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Evaluation of recycled asphalt mixtures rejuvenated with Madhuca longifolia (Mahua) oil

Sujit Kumar Pradhan[a]*, Umesh Chandra Sahoo[b]

[a] *Indira Gandhi Institute of Technology Sarang, Odisha, India*
[b] *Indian Institute of Technology Bhubaneswar, Odisha, India*

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Abstract

Reuse of reclaimed asphalt pavement (RAP) material not only leads to environmental sustainability, but also lowers down the of construction cost. However successful addition of RAP is limited to replacement level of 50%, as it is believed that higher quantity of the RAP makes the asphalt more susceptible to fatigue and thermal cracking. Studies on rejuvenation of aged binders recommend that it is possible to use higher percentage of RAP by using recycling agents or rejuvenators. Different types of oils such as vegetable oil, tall oil, cotton seed oil, waste engine oil, pongamia oil and soybean oil etc. have been explored as rejuvenators. In this study, Madhuca longifolia oil (Mahua oil), another oil produced largely in eastern part of India has been assessed as a potential rejuvenator to design recycled Hot Mix Asphalt (HMA) with high RAP content. Suitable dosage of the rejuvenator was decided based on the evaluation of rheological characteristics of the rejuvenated aged binder using a Dynamic Shear Rheometer (DSR). Performance of the conventional asphalt mixture and rejuvenated mixtures containing RAP with varying (30-70 %) RAP percentages was assessed in terms of volumetric properties, indirect tensile strength, moisture sensitivity, resilient modulus, rutting, fatigue, low temperature cracking. Results were compared with the performance of recycled HMA made using softer binder grade. Results indicate that recycled mixtures with RAP content up to 60% can be successfully designed with addition of Madhuca longifolia oil to meet the without notably influencing the performance of the pavement.

Keywords: Reclaimed asphalt pavement; Recycling; Sustainability; Rejuvenator; Mahua oil; Softer binder

1. Introduction

About 80% of the pavements across the globe are asphalt pavements, which are normally designed for a period of 15 years. However due to overloading, the asphalt pavements in India are experiencing various distresses causing failure of these pavements. In urban areas, the top few centimeters of asphalt is usually scarified to overlay with fresh mix and to match the adjacent geometrics of the road. This results in huge quantity of RAP material produced every year from pavement maintenance. Effective utilization of this RAP to make new HMA mixtures not only leads to environmental sustainability in terms of saving natural resources and reduced energy consumption, but also lowers down the of construction cost. The main problem for utilizing high percentages of RAP in producing new asphalt pavement is due to the presence of aged binder. This aged binder makes high quantity RAP mixture highly susceptible to fatigue, cracking etc. As the quantity of RAP increases, content of the aged binder also increases that affects the performance characteristics which leads to pavement failure. To alleviate this problem, rejuvenators or softer binder added which help in restoring the performance properties of aged binder in RAP. Rejuvenator softens the aged binder by increasing the maltene content.

Two methods are generally adopted to reuse the aged binder in the recycled mixtures to match the performance with the virgin binder, i.e. use of a softer binder with lower PG or by adding a rejuvenator (usually a low viscosity oil) that is capable of restoring the initial rheological properties of the aged binder and help replacing the oils lost during hardening. Different types of rejuvenators have been tried, out of which the oil type rejuvenators have shown promising results in restoring the original binder properties as discussed below. Different oils i.e. waste cooking oil, vegetable oil, cotton seed oil, palm oil, soyabean oil and pongamia oil etc. have been studied by various researchers as potential rejuvenators.

Addition of rejuvenators improve the cracking resistance, rutting resistance and durability of the RAP mixes, which indicates that the rejuvenators reduce the stiffness of the aged binder [1]. Rejuvenators have the ability to recuperate the penetration, softening and ductility of aged binder to an extent to virgin binder, improvement in the workability, flow properties of rejuvenated asphalt, extended fatigue life and improved low-temperature

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* Corresponding author

E-mail addresses: skp14@iitbbs.ac.in (S. K. Pradhan); ucsahoo@iitbbs.ac.in (U. C. Sahoo).

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characteristics with increase in the dosage of waste vegetable oil [2,3].

Waste cooking oil (WCO) as an alternative rejuvenator for aged asphalt by comparing the physical, chemical, and rheological properties of aged asphalt and achieves better rejuvenating effective in resemble with original bitumen [4,5]. Polanga oil effectively rejuvenate the aged binder in attaining the desired rheological properties in level with virgin binder [6]. Positive softening effect of acrylated epoxidized soybean oil (AESO), cotton seed oil on the asphalt binder with minimization of viscosity used for softening of the aged binder, potential of reducing the complex modulus of binder, failure temperature, rutting, viscosity which may result in the advantage of reducing mixing and compaction temperatures and better elastic recovery [7-10]. Another rejuvenator developed using rubber oil, plasticizer and anti-ageing agent was established and reported improved non-recoverable creep compliance value and better ageing resistance, enhancing thermal cracking resistance and reduce the ageing speed of the rejuvenated binders [11]. Crude tall oil derived from the paper industry, mix of different chemical, and organic refined additive also resulted in improved rheological behaviour of aged asphalt, modify the bitumen chemistry and has the potential to restore rheology and chemical components of aged bitumen [12]. It is possible to construct high-quality HMA by utilizing RAP up to 50% with addition of rejuvenators that encounters appropriate volumetric and performance properties with no notable variability in mechanical properties between the recycled and virgin mixture as the rejuvenators improve the workability of mixture [13]. Stiffness of asphalt mixtures improves with addition of RAP up to 40% [14]. Good stripping, rutting resistance for mixtures containing 50% RAP with and without the addition of rejuvenator can be achieved. The study also observed better rutting performances for rejuvenated mixtures than those with softer binder [15]. Cracking resistance and stiffness of HMA mixtures with addition of RAP in the range of 20 to 40% and reported decrease in fatigue life with increase in RAP content [16]. Another comparative study carried out between rejuvenated HMA containing 50% RAP and conventional HMA with 20% RAP reported enhanced properties of rejuvenated mixtures [17]. Low and intermediate temperature cracking resistance also improved by addition of the rejuvenator. Blends containing RAP and rejuvenator produced superior mechanical and rutting performance properties than blend containing RAP and softer binder. Using waste oils (waste engine oil and waste vegetable oil) made viable to use large quantity of RAP which increases rutting [18,19], reduction in tensile strength, decrease rutting, improve cracking resistance and improve fatigue resistance [18,20]. Different commercial rejuvenator utilized in the RAP mixture which decrease or increase in rutting resistance, improved cracking resistance [21-23], improve fatigue life [24] and TSR value lies within limits [19,22,23]. Also asphalt with high RAP content (70% RAP) was evaluated with and without bio-based rejuvenating agent which shows stiffness modulus higher than the control mix but having low temperature cracking susceptibility [25]. About 70-80% of RAP can be utilized in the surface courses without adverse effects [26].

Many investigations also presented that compared to non-rejuvenated RAP mixes, rejuvenated mixes are less brittle and more durable.

In this study, Mahua oil (Biological name: *Madhuca longifolia*), a non-edible oil produced largely in the eastern part of India was used as a potential rejuvenator to improve the properties of the aged binder. The study assessed the performance of recycled HMA at varying proportions of RAP (30%-70%), with addition of the rejuvenator and a softer binder. Resilient modulus, indirect tensile strength, rutting, fatigue, semicircular bending and moisture susceptibility tests were carried out on the HMA samples to assess their performance.

2. Materials and methods

2.1. Materials

2.1.1. RAP and virgin binder

Binder content in the RAP was determined as per the process laid down in ASTM [27] using a centrifuge extractor. Subsequently, the binder was recovered by separating the solvent using a rotary evaporator as per ASTM guidelines [28]. The percentage of binder in the RAP was found to be 3.64%. However it was separated into two categories, i.e. coarse fraction (retained on 4.75 mm sieve) and fine fractions (passing 4.75 mm sieve). For coarse fraction the binder content was separately found to be 1.58% and for fine fraction it was 2.06%.The recovered binder was then subjected to further testing for characterization. Virgin binder of grade AC30 and softer binder grade obtained from Indian Oil Corporation Limited, were used in the present study. Basic properties of the RAP and virgin binders are shown in Table 1.

2.1.2. Rejuvenator

Mahua oil was extracted from the Mahua seeds (Fig.1) of an Indian tropical tree found largely in the eastern India. This tree is locally called as mahuwa, mahua or mohulo and available in large quantity in the state of Odisha (21º 32'17.9340" N, 84º 43' 44.1948"E), West Bengal and Jharkhand.

Mahua seeds usually contain up to 50% oil. Mahua seeds are first broken and flaked and then the resulting flakes are dried for 15 days for removal of moisture up to 0.01%. After that, it is taken to an expeller (locally known *Ghani*) for oil extraction. The total cost involved starting from collection of seeds to extraction of oil is about 0.5 US$ per one liter of production of this oil. The physical

Table 1
Primary properties of binders

Characteristics	Unit	Virgin binder (AC30)	RAP binder
Penetration at 25°C	mm	62	28
Kinematic viscosity at 135°C	cSt	380	259
Softening point	°C	48	62
Ductility at 25°C	cm	More than 100	18
Flash point	°C	220	228

Fig. 1. Photograph of Mahua seeds and oil.

and chemical properties of the oil are provided in Tables 2 and 3 respectively.

2.1.3. Blend preparation

For rejuvenation, RAP binder was heated at 135°C for 45 minutes and then rejuvenator was mixed by simultaneous heating and mechanical stirring for a minimum period of 30 minutes.

2.1.4. Virgin aggregate and RAP aggregate

The RAP used in this study was obtained from a stretch of a state highway SH 60 (location: Cuttack, India, 20°8'29.6268"N 86°3'32.9688"E), which was approximately 7 to 9 years of old. The fresh aggregates used in the control HMA are crushed granites obtained locally, that meets the requirement of high quality HMA**.**

2.2. Methodology

2.2.1. Characterization of the binders

Characterization of the extracted RAP binder, virgin binder and rejuvenated binder was carried out as per the methodology presented in Fig.2.

2.2.2. Experimental programme for the mixtures

Fig. 3 shows the experimental programme conducted for mix design and performance assessment of the asphalt mixtures.

Table 2
Physical properties of Mahua oil.

Property	Unit	Mahua oil
Density	kg/m^3	890
Specific gravity	-	0.905
Kinematic viscosity at 40°C	mm^2/s	35.26
Flash point	°C	234

Table 3
Chemical composition of Mahua oil [29].

Composition	Content
Palmitic acid	21.36%
Stearic acid	18.97%
Linoleic acid	19.47
Oleic acid	38.98%
Linolenic acid	0.16%

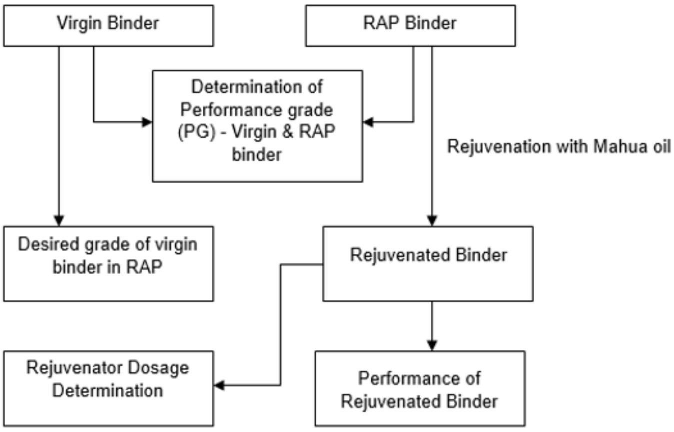

Fig. 2. Experimental programme for the binders.

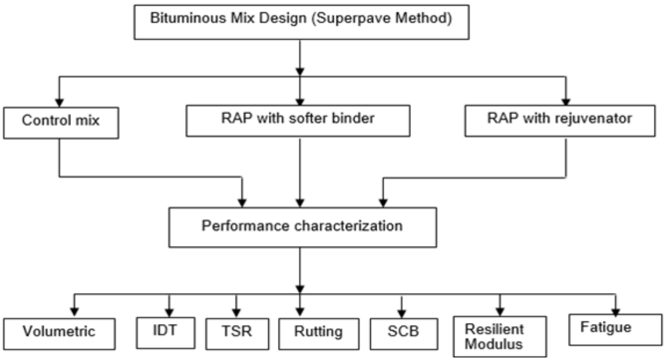

Fig. 3. Experimental programme for the mixtures.

2.2.3. Mix design

Control mix was prepared using the virgin materials and the recycled mixtures were prepared at varying (30-70%) RAP content with addition of the rejuvenator and the softer binder. All the mixtures are targeted to meet the required volumetric properties, i.e. voids in the total mix (3.0–5.0%), voids in the mineral aggregates (VMA ≥13%), voids filled with asphalt (VFA: 65–75%) and compaction parameters (% Theoritical maximum specific gravity (G_{mm}) at Initial number of gyrations ($N_{initial}$) ≤89, % G_{mm} at Maximum number of gyrations (N_{max}) ≤98) and dust to binder ratio (0.6-1.2%). Superpave asphalt mix design (with $N_{initial}$ = 8, N_{design} = 100 and N_{max} = 160 gyrations) was followed according to [30] for 12.5 mm nominal size aggregates. The control mixture contains neither RAP nor the rejuvenator. First series of mixtures prepared using the softer binder are designated as R30, R40, R50, R60 and R70 which contain 30%, 40%, 50%, 60% and 70% RAP respectively. The second series of the mixtures prepared using the rejuvenator are designated as R30M, R40M, R50M, R60M and R70M for similar replacement levels of RAP. The RAP gradation was assorted in the stockpiles, the recycled mixtures were prepared in the laboratory by sieving, weighing and mixing with different percentages replacement of virgin materials by RAP. Fig. 4 presents the particle size distribution of all the mixtures, which shows that all of them satisfied the requirements of the superpave specification as mentioned in Table 4. Table 5 presents the mix gradation for different percentages of RAP.

2.2.4. Indirect tensile strength (ITS)

Fatigue cracking in asphalt pavement is associated with the tensile strength of an asphalt mixture. It indicates that flexible pavement can sustain higher strain before it fails in fatigue. ITS of

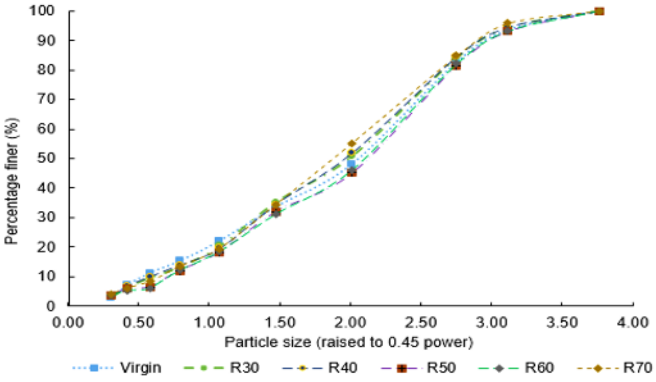

Fig. 4. Grain size distribution of mixes.

Table 4
Control and restricted points (Superpave criteria).

Sieve size	Controls		Restricted zone	
	Lower limit	Upper limit	Lower bound	Upper bound
19	100			
12.5	90	100		
2.36	28	58	39.1	39.1
1.18			25.6	31.6
0.6			19.1	23.1
0.3			15.5	15.5
0.075	2	10		

Table 5
Gradation requirements of different mix.

Sieve size(mm)	Virgin	R30	R40	R50	R60	R70
19	100	100	100	100	100	100
12.5	93.56	94.22	94.52	95.21	95.32	95.8
9.5	82.61	84	84.45	83.65	84.25	84.75
4.75	48.14	50.84	51.98	50.87	52.08	55.24
2.36	33.54	35.22	34.44	36.22	35.34	34.25
1.18	22.12	20.42	19.55	21.01	19.35	19.45
0.6	15.26	13.43	14.02	13.22	13.01	13.4
0.3	11.18	9.71	10.05	10.06	8.72	8.2
0.15	7.15	6.58	6.87	6.85	6.35	6.14
0.075	2.95	3.21	3.39	3.48	3.59	3.9

the samples of size 100 mm diameter and 63.5 mm height were measured at 25 °C as per the method given in [31].

2.2.5. *Moisture sensitivity*

Asphalt samples of 150 mm diameter and 95 mm thickness were used for the moisture sensitivity tests as per [32]. All the specimens were compacted using a superpave gyratory compactor at nearly 7% air voids to determine the ITS values in dry and wet state. The tensile strength ratio (TSR) was estimated as ratio between soaked strength to the dry strength. The average TSR of three specimens is reported as the measure of moisture sensitivity.

2.2.6. *Resilient modulus*

Resilient modulus (M_R) tests were conducted as per [33] to analyse the fatigue properties of the asphalt mixtures. Cylindrical specimens of diameter is 100 mm and thickness 42 mm were used for testing. Twenty percent of the peak load (obtained from the tensile strength measured at 25°C) was applied during the test. Samples were subjected to a cyclic load with fixed loading duration of 0.1 sec and rest period of 0.9 sec. Horizontal deformation was determined by connecting two linear variable differential transformers (LVDT) at the mid-point of each end of the horizontal diameter and vertical deformation was measured by attaching two LVDT at the top of the strip. The applied load and corresponding horizontal and vertical deformations were recorded. Resilient modulus was estimated using Eq. (1).

$$M_R = \frac{P_{cyclic}}{\delta_h t}(.2734 + \mu) \tag{1}$$

where, M_R = Resilient modulus of elasticity (MPa), δ_h = recoverable horizontal deformation (mm), μ = Poisson's ratio, t = thickness of specimen (mm), P_{cyclic} = cyclic load applied to specimen (*N*).

2.2.7. *Rutting potential*

To determine the rutting potential of the asphalt mixes, a wheel tracking machine was used as per the European specification [34]. Experiments were conducted at a temperature of 60°C, using 700 N wheel load. Specimens of size 305 mm x 305 mm and 50 mm thickness were compacted at 7% air voids by a roller compactor. The test was performed for 10,000 cycles of wheel and the rut depth was read from the rutting curve.

2.2.8. *Semi-circular bending (SCB)*

This method determines the fracture energy of asphalt mixes in terms of strain energy release rate by semi-circular bend geometry [35]**.** It consists of two supporting rollers at the bottom edge and a loading roller at the mid-point of the semi-circular bend. The distance between the two supports is 127 mm. SCB test generally requires a half disc with a notch having depth 25 mm, 28 mm, and 32 mm at the centre of the specimen. Load applied to the sample at a deformation rate of 0.5 mm/min. The critical value of J-integral (J_c) was calculated using Eq. (2).

$$J_c = \frac{-1}{b}\left(\frac{dU}{da}\right) \tag{2}$$

where, J_c= critical strain energy (kJ/m^2), b = specimen thickness (m), dU/da = change of strain energy with notch depth (kJ/m)

2.2.9. *Fatigue cracking*

Fatigue is considered as primary mode of failure in asphalt pavements, which results in modulus degradation of the pavement materials and evaluate the resistance to fatigue failure of asphalt mixes. Fatigue tests were conducted at 25°C in a controlled stress mode [36] at a frequency 1 Hz on cylindrical specimens of diameter of 100 mm and height 38 mm. Repeated loads were applied across the vertically diametric axis at a loading period of 0.1 sec and rest period 0.9 sec. Failure of the specimen was considered at 9 mm of vertical deformation.

3. Results and discussions

3.1. *Superpave performance grading*

DSR test was performed on the RAP binder to determine the critical high temperature. Based on rutting parameter ($G^*/sin\delta$) of unaged RAP binder ≥1 kPa.

Critical temperature was calculated as follows:

$$T_c(High) = \left(\frac{Log(1.00) - Log(G_1)}{a}\right) + T_1 \tag{3}$$

where, $T_c(High)$ = Critical high temperature; G_1 = $G^*/sin\delta$ value at a specific temperature T_1; a = slope of the stiffness-temperature curve.

Any temperature (T_1) and corresponding stiffness G_1 can be selected, but to minimize the extrapolation error, $G^*/sin\delta$ value closest to the criteria (1.00 kPa) was taken.

Similarly, based on rutting parameter of Rolling Thin Film Oven (RTFO) aged RAP binder ≥ 2.2 kPa, Critical high temperature was calculated as follows:

$$T_c(High) = \left(\frac{Log(2.20) - Log(G_1)}{a}\right) + T_1 \tag{4}$$

where, G_1 = $G^*/sin\delta$ value at a specific temperature T_1; a = slope of the stiffness-temperature curve.

Any temperature (T_1) and corresponding stiffness G_1 can be selected, but to minimize the extrapolation error, $G^*/sin\delta$ value closest to the criteria (2.20 kPa) was taken.

The critical high temperature of the RAP binder was taken as the lower value obtained from Eqs. (3) and (4). Then high temperature PG of the binder was determined based on the single critical high temperature.

Performed intermediate temperature fatigue testing on the RTFO–aged RAP binder to determine the critical intermediate temperature T_c (Int) based on fatigue criteria G*/sinδ closest to 5000 kPa. Critical intermediate temperature calculated as follows (Eq. (5)):

$$T_c(Int) = \left(\frac{Log(5000) - Log(G_1)}{a}\right) + T_1 \qquad (5)$$

where, $G_1 = G^*sin\delta$ value at a specific temperature T_1; a = slope of the stiffness-temperature curve.

To minimize the extrapolation error, G*sinδ value closest to the criteria (5000 kPa) was taken.

Table 6(a) presents different critical temperatures of the RAP binder. Similarly, critical temperatures of the virgin binder (target binder) were determined and presented in Table 6(b).

3.2. Rejuvenator dosage

Rejuvenator dosages was determined based on the blending chart given by Asphalt Institute MS-2 [37], considering the binder rutting and fatigue cracking. The dosage required to achieve the target binder of PG70-X are presented in Table 7.

The dosage of the rejuvenator needed for the RAP binder to achieve the target binder of PG70-28 was determined using blending chart technique. Blends were prepared by mixing the rejuvenator with RAP binder at varying percentages such as 2, 4, 6, 8, 10, 12, 14, 16 and 18 % by weight of the RAP binder. Then the rutting parameter and fatigue parameter of all the blends were found from DSR testing using the SHRP criteria as given in Table 7.

To control the rutting and fatigue cracking, dosage of the rejuvenator should be less 12.1% and more than 4% respectively. As the optimum dosage lied between 4% and 12%, further studies were conducted at three different dosages, i.e. 4%, 8% and 12%. Considering economy, the minimum percentage of the oil that satisfied all the criteria was chosen as the optimum dosage of the rejuvenator, which was found to be 4%. Therefore, 4% Mahua oil was further used in preparing all the recycled mixes in this study.

3.3. Desired grade of soft virgin binder

Asphalt Institute MS-2 [37] provides guidelines for selection of an asphalt binder grade to use in HMA containing RAP. The recovered binder from the RAP was found to be PG87-X (Actual) and according to [38] PG82-X. The Asphalt Institute recommends to select the binder grade based on the blending chart based using Eq. (6), in case the use of RAP is more than 25% in the asphalt.

$$T_{virgin} = \frac{T_{blend} - (RPBR \; X \; T_{RAP})}{1 - RPBR} \qquad (6)$$

where, T_{virgin}: required critical temperature of virgin binder, T_{blend}: critical temperature of blended binder grade of PG70-X, RAP pavement binder ratio (RPBR): (0.3, 0.4, 0.5, 0.6, and 0.7 in case of 30, 40, 50, 60, and 70% RAP), T_{RAP}: critical temperature of recovered RAP binder

Table 8 presents the required grades of the softer binder for different recycled mixtures to achieve the target binder grade PG70-X. It may be seen that for R30 and R40, the required virgin binder grade is one grade softer than the target binder grade. However, for R50, R60 and R70, it is two grade, three grade and four grade softer than the target binder grade respectively. Therefore for all the mixes (R30 to R70), softer binder grade of required grade was added to the respective mixture and for control mixture the binder grade used was AC30 (PG 70-X).

3.4. Volumetric properties

Table 9 presents the volumetric properties of all the asphalt mixes. For each mix design, the optimum binder content (OBC) was determined considering the desired air voids after the specified number of gyrations. It may be observed that the average OBC of the recycled mixes reduced slightly with increase in the RAP percentage.

Table 6(a)
Critical temperature of recovered RAP binder.

Aging	Property	Critical Temperature (°C)	
Unaged(Original)	G*/sinδ	High	87°C
RTFO	G*/sinδ	High	88.1°C
PAV	G*sinδ	Intermediate	34°C

Table 6(b)
Critical temperature of Target binder.

Aging	Property	Critical Temperature (°C)	
Unaged	G*/sinδ	High	70.8°C
RTFO	G*/sinδ	High	72.3°C
PAV	G*sinδ	Intermediate	28°C

Table 7
Rejuvenator dosage to achieve Target binder PG70-X.

Failure	Criteria	Rejuvenator dosage (%)
Rutting (unaged RAP binder),at 70°C	G*/sinδ ≥ 1 kPa	RC ≤ 17.12
Rutting (RTFO residue), at 70°C	G*/sinδ ≥ 2.2 kPa	RC ≤12.1
Fatigue Cracking (RTFO+PAV residue), at 28°C	G*/sinδ ≤ 5000 kPa	RC ≥ 4

Table 8
Target virgin binder grade.

Recovered RAP binder	Process	Target binder grade	RAP	Target softer binder grade
PG87-X (Actual) PG82-X [37]	Blending chart technique	PG70-X	R30	PG64-X
			R40	PG64-X
			R50	PG58-X
			R60	PG52-X
			R70	PG46-X

Table 9
Volumetric of different mixtures.

	Virgin	RAP with softer binder					RAP mixed with Mahua oil				
Specification	Control	R30	R40	R50	R60	R70	R30M	R40M	R50M	R60M	R70M
%Max density at N_{ini}	85.5	85.6	86.1	86.3	86.5	86.6	85.7	85.62	86.3	86.29	86.38
%Max density at N_{des}	95.7	95.18	95.26	95.36	95.4	94.8	95.2	95.3	95.4	95.6	94.96
%Max density at N_{max}	97.58	97.45	97.23	97.1	96.97	96.85	97.48	97.19	97.21	96.82	96.88
OBC (%)	5.5	5.4	5.36	5.31	5.28	5.24	5.3	5.28	5.25	5.23	5.21
Binder, RAP by weight of total mix (%)	Nil	1.12	1.49	1.85	2.22	2.58	1.12	1.49	1.85	2.22	2.58
Binder (%), Virgin	5.5	4.28	3.87	3.45	3.06	2.66	4.28	3.87	3.45	3.06	2.66
Gsb	2.686	2.685	2.659	2.649	2.648	2.645					
Gse	2.746	2.746	2.741	2.739	2.738	2.738					
Gmm	2.562	2.569	2.548	2.538	2.542	2.545	2.571	2.552	2.542	2.546	2.549
%VMA	13.55	13.30	13.28	13.27	13.07	13.03	13.22	13.20	13.18	13.04	13.01
%VFB	70.42	69.85	69.75	69.69	69.21	69.06	69.65	69.57	69.49	69.17	69.02
$P_{0.075}$	2.95	3.21	3.39	3.54	3.73	3.9					
P_{be}	3.39	3.45	3.52	3.57	3.61	3.71					
Dust proportion	0.87	0.93	0.96	0.97	0.99	1.05					

The average OBC of rejuvenated recycled mixes (R30M to R70M) is lower than the mixes containing softer binder as shown in Fig. 5. This may be due to the difference in viscosities of the rejuvenator and the softer binder. Viscosity of the oil is less compared to softer binder.

Usually, the temperature at which RAP and rejuvenator are mixed and compacted is less than the temperature at which rejuvenator is thermally stable. This ensures that at the mixing and compaction temperatures, loss of rejuvenator is negligible. However, in case of the softer binder, the binder gets aged itself during mixing and compaction, and therefore more quantity of binder is required to compensate the hardened binder.

The OBC of control mixture was found to be more than all the recycled mixes, which may be attributed to the variation of the binder consistency in the mixtures. VMA for all mixtures are found to be greater than 13% and the control mixture resulted in higher VMA as compared to all the recycled mixtures. Changing particle size distribution of a mixture influences the amount of space in the aggregate structure, and therefore lowering the dust content (lower the minus 0.075 mm) in a mixture increases the VMA. Compared to the all the recycled mixtures, the dust content in the control mixture is less. This effect may not be entirely due to gradation, but nevertheless it has one of the stronger effect on VMA.

The VMA for all rejuvenated mixtures was found to be less than with the control mixture, which indicates that VMA reduced with addition of the Mahua oil. This could be the effect of softened binder that reduces the VMA and VFA as presented in Fig. 6 and Fig. 7 respectively. It may also be the effect of extra binder content due to the incorporation of rejuvenator. This perception showed that the rejuvenator serves as a viscosity-reducing agent which enhance the workability of asphalt mixture.

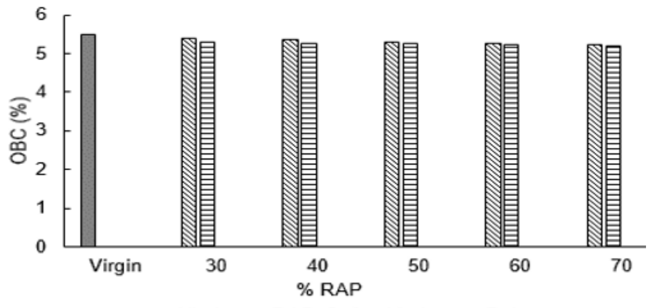

Fig. 5. Optimum binder content of various mixes.

Since the compactive effort for all the mixtures is same, variability of VMA can be due to the alternation in consistency of binder produced by the combining consequence of RAP binder and the rejuvenator. The percent voids filled with binder decreased when the rejuvenator was added to the mix compared mixes with the softer binder.

The high dust content resulted in a very thin asphalt film thickness as can be seen in Fig. 8. VMA and dust binder ratio for all the asphalt mixtures satisfied the Superpave specification criteria.

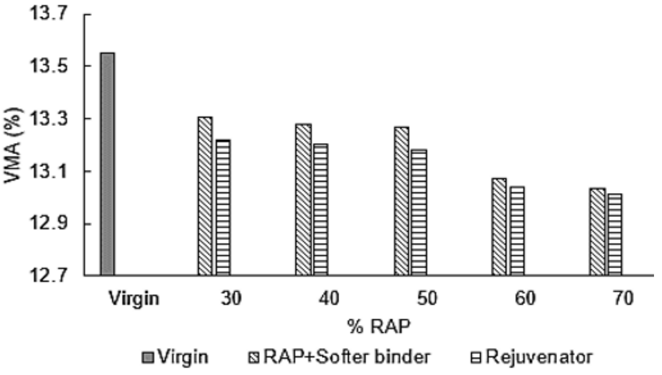

Fig. 6. VMA of the asphalt mixtures.

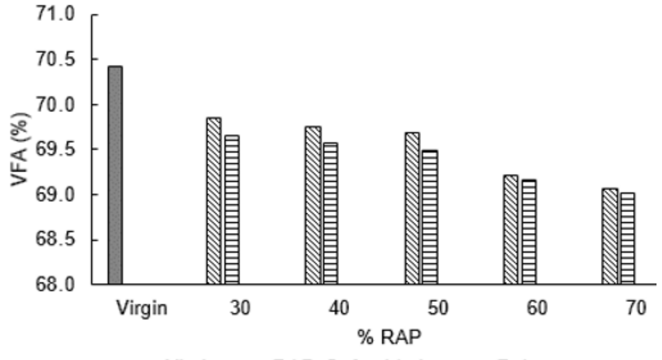

Fig. 7. VFA of the asphalt mixtures.

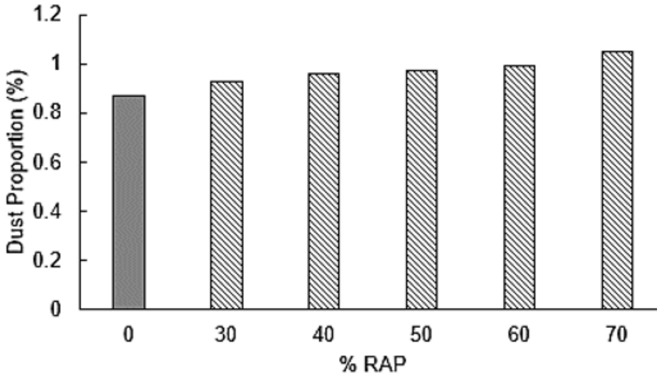

Fig. 8. Dust proportion of the asphalt mixes.

3.5. *Indirect tensile strength (ITS)*

Average ITS of unconditioned specimens are presented in Fig.9, from which it may be observed that ITS of the recycled mixtures increased with increase in the percentage of RAP. Also, it may be noticed that mixes with the softer binder showed higher values compared to the rejuvenated mixes. This may be due to presence of stiffer aged binder in the recycled mixes.

The ITS values of the mixtures prepared with the virgin AC30 binder and softer binder was found to be 1.05 MPa and 0.82 MPa respectively. When softer binder was used in the RAP mixes, ITS values increased by 7%, 32%, 43%, 54% and 70% for 30%, 40%, 50%, 60%, 70% RAP mixtures compared the control mix with AC30 binder. However in case of rejuvenated mixes, ITS value increased by 3.80%, 21.90%, 34.28%, 49.52% and 60% for same replacement levels. A decrease in the ITS values for rejuvenated mixes may be attributed to the softening effect of Mahua oil to certain extent [17,39]. Due to the presence of some polar group chemical compounds in the rejuvenator, it has the ability to dissolve the asphaltenes in the aged binder. The chemical reaction between the polar group of the rejuvenator and asphaltene molecules helps to restore the colloidal structure of the aged binder. However, dissolving effect of the softer binder is less as compared to the rejuvenator.

3.6. *Moisture sensitivity*

It may be seen from Fig.10 that all the mixes satisfy the minimum TSR value of 80% [30]. Previous studies [15] also reported that rejuvenated mixes with higher RAP content have better resistance to moisture damage compared to control mixture or the mixture with lower RAP content. This indicates that the use of rejuvenators do not influence the resistance to moisture damage. However, it may be observed that with increase in RAP content, TSR values decreased. This indicates that inclusion of RAP increases the viscosity of binder, and eventually stiffen the mixture. This effect may result in excessive hard and brittle behaviour, a binder with lower adherence ability, and a mixture with decreased moisture susceptibility.

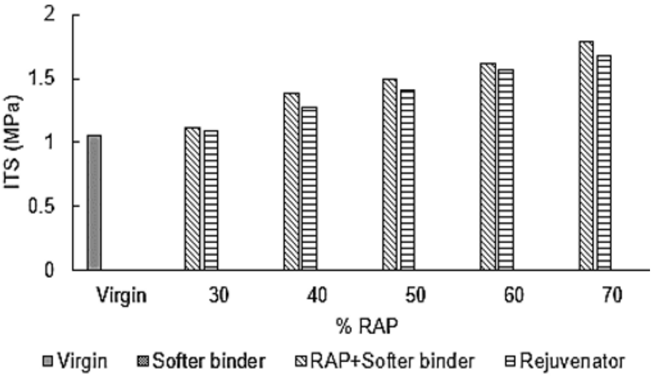

Fig. 9. Unconditioned ITS values of all the asphalt mixes.

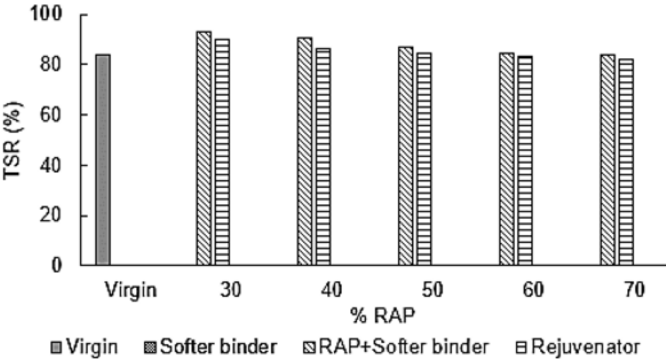

Fig. 10. Tensile strength ratio of different mixes.

In case of rejuvenated mixes, the oil leads to weakening of the bond between the bitumen and the aggregate. Therefore the moisture reaches to the aggregate-binder interface and displaces the asphalt binder from the aggregate surface. This leads to the reduction of the adhesive bond between the aggregate and binder, or breakage of the bond in severe conditions [40].

3.7. *Rutting potential*

Fig. 11 shows the average rut depth obtained from the wheel tracking test of all the asphalt mixtures. A limiting criteria of 12.5 mm rut depth after 10,000 cycles for a 7% air void roller compacted sample was adopted according [34]. Rut depths for all the mixtures were within the specified limits. With the increase in RAP content, rut depth decreases. The rejuvenated mixes were found to have more rutting depth as compared to the recycled mixes made with the softer binder. Maximum deformation of 6.63 mm was observed in case of the mixture made with only the softer binder and 4.46 for the control mixture containing the target virgin binder. This may be attributed to the lower stiffness of the mixtures in case of virgin binders.

Table 10 presented the Conditioned and unconditioned strength of all asphalt mixes.

Table 10
Conditioned and unconditioned strength of all asphalt mixes.

Sample	Virgin	Softer binder	R30	R40	R50	R60	R70	R30M	R40M	R50M	R60M	R70M
Unconditioned (MPa)	0.98	0.76	1.03	1.3	1.39	1.54	1.65	0.99	1.15	1.27	1.39	1.57
Conditioned (MPa)	0.82	0.62	0.96	1.18	1.21	1.3	1.38	0.89	0.99	1.07	1.16	1.29
TSR (%)	83.67	81.58	93.20	90.77	87.05	84.42	83.64	89.90	86.09	84.25	83.45	82.17

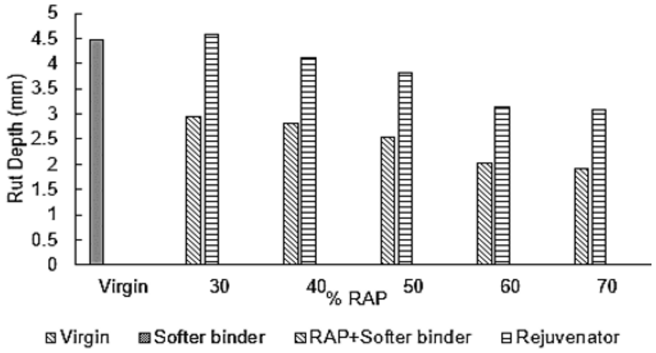

Fig. 11. Rut depth from wheel tracking device.

3.8. *Semi-circular bending test*

Higher critical strain energy (J_c) is preferable for fracture-resistant mixtures. A minimum J_c value of 0.50 kJ/m^2 is considered as a failure criterion. Fig. 12 presents the J_c values obtained from semi-circular bending tests for all the asphalt mixtures. It may be seen that as the RAP percentage increases, the J_c of the asphalt mixtures decreases. This indicates that with decrease in the fracture energy, sensitivity of the mixes to thermal cracking increases [41]. It may be concluded that incorporating RAP in HMA leads to decrease in the J_c values and therefore it needs to be considered in the design of RAP mixtures. It may also be observed that all the recycled mixtures performed well and passed the design criteria along with the control mixture. However, the mixtures containing 70% RAP with or without recycling agent failed the design criteria. This may be a problem as higher strength and lower fracture energy results in a brittle mixture.

Inclusion of the rejuvenator affected the intermediate temperature properties and increased the critical strain energy, which indicates improvement in the resistance to fracture damage over the mixture without containing rejuvenator.

Fracture energy can be directly calculated by dividing the work of fracture by the ligament area (product of ligament length and thickness of the specimen) of the SCB specimen prior to testing as given below:

$$FE = \frac{W_f}{A_{Lig}}$$

where, FE = Fracture energy (J/m^2); W_f= Work of fracture (J); A_{Lig} = Ligament area (m^2); A_{Lig} = (r-a) t; r = specimen radius (m); a = notch length (m); t = specimen thickness (m);.

Fracture energies calculated for all the mixtures with different notch lengths are presented in Figs. 13 and 14.

3.9. *Resilient modulus*

From Table 11, it may be observed that incorporation of RAP increases the resilient modulus of the recycled HMA. This implies that stiffer blend and lower fatigue cracking resistance of the mixes occurred due to the high RAP content. Mixes containing 30 to 70% RAP with softer binder showed lower but acceptable variation in modulus in comparison with the control mixture. Modulus values of rejuvenated mixtures are found to be less than the recycled mixtures made with the softer binder similar to the observations by other studies [17,39].

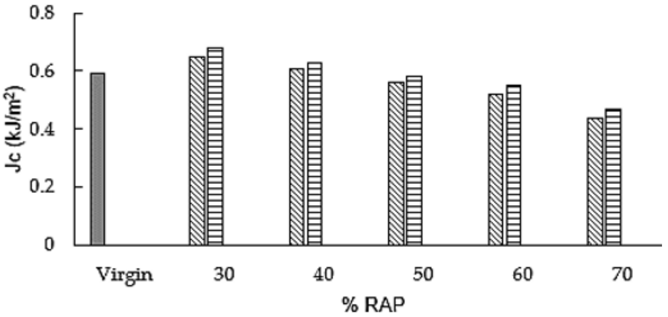

Fig. 12. Strain energy value of RAP and rejuvenated RAP mixes.

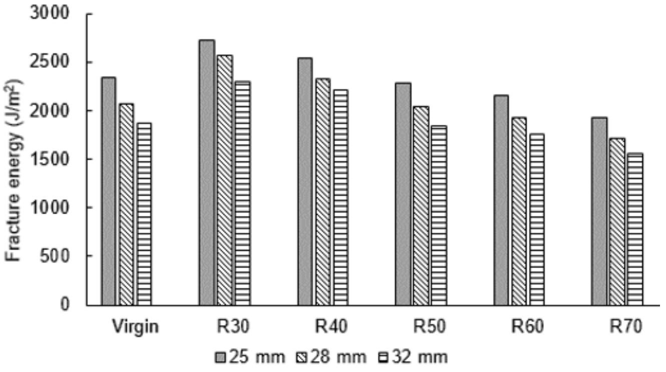

Fig.13. Fracture energy for different notch depth for RAP containing softer binder.

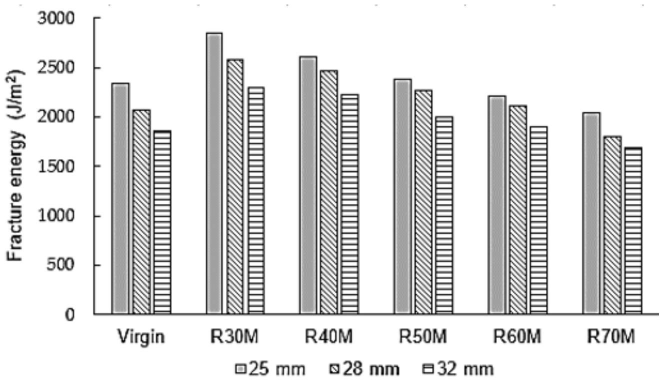

Fig. 14. Fracture energy for different notch depth for rejuvenated RAP.

Table 11
Modulus value of mixes.

Mix without rejuvenator	Resilient modulus, MPa	Mix with rejuvenator	Resilient modulus, MPa
V	4790	-	-
S	3230	-	-
R30	4850	R30M	4819
R40	5436	R40M	5126
R50	6120	R50M	5741
R60	6982	R60M	6253
R70	7258	R70M	6788

3.10. Fatigue cracking

Fig. 15 shows the results from the indirect tensile fatigue tests (ITFT). Enhancement in the fatigue life of asphalt mixture with incorporation of RAP was noted in comparison to the control mixture [42]. As the percentage of RAP in the mix increased, the nature of failure of the specimens was observed to be increasingly brittle. This could be the reason of increased stiffness in the mix and the relatively smaller crack propagation lives. A significant reduction in the fatigue life was observed in the recycled mixes with 70% RAP content as compared to 60% RAP mixture. While the quality of the binder is represented, to a certain degree in terms of the resilient modulus of the mix, the thickness of the film also will have a crucial effect on the fatigue life. Probably, the fatigue lives increase with increase in the film thickness. As fine aggregates have a thicker film than the coarser aggregates [43] and in case of 70% RAP, due to lower film thickness, the fatigue life may have reduced.

Inclusion of rejuvenator enhanced the fatigue life of the rejuvenated mixtures compared to recycled mixtures made with the softer binder. Reduced stiffness of the rejuvenated mixtures can be the primary cause for their increased fatigue lives. Also, the mixes with mahua oil fulfilled the lower air voids requirement, which is believed to be the cause of higher fatigue life of the rejuvenated mixtures. It may be concluded that the rejuvenator has the ability to improve the fatigue performance.

HMA should have an appropriate film thickness around the aggregate to ensure durability (resistance to ageing) of the mixture. Film thickness is a function of surface area of aggregate and the percentage of binder used in the mixture. For particles of size > 4.75 mm, 4.75 mm, 2.36 mm,1.18 mm, 0.6 mm, 0.3 mm, 0.015 mm and 0.075 mm, the surface area factors are 0.41, 0.41, 0.82, 1.64, 2.87, 6.14, 12.29, 32.77 respectively. Then surface area (SA) is calculated by multiplying percentages passing the sieve and surface area factor [37]. Film thickness (according to NCAT) was determined by the formula given by Eq. (7).

$$\text{Film thickness} = \frac{\text{Effective volume of asphalt}}{\text{Weight of aggregate X SA}} \qquad (7)$$

where, Film thickness is expressed in µm, effective volume of asphalt in m^3, surface area in m^2/kg and weight of aggregate in kg.

Table 12 shows the film thickness for all the mixtures. With increase in RAP content up to 60%, film thickness increased and afterward decreased, even below the control mixture. Asphalt film thickness can be used to guarantee an appropriate effective asphalt volume (V_{be}) in the asphalt mixtures. Film thickness determination is based on the aggregate surface area (SA) and V_{be}. The minimum V_{be} essential for appropriate film thickness depends upon the aggregate's surface area (presented by the particle size distribution).

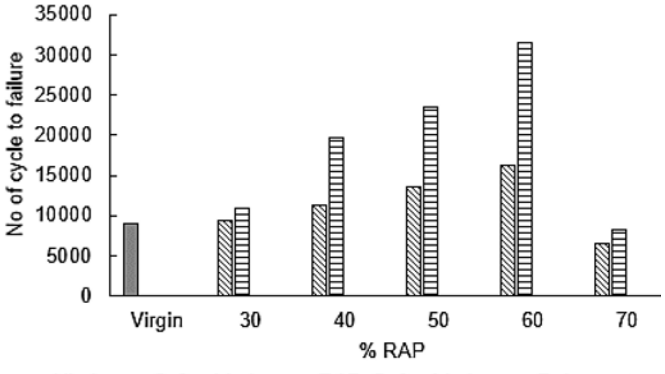

Fig. 15. Fatigue lives of the asphalt mixes from ITFT.

Table 12
Film thickness of control and RAP mixes.

Mix	Control	R30	R40	R50	R60	R70
Film thickness in µm	11.79	11.86	12.52	12.54	12.61	11.29

The fatigue lives were observed to increase with increase in the film thickness. A study by John W.H. Oliver [44] also reported that increase in film thickness increases the fatigue life of the asphalt at different air voids level.

4. Conclusions

This research focussed on evaluating the effect of Mahua oil as a potential rejuvenator for the recycled HMA in terms of different performance tests. Some of the critical observations made from this study are as follows:

1. With increase in the RAP content, ITS and resilient modulus values increased, which is attributed to the presence of stiffer aged binder in the recycled mixes.
2. In terms of moisture sensitivity, all the mixtures achieved in an acceptable range of TSR value.
3. From wheel tracking test, all the recycled mixes showed lower rut depth compared to the control mix. However, the rejuvenated mixes showed higher rut depth compared to the recycled mixes made with the softer binder, which may be due to softening effect of the rejuvenator.
4. Low temperature cracking tests using SCB showed higher critical strain energy for rejuvenated mixes.
5. Higher fatigue lives were recorded for rejuvenated mixtures except for the mixture containing 70% RAP, which may be attributed to aggregate gradation and reduction in asphalt binder film thickness. This may be a case of higher strength and lower fracture energy, which resulted in a brittle mixture.

From the above observations, it may be inferred that asphalt containing RAP up to 60% and rejuvenated with about 4% Madhuca Longifolia oil can be endorsed without notably influencing the performance of the pavement based on the laboratory performance test. For higher RAP utilization, it is necessary to ensure better quality control in terms of gradation, adequate temperature and uniform mixing in producing the recycled mixes. Therefore Mahua oil, as rejuvenator may allow incorporation of higher RAP content through hot in- plant recycling process.

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