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Assessing the Performance of Recycled Asphalt Mixtures Using Rejuvenators

Sameer Ahmed Mufti[a], Fazli Karim[b*], Qaiser Iqbal[a], Sher Afzal Khan[b], Hanif Ullah[b], Shahid Iqbal[c], Noman Khan[b*], Diyar Khan[d]

[a]*Creative Engineering Consultants, Peshawar, Pakistan*

[b]*Department of Civil Engineering, Sarhad University of Science & Information Technology, Peshawar, Pakistan,*

[c]*University of Technology, Nowshera,*

[d]*Department of Road Transport, Faculty of Transport and Aviation Engineering, Silesian University of Technology, 40-019 Katowice, Poland*

**Corresponding author: engr_fazli@yahoo.com*

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ABSTRACT

After serving their intended purpose, traditional asphalt pavements are destroyed and dumped across the neighboring fields in Pakistan, affecting the natural environment. Only 15% of the old asphalt material has been recycled on the Motorway (M-2) near Shekhupura. Thus, the current study was intended to increase the amount of recycled asphalt, utilizing waste engine oil (WEO), waste cooking oil (WCO), and waste brown grease (WBG) as rejuvenators. Therefore, the asphalt mixture containing 50% recycled materials, rejuvenated with 5%, 10%, 15%, 20%, and 25% WEO, WCO, and WBG, respectively, were investigated. The asphalt samples for Marshall Stability, indirect tensile strength, and rut resistance were prepared and tested as per ASTM D1559, ASTM D979, and ASTMD8360, respectively. The results showed that WEO, WCO, and WBG of 15% and 20%, respectively, are best for equating the properties of recycled binder to those of neat binder, except for ductility characteristics. The results also demonstrated that, in comparison to the traditional asphalt mixture, asphalt mixes with 50% recycled materials performed significantly better in terms of Marshall stability at 15% utilization of WEO, WCO, and WBG, respectively. Additionally, it is established that recycled asphalt mixture, at WEO of 15%, displayed equivalent rut resistance to virgin asphalt mixture. The results of this study will help recycle old asphalt materials for practical engineering purposes, lowering the dependence on natural resources and benefiting the environment.

Keywords: Recycled asphalt materials marshall mix design; rejuvenators; moisture susceptibility; rutting resistance

INTRODUCTION

Traditional asphalt pavements are demolished once they have served their purpose and are then thrown by the roadside or scattered across nearby areas, according to existing practice in Pakistan. The ecosystem is harmed by this practice in addition to the squandering of natural resources. When bitumen oxidizes as a result of exposure to the environment and traffic, substances known as Saturates Aromatics, Resins, and Asphaltenes (SARA) are released. So far, only 15% aged asphalt material has been recycled on Motorway (M-2) near Shekhupura as per guidelines for asphalt recycling in Pakistan. This low percentage of asphalt recycling is particularly due to lack of research because of poor linkages between academia and industry. Therefore, the current research was aimed at expanding the quantity of asphalt recycling in Pakistan using Waste Engine Oil (WEO), Waste Cooking Oil (WCO), and Waste Brown Grease (WBG) as rejuvenators. The major objective of utilizing rejuvenators in recycled asphalt materials is not only to recycle old asphalt materials for beneficial technical uses but also to reduce environmental pollution. The use of rejuvenators in asphalt recycling has significant sustainability advantages over other conventional asphalt building materials. These benefits include resilience to dangers like fire, thermal stress, and local availability, as well as strength, durability, and resistance to extreme weather. The paving industry has been looking for practical ways to enhance pavement performance, protect diminishing natural resources, and maintain a safe environment (Karim and Hussain 2021; Karim et al. 2021).

China leads the world in the production of WCO, with an annual output of over 826 million gallons (Kumandas et al. 2022). WCO is difficult to manage because it is regarded as a solid waste. WCO disposal or discharge into sewage systems or landfills may have negative environmental effects, clog sewers, and interfere with wastewater treatment plants' ability to pre-treat sewage (Foo et al. 2022). Rehabilitating the existing pavement systems has become necessary in recent years in order to provide a safe and cost-effective transportation system. Recycled asphalt pavement (RAP) is gaining acceptance as cost-effective alternative to natural occurring neat bitumen, as the price of crude oil rises. Waste that is dumped into landfills without any further processing is what has a undesirable influence on the atmosphere. Recyclable oils are emerging as a viable solution to the issues of high construction costs and the preservation of natural resources (Mufti et al. 2020). The continual rise in automobile ownership around the world has led to an expansion in WEO production, which also meets customer demand for practical mobility. China produces 1.2 billion liters of WEO yearly, but less than 20% of that is actually recycled (Kuczenski et al. 2014). The oil and grease wastes collected from six cafeterias in Malaysia ranged from 8.8 mg/L to 25.5 mg/L, according to Nurul Syazrina (2017). This indicates that cooking activities are the cause of oil and grease pollution problems, necessitating the installation of oil and grease traps at each cafeteria and recycling the wastes for beneficial engineering uses. A substantial amount of serviceable and structural illnesses impact the asphalt surface as pavement ages, and during yearly repair and reconstruction, a sizable quantity of rejuvenated modified recycled pavement is produced. Soft asphalt mixture, foam asphalt mixture, asphalt lotion, and softening agents are currently the most widely used substances for asphalt regeneration worldwide. Even these goods, though, have problems, such as high production costs, exorbitant prices, and a tendency to contaminate the environment. As a result, the asphalt surface is affected, and a significant amount of regenerated recycled pavement is produced during the yearly reconstruction and repair (Qin and Meng et al. 2021). Rejuvenator is a softening agent that primarily works by decreasing the viscosity or modulus of the aged binder. However, rejuvenation entails bringing back the asphalt fractions, lowering brittleness and stiffness, and exhibiting ageing behavior that is comparable to that of the virgin (unaged) binder. Rejuvenation has received a lot of attention in the recent several decades since it has several advantages and allows for the addition of higher recycled material in asphalt mixtures (Zahoor et al. 2021). As part of the rejuvenation process, the rheological properties of asphalt must be restored in order for the RAP binder to be considered a brand-new material. Rheological properties of asphalt binder can be recovered by rejuvenating chemicals. A rejuvenating agent is a chemical that regenerates RAP and is defined as "the ultimate products of hydrocarbon with the physical qualities to regenerate the RAP, fulfilling the requirements of the actual criteria for asphalt." In order to recover the RAP's vital components during hot mixing, a material also needs to have a high flash point. Due to the minimal volatile loss that arises from this, consistency is then required (Huang et al. 2005). Rejuvenating substances with high carbon concentrations can enhance the mechanical qualities of asphalt mixtures. By adding softeners and rejuvenators, RAP binder's stiffness could be managed. The softening agents can reduce the viscosity of aged bitumen. They often have a high percentage of maleness components. Rejuvenators have the ability to restore the asphaltenes-maleness ratio, and imparting flexibility to the recycled binder. The most significant impact on the surface of aggregates is the homogeneous diffusion of rejuvenators.

Asphalt with deteriorated basic physical qualities can be efficiently improved with WEO. As WEO content increases, aged asphalt performs slightly worse in high temperatures but better in low temperatures. The essential performance of rejuvenated asphalt is carefully considered, and it can perform just as well as the original asphalt (Zhang et al. 2022). Waste cooking oil (WCO) as a rejuvenator is gaining attention in the pavement industry to incorporate higher reclaimed asphalt (RA) in asphalt mixture. WCO can be determined to be a viable material to revitalize asphalt mixtures with a higher percentage of recycled asphalt. Additionally, research showed that moisture damage and higher temperature qualities are affected even if WCO improves low-to-intermediate temperature performance. Future research should focus on quantifying the financial and environmental benefits of recycled asphalt mixtures containing WCO, improving the transesterification process of WCO to improve its quality, understanding the rejuvenation capabilities of various WCOs and blends of different types of WCO, and conducting field performance studies (Shobhit and Chandrappa, 2023). According to Ayushi Jain (2017), a decrease in the marshal quotient caused by an increase in the rejuvenator proportion results in less stiffness of recycled asphalt mixture when a rejuvenator of 10% of the edible oil was mixed with 10% - 20% RAP in the asphalt mixture. In the presence of 10%

rejuvenator, Marshall Stability improves up to 1860 kg; making 10% the optimal rejuvenator proportion (Ayushi Jain et al. 2017). Three failure modes are connected to recycled asphalt mixtures: cohesive failure (internal failure of the asphalt), adhesive failure (failure of the interfacial zone), and aggregate failure. However, the impact of the asphalt binder film thickness on the functionality of asphalt pavements is typically disregarded, especially when the functionality falls short of expectations. Therefore, it is crucial to comprehend how the mechanical characteristics of compacted recycled asphalt mixtures are affected by the thickness of the asphalt binder layer (Karim et al. 2021). The influence of waste cooking oil and waste engine oil on recycled aged asphalt was investigated by analyzing the improvement of its rheological, chemical, and physical properties. This was done in order to investigate the relevance of waste engine and cooking oil utilized in aged asphalt. With the Thin Film Oven Test conducted indoors at 163 degrees Celsius, six aged asphalt binders with various ageing times were achieved. To further explore improved capabilities, five different dosages of waste cooking oil (WCO) and waste engine oil (WEO) were introduced. The outcomes showed that waste cooking and engine oil may successfully soften aged asphalt and restore its workability. Furthermore, if the amount of waste cooking or engine oil was appropriate, the physical, chemical, and rheological performances of six aged asphalts may be increased to the typical level of virgin asphalt. When waste cooking oil was added to old asphalt, its rheological qualities improved more than when waste engine oil was added. All things considered, waste oil would have far greater service options in the field of recycling asphalt pavement thanks to the good applicability. Additionally, it offered a way to create a novel renewing agent by combining the two waste oils to create a complex synergistic action. Additionally, it realized the protection of the environment and the cycle of waste utilization (Haibin et al. 2019). Chung et al. (2021) investigated the odour and waste concentration at the palm oil mills' and how it affected the engineering infrastructures. As a result, in order to recycle these wastes, alternative strategies must be counter proposed in the legislation drafting, and mill owners should be required to abide by safety regulations (Chung et al. 2021). According to Akabar et al. (2019), the incorrect WCO disposal is the main contributor to environmental, ecological, and municipal problems. The fifty two (52) locations of fast food restaurants in Trinidad and Tobago alone utilised 409,000 L of oil annually or 151 L each week on average. One million litres of clean water are contaminated by one litre of old oil. Third-world countries lag behind when it comes to recycling trash. A whole gallon of WCO was retrieved from a South Trinidad restaurant. According to the results, raising the ultra-clarifying face oil (UFO) dose had the same effect on stiffness reduction, and increasing the elasticity dosage. Asphalt recycling is the process of recovering the binder characteristics by adding recycling agents with high quantities of oil (aromatics, saturates). When high oil content or another type of recycling agent is put to asphalt, the asphaltenes and resins ingested and dissolved the oil. The performance of roads can be enhanced and worn-out asphalt can be rejuvenated as per wet method of mixing. The recycled asphalt concrete, which contains 100% recycled aged asphalt materials, expressively decreases the contamination produced by the manufacture and dispensation of materials to manufacture asphalt paving mixtures (Jahanbakhsh et al. 2020). Mamun and Wahab (2018) used additional RAP at greater percentages (30%, 40%, and 50%) to overcome stiffness difficulties. A mix design test was done to find the optimum binder content (OBC). The upsurge in aged asphalt material was responsible for the rigidity and lack of permanence. As a result, when using WEO, the results complied with the specifications' requirements, where WEO modified recycled mixture had a 7% higher indirect tensile strength value than other conventional materials. As a result, it was discovered that 7–13% of WEO can be used in RAP and produce the same outcomes (Mamun and Wahab, 2018). In accordance with National Highway Authority, Pakistan's standards for recycling asphalt, only 15% of the old asphalt material has been used so far on the Motorway-2 (M1), Lahore. Therefore, the current study's goal is to increase the amount of recycled asphalt in Pakistan, utilizing waste engine oil, waste cooking oil, and waste brown grease.

RESEARCH OBJECTIVES

The asphalt pavements, after fulfilling their purpose, are demolished and the leftover waste is thrown out rather than being utilized. On the Motorway (M-2) near Shekhupura, just 15% of the old asphalt material has been recycled in accordance with the present guidelines. Therefore, the current research was aimed at expanding the quantity of recycled asphalt in Pakistan, using Waste Engine Oil (WEO), Waste Cooking Oil (WCO) and Waste Brown Grease (WBG) as rejuvenators. The study aims to compare the performance of recycled asphalt binder and recycled asphalt mixture to neat binder and conventional asphalt mixtures, respectively, in terms of Marshall Stability, Moisture damage, and Rut Resistance, using WEO, WCO, and WBG as rejuvenators.

MATERIALS AND METHODS

Waste engine oil (WEO), waste cooking oil (WCO), waste brown grease (WBG) as rejuvenators, virgin aggregate from the Margalla quarry, and recycled materials from Peshawar's Ring Road comprise the materials used in the present investigation.

AGGREGATE

According to traditional index characteristics, the virgin aggregate used in the current investigation was described, as shown in Table 1.

TABLE 1. Characterization of the Margalla aggregate

Property	Reference	Value
Los Angeles abrasion value, (%)	ASTM C131	20.96
Water absorption, (%)	ASTM C127	1.03
Flakiness index, (%)	BS 933-3	12.6
Elongation index, (%)	ASTM D4791	7.8
Soundness (%)	ASTM C88	3.79
Impact Value, (%)	BS-812	11.9
Specific gravity of Coarse aggregate	ASTM C128	2.61

ASPHALT CEMENT

Table 2 lists the physical characteristics of the 60/70 penetration grade asphalt binder used in current study.

TABLE 2. Description of the 60/70 penetration grade asphalt binder

Property	Reference	Value
Penetration (25°C, 1/10th of mm)	ASTM D5	63
Softening point, (°C),	ASTM D36	56
Ductility, (cm)	ASTM D113	103
Flash and fire point, (°C)	ASTM D 3143	305°C & 312°C
Viscosity, (Pa.s)	ASTM D4402	0.412

METHODOLOGY

The experimental work was carried out at the laboratory of highway engineering of Sarhad University, Peshawar, Pakistan. Aggregates from the Margalla quarry, and 60/70 Penetration grade bitumen, collected from Attock Refinery Limited (ARL), were employed in this study. The aged recycled asphalt materials was collected from Peshawar's Grand Trunk Road (G.T. Road), where the aged asphalt surface was milled due to failures on the existing pavement surface. Before recovery of the recycle binder, optimal binder content (OBC) was determined for the conventional asphalt as per Marshall method of mix design, described in ASTM D1559. The recycled binder from the aged materials was collected using centrifuge method, and the observation recorded during the recovery of the recycled binder was presented in Table 4, provided in results and discussion section.

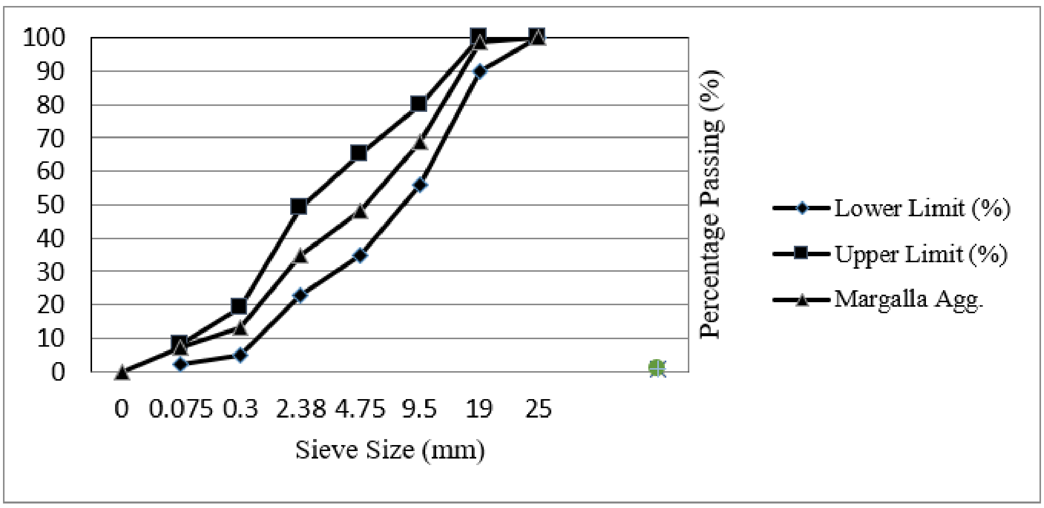

FIGURE 1. Grain size distribution curve of virgin and recycled aggregate blends

OBC already determined for the conventional asphalt mixture was further used in recycled asphalt mixture to mobilize aged binder. The resulting asphalt mixtures consisted 50% recycled materials, were rejuvenated with 5%, 10%, 15%, 20%, and 25% WEO, WCO and WBG, respectively. The combined blend of virgin and recycled aggregate was prepared as per Asphalt Institute gradation, as shown in Figure 1. The detail methodology is described in Figure 2.

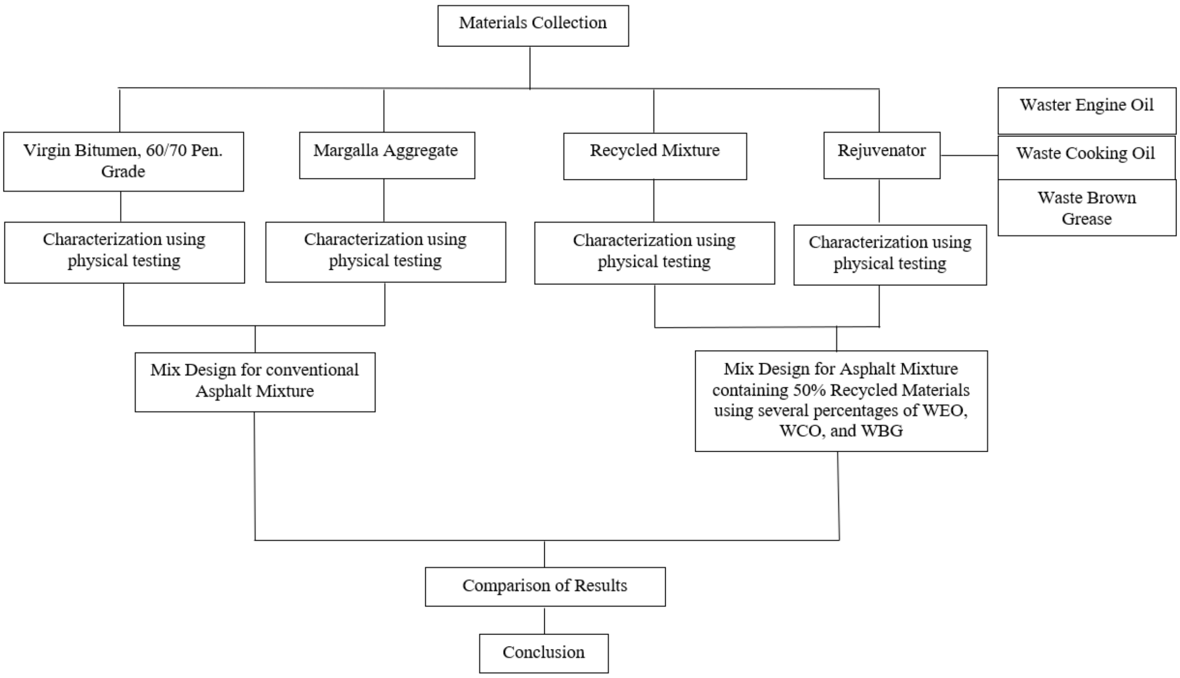

FIGURE 2. Research Methodology

Following the steps outlined in ASTM D2172, the centrifuge method was used to recover the RAP binder. The recycled binder collected from the aged asphalt materials through centrifuge method is 3.2 % by weight of Marshall Specimen. Asphalt Mixture design, following the asphalt institute (AI) gradation, as exposed in Figure 3, was prepared for the combined blend containing 50% virgin and 50% recycled mixtures, at rejuvenator content of 5%, 10%, 15%, 20%, and 25% WEO, WCO, and WBG, respectively. The aggregate sample was heated at 180 degrees Celsius for three hours. In metal pans, the RAP fractions were dispersed, and they were subsequently heated for one hour at 160 °C. The rejuvenator was sprayed on the RAP materials after the RAP binder had been mobilized, and it was allowed to diffuse in the recycled binder for 30 minutes. Separate mixtures of the binder and virgin aggregate were mixed at 160 ^{o}C. Due to the rejuvenated RAP binder's temperature-viscosity relationship, the virgin and rejuvenated recycled mixtures were combined at a mixing temperature of 160 ^{o}C. For the mix design of recycled mixes, the percentage of virgin binder required was calculated using Equation (1).

$$P_{nb} = \{(100^2 - rP_{sb})Pb/100(100-P_{sb})\} - \{(100-r)P_{sb}/(100-P_{sb})\} \quad (1)$$

where:

P_{nb} = Stated as a whole number, fresh asphalt binder percentage in recycled mix,

r = New aggregate represented as a percentage of the entire amount of aggregate in the recycled mixture,

P_b = Estimated asphalt content of recycled mix, based on the assumption that it is identical to 100% virgin HMA mixture.

P_{sb} = Percent binder content of recycled mixture.

Total 270 (90×3) number of samples containing neat binder and recycled binder at various rejuvenator contents were prepared to determine the consensus properties as presented in table 5. Total sixty (60) number of Marshall briquettes containing 50% virgin and 50 % recycled aggregate were prepared at each rejuvenator content of 5%, 10%, 15%, 20%, and 25% WEO, WCO, and WBG, respectively, and presented in Table 7. After determining optimum rejuvenator content of WEO, WCO, and WBG, total 30 number of samples were prepared using Marshal compactor, where 6 samples for each conventional, 50% RAP+15% WEO, 50% RAP+15% WCO, and 50% RAP+15% WBG, respectively. A cylindrical specimen was loaded across its vertical diametral plane at a deformation rate of 50 mm per minute and a test temperature of 25 °C to determine the indirect tensile strength (ITS) of bituminous mixes. The peak load upon failure was noted and utilized to determine the specimen's indirect tensile strength (IDT). After conditioning the specimen by wetting them with water from 55% to 80% while applying 13-67 KPa vacuum pressure for 5–10 minutes, moisture damage was determined. Following saturation, the samples were sealed in a plastic bag containing 10 cc of water and put in the freezer for 14 hours. After freezing, the samples were held at room temperature of 25 °C for 2–3 hours before being kept in a water bath at 60 °C for 24 hours. After that, the samples were put into the testing equipment. Equation (2) was used to calculate indirect tensile strength, while equation (3) was used to get the tensile strength ratio (TSR).

$$S\_t=2000P/_{\pi t D} \quad (2)$$

where, S_t = Tensile strength (KPa), t = thickness of the ample (mm), D = diameter of the sample (mm), and P = load (N).

$$TSR=S_{cond.}/S_{Uncond} \quad (3)$$

where, $S_{cond.}$ = Tensile strength of conditioned samples, and $S_{uncond.}$ = Tensile strength of unconditioned samples.

In order to determine rut resistance, each sample for wheel tracking test consisted 125 mm height, and 150 mm diameter, and subjected to 160 °C mixing temperature. The samples were tested under carefully controlled circumstances at a temperature of 60 °C, 10,000 revolutions of a standard wheel, and recording of the rut depth after 10,000 revolutions.

RESULTS AND DISCUSSION

The aged asphalt materials were collected from ring road, Peshawar, which was milled due to severe cracking and permanent deformation. The milled asphalt materials were subjected to centrifuge method, using carbon tetra chloride, for the recovery of recycled binder. Table 3 describes the complete observations and calculation of the recovery of recycled binder of 3.2% by weight of the Marshall sample.

TABLE 3. Recovery of Recycled binder using centrifuge method

Observations	Results
Sample's weight (prior extraction) (W_1), gram	1224
Filter paper's weight (prior extraction) (B) , gram	13.7 g
Sample's weight (After extraction) (W_2) , gram	1173.
Filter paper's weight (After extraction) (D) , gram	14.4
Filler's weight (After Extraction) ($W_{4)}$, gram	13.6
Filler's weight gathered in filter paper (B - D) = W_3, gram	0.7
Aggregate weight + Filler's weight (After extraction) = $W_2 + W_3$, gram	1171.5
Recovered Bitumen '[W1 – (W2 + W3 + W4)] x 100/W1], %	3.2

After extracting the recycled asphalt binder, the consensus properties of the recycled binder, and rejuvenated recycled binder at each rejuvenating content of 5%, 10%, 15%, 20%, and 25% respectively, were determined, and presented in Table 4. As it is well known that penetration refers the degree of hardness and softness of a particular asphalt binder, therefore, while looking at the findings presented in Table 4, it can be seen that when 5%, 10%, 15%, 20%, and 25% WEO, WCO, and WBG were added to the recycled binder, the penetration values increased from 4.7mm to 7.4 mm, 4.4mm to 7.6mm, and 4.2mm to 6.9 mm respectively, as compared to that of recycled binder with penetration value of 3.9mm. WEO, and WCO of 15%, and WBG of 20% are almost optimum to accelerate the value of recycled binder's penetration to that of neat binder's penetration of 6.3mm.The mechanism behind this phenomenon of accelerating penetration's value of binder to that of virgin's binder is due to stimulation and mobility of the aged binder by the use of specified rejuvenators. WEO, and WCO of 15%, are effective in declining the values of binder's softening point to that of neat binder's softening point of 56 °C. This declining in softening point is attributed to the thinning behavior of WEO, and WCO when used as rejuvenators. However, the WBG did not show any satisfactory performance to decline softening point comparable to that of neat bitumen. Any percentage of the aforesaid rejuvenators failed in raising the ductility of the aged binder to that of neat binder. Large percentages of the specified rejuvenators are required to improve ductility of the neat binder. However, large percentages of rejuvenators will adversely affect penetration and softening values of the aged binder. The flash and fire point showed an increasing trend by incorporating rejuvenators, none of the values of flash and fire point of the recycled binder exceeded that of neat binder. The WEO, and WCO of 15% proved to be optimum in restoring the viscosity of aged recycled binder to that of neat binder. The findings nearly coincide with the study presented by Karim, F., and

Hussain, J. (2022), where the recycled binder was rejuvenated with 3%, 6%, 9%, and 12% WEO. WEO of 12% was concluded as optimum in restoring the penetration value of recycled binder from 3.1mm

to 6.7mm, and softening point from 76 °C to 48 °C respectively. However, WEO at each specified dasage of WEO content failed to raise the ductility of recycled binder to that of neat binder. The flash and fire point showed a decreasing trend with the rise in rejuvenator content upto 12% but never reached to the value of neat binder. However, WEO of 6% proved to be optimum in restoring the viscosity of recycled binder to that of neat binder at 135 °C. Additionally, the findings broadly correspond with the research done by Zargar et al. (2012), who evaluated the consensus properties of aged bitumen of penetration grades 30/40, 40/50, and 50/60, rejuvenated with 2%, 4%, 6%, and 8% WCO. The WCO of 6% was found to be optimum in restoring the specified penetration of aged binders to that of virgin binder of 60/70, and 80/100 penetration grades. Another study that added WCO of 3% to the aged bitumen revealed similar outcomes, where the aged bitumen with a 40/50 penetration grade was restored to an 80/100 penetration grade (Abdullahi et al. 2018). The current findings partially agree to the findings of the study conducted by Dong et al. (2018). According to Dong et al. (2018), the consensus properties of recycled binder accelerate with the increase in concentration of bio-oil (WCO). The penetration value was reported to be below 90 for 3% bio-oil, 100 for 10% bio-oil, and 110 for 20% bio-oil dosage. On the other hand, when the dosage of bio-oil increased, the bio oil residue showed a rapid increase in the penetration value. The penetration values with 3%, 10%, and 20% bio-oil were 90, 120, and 160 (0.1 mm), respectively. Zargar et al. (2012) used aged bitumen (pen grade 40/50 with a softening point of 50°C) to investigate the rejuvenation capability of WCO. It has been demonstrated that the aged bitumen's softening point decreases when WCO is added. The aged bitumen's softening point value at 3% WCO dose was comparable to that of virgin 80/100 penetration grade bitumen.

TABLE 4. Properties of the recycled asphalt binder at various rejuvenator contents

Property	Recycled Binder	Recycled binder modified with rejuvenators														
		Waste Engine Oil (WEO)					Waste Cooking Oil (WCO)					Waste Brown Grease (WBG)				
		5%	10%	15%	20%	25%	5%	10%	15%	20%	25%	5%	10%	15%	20%	25%
Penetration (25°C, 1/10th of mm)	39	47	56	61	69	74	44	55	64	69	76	42	51	57	62	69
Softening point (°C)	76	70	64	57	54	51	72	61	55	50	43	74	71	67	62	51
Ductility, (Cm)	37	44	48	52	59	67	52	59	63	70	72	40	49	51	52.5	53
Flash point, (°C)	278	271	268	266	261	239	289	269	257	251	246	257	255	240	229	227
Fire Point, (°C)	285	279	276	274	270	243	299	278	270	266	261	266	261	252	236	234
Viscosity, (Pa.s)	0.664	0.551	0.447	0.414	0.353	0.301	0.594	0.514	0.419	0.384	0.332	0.451	0.397	0.354	0.301	0.298

Marshall Specimens at mixing temperature of 160 °C, and binder contents of 3.5%, 4%, 4.5%, 5%, and 5.5% by the weight of Marshall briquette, for the conventional mix, were prepared, and the OBC was calculated in accordance with ASTM D1559 methodology. Table 5 provides the volumetric properties for standard mix design that were discovered. At a mixing temperature of 160 °C, a conventional mix with an OBC of 4.42% by weight of the Marshall briquette was determined. With the prescribed flow under the design conditions, the mixtures met the lowest stability criteria of 8.0 KN. The VMA, VFA, and VTM, all met the requirements of the 14 percent (minimum), 65 percent to 75 percent, and 3 to 5 percent standards.

TABLE 5. Mix design parameters of conventional asphalt mixture

Specimen	Symbol	Unit	Mix Design Results				
Asphalt binder by total mix	Pb	%	3.5	4	4.5	5	5.5
Bulk specific gravity	Gmb	-	2.327	2.360	2.393	2.390	2.380
Theoretical specific gravity	Gmm	-	2.492	2.766	2.477	2.458	2.449
Air voids in total mix	VTM	%	6.64	4.67	3.39	2.76	2.81
Voids in mineral aggregate	VMA	%	14.47	13.69	13.10	13.21	13.85
Voids filled with asphalt	VFA	%	54.17	65.86	73.83	79.55	80.45
Stability	S	KN	10.36	11.80	12.22	11.39	9.45
Flow	F	mm	2.13	2.49	2.90	3.42	4.33

The Marshall Specimens containing 50 % RAP were produced at previously concluded OBC according to ASTM D1559. Every aforementioned asphalt mixture containing 50 % recycled mixture was rejuvenated with 5 %, 10 %, 15 %, 20 %, and 25 % WEO, WCO, and WBG respectively, and assessed permitting to ASTM D1559. Results of the mixture design were provided in Table 6. WEO, WCO, and WBG of 15 % showed better performance of 13.36 KN, 12.97 KN, and 12.78 KN in terms of Marshall stability as compared to that of conventional asphalt mixture. Therefore, WEO, WCO, and WBG of 15 % were determined as optimal in terms of Marshall Stability and Flow for asphalt mixture containing 50% recycled mixture. The improvement in performance of recycled mixture is attributed to the adequate interlocking in asphalt mixture due to stimulation and mobility of recycled binder through rejuvenator. The flow values indicate that the stiffness of the recycled mixture has been declined to the stiffness of the conventional asphalt mixture. So the recycled asphalt mixture may not be open to fatigue failure.

TABLE 6. Mix design parameters of Marshall Specimen at several rejuvenator contents

Virgin Binder (%)	RAP Binder (%)	RAP Mix (%)	Virgin Mix (%)	Rejuvenator Type	Rejuvenator (%)	VMA (%)	VFA (%)	VTM (%)	Stability (KN)	Flow (mm)
4.42	3.2	50	50	WEO	5	13.37	59.0	5.87	10.11	4.55
					10	14.86	56.61	5.56	11.74	4.15
					15	14.97	71.43	3.60	13.36	3.12
					20	14.30	71.67	3.87	13.10	3.42
					25	15.51	71.83	5.67	11.21	4.27
				WCO	5	14.77	73.86	6.22	10.73	5.46
					10	14.23	74.94	5.37	11.12	4.65

continue ...

... cont.

		15	14.68	74.61	3.77	12.97	3.51
		20	13.17	77.58	4.46	11.40	3.98
		25	13.66	72.66	5.55	10.33	4.78
	WBG	5	15.41	64.76	5.49	10.77	4.50
		10	14.78	65.44	5.67	11.74	4.37
		15	13.33	68.32	4.11	12.78	3.66
		20	14.21	68.48	3.48	12.62	4.21
		25	14.76	70.33	5.66	11.20	5.39

MOISTURE DAMAGE USING INDIRECT TENSILE STRENGTH

The variation of indirect tensile strength (ITS) with respect to mix type for the conditioned and unconditioned mode is presented in Table 7. Moisture susceptibility test revealed that the test conditions, such as vacuum saturation, freezing, and thawing of samples accelerate the water damage. It is evident that the values of TSR increased with the increase of rejuvenator content. The TSR values of recycled mixture containing 15 % WEO and WCO showed comparable results to those of conventional mix. This is attributed to the excessive amount of recycled materials, effective mobilization of the recycled binder by rejuvenator, and adequate compaction of the recycled mixture. The findings partially confirm those of the study by Hasan et al. (2020), which examined the rejuvenating effects of waste engine oil (WEO) and waste cooking oil (WCO) in asphalt concrete mixes containing RAP (25, 50, and 75% by weight of total aggregates) and WCO and WEO (5, 10 and 15% by weight of total binder, respectively). As predicted, it was discovered that the ITS raised as RAP content rose and fell as oil content raised. Results also showed that adding WEO to asphalt mixes increased its ITS when compared to adding WCO. The results showed that the ITS with 75% RAP and 5% WEO produces the mixture's maximum indirect tensile strength. The current study is also consistent with the research by Mamun et al. (2020), which examined the indirect tensile strength of three different percentages (30%, 40%, and 50%) of reclaimed asphalt pavement after being rejuvenated using waste cooking oil and waste engine oil. In terms of superior indirect tensile strength, it was found that 7% of WEO performs better up to 40% of reclaimed asphalt pavement and 13% of WCO up to 50% of reclaimed asphalt pavement.

TABLE 7. Indirect tensile strength and tensile strength ratio

Sample Type	Indirect Tensile Strength (Unconditioned) (KPa)	Indirect Tensile Strength (Conditioned) (KPa)	Tensile Strength Ratio (%)
Conventional	178.46	171.67	0.96
50% RAP	292.98	260.50	0.89
50% RAP + WEO	222.55	195.28	0.87
50% RAP + WCO	197.57	170.87	0.86
50% RAP + WBG	291.76	233.32	0.80

PERMANENT DEFORMATION IN ASPHALT MIXTURES

After determining 15 % optimum rejuvenator content of WEO, WCO, and WBG, total fifteen number (15) of samples were prepared using Marshal compactor, where 3 samples for each conventional, 50% RAP, 50% RAP+15% WEO, 50% RAP+15% WCO, and 50% RAP +15% WBG, respectively, and subjected to wheel tacking test for finding rut depth or rutting resistance. The average results of rut depth against 10,000-wheel tracking machine passes for four different samples are displayed in Figure 3 respectively. All the asphalt samples qualified the criterion of maximum rut depth of 12.5mm. According to Figure 3, utilizing 15% WEO lead to comparable rut depth to that of conventional asphalt mixture after ten thousand passes (6.65 mm), whereas the recycled mixture without any rejuvenator resulted in the minimum rut depth after ten thousand passes (2.34 mm), which is open to fatigue failure due to high stiffness or low rut depth. The recycled mixture comprising

15% WCO, or WBG show low rut depth of 5.81mm, 4.23mm, respectively, after 10,000 passes. It is credited to the rejuvenator's long-lasting integrity, which is formed in the recycled asphalt mixture containing WEO, for the asphalt mixture's ability to sustain repeated wheel loads. The results generally support those of the study by Hashim et al. (2022), in which they examined asphalt mixtures comprising 20%, 40%, and 60% RAP, rejuvenated with 0-10%, 12.5-17.5%, and 17.5-20% waste cooking oil (WCO) and waste engine oil (WEO), respectively. The rutting performance of the generated mixtures was assessed using the Hamburg wheel-track test. The results showed that the recycled mixture containing 40% RAP, at optimum dosage of 17.5%, and 12% of WEO, and WCO, respectively, performed well in comparison to the control mixture at accumulated rut depth of 7.4mm, and 6.2mm, respectively.

The results partially support those of the study by Hasan Taherkhani, H. and Noorian, F. (2018), in which they studied the effect of using 5%, 10%, and 10% (by weight of the recycled binder) waste engine oil (WEO) and waste cooking oil (WCO) as rejuvenators on the performance of asphalt concrete, comprising 25%, 50% and 75% recycled mixture in terms of permanent deformation, Marshall stability, and indirect tensile strength (ITS). The findings revealed that addition of WEO results in lower accumulated rut depth in the mixtures than adding WCO. In addition, at 5% optimum rejuvenator content, the accumulated rut depth in the mixtures containing 50% of RAP is 8.20mm, which is higher than that in the mixtures containing 25% and 75% of RAP.

Karim, F. and Hussain, J. (2021) prepared Marshall Specimens containing 40%, 50%, and 60% recycled asphalt mixtures at an OBC of 4.12%, by weight of Marshall specimen. Each aforesaid asphalt mixture was rejuvenated with 3%, 6%, 9%, and 12% WEO, respectively, and evaluated as per ASTM D1559 guidelines. A rejuvenator content of 3%, 6%, and 9% was concluded as optimum in terms of Marshall Stability and flow, for 40%, 50%, and 60% recycled asphalt mixtures, respectively. The finding of the current study does not agree to the findings of Karim, F. and Hussain, J. (2021) in terms of optimum rejuvenator content (WEO) of 6% for asphalt mixture containing 50% RAP. However, the general trend of outcomes is merely consistent with the current study.

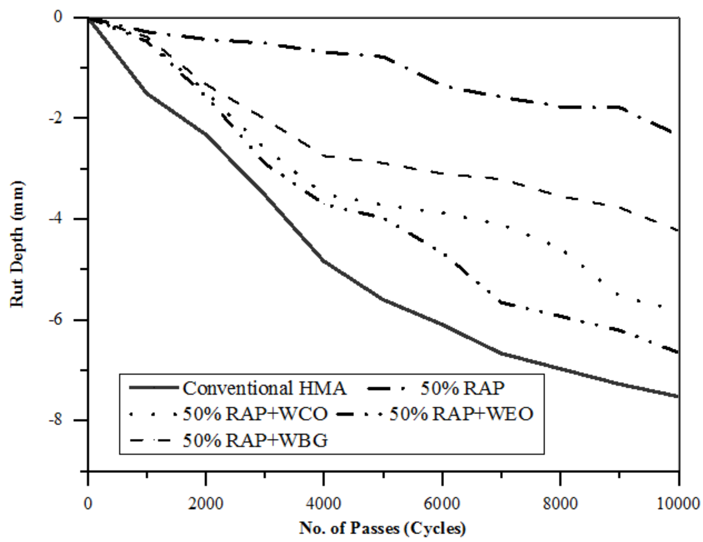

FIGURE 3. Rut depth recorded against no. of passes during wheel tracking test

CONCLUSION

The study led to the following conclusions:

1. The WEO, WCO, and WBG of 15% were found to be most effective for restoring the penetration value, softening point, flash and fire point, and viscosity of the 50% recycled binder to that of virgin 60 -70 pen. grade binder, with no significant improvement in ductility.
2. The asphalt mixture containing 50% recycled materials, at 15% WEO, WCO, and WBG as rejuvenator, showed better performance in terms of Marshall stability as compared to conventional asphalt mixtures.

3. The asphalt mixture comprising 50% recycled materials at 15% WEO content as rejuvenators showed high rut resistance thereby showing rut depth comparable to that of conventional asphalt mixture due to the adequate interlocking in asphalt mixture because of stimulation and mobility of recycled binder through rejuvenator.
4. The flow values of asphalt mixture comprising 50% recycled materials at 15% WEO content as rejuvenators indicated the stiffness of the recycled mixture, almost comparable to the stiffness of the conventional asphalt mixture.
5. The asphalt containing 50% recycled mixture at 15% WEO, WCO, and WBG as rejuvenator met the minimum TSR requirement of 80% because of the effective mobilization of the recycled binder by rejuvenator, and adequate compaction of the recycled mixture.
6. WEO proved to be the best rejuvenator to improve performance of recycled asphalt mixture when subjected to traffic and environment.

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DECLARATION OF COMPETING INTEREST

None.

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