Trends in Advanced Sciences and Technology

Manuscript 1005

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Aya Refaat

Amina M. Saleh

Reem K. Farag

Abdelzaher E. A. Mostafa

REVIEW

Toward Sustainable Green Asphalt Pavement Mixture Using Reclaimed Paving Material and Waste Engine Oil

Aya Refaat Abdelrahman [a,*], Amina Mohamed Saleh [b], Reem Kamal Kamel Farag [b], Abdelzaher Ezz Eldin Ahmed Mostafa [c]

[a] Department of Civil Design, Cairo Oil Refining Company, Cairo, Egypt
[b] Department of Petroleum Applications, Egyptian Petroleum Research Institute (EPRI), Cairo, Egypt
[c] Department of Civil Engineering, Faculty of Engineering – Mataria, Helwan University, Helwan, Egypt

Abstract

Recently, reclaimed paving material (RAP) has the highest priority in road paving as a solution for the depletion of natural resources and bad effect on environment. Restoring RAP properties as a gradation of solid materials and aged asphalt characteristics and content is necessary. This research aims to prepare an economical asphalt paving mix consisting of 100% RAP and waste engine oil (WEO) as a rejuvenator for aged asphalt to reuse in road paving. To achieve this aim, aged asphalt was extracted from RAP and characterized for physical, chemical, and molecular structure. RAP was characterized for sieve analysis. Maximum proper content of WEO needed for aged asphalt rejuvenation (by weight of aged asphalt and WEO blend) was determined by establishing a blending chart, while an optimum percent was determined by forming HMA that consisted of 100% RAP and different rejuvenator contents using the Marshall test; 17% was found to be suitable. Rejuvenated asphalt was characterized for same analyzes as conduced on an aged sample. The rejuvenated RAP was tested for mechanical tests, namely, Hamburg wheel tracking, index retained strength, Cantabro loss, indirect tensile strength, tensile strength ratio, and compared with fresh HMA. Test results revealed that WEO is an effective rejuvenator for aged asphalt and rejuvenated 100% RAP, complying standard limits for binder and surface courses while also improving in rut, raveling, fatigue, and moisture resistances. Lastly, reuse rejuvenated RAP with WEO is considered an economically attractive solution for paving secondary roads helping in sustainable development of Egypt.

Keywords: Aromatic, Dynamic shear rheometer, Reclaimed asphalt pavement, Resin and asphaltene, Saturate, Tensile strength ratio, Waste engine oil

1. Introduction

Nowadays, there is a need to incorporate sustainability criteria in the design and construction of roads among which include low-cost and minimized environmental impacts (Abdelzaher, 2008; Raja et al., 2014; Abdelrahman et al., 2019; Gede et al., 2020). A total of 1.6 trillion tons of asphalt has been produced for road construction worldwide in the last decade (Aner et al., 2023). Asphalt is an essential material which acts as a binder for mineral aggregates to form pavement mixes (Amina, 1990; Abdelzaher et al., 2016; Okan et al., 2018; Guojing et al., 2023), and consists mainly of several chemical elements (mainly carbon and hydrogen) and some trace elements (Tongyan, 2012). Asphalt is generally divided into four fractions namely: saturates, aromatic, resin, and asphaltene (Shuang et al., 2022), which are separated based on their difference in insolubility and

Received 19 December 2023; revised 6 February 2024; accepted 26 February 2024.
Available online 19 July 2024

* Corresponding author.
E-mail addresses: ka.civilengineer@gmail.com (A.R. Abdelrahman), aminaepri@yahoo.com (A.M. Saleh), reem-kamal.kamel2009@yahoo.com (R.K.K. Farag), prof.abdelzahermostafa@m-eng.helwan.edu.eg (A.E.E.A. Mostafa).

https://doi.org/10.62537/2974-444X.1005

polarity of each fraction in a standard solvent (Ahmed et al., 2022; Jin et al., 2022). It is a known fact that asphalt pavement is exposed to light, heat, and oxygen during both of its preparation in a mixer as well as during its service life, which make asphalt easy to age (Shaopeng et al., 2017; Eva and Dusan, 2023). The aging of asphalt is mainly oxidation reaction, in which oxygen from air reacts with its active components. The reaction changes the molecular structure of asphalt and its properties, making it to become harder and more brittle, thus reducing the performance of pavement and accordingly its service lifetime (Fang et al., 2023). Recently, with the drastic increase in road paving in Egypt, there is a significant need for keeping the natural sources of pavement materials namely asphalt and solid aggregate for the longest period of investigating the potential incorporation of various byproducts in road construction. Nowadays, reclaimed paving material (RAP) has become a material known as another 'black gold' (Abdelzaher, 2015). The primary factor limiting use of RAP is performance of an aged binder within the RAP itself. Rejuvenators or softening agents have been suggested to soften aged asphalt in RAP to improve pavement performance and lifespan (Jianmin et al., 2023). The Asphalt Institute suggests that when a content of 20% or less of RAP is used in a mix, the viscosity of the extracted asphalt is unnecessary, and the grade of asphalt used in the recycled mix will typically be the same grade used for conventional mixes (Ahmad et al., 2017). In 2011, the Federal Highway Administration defined asphalt concretes containing more than 25% of RAP by total weight of the mix as high-content RAP mixture. The content of RAP in HMA mixtures can be categorized into four categories: the quality of RAP aggregates, technology of the production plant, mix design methodology, and performance of the final mix containing RAP (Giulia et al., 2020). Softening agents aim solely to lower the viscosity of aged asphalt in RAP, while regeneration agents can restore, even if partially, RAP binders' physical, chemical, and rheological (reduction of dynamic shear modulus and increase of phase angle) properties lost during the aging of asphalt pavements. Consequently, an efficient regeneration agent should improve the RAP mixture's workability and cracking resistance without overly softening it (Jianmin et al., 2023). There are different types of wastes that can be used to soften aged asphalt such as polanga oil, cooking oil, and engine oil (Amira et al., 2019; Sujit and Umesh, 2019; Sujit and Umesh, 2020; Eslam et al., 2023; Ingrid et al., 2023). Waste engine oil (WEO) is typically a petroleum product and is often naturally contaminated by impurities during the physical and chemical processes to the extent that oil is no longer appropriate for its original purpose and must be replaced by virgin or re-refined one. WEO consists of nondegradable components that are hard to decompose and may cause irreparable environmental damage. During engine operation, heavy metals, including lead, zinc, calcium, and magnesium, gradually accumulate in the oil. These metals are proven to cause permanent contamination of groundwater and soil when waste oil is dumped into the ground or water streams (Khan et al., 2021). However, 9% of WEO was reported to be an optimum dosage to efficiently restore the original values of penetration, softening point, and viscosity of aged asphalt by ~100% and ductility by 84% (Xiaoyang et al., 2015). Implementing WEO and waste vegetable oil as rejuvenators for aged asphalt make a possibility to involve high amounts of RAP of up to 70–80% for use within HMA-wearing courses without adverse effects (Abdelrahman et al., 2018; Mohammed, 2022). The use of waste electrical power plant oil as a rejuvenating agent for aged asphalt reduces both of carbonyl (IC=O) and sulfoxide (IS=O) indices, and the asphaltene amount (large polar molecules) to be identical to the virgin binder. Also, adding waste electrical power plant oil to RAP reduces the rejuvenated mixes' dynamic modulus making it more resistant to fatigue cracking, meaning, reduced rutting resistance (Peyman et al., 2017; Abdelzaher et al., 2019). Using 7 and 13% of WEO and waste cooking oil, respectively, cause rejuvenated asphalt pavement characteristics better till 40 and 50% of RAP, respectively (Eman et al., 2022). Moreover, using waste cooking oil and WEO as rejuvenators ranging from 3.5 to 4.0% and from 5.5 to 6.0%, respectively, of weight of solid materials of HMA is feasible. Rejuvenated 100% RAP mixes were found to cope with Egyptian requirements for heavy traffic as binder courses and medium traffic as wearing courses regarding Marshall stability and flow as well indirect tensile strength tests (Abdullah et al., 2020).

2. Objectives and scope of work

The main objective of this study is to evaluate the applicability of using HMA containing 100% of RAP for the wearing surface in Egypt as well as to evaluate the use of WEO as a rejuvenator for aged asphalt with the final objective of reserving the natural resources for the longest period of time and helping in obtaining a clean environment in addition to decreasing the cost of construction and maintenance of roads.

3. Materials

The materials used in this study were:

(1) Virgin asphalt cement (AC) of penetration-grade 60/70 (as a control sample) was obtained from El-Nasr Petroleum Company (NPC) in Suez, Egypt.
(2) RAP sample was collected and obtained from full depth of asphalt pavement from the road section of Mostorod to Umm Bayoumi Bridge that was constructed by the Arab Contractors Company in June 2007. The road structure design consists of binder course 3D and surface course 3B with a service life of about 16 years.
(3) Collected WEO and Fresh Engine Oil [(SJ 20 W/50) sample for comparison purpose] were obtained from Cooperative of Petrol car station in Mostorod region.
(4) New solid materials consisting of siliceous lime stone aggregate (size 2, 1.5, and 1 inch), crushed stone, siliceous sand, and limestone powder.
(5) Trichloroethylene chloride as a solvent (has a boiling point of 87 °C) for the RAP sample.

4. Methodology and experimental program

To achieve the research objectives, the experimental program is shown in detail in Fig. 1. Generally, the experimental work includes five main steps as mentioned in the following.

4.1. Step 1: characterization of raw materials

(1) In which aged asphalt pavement was extracted from old asphalt pavement using trichloroethylene according to ASTM D 2172. Aged asphalt was separated from asphalt/solvent mixture by the evaporation procedure. The aged, rejuvenated, and virgin asphalt samples were tested for physical properties, chemical constituents IP 469 (Diana and Konrad, 2019; Azadeh et al., 2022), and molecular structure, in addition to

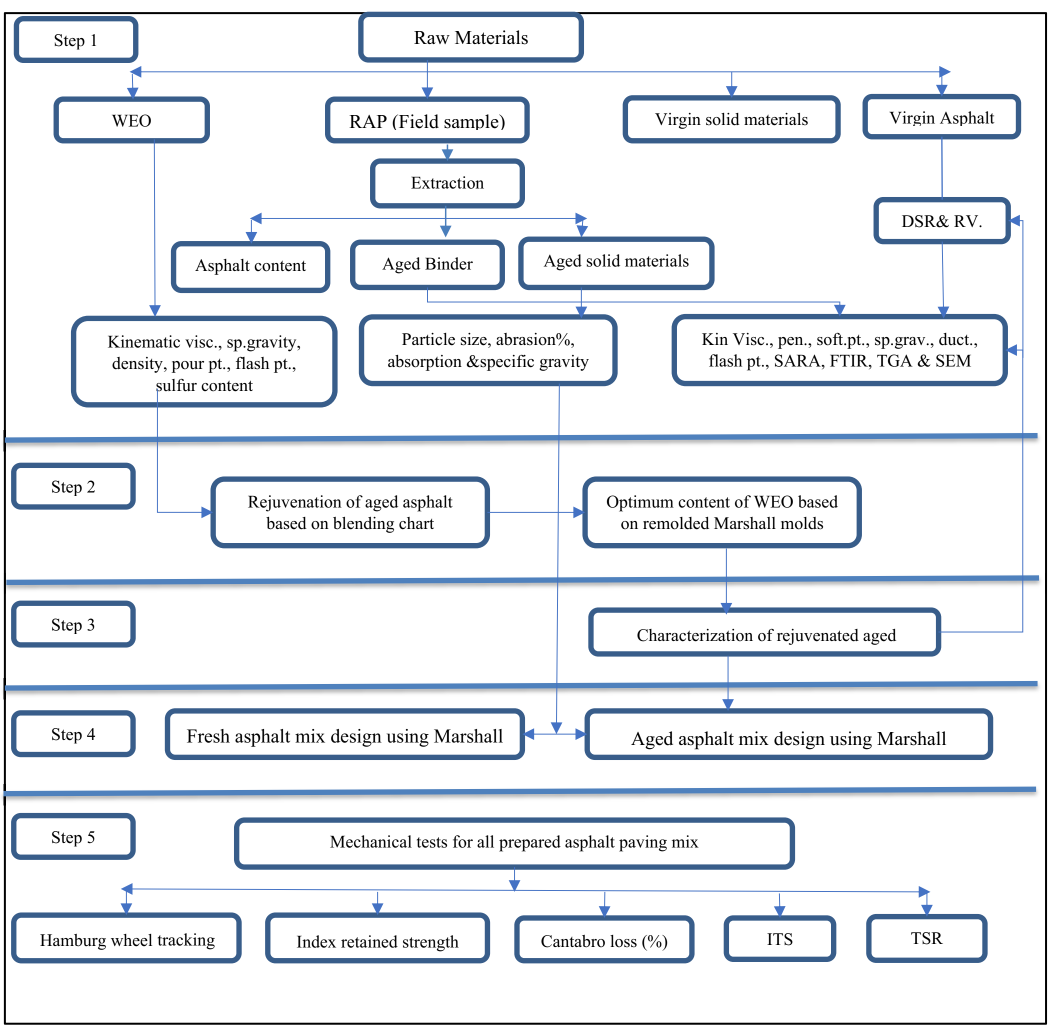

Fig. 1. Experimental program chart.

rotational viscosity and rheological properties to measure the asphalt complex shear modulus (G*) and phase angle (δ) at high temperature in accordance with ASTM D7175.
(2) The obtained aged and new solid materials were tested for sizing, specific gravities, and abrasion resistance.
(3) WEO was characterized for physical properties, and sulfur content at the Cairo Oil Refining Company (CORC).

4.2. Step 2: rejuvenation of aged asphalt based on a blending chart

In which, the proper suitable content of WEO for rejuvenating aged asphalt was determined using the viscosity blend chart (ASTM D4887). Based on the Egyptian standard lower limit of kinematic viscosity at 135 °C of virgin AC 60/70, the optimum percent of WEO in the blend was determined. Remolding three Marshall molds containing different percentages of WEO in the blend of aged asphalt and rejuvenator were prepared. The Marshall characteristics were measured and compared to choose the best values of stability, flow, and air voids in the mix and accordingly the optimum content of WEO in the blend was determined.

4.3. Step 3: characterization of the rejuvenated aged asphalt

In which, the rejuvenated asphalt at an optimum content of WEO in the blend was characterized for the same characteristics as previously mentioned in step 1, and compared with virgin AC sample. Also, DSR was conducted to measure G* and δ to define the highest temperature at which the asphalt sample would stand safe.

4.4. Step 4: fresh and aged asphalt mix design using Marshall

In which, hot mix asphalt containing the rejuvenated and virgin binders separately were prepared and evaluated using the Marshall test to determine the optimum binder content.

4.5. Step 5: mechanical tests for all prepared asphalt paving mix

In which, the prepared hot mixes asphalt at optimum binder content were tested for Hamburg Wheel-Track (AASHTO T324), Index Retained Strength (not standardized) (Rais, 2023), Cantabro abrasion loss (not standardized) (Safa et al., 2022), indirect tensile strength (ASTM D6931), resistance of compacted asphalt mixtures to moisture-induced damage (tensile strength ratio test) (ASTM D4867) to evaluate the final performance of rejuvenated compared with virgin hot mix asphalt.

5. Results and discussion

5.1. Effect of aging on the characteristics of reclaimed paving material

5.1.1. Characterization of solid materials

The characteristics of RAP components (aged asphalt and solid materials) properties compared with original paving mix as was obtained from Arab Contractors Company are illustrated in Tables 1–3, while Table 4 illustrates characteristics of aged asphalt. However, Fig. 2 shows the change in gradation.

Results in Fig. 2 show that the gradation of aged pavement is finer in all sieves than mix gradation of binder 3D and surface 3B layers and it is within surface course 4 G specification limits. The degradation of aged pavement may be attributed to the action of rolling during the construction of mix on the road including laying and compaction as well the action of continued traffic during road service life and action of water as rainfall. Table 1 illustrates that the hardness of aged solid materials is weaker than the original one as it has a higher abrasion loss percentage, and this may due to the continuous action of traffic loads. Also, asphalt content of aged paving is 4.18% lower than the original surface, and binder mixes are 5.1 and 4.75%, respectively. The decrease is 0.92 and 0.57 (% wt. of

Table 1. Physical properties of solid materials.

Test	Aged solid materials	Original solid materials		Standard limits
		Binder course	Surface course	
Specific gravity (bulk)	2.524	2.670	2.612	
Specific gravity (SSD)	2.588	2.706	2.666	
Specific gravity (apparent)	2.64	2.765	2.759	
Absorption %	1.72	1.3	2	<5
Resistance to abrasion using Los Angeles machine (%) after 500 revolutions	30	24		40% max

Aggregate type: siliceous limestone aggregate.

Table 2. Physical characterization for aged and original asphalt.

Property	ASTM	Aged asphalt	Original asphalt of design mix	Egyptian standard limits of AC60/70
Penetration (at 25 °C, 100 g, 5 s), 0.1 mm	D5	12	61	60/70
Softening point (ring and ball), °C	D36	80	50	45/55
Penetration index[a]	NS[b]	1.28	−0.74	−2: +2
Specific gravity @ 25 °C	D70	1.07	1.019	
Kinematic viscosity@135 °C, cSt	D2170	1401	401	>320
Flash point (Cleveland Open Cup), °C	D92	90	+250	>250
Ductility (@ 25 °C, 5 cm/min), cm	D113	10	+150	>90

[a] According to reference Ahmed et al. (2022).
[b] Not standardized.

Table 3. Marshall characteristics.

Sample name	Specific gravities		Av%	VMA%	Stability		Flow (mm)	Marshall quotient (MQ) kg/mm
	Gmb	Gmm			KN	KG		
RAP	2.20	2.57	14.21	20.20	23.6	2407.2	1.67	1444.32
Original mix	2.35	ND ([a])	5.1	14.56	15.88	1300	3.2	406.25
Standard limit			(3–5)	>13	–	>1200	2–4	–

RAP, reclaimed paving material.
[a] Not determined for original mix.

Table 4. Physical characteristics of used waste engine oil compared with the fresh oil sample.

Property	ASTM	Waste engine oil SJ 20 W/50	Fresh engine oil SJ 20 W/50
Kinematic viscosity @ 40 °C, cSt	D-7042	70	155.56
Kinematic viscosity @ 100 °C, cSt		5.5	18.29
Flash point (closed cup), °C	… SD.[a]	104	236
Density @ 15 °C, g/cm^3	D4052	0.878	0.865
Density @ 40 °C, g/cm^3		0.862	0.833
Pour point (°C)	D97	−15	−27
Sulfur content, %wt	D4294	0.302	0.0014

[a] Specially determined according to IP170 (Bablu et al., 2023).

solid materials) for original binder and surface courses, respectively, and it may be due to aging of asphalt as it becomes harder than original. All the mentioned results may have attributed to the effect of aging of asphalt during construction and to the service lifetime of the mix.

5.1.2. Characterization of aged asphalt

Comparison of aged asphalt characteristics with the original binder is illustrated in Table 2. The results illustrate that aged asphalt has physical properties completely different from its original state. Compared with original binder results, aged asphalt

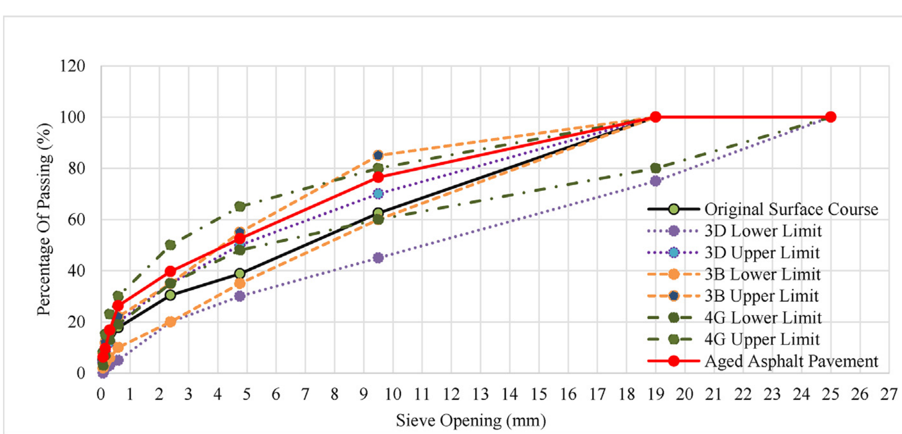

Fig. 2. Sieve analysis and gradation of aged and original solid materials.

has lower penetration and ductility values in percentages of 80.333 and 93.33, respectively while it possesses a significant increase in softening point and kinematic viscosity values by percentages of 62.5 and 71.45, respectively. All results are due to evaporation of light components of asphalt as well to oxidation and polymerization reactions during preparing, laying, and service time of the paving mix, represented by a decrease in maltene and an increase in the asphaltene content. The specific gravity of aged asphalt is higher than the original one, and this may be due to polymerization reactions and increase in the asphaltene content which is a friable material. Also, the flash point of aged asphalt is lower than the original asphalt and specification limits due to the aging phenomena.

5.1.3. Marshall characteristics

Marshall characterization of RAP is compared with characteristics of the original mix as illustrated in Table 3. The results revealed that stability, Marshall quotient, air voids, and voids in mineral aggregates of aged asphalt pavement increased by 64.95, 71.87, 64.12, and 27.92%, respectively, while the flow and bulk specific gravity decreased by 47.81 and 6.38%, respectively, as compared with original mixes. The results confirmed the aging effect of the asphalt binder on mix characteristics as it became very stiff, hard, and brittle in addition to the lowering in the binder percentage. The increase in air void percentage would affect moisture susceptibility of the aged mix causing the solid materials to be weak and finer than the original state.

5.2. Rejuvenating of the aged asphalt using waste engine oil: characterization of waste and fresh engine oil

The basic properties of WEO that have been tested and comparison of results with the fresh engine oil sample are illustrated in Table 4. The data illustrates that WEO has lower kinematic viscosity at both 100 and 40 °C and lower flash point but higher pour point and sulfur content. The decrease and increase in the properties of WEO result from the decomposition of the additive used in oil reforming and its consumption during use in engine. At the end of engine oil use, the engine sometimes corroded due to the formation of mineral acids in oil resulting from the oxidation of sulfur and used additives.

5.3. Needed content of waste engine oil to rejuvenate aged asphalt

The sample was prepared as follows:

(1) The amount of WEO needed is weighed into a container. The aged asphalt is then heated to just over its softening point until it is pourable. Aged asphalt is then added to the rejuvenator in the container to obtain 100 g. The blend is loosely covered, and heated to 135 °C for 10 min, with occasional stirring to ensure good heating distribution. The process is topped when no resistance to stirring is obtained and when this happens the sample is removed from heat, left to cool, and kinematic viscosity test was run and the results are plotted on a semi-log graph.

The proper WEO content required for rejuvenating aged asphalt is determined using kinematic viscosity values of aged asphalt and WEO at 135 °C to establish the blending chart (ASTM D4887) as shown in Fig. 3. According to the Egyptian standard, the lower limit of the kinematic viscosity of virgin AC 60/70 is 320 cSt and by signing this lower limit on the graph, the proper percentages of WEO/aged asphalt and rejuvenator blend is found to be 21%.

Preparation of rejuvenated asphalt pavement mixtures using the Marshall standard method.

(1) The preparation of samples: the aged asphalt mixture sample, which is sufficient for three Marshall molds amounting to 3600 kg, was heated in the oven at 165 °C for 45 min until it was hot enough to mix with the WEO. After that, the mix was added using an automatic laboratory mixer and WEO was quickly poured to the aged asphalt mix in proportion of 17, 19, and 21% (by the weight of the blend), which are 47.52, 51.12, and 58.32 g, respectively, with continuous mixing for 10 min until completely homogeneous, then the rejuvenated paving mix return back to the oven to heat for 20 min at 165 °C before compaction.

Three Marshall testing specimens with different WEO contents as 21, 19, and 17% (%wt of the blend) are prepared separately and characterized as illustrated in Table 5. The results revealed that stability and MQ values decreased while flow values increased gradually with increasing WEO content in the mix that attribute to the softening of aged asphalt. Decreasing of AV% values and increasing of VMA% values means that with increasing WEO

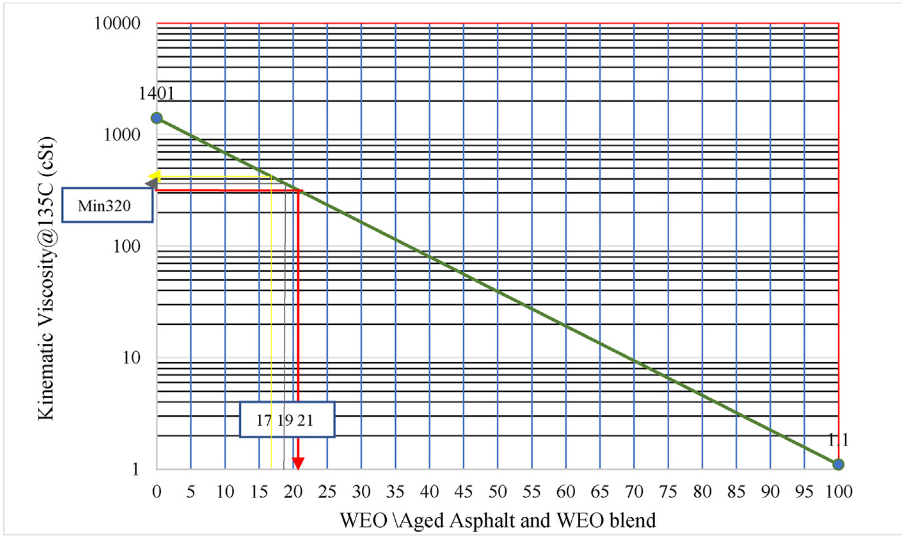

Fig. 3. Blending chart.

Table 5. Marshall characteristics.

WEO content (% in the blend)	Specific gravities (kg/m^3)		AV%	VMA%	Stability (kg)	Flow (mm)	MQ (kg/mm)
	Gmb	Gmm					
17	2.34	2.44	4.26	16.33	1258	2.793	450.36
19	2.34	2.43	4.03	16.33	1179.8	2.9	406.83
21	2.33	2.42	3.72	16.69	1074.4	3.133	342.89

WEO, waste engine oil.

content in the blend, the mix moisture susceptibility properties improved. The 17% WEO content in the blend is the optimum percentage of addition that gives the best characteristics of the paving mix. Based on calculations, the three percentages of WEO in the blend, as 21, 19, and 17%, represent asphalt content in the mix (%wt. of solid materials) as 5.8, 5.6, and 5.5%, respectively.

5.4. Characterization of rejuvenated asphalt

Physical, chemical, DSR, and molecular structure analysis (Fourier transform infrared spectroscopy, thermal gravimetric analysis, and scanning electron microscopy) results of rejuvenated asphalt compared with aged and virgin AC 60/70 are shown in the following subsection.

Figure 4a–e shows the photos of instruments and machines used for physical, chemical, and DSR tests on asphalt.

5.4.1. Physical and chemical characteristics of asphalt

Physical properties of all asphalt samples are illustrated in Figs. 5a–b and 6. It is observed that using WEO as a rejuvenator, the penetration of aged asphalt increased from 12 to 63 (0.1 mm), while the softening point decreased from 80 to 53 °C. The increase in penetration is due to the decrease in the ratio of asphaltenes to maltenes as shown in Fig. 5. Flash point of the aged asphalt value increased and the specific gravity decreased, which is attributed to a decrease in viscosity and to the decrease in the asphaltene content.

(1) Chemical analysis is determined according to IP469 and revealed that aged asphalt contains the highest asphaltene/maltene ratio value as it is 53.14%, and this is attributed to the oxidation and polymerization reactions as a result of aging. Also, it is found that adding 17% WEO decreases this polar component type (asphaltenes) percent by 26.835%, which means a softening of aged asphalt occurs, but it is still more viscous than virgin asphalt AC 60/70.

5.5. DSR testing result for virgin and rejuvenated asphalt samples

Data shown in Figs. 7 and 8 show that WEO works as a good softening agent to the aged asphalt sample compared with virgin AC 60/70 (PG 64). The rejuvenated aged asphalt has a lower failure

Fig. 4. (a) Penetration test, (b) softening point, (c) rotational viscometer, (d) ICP equipment, and (e) DSR test equipment.

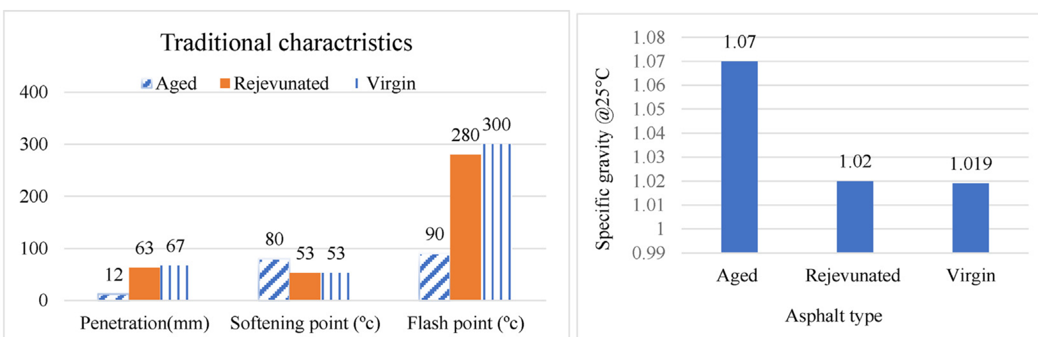

Fig. 5. (a) Penetration, softening point, flash point. (b) Specific gravity @ 25 °C.

temperature of 46 °C, so the performance grade must be raised which will be the objective of the second part of this research.

5.6. Molecular structure analysis

5.6.1. Fourier transform infrared spectroscopy

The Fourier transform infrared spectroscopy spectrum analysis results of asphalt samples were conducted according to ASTM E1252 and represented on the wave number scale (4000–400 cm^{-1}) as shown in Fig. 9 and illustrated in Table 6. The results revealed the increase in peaks of sulfoxide (S=O) and carbonyl (C=O) groups at wave lengths of 1030–1044 and 1700–1720, respectively, for aged asphalt, which revealed the oxidation of hydrocarbons (the short-term and long-term aging, respectively). However, this peak decreased for

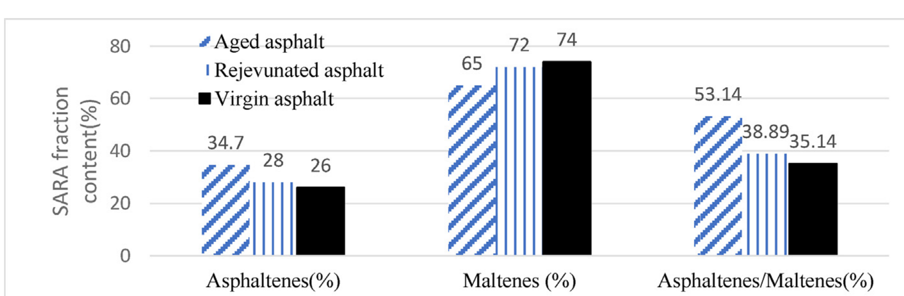

Fig. 6. Asphalt chemical analysis.

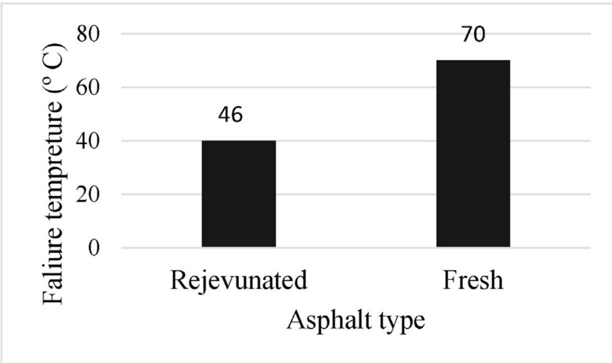

Fig. 7. Failure temperature.

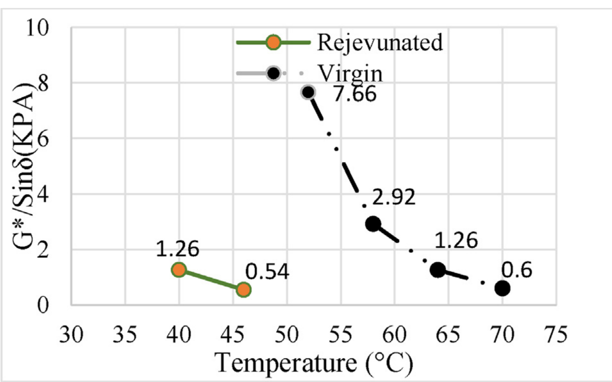

Fig. 8. Rutting factor.

rejuvenated asphalt because of the high compatibility, dispersion, and chemical reaction of WEO with aged asphalt. Aromatics groups of aged asphalt at 1600–1634 has a lower peak due to aging while for rejuvenated asphalt the same peaks intensity increased due to the softening effect of WEO. Also the polar group (O–H) that represents high amounts of asphaltenes sharply appeared in the aged asphalt at 3450 and decreased in the rejuvenated asphalt. Generally, rejuvenated asphalt has nearly the same functional groups as virgin asphalt AC 60/70.

5.6.2. Thermal gravimetric analysis

The thermal stability results of different asphalt samples in high temperatures are determined according to ASTM E1131 and shown in Fig. 10 and illustrated in Table 7. Compared to virgin AC, aged asphalt showed several degradation steps which started to decompose at lower temperatures as 26.86 °C and the final degradation temperature recorded is 490.17 °C with weight loss equalling 100%. This is due to the aging effect resulting in an increase in the asphaltene content. For rejuvenated samples, the thermal stability improved as the initial degradation temperature raised from 26.86 to 280.01 °C, and the weight loss decreased by ~35% at a final temperature of 566.41 °C as a result of adding WEO. For virgin asphalt, the weight loss is highest percent as 73% at 552.89 °C, which is an expected result because the presence of light fraction in fresh asphalt. All these results revealed that WEO is an effective rejuvenating agent for aged asphalt.

5.6.3. Scanning electron microscopy/energy-dispersive X-ray spectroscopy result

The morphological surface of all investigated asphalt samples was conducted according to ASTM E2809 and shown in Fig. 11a–c.

Figure 11a shows that aged asphalt includes coarser particles of irregular shape with a porous structure that makes the surface rough as a result of the aging effect due to an increase in asphaltene content (high polar constituents) and a decrease in saturated content (low nonpolar constituents).

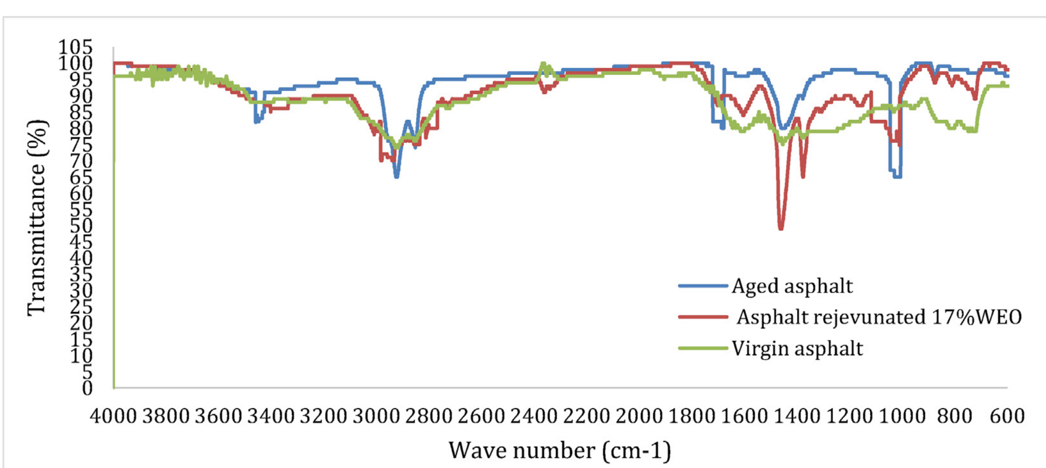

Fig. 9. Fourier transform infrared spectroscopy wave spectrum.

Table 6. Functional group for asphalt samples.

Aged asphalt		Rejuvenated asphalt		Virgin asphalt	
Wavelength (cm^{-1})	Functional group	Wavelength (cm^{-1})	Functional group	Wavelength (cm^{-1})	Functional group
3450	Polar (O–H group)	3450–3330	Polar (O–H group)	3450–3300	Polar (O–H group)
2924–2850	Aliphatic (CH_2, CH_3)	2924–2850	Aliphatic (CH_2, CH_3)	2921.94–2852.00	Aliphatic (CH_2, CH_3)
1460	Aliphatic (asymmetric) C–CH_3	1460–1375	Aliphatic (asymmetric) C–CH_3	1460–1379	Aliphatic (asymmetric) C–CH_3
1600–1634	Aromatics (C=C)	1600	Aromatics (C=C)	1630	Aromatics (C=C)
1030–1044	Sulfoxide (S=O)	1030–1043	Sulfoxide (S=O)	1030–1041	Sulphoxide (S=O)
1700–1720	Carbonyl (C=O)	1700–1706	Carbonyl (C=O)	1700–1723	Carbonyl (C=O)

Figure 11b shows that all bores and coarse particles disappeared and the asphalt surface is smooth with dark color and this is due to that WEO is completely blended in a compatible form with aged asphalt and it seems as a virgin sample as shown in Fig. 11c. All these results due to that WEO is a suitable rejuvenator for aged asphalt.

5.7. Marshall characteristics

A fresh asphalt paving mix using siliceous limestone aggregate type was prepared for comparison purpose according to surface course 4 G, and the gradation design curve is shown in Fig. 12. Also, its Marshall characteristics at optimum asphalt content are illustrated in Table 8. Marshall characteristics of all mixes are shown in Fig. 13a and b.

Compared with fresh asphalt mix, the data in Fig. 13a, b reveals that aged RAP has the highest hardness, Marshall quotient, air voids in mix, and in mineral aggregate in percentages of 43.92, 68.74, 71.57, and 22.57, respectively, and a decrease in flow and specific gravity by 44.15 and 5.98, respectively. All these results are due to the aging of asphalt which caused the stiffness of the mix to increase. The effect of adding WEO on RAP obviously affects the characteristics on the final rejuvenated mix as there is a noticeable decrease in its all-Marshall properties as compared with RAP in stability, Marshall quotient, air voids in mix, and in mineral aggregate in percentages of 47.74, 68.82, 70.02, and 19.31%, respectively, and an increase in flow and specific gravity in percentages of 67.66 and 6.36%, respectively.

5.8. Mechanical characteristics

5.8.1. Preparation of samples for all mechanical tests

(1) Retained strength index of asphalt pavement mixture is a ratio between the stability of the Marshall mix sample after soaking for 24 h to the stability of the mix soaked for 0.5 h in water bath at 60 °C.
(2) Hamburg wheel tracking test: asphalt paving mix is prepared at its optimum asphalt content and put in the mold and compacted with the manual compactor and leave for not less than 6 h in air. After then, the sample mold is put in the device under the wheel at a frequency of 26 ± 1.0 cycles per minute.
(3) Abrasion mass loss: the Marshall sample is prepared, then it is inserted in to the Los

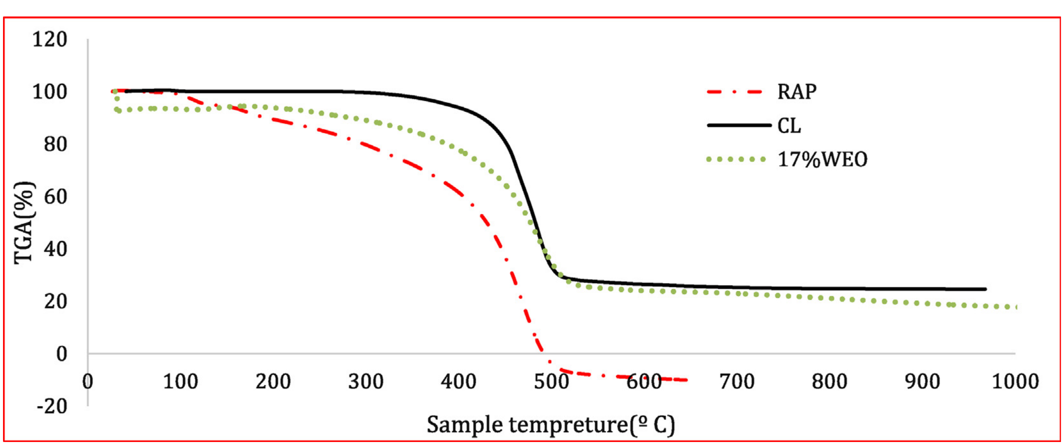

Fig. 10. Thermal gravimetric analysis.

Table 7. Thermal gravimetric analysis result.

Item	Aged asphalt	REJ with 17% WEO	Virgin asphalt
Initial decomposition temperature (°C)	26.86	280.01	310.34
Final decomposition temperature (°C)	490.17	566.41	552.89
Weight loss (%)	100	65	73

WEO, waste engine oil.

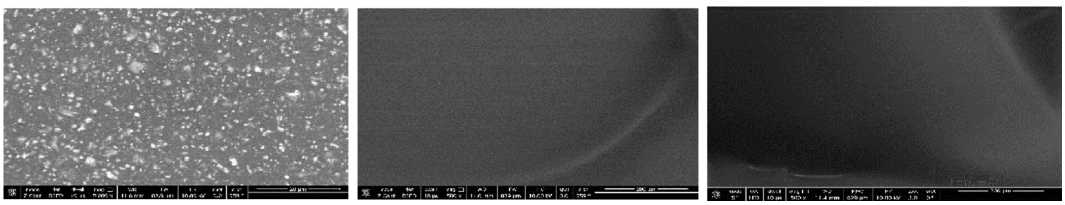

Fig. 11. (a) Aged asphalt, (b) rejuvenated asphalt, and (c) virgin asphalt.

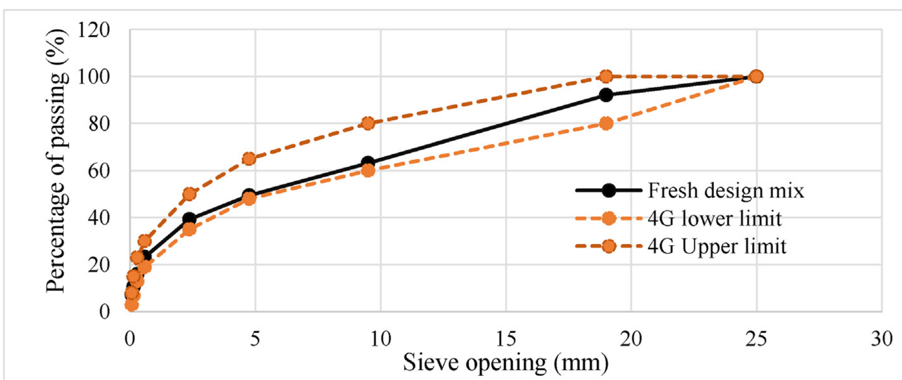

Fig. 12. Sieve analysis and gradation of fresh solid materials.

Angeles machine without steel balls at speeds between 30 and 33 rpm for 300 rounds.

(4) Indirect tensile strength: in this test, the compacted three Marshall molds with diameters of 100 and heights of 63.5 mm of asphalt paving mix for each mold are prepared, and compacted at 4% air voids and placed in a water bath at 25 °C for a minimum of 30 min before testing.

Table 8. Marshall characteristics of the prepared fresh asphalt paving mix at an optimum asphalt content.

Marshall characteristic	The result	Specifications
Asphalt content ([a])	5.1 ± 0.25	
Stability (kg)	1350	≥1200
Flow (mm)	2.99	2–4
Marshall quotient (kg/mm)	451.51	300–500
Specific unit weight (Gmb) (t/mm^3)	2.341	–
Air voids (%)	4.04	3–5
Voids in mineral aggregates (%)	15.64	>15

[a] By weight of solid materials.

(5) The tensile strength ratio test: in this test six Marshall specimens with diameters of 100 and heights of 63.5 mm asphalt paving mix of each mold with target air voids of 7.0 ± 0.5% were prepared and were divided into two groups (wet and dry conditioning).

Figure 14a–d shows the photos of different instruments and machines used in applying mechanical tests.

Data in Figs. 15–19 show rut depth, Cantabro mass loss, index retained strength, indirect tensile strength, and tensile strength ratio, respectively. From all figures the following results were obtained compared with the fresh asphalt mix.

(1) The obtained rut depths after 10 000 cycles for aged, recycled, and fresh paving mix samples are 30, 10, and 4.7 mm, respectively, which revealed that the RAP sample has hardness without any flexibility while adding WEO rejuvenated RAP and increasing the flexibility of the aged paving mixes which decreased the rut

Fig. 13. (a) Stability, flow, and MQ and (b) Gmb, AV%, and VMA.

Fig. 14. (a) Hamburg wheel-tracking machine, (b) abrasion Los Angeles machine, (c) (IDT) strength tester machine and (d) Marshall testing machine.

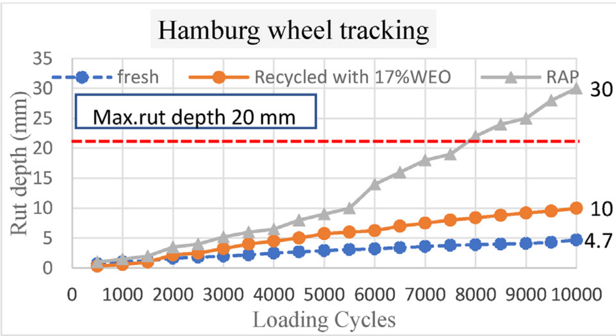

Fig. 15. Rut depth after 10 000 cycles.

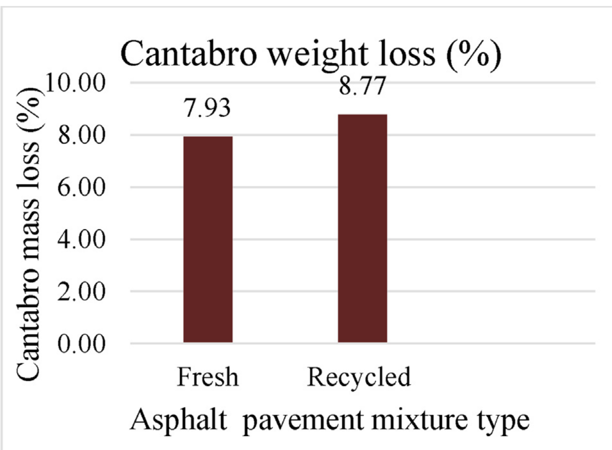

Fig. 16. Cantabro mass loss (%).

depth by 66.66%. This means that the recycled mixture cannot withstand the temperature of the test (60 °C), but it is still within the specifications and is safe for use on road.

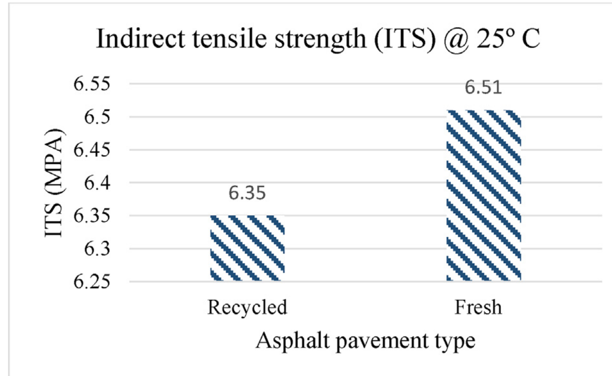

Fig. 18. Indirect tensile strengths (ITS) at 4% AV.

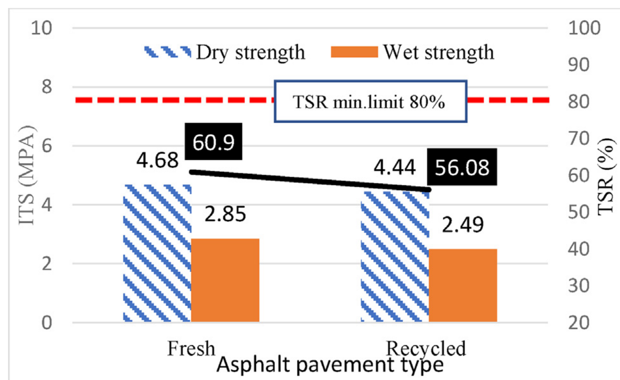

Fig. 19. Tensile strength ratio (TSR) at 7 ± 1 AV.

(2) Contabro mass loss value of recycled sample is higher than that recorded for the fresh one by 8.58%, which revealed that WEO increases the cohesion between aged solid materials and rejuvenated binder, which attributed that WEO

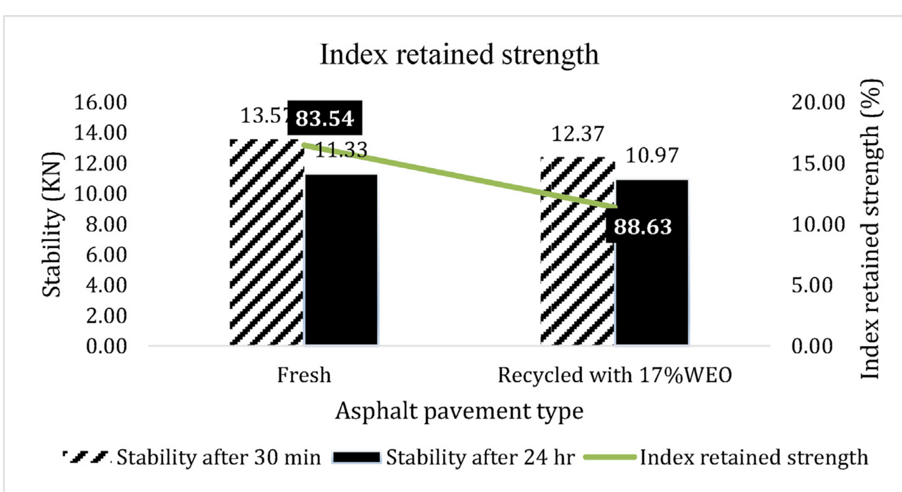

Fig. 17. Index retained strength (%).

enhances raveling resistance of the RAP sample to be approximately near the fresh mix sample performance.

(3) Index retained strength percentage value of the recycled sample is 88.63%, which is higher than the fresh sample by 5.74% because of the RAP raised hardness, and WEO strengthens the bonding between the aggregates provided by the binder and thereby enhancing the stone-to-stone contact which results in a higher amount in compressive strength.

(4) Indirect tensile strength of the recycled sample is approximately as the fresh one which revealed that WEO improved the fatigue resistance of the recycled paving mix.

(5) Tensile strength ratio percentage of the recycled sample is improved after mixing with WEO due to the significant decrease of AV% and VMA% of the aged paving mix. The recycled and fresh samples have less values than the minimum standard limit of 80%, which means the requirement of using modifiers such as anti-stripping to improve moisture susceptibility of paving mixes.

All the results revealed that WEO is an effective rejuvenator for RAP and accordingly the paving mix can be used for binder course for roads that have low volume traffic or surface course for roads that have no loads.

6. Conclusions

The aim of this research is to use 100% RAP in road paving to keep the natural resources of pavement materials as asphalt and solid materials for the longest time. To achieve the research aim, WEO was used as the rejuvenating agent for aged asphalt. The kinematic viscosity of WEO and aged asphalt were determined to establish a blending chart. A 19% WEO (by weight of aged asphalt and WEO blend) addition was found to justify the lower limit of viscosity of AC 60/70 according to Egyptian standard. The optimum WEO in blend was determined be remolding Marshall molds containing 17, 18, and 19 percentages and characterized for stability, flow, and air voids percent. A 17% addition of WEO was found to be the optimum content. The rejuvenated RAP containning17% of WEO (by wt. of blend) was characterized for mechanical tests, while the rejuvenated asphalt was analyzed for physical, chemical, and molecular structure characteristics and the final results were obtained as follows:

(1) WEO works as a good softening agent that can rejuvenate the local aged asphalt in Egypt and restores aged binder physical and chemical properties. The Fourier transform infrared spectroscopy, scanning electron microscopy, and thermal gravimetric analysis results have shown that WEO has restored the maltenes to asphaltenes ratio and fluidity of aged binder, while it introduces an economical and environmental alternative for recycling this type of wastes in pavement construction.

(2) By adding the optimum percentage (17%) of the WEO, the rutting parameter ($G^*/\sin\delta$) of the aged asphalt was improved and can be applicable in areas having a maximum temperature of not more than 46 °C (PG40) and in my future researches green polymers will be added to improve its performance and became almost identical to the $G^*/\sin\delta$ of the control asphalt of PG 64.

(3) Recycled RAP is applicable for use up to 100% in hot asphalt mix using the softening agent WEO in binder course for roads having low volume traffic or surface course for roads having no loads. The mechanical test results showed that the recycled asphalt pavement improves rutting resistance, raveling, fatigue resistance, and tensile strength ratio% value due to the decrease of voids after mixing with WEO. However, it still falls short of the Egyptian Code (minimum 80%) as fresh hot mix asphalt is lower than the specification, which means there is a need of using polymers to improve low temperature crack resistance.

(4) Ultimately, the results of this paper point to a new perspective concerning using 100% of RAP material, while the capability of using waste oils into aged asphalt would help minimize water and land pollution, reduce dependence on nonrenewable resources, and diversify asphalt pavement recycling options and polymer-modified binders, which can play a vital role to improve the performance of recycled asphalt mixtures to be used in surface course for roads having high traffic loads. So, the future research's main objective is to improve rejuvenated aged asphalt performance using green modifiers in continuation of the goals of achieving sustainable development of Egypt, which we will seek to achieve in my future research.

Conflicts of interest

None declared.

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