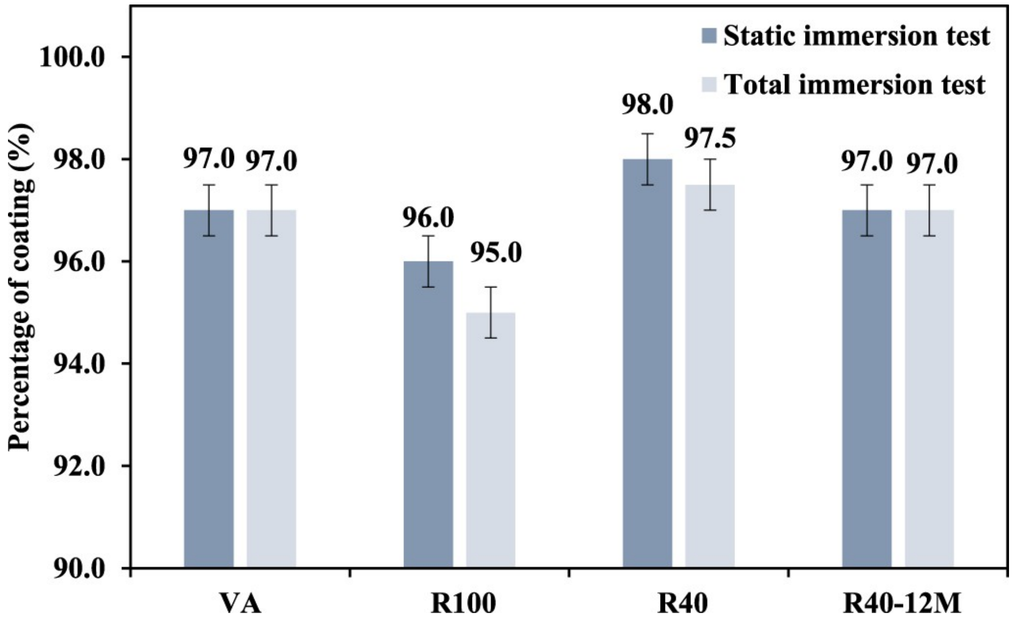

Figure 16. Water immersion test results.

6.9. Aggregate coating test

Figure 17 presents the outcomes of the aggregate coating test. Both R100 and R40 reduced their coating to 89% and 93%, respectively. Based on AASHTO T 195 (2011a), the minimum coating requirement is 95%. Because that incomplete coating can speed up the loss of binding between the asphalt and aggregate where the water permeates through the asphalt films and direct access in the aggregates. However, the addition of maltene significantly conversed the results, where the aged asphalt was softened by the aromatic components existed in the maltene, and this enabled the coating of aggregates. Particularly, R40-12M exhibited about 98% of coating, which is very close to the coating value of VA mixture (99.5%). The outcomes are in line with those reported by Farooq *et al*. (2018).

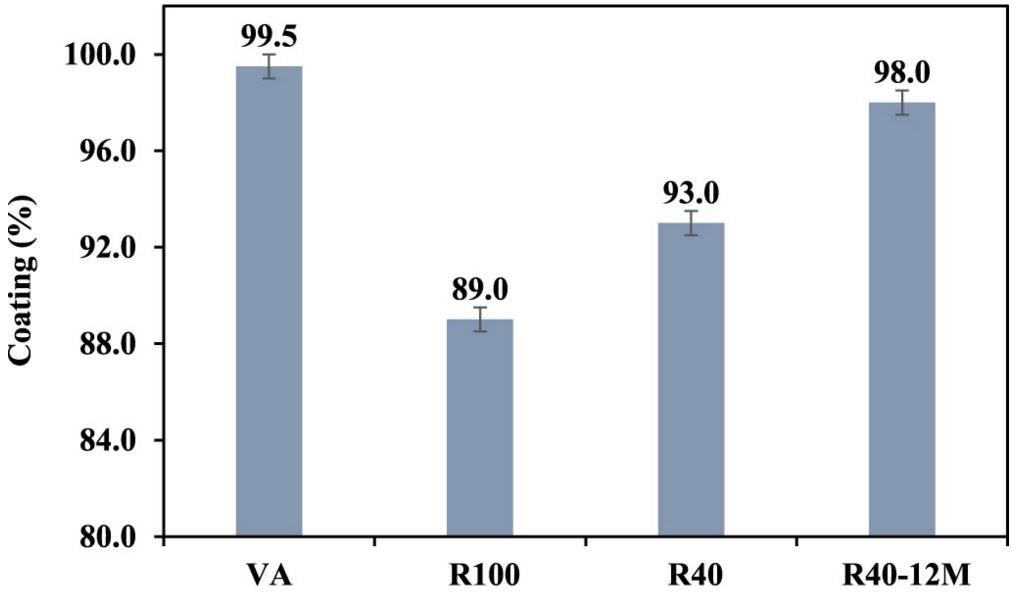

Figure 17. Aggregate coating test results.

6.10. Economic analysis

A cost analysis was carried out to identify the cost of reclaimed HMA mixtures with maltene. Copeland (2011) listed four cost categories for the production of asphalt, namely materials, plant production, trucking, and lay down. The costliest category refers to materials as it takes up 70% of the total cost in producing HMA (Im *et al*. 2014). This study only considered cost of materials, such as, virgin aggregates, asphalt binder, RAP, and maltene (rejuvenator), based on their normal price. Table 8 presents the costs involved to produce a tonne of HMA based on the details of VA and R40-12M, along with optimum maltene content. As a result, inclusion of RAP and maltene into the mixture had substantially slashed the cost of asphalt mixtures by 26.98%. The price of maltene was higher than other rejuvenating agents (e.g. waste cooking oil, waste vegetable oil, and waste engine oil). However, the addition of maltene had decreased OAC. The cost analysis revealed significant cost saving, as the price of rejuvenated mixture (R40-12M) was 28.55 $/ton, while the price of VA mixture was 39.1 $/ton. On the other hand, it can be seen that the prices of R100 and R40 are much cheaper than VA and R40-12M. However, they could not be re-used in pavement due their brittleness property, which causes durability issues (such as fatigue and moisture damage failures), especially after ageing.

Table 8. Cost analysis of HMA mixtures. (Table view)

Material	Cost ($/kg)	VA	R100	R40	R40-12M
Virgin asphalt	0.50	24.85	-	14.91	14.04
Virgin aggregate	0.015	14.25	-	8.55	8.58
RAP	0.005	-	5.0	2.0	2.0
Maltene	0.70	-	-	-	3.93
Total price ($)/Ton		39.10	5.0	25.46	28.55

7. Conclusion

The present experimental study looked into the use of maltene as a rejuvenator in recycled asphalt mixture. Based on the scope and the purpose of this study, as well as the results of the tests conducted, the following conclusions are drawn:

1. FTIR results showed an increment in the (C = O) and (S = O) indices with the addition of aged

asphalt. However, incorporating maltene into the aged asphalt reduced the effect of ageing by decreasing the oxygenated groups, indicating the capability of maltene in restoring the chemical properties of aged asphalt to some degree.

2. Inclusion of RAP into the asphalt mixtures significantly increased the stiffness, leading to increase the stability and A_V, as well as decreased flow, B_{SG}, and VFA. Meanwhile, adding maltene had enhanced and restored Marshall properties, which appeared close to the VA mixture. Furthermore, the OAC decreased by addition of RAP and maltene into the mixtures.
3. ITS and TSR values of asphalt mixtures increased by adding 40% of RAP. Meanwhile, employing 12% of maltene resulted a decrease in these parameters. However, R40-12M recorded the highest value of TSR than RAP and VA mixtures after LTA, reflecting the ability of maltene in the rejuvenation of aged asphalt.
4. M_R, CSM, and rutting resistance of the asphalt mixtures increased by adding RAP, whereas using maltene had substantially reduced these parameters, signifying reduced stiffness in RAP mixtures. Nevertheless, all the aforementioned values are still higher than that of VA mixture.
5. Inclusion maltene had also reduced the Cantabro loss to be close to that of VA mixture, indicating an increase in the durability of the mixture.
6. The water immersion tests indicated that, in comparison to VA mixture, the rejuvenated asphalt appeared to be less susceptible to the effect of water. Coating test showed an increase in the percentage of coated aggregate after inclusion maltene, as a result of softening the RAP binder after rejuvenation.
7. The incorporation of 12% maltene for rejuvenation of HMA containing 40% of RAP was indeed suitable and cost-effective to recycle pavement.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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