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Analytical review on potential use of waste engine oil in asphalt and pavement engineering

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A R T I C L E I N F O

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Asphalt binder
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Sustainable recycling
Waste engine oil

A B S T R A C T

This article provides a comprehensive overview of the research utilising waste engine oil (WEO) in asphalt binders for multiple application purposes and the economic and environmental implications. It covers the various types and sources of WEO for information on their characteristics and the process of preparing WEO-asphalt binders. The study collects the effects of WEO in different applications, including asphalt modification, aged asphalt rejuvenation, self-healing asphalt agents, and WEO composites. It also discusses works on the economic and environmental appraisal associated with a wide WEO utilisation. WEO exhibits both positive and negative influences on asphalt properties. Generally, it improves the performance of asphalt at low temperatures, specifically in terms of reducing issues like thermal cracking and enhancing fatigue resistance. However, it may have a negative impact on the performance of modified asphalt binders at high temperatures. WEO, due to its high concentration of light components, improves the overall performance of aged asphalt. The integration of WEO and reclaimed asphalt binders can enhance the crack resistance, which however highly relies on the added WEO quantity. Future research should be prioritised to understand the comprehensive impact of WEO on reclaimed asphalt binders for the compatibility between the rejuvenator compound and reclaimed aged asphalt, and the effect of WEO on the durability of modified asphalt mixes. In addition, field investigations and analyses are required for a bigger, inclusive, and more detailed picture of the economic and environmental impacts.

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1. Introduction

There have been remarkable achievements in highway infrastructure construction worldwide in the past 40 years [1–5]. In the meantime, considerable non-renewable natural resources, such as natural aggregate and asphalt, have been consumed on an unsustainable scale [6–12], which has generated adverse impacts on the natural environment and has also constantly been raising the cost of construction [13-18]. Approximately, 1.5 billion tons of construction wastes are generated annually, which are still keeping a trend of increase. Storing, handling, and transportation of these wastes represent a huge challenge [19-23]. So far, the most commonly used measures for handling the wastes are landfilling and burning, which have not only consumed previously available land but also produced irreversible contamination of the environment [24-26]. Thus, it is vital to find innovative solutions for waste management [27-30]. Using waste materials to replace asphalt binder and aggregates in pavement engineering has been proved as a promising way, which not only reduces the consumption of asphalt binder but also can meet the material properties requirement for asphalt mixtures [31]. Meanwhile, it helps reduce the emission of carbon dioxide (CO_2) [32-35].

Significant amounts of oil wastes, such as waste plastic oil, waste cooking oil (WCO), and waste engine oil (WEO), are being produced worldwide every day [36,37], which, WEO alone poses superabundant pollution with a generated rate of 45 million tons per year, but so far 40% of the waste is only adequately disposed or collected, of which only 8% is recycled for reuse [38]. The major generation of WEO is from oil/gas refineries, fossil fuel-powered vehicles, automotive manufacturers and service workshops, manufacturing companies, power generating plants, HVAC companies, mining/smelter companies, etc [36,39].

WEO contains considerable amounts of heavy metals including zinc, calcium, barium, lead, and magnesium, which pose a potential danger to living organisms [40], including human beings and all wide ecosystems [41]. According to the report by the U.S. Department of Energy, most of WEO is recycled for fuel [33], such as diesel [36], lubricant oil after additional processing treatment [42], or roofing tiles [43]. Meanwhile, being approximately similar to petroleum asphalt in terms of physical and chemical properties, researchers have examined the use of WEO in pavement engineering [44], particularly, in conjunction with asphalt binders [45,46], such as directly using WEO in asphalt binders [42,47,48].

2. Research significance

The current article provides a summary of studies on the composition and characteristics of asphalt concrete manufactured from used engine oil. For more than ten years, academics have been interested in the issue of the roads surface's quality and endurance. Using recycled materials is necessary with today's road construction technologies to reduce waste. For instance, it has been discovered that recycled machine oil rejuvenates asphalt and increases its lifespan. This study aims to provide helpful guidance for the usage of WEO in various applications of asphalt pavement, giving deep knowledge of the performance of WEO-asphalts. So far, only a few short reviews have been reported for the use of the WEO sources and their impacts on the engineering characteristics and behaviour of the modified asphalt binders, though little attention has been given to the impact of WEO on other wide applications in pavement construction practice. While covering the most up-to-date relevant research publications, this article pays extra attention to the influence of the utilisation of WEO on different applications in pavement engineering. It represents a state-of-the-art comprehensive review, providing a thoughtful understanding of the topic for engineers in the industry and researchers in academia. To the best of the authors' knowledge, there is not much comprehensive review information about the use of WEO in asphalt pavements, employing a unique approach to address the contradictory findings present in the existing literature. Additionally, this article discusses recent studies that were just published and were not discussed in earlier review articles. A systematic literature review strategy was used to review and assemble a significant body of the literature that was published in the last 20 years. There were several research databases utilised for this issue, including Scopus, Web of Science, and Google Scholar.

The impacts of the used motor oil in a variety of applications, such as modifying asphalt, rejuvenating old asphalt, and creating composites and self-healing bituminous agents, were researched by the authors. This review discusses such scientific concerns as the asphalt's longevity, the environmental effects of its use, and the affordability of suggested solutions. The review consists of several subsections. The first subsection introduces the topic and general information about asphalt concrete and its production. The second subsection focuses on the properties of the WEO preparation of WEO-asphalt binders. The third section describes the previous results and the main findings for the impact of using WEO in asphalt binders for different asphalt pavement applications. In the last section, the economic and environmental effects of the use of WEO-asphalt mixes and their production are discussed. In the end, the current knowledge gap is highlighted for future research directions.

3. Asphalt concrete

Asphalt as a historical building material initially used in Sumeria in 6000 B.C. as a sealing material for ship hulls. It was also implemented as natural asphalts for other applications, such as waterproofing masonry in the Indus Valley and mummification in Egypt [49]. Using natural asphalts for pavement was reported in the early 1800s in the USA and France to construct sidewalks. The first asphalt pavement road was constructed in Washington, D.C. in the USA in 1876 using sediment in lakes [50]. The discovery of petroleum refinement in the 1900s has led to the modern asphalt that is widely utilised today [49].

Asphalt concrete is referred to as pavement in North America and is known as asphalt, tarmac, or blacktop in the UK. It is also identified by various scientific terms such as plant mix, bituminous mix or concrete, cold mix asphalt, warm mix asphalt, and hot mix asphalt. Asphalt concrete consists primarily of two main components: asphalt cement or binder and aggregates. These components are present in the proportions of 5–10% and 90–95%, respectively, based on the total weight of the asphalt concrete mixtures [51]. Asphalt binder is a viscous and sticky material with a semi-solid state at normal temperatures with a black colour. When making pavement concrete, it is heated to the temperature of about 160 °C and then mixed with aggregates. Once cooling down, the binder restores the semisolid state with aggregates suspended inside the concrete matrix and binder. For its functional working purpose, the binder should not only have adequate stiffness for the strength but also have sufficient softness for dissipating stresses within the matrix [52,53].

On a molecular level, asphalt binder primarily comprises maltenes and asphaltenes. Asphaltenes represent large polar compounds with black or dark brown colour, and they play a crucial role in the adhesion and viscosity of asphalt binder. On the other hand, maltenes are a mixture of resins and oils that disperse and stabilise asphaltenes [54,55]. The maltenes can be further divided into non-polar and polar saturated aromatics, which contribute to different adsorption characteristics. However, advanced technologies, such as modified clay-gel absorption chromatography and advanced solubility test, are required to break down maltenes [56]. The relationship between asphaltenes and maltenes can be compared with that between aggregates and asphalt binder of asphalt concrete by the analogy that maltenes for asphaltenes are like asphalt binder itself for aggregates. The size of maltenes is much smaller than that of asphaltenes. Asphaltenes provide the structure and the final form of asphalt binders, while resin composites in maltenes peptise asphaltenes and oil composites to deliver the homogeneity of the final asphalt binder [49,55].

4. WEO

4.1. Composition and properties

During the operation of engines, heavy metals accumulate gradually in the oil due to the wear of metals, which contain considerable amounts of lead [52]. Therefore, WEO is not suitable for original purposes and requires replacement for a period of time [57]. These non-degradable substances are difficult to decompose, however, from a recycling point of view, WEO can be used to modify asphalt binders or in reclaimed asphalt pavement (RAP), etc [58,59].

The physical and chemical characteristics of WEO depend upon the combustion process, which influences the operational temperature and the final contaminants including rust, metal particles of engine wear, detergents, diluents, soot, and moisture [60–62]. Table 1 summarises the basic properties of WEO from various references. The characteristics of the wastes differ depending upon the sources of the oil and test methods. It mainly consists of resins (SARA), asphaltenes, saturates, and aromatics. Table 2 presents the contents of SARA and metal components of WEO from various references. The SARA components can impact the WEO stability and the characteristics of the modified or rejuvenated asphalt binders. WEO contains about 3.9 ~ 5.7% metals in the form of ash, which cannot be organically identified until years of mechanical wear. This ash content was reported in some studies to adversely impact asphalt mixtures being very susceptible to cracking and deterioration [32,63]. Using conventional tests for WEO, Yan et al. [64] found that all the WEO components have closely similar solubility. Different composite test approaches may bring in errors due to the poor separation. Among them, the thin layer chromatography-flame ionization detector (TLC-FID) technique has proved the fast separation speed and high sensitivity. In addition to requiring a small sampling volume, this approach has been widely used for detecting the components of WEO [65,66].

Abdullah et al. [36] used the distillation to characterize WEO components by five fractions, as shown in Fig. 1, which displace different colours, from a transparent gold colour to dark black. They also measured nitrogen, carbon, and sulphur contents using the TruMac determinator. By computer numerical control analysis, they found the contents of nitrogen and sulphur were below 0.2% and 0.09%, respectively, while the content of carbon was more than 69% in each fraction. Moreover, the gas chromatography-mass spectrometry (GC-MS) analysis reveals that WEO is a blend of low and high molecular weight substances of aliphatic hydrocarbon and aromatic hydrocarbon, respectively, as indicated in Fig. 2. The determined components of hydrocarbons are aliphatic alcohol, trimethyl benzene, cyclohexylmethyl hexyl ester, and hexacontane, as listed in Table 3. The major hydrocarbon structures are classified as aliphatic hydrocarbons and benzene-based components. In all fractions, a low average distribution of molecular weight was revealed. Most components are mononuclear aromatics and are of a low alkyl chain length. All the hydrocarbons are primarily in a form in the range of 8–18 m/z. Their fractionation process successfully separated the heavy hydrocarbons from lighter hydrocarbons.

Similarly, Liu et al. [39] used GC–MS chromatograms of WEO and concluded that the chemical components of WEO have lower than 200 g/mol of molecular weights. It was suggested that WEO's main components have low molecular weights. Table 4 and Fig. 3 provide an overview of their findings and demonstrate that polyolefin oil, paraffin oil, and aromatic solvents are the main components.

Table 1
Physical properties of WEO from different studies.

Property	Ref. [32,64]	Ref. [27]	Ref. [67]	Ref. [39]	Ref. [68]	Ref. [69]	Ref. [70]	Ref. [71]
Colour	Dark brown	-	-	-	Black	-	-	Black brown
Density (g/cm^3)	0.92 (25 °C)	-	-	0.8816	-	0.876	0.86	0.9605
Kinematic viscosity (mm^2/s)	63.5 (60 °C)	41.2 (40 °C)	41.2 (40 °C)	101.52 (40 °C)	0.097	38.4 (60 °C)	95 (60 °C)	0.236 (60 °C)
Flash point (°C)	-	214	214	220	159	230	200	295
Mechanical admixtures (%)	-	0.063	0.063	0.362	-	-	-	-
Oxidation stability (min)	-	35	35	-	-	-	-	-
Acid value (mg KOH/g)	≤ 0.4%	-	-	-	5.6	-	-	-

Table 2
SARA components and metals' content of WEO from different studies.

Property	Ref. [32]	Ref. [72]	Ref. [73]	Ref. [74]	Ref. [70]	Ref. [52]
Asphaltenes (%)	3.7	11.5	0.56	2.5	-	-
Aromatics (%)	63.2	4.68	26.32	-	-	-
Saturates (%)	4.9	27.5	71.29	52.7	-	-
Resins (%)	24.3	56.32	1.83	44.8	-	-
Ash (%)	3.9	-	-	5.7	-	0.66
Carbon (%)	-	-	-	-	15.9	-
Hydrogen (%)	-	-	-	-	0	-
Nitrogen (%)	-	-	-	-	28.7	-
Sulphur (%)	-	-	-	-	0.3	0.19
Oxygen (%)	-	-	-	-	55.1	-
Arsenic (ppm)	-	-	-	-	-	< 1.0
Lead (ppm)	-	-	-	-	-	14

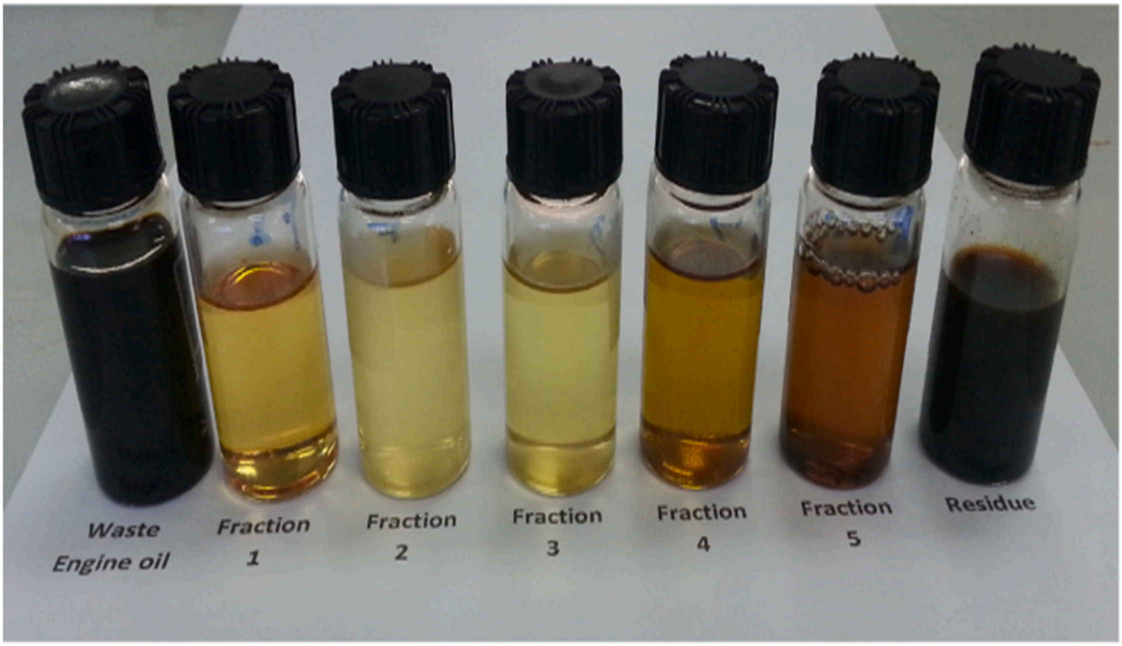


Fig. 1. WEO fractions, following fractional distillation, were heated to 400 °C and then treated for 3 h. Fraction 1 (F_1) 0.9% distilled at 100–150 °C, fraction 2 (F_2) 1.9% distilled at 150–200 °C, fraction 3 (F_3) 4.4% distilled at 200–250 °C, fraction 4 (F_4) 11% distilled at 250–300 °C, and fraction 5 (F_5) 43% distilled at 300–400 °C [36].

These elements resemble the aromatics in asphalt. Alkylbenzene and alkanes in the C_9–C_{12} range make up the majority of the aromatics.

On the other hand, Wang et al. [75] studied the chemical compositions of WEO bottom (WEOB), a common type of WEO. Their findings are illustrated in Table 5, which displays that linear alkanes with a carbon number range from C_4 to C_{28} and an alkylbenzene structure are the main components of WEOB. Consequently, it may be inferred that WEOB primarily constitutes similarly aromatic solvents, namely paraffin oils and polyolefin, which are identical to aromatics found in asphalt. Downstream and maleic anhydride compounds, such as 2-Dodecen-1-yl succinic anhydride, were also found, indicating that there were chemical reactions taking place with the additives while they were used.

4.2. Preparation process

Table 6 lists the reported WEO-asphalt binders, including raw materials, mix preparing conditions, tests conducted, and the standards followed. The WEO-asphalt mixtures were normally prepared by the use of a shear mixer [27,39,76,77]. Asphalt is at first oven heated up to a temperature in the range of 130–190 °C to reach a liquid state. Thereafter, WEO is poured in slowly to mix with the asphalt while the mixer rotates at a speed between 3000–6000 r/min. The time of mixing depends on whether WEO is added along with or without other additional additives. When used together with other additives, the mixing WEO asphalt first needs to last for 10

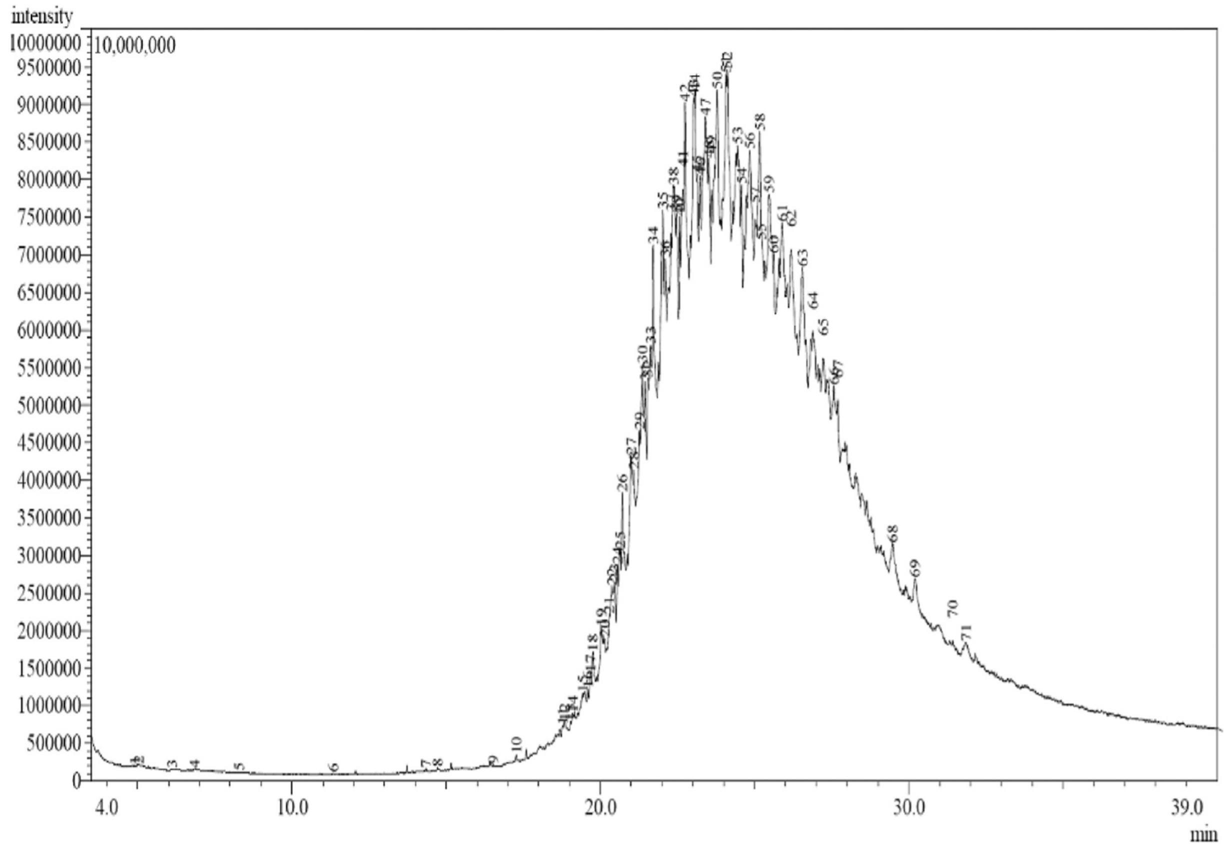
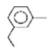
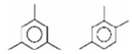
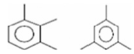
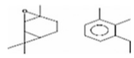
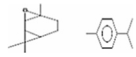
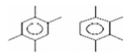
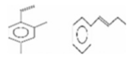
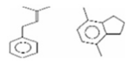


Fig. 2. GC-MS results of WEO [36].

Table 3
WEO compounds from GC-MS test [36].

Peak	Compounds	Formula
WEO 1, 2	Dimethylbenzene	C_8H_{10}
3, 4	1,2,3-Trimethylbenzene	C_9H_{12}
5	1-Ethyl-2,4-dimethylbenzene	$C_{10}H_{14}$
6	2,4,4,6,6,8,8-Heptamethyl-1-nonene	$C_{16}H_{32}$
8	2-Ethylisohexanol	$C_8H_{18}O$
7, 9	Sulphurous acid, cyclohexylmethyl hexyl ester	$C_{13}H_{26}O_3S$
10	2-Thiopheneacetic acid, decyl ester	$C_{16}H_{26}O_2S$
11	n-Eicosane	$C_{20}H_{42}$
13	n-Pentatriacontane	$C_{35}H_{72}$
12, 14	n-Heneicosane	$C_{21}H_{44}$
16, 21, 22, 26, 30, 31, 32, 35, 37, 38, 39, 40, 41, 42, 43, 46, 47, 49, 52, 53, 54, 58, 59, 62, 63, 64, 68	Tetrapentacontane	$C_{54}H_{110}$
15, 17, 23, 24, 25, 27, 34, 36, 50, 56, 57	n-Tetratetracontane	$C_{44}H_{90}$
28	Octacosane	$C_{28}H_{58}$
18, 19, 29, 65	n-Tetracontane	$C_{40}H_{82}$
20	Sulphurous acid, cyclohexylmethyl octadecyl ester	$C_{25}H_{50}O_3S$
45	n-Hexatriacontane	$C_{36}H_{74}$
33, 44, 69	Hexacontane	$C_{60}H_{122}$
51, 55, 60	8-Hexylpentadecane	$C_{21}H_{44}$
48, 71	Dodecahydrosqualene	$C_{30}H_{62}$
61, 66	9-Octylhexacosane	$C_{34}H_{70}$
67	9-Dodecyl tetradeca hydro anthracene	$C_{26}H_{48}$
70	2-Heptylthiophene	$C_{11}H_{18}S$

Table 4
GC-MS analysis results presenting chemical compositions of WEO [39].

Label	Retention time (min)	Synonyms	Formula	CAS	Molecular weight	Structure
W1	4.929	Benzene, 1-ethyl-3-methyl-	C_9H_{12}	620-14-4	120.19200	
W2	5.329	Benzene, 1,3,5-trimethyl-; Benzene, 1,2,4-trimethyl-	C_9H_{12}	108-67-8; 95-63-6	120.19200	
W3	5.704	Benzene, 1,2,3-trimethyl-; Benzene, 1,3,5-trimethyl-	C_9H_{12}	526-73-8; 108-67-8	120.19200	
W4	6.118	2,3-Epoxycarane, (*E*)-; Benzene,1-ethyl-2,3-dimethyl-	$C_{10}H_{16}O$ $C_{10}H_{14}$	20053-58-1; 933-98-2	152.23300; 134.21800	
W5	6.477	3-Epoxycarane, (*E*)-; 1-Methyl-4-(1-methylethyl)	$C_{10}H_{16}O$ $C_{10}H_{14}$	20053-58-1; 99-87-6	152.23300; 134.21800	
W6	6.932	Benzene, 1,2,4,5-tetramethyl-; Benzene, 1,2,3,4-tetramethyl-	$C_{10}H_{14}$	95-93-2; 488-23-3	134.21800	
W7	7.346	2,4-Dimethylstyrene; 1-Phenyl-1-butene	$C_{10}H_{12}$	2234-20-0; 824-90-8	132.20200	
W8	7.796	2- Naphthalenol,1,2-dihydro-, acetate-; N-Methyl-9-aza-tricyclo[6.2.2.0(2,7)] dodec-2,4,6,11-tetraene-10-one-	$C_{12}H_{12}O_2$ $C_{12}H_{11}NO$	132316-80-4; 13131-19-6	188.22200; 185.22200	
W9	8.540	Benzene,(3-methyl-2-butenyl)-; 1-H-Indene, 2,3-dihydro-4,7-dimethyl-	$C_{11}H_{14}$	4489-84-3; 6682-71-9	146.22900	
W10	9.140	Naphthalene, 1-methyl-; Naphthalene, 2-methyl-	$C_{11}H_{10}$	90-12-0; 91-57-6	142.19700	

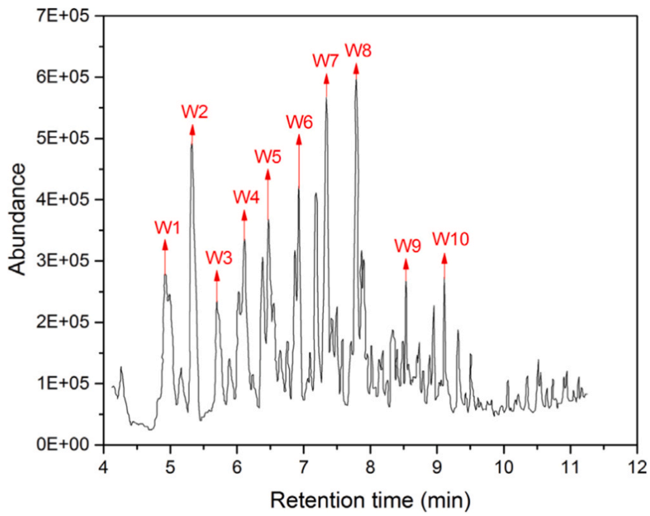


Fig. 3. GC-MS chromatogram of WEO [39].

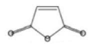
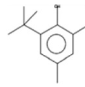
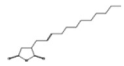
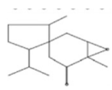
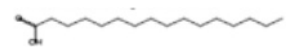
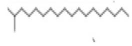
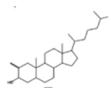
to 30 min followed by another 22–40 min extra mixing with the other added additives. The mixing time of WEO usually ranges between 30 to 90 min. For the WEO-asphalt mixture, the WEO content ranges between 2 to 10% by the weight of asphalt binder. Fig. 4 depicts an example of the shear mixing procedure for the type of WEOB when mixed with styrene-butadiene-styrene copolymer (SBS)-modified asphalt [75].

5. Functional roles or applications of WEO

5.1. Database

Scopus database was employed as it represents a main internationally recognized and prominent peer-reviewed database [84,85].

Table 5
Compositions of WOEB determined from GC–MS analysis [75].

Retention time (min)	Synonyms	Formula	Molecular weight	Structure
6.72	Maleic anhydride	$C_4H_2O_3$	98	
8.19	Butylated hydroxytoluene	$C_{15}H_{24}O$	220	
9.10	2-Dodecen-1-yy(-)succinic anhydride	$C_{15}H_{32}$	212	
9.63	Eicosan	$C_{20}H_{42}$	282	
10.75	Spiro[4.5]decan-7-one, 1,8-dimethyl-8,9-epoxy-4-isopropyl	$C_{15}H_{24}O_2$	236	
11.36	n-Hexadecanoicacid	$C_{16}H_{32}O_2$	256	
12.93	7-Methyl-Z-tetradecen-1-ol acetate	$C_{17}H_{32}O_2$	268	
13.57	Octadecane, 2-methyl	$C_{19}H_{40}$	268	
14.30	Cholestan-3-ol, 2-methylene-, (3 ά, 5ά)-	$C_{28}H_{48}O$	400	
14.87	cis-13-Eicosenoic acid	$C_{20}H_{38}O_2$	310	

The keywords “waste” And “engine” And “oil” And + “asphalt” OR “bitumen”; “waste engine oil” + “asphalt” OR “bitumen”, were used to probe articles, titles, abstracts, and keywords. In order to obtain extensive literature on the subject and cover regional preferences, bitumen and asphalt were utilised as synonyms.

The analysis identified 189 articles from the period 2002 to 2023. Figs. 5 and 6 show the Scopus database and their authorship countries, respectively. It can be seen that 2014 and between 2019 to 2022 demonstrate a substantial increase in publishing. The highest increase occurred from 2020 to 2022, with more than 60% of the publications. However, the number of publications dropped in 2023, though it should be noted that this analysis was conducted in September 2023 and the publications may increase at the end of 2023. Fig. 6 illustrates the distribution of publications across the globe, with China having the highest authorship of more than 60 publications. Next is India with 20 publications, followed by Malaysia, the United States, Iraq, and Iran with more than 10 publications. Overall, the database analysis revealed that the topic is a recent and innovative subject in asphalt pavements.

5.2. Modification of asphalt binders

Due to having similar molecular components as those of asphalt, WEO was utilized to modify asphalt binders [86,87]. Villanueva et al. [88] found that the use of WEO caused a reduction of the softening point of asphalt binders. They also concluded that using lubricating oil had minor enhancement on the behaviour of modified asphalt at low temperatures through the use of a BBR test. Borhan et al. [89] reported that the modified binders experienced a decrease in the ductility and specific gravity. However, Zargar et al. [90] stated that the addition of 3.4% WEO resulted in an increase in the penetration value of asphalt. The penetration value increased from 45 dmm to the standard value of 80/100 grade asphalt. Based on some investigations, increasing the amount of WEO reduced the fatigue and rutting of asphalt [59,91]. Nevertheless, Borhan et al. [89] concluded the increased fatigue resistance of WEO-modified asphalt in comparison with SBS-modified asphalt.

Additionally, Liu et al. [39] evaluated the influence of WEO on the modified asphalt. The chromatographic profiles of the utilized asphalt samples were divided into 9 slices. The slices with labels 1–4 were identified as large molecular size (LMS), the slices with labels 5–7 as medium molecular size (MMS), and the slices with labels 8–9 as small molecular size (SMS). The definition of LMS was per the hypothesis that LMS should refer to the area under 1/3 of the total elution time. They noticed that there was a reduction in the contents of LMS and MMS but an increase in SMS, as displayed in Table 7. The results of FTIR tests in Fig. 7 point out that WEO-modified binders consist of similar functional groups as those of original asphalt. It suggests the non-occurrence of chemical reactions between asphalt and WEO. Quantitative research revealed that WEO-modified asphalt included more sulfoxide functional groups and fewer carbonyl functional groups. The absorption peak in the range of 3200 cm^{-1} and 3500 cm^{-1} is related to the stretching vibration of the -OH groups in the molecules of asphalt. The C@H stretching of an alkane is represented by a number of peaks in the

Table 6
Preparation of WEO-asphalt binders with conducted tests and their standard methods.

Ref.	WEO	Asphalt	Mix	Temperature	Stirring time	Test	Standard
[27]	Refined WEO	SK-90 asphalt	WEO (2%, 4%, and 6%) PPA (1% and 2%)	135 °C	30 min	Conventional tests	T0605, T0604, and T0606 of JTG E20-2011, China (2011).
						Entropy weight method	Zhao et al., 2016; Ma et al., 2021b.
						Optical microscope observation test	-
						Fourier transforms infrared (FTIR) spectroscopy	AASHTO (2006)
						Dynamic shear rheological (DSR) tests	T0625-JTG E20-2011 in China (2011)
						Brookfield viscosity test	-
[46]	Local auto repairshop	PG64-22 (100%) PG76-22 SBS asphalt (100%) RAP	WEO (2.5%, 5%, 7.5%, and 10%) PG64-22 (100%) PG76-22 SBS (100%) RAP-A /aged binder (90:10) and RAP-B/ aged binder (70:30)	-	-	DSR master curve	-
						DSR linear amplitude sweep (LAS)	AASHTO TP 101-12
						DSR multiple stress creep recovery (MSCR)	AASHTO TP70
						DSR rutting index	-
						Infrared (IR) spectra analysis	-
[76]	Re-refined engine oil bottom (REOB) (Ontario source)	Laguna (Venezuela), Cold lake (Alberta), and Ural (Russia) crude oils	REOB (6% or 8%) SBS D1101 (3.5%, 7%) OPE EE (4%) SBS D1118 (3%) SBS D1192 (3%, 5%)	163 °C, 100 °C	-	Superpave grading	AASHTO M320 standard
						Double-edge-notched tension testing	Ontario ministry of transportation laboratory standard 299
[78]	Refine waste oil Motor oil (RW)	Wisconsin asphalt	RW (5%)	-	-	Aging procedures	AASHTO T 240 and AASHTO R 28
						LAS test	AASHTO M320
						Bending beam rheometer (BBR) test	AASHTO T 313
						MSCR tests	AASTO T350
						Rheological properties of binder	ASTM D6373 and AASHTO M 320
[79]	WEO (vehicles) RB (recycled engine oil bottoms)	Commercial PMB (PMB45-80/60, EN 14023, and bitumen (B35/50, EN 12591)	EO and RB (20%) crumb rubber (20%) SBS (5%) HDPE (6%)	150–180 °C	40 min	Basic properties	EN 1426 standard, EN
						MSCR tests	AASHTO TP 70-11
						Rheological properties	1427 standard EN 14770 standard
[80]	WEOB (petroleum refinery)	SBS three-block polymer asphalts	WEO (8%)	-	-	Double-edge notched tension (DENT) test	-
						LAS test	AASHTO T 315 (DSR)
						MSCR tests	AASHTO T315 (DSR)
[39]	WEO (directly collected from a garage, China)	60/80 base asphalt (PB) and two \ SBS asphalt (PMB-A and PMA-B)	WEO (4%, 8%)	150 °C, 160 °C	30 min		-
						DSR	
						FTIR spectroscopy	-
						Gel-permeation chromatography (GPC)	-
						Gas chromatograph mass spectrometry (GC–MS)	-
[77]	WEO (from vehicle service station)	Base asphalt (AH-50)	WEO (25%, 35%, and 45%) + ground tire rubber (GTR) (20%, 30%, and 40%)	170 °C	50 min	Conventional tests (softening point, penetration test, ductility, storage stability, and viscosity)	(GB/T0606-2011, GB/T0604-2011, GB/ T0605-2011, GB/T0661-201, and GB/T0625-2011)
						FTIR	-
						Thermogravimetric analysis	-
						Morphological analysis	-
						Dynamic mechanical analysis	-

(continued on next page)

Table 6 (*continued*)

Ref.	WEO	Asphalt	Mix	Temperature	Stirring time	Test	Standard
						DSR test	-
[75]	WEOB (Waste engine oil bottom)	Base binder (60/80) and SBS binder (SBS, 4.3%)	WEOB (2%, 4%, and 6%)	140–175 °C	10-40 min	GC–MS test FTIR test Rotational viscosity test Temperature sweep test MSCR test Fluorescence microscopy	- - ASTM 4402 ASTM D7175 ASTM D7405-15 -
[68]	WEO (reclaimed from vehicle maintenance)	Karamay 70# asphalt	WEO + WCO (0-4%), limestone	-	-	Road performance tests Micro test Basic performance test (penetration, softening point, ductility, and viscosity tests) Aging test	- (ASTM D5, ASTM D36, ASTM D113, and ASTM D4402) JTG E20 T0609
[81]	WEO	Esso #90 base asphalt, rubber asphalt containing WEO, microwave treated rubber asphalt, conventional rubber asphalt, and highly dissolved rubber asphalt using WEO and microwave desulfurization method	40 mesh crumb rubber (5%, 15%, 25%, and 35%) polyethylene (3%) WEO (25%)	185 °C	90 min	Storage stability test and corresponding indicators Rheological indices at low temperatures Rheological indices of MSCR test at high temperatures Solubility test and corresponding index	ASTM D7173 - AASTO TP70-09 -
[69]	WEO (from cars after 5000–6000 km of service mile)	A road petroleum asphalt (Pen60/80)	WEO rejuvenator (WEO 4.5%, furfural extraction oil 5%, and epoxy resin 0.5%), water-borne epoxy resin, and water-borne curing agent (2:1)	130 °C	30 min	High temperature rheological properties Fatigue test Semi-circular bending test Hamburg wheel tracking test Dynamic uniaxial compression test Freeze-thaw split test Molecular weight test Thermogravimetric test Chemical structure test Physical properties (penetration, ductility, and softening point) Low-temperature rheological properties	- - ASTM D3497 AASHTO T324 - - - - - (ASTM D5, ASTM D113, and ASTM D36) -
[82]	WEO (synthetic 5W30 gasoline oil)	Asphalt binder PG 64–22 RAP	Asphalt binders (virgin binder, 30% and 50% RAP binders, WEO-SBS-rejuvenated binders containing 30% and 50% RAP (30 R+WS, and 50 R+WS), SBS/WEO (10/90, 20/80, and 30/70)	140 °C	15 min	Accelerated rutting test BBR test Aggregate coating test RTFO, PAV, and DSR tests Indirect tensile strength test SARA analysis Marshall stability-flow test Thermal gravimetric analysis FTIR test	AASHTO T324-11 ASTM D6648 AASHTO T195 - ASTM D6931-2017 ASTM D4124 ASTM D6927 ASTM E1131 -
[71]	REOB	Base asphalt (GS-70)	REOB with different contents (5, 10, 15, 20, 25, and 30 wt%)	150 °C	30 min	DSR test Physical property test (penetration, ductility, softening point and viscosity) FTIR test TLC-FID test BBR test	ASTM D7175 (ASTM D5, ASTM D113, ASTM D36 and ASTM D4402) - - ASTM D6648
[42]	WEO (a petrol vehicle stationed in a local auto repairshop)	VG-30 grade asphalt binder RAP material (damaged pavements)	WEO (0%, 2%, 4%, 6%, and 8%) RAP (0, 25%)	160 °C	30 min	Dynamic shear rheometer FTIR Softening point	ASTM D 7175-08 AASHTO T53

(*continued on next page*)

Table 6 (*continued*)

Ref.	WEO	Asphalt	Mix	Temperature	Stirring time	Test	Standard
[83]	WEO	80/100 asphalt	WEO (2%, 4%, and 6% mass of asphalt) PPA (1% and 2%)	135 °C	30 min	Viscosity Fatigue-healing test Radar chart method Differential scanning calorimetry test LAS test	ASTM D4402 - - ASTM D3418 ASHTO TP 101-14

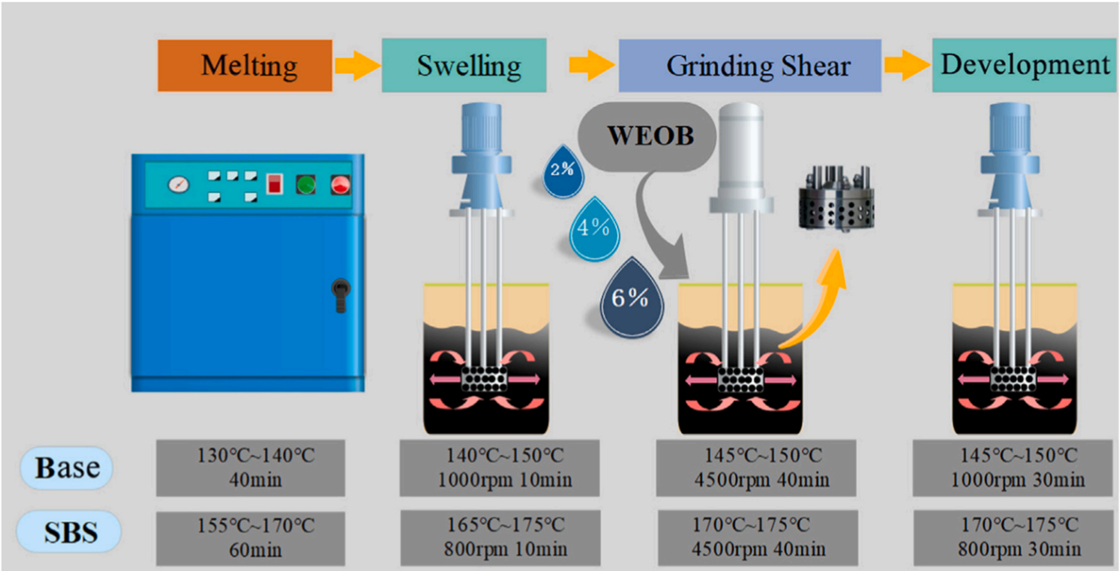


Fig. 4. Steps involved in preparation process of WEOB and WEOB-SBS modified asphalt binders [75].

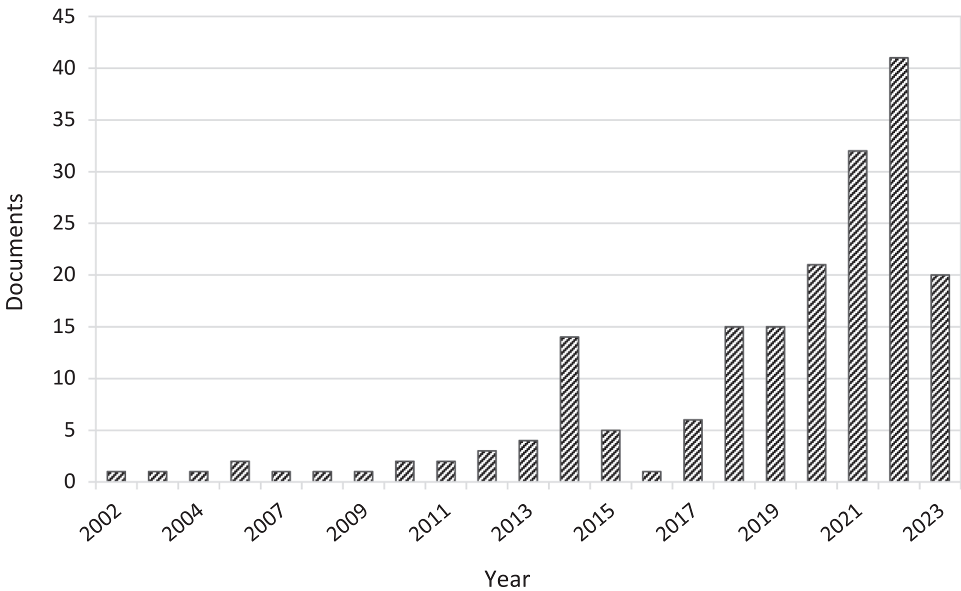


Fig. 5. Number of scientific publications per year from Scopus.

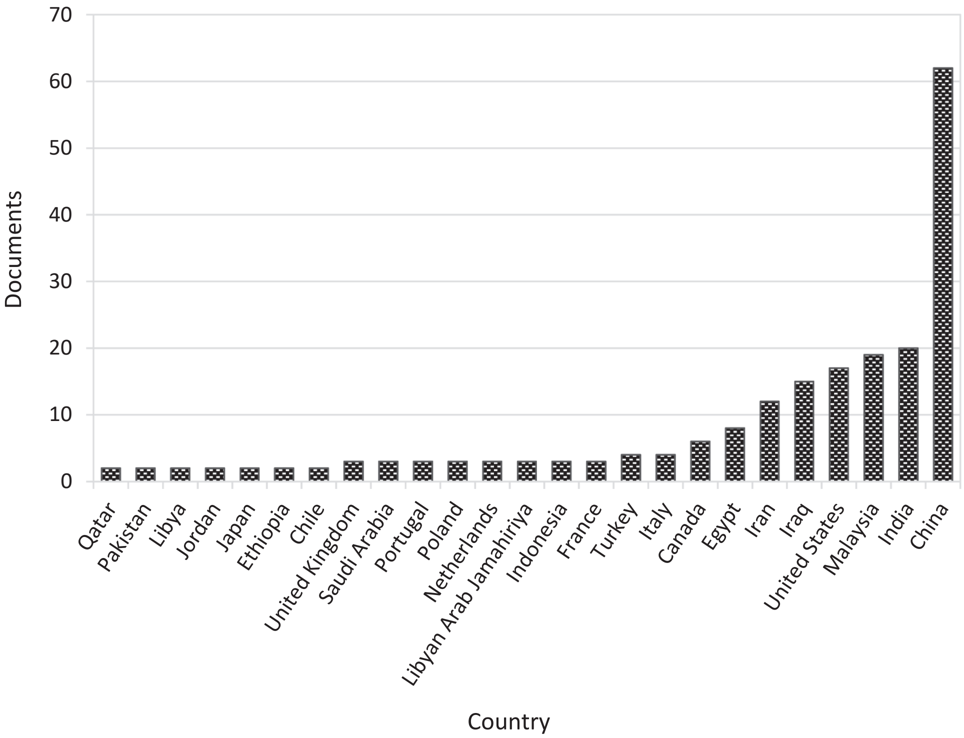


Fig. 6. Number of scientific publications per country from Scopus.

Table 7
Sizes of molecules in WEO-asphalt mixtures [39].

Asphalt type	SMS (%)	MMS (%)	LMS (%)
PMB-A	3.008	82.476	14.516
PMB-A + 4% WEO	2.926	82.785	14.289
PMB-A + 8% WEO	2.834	83.271	13.895
PMB-B	4.573	81.678	13.749
PMB-B + 4% WEO	4.433	82.511	13.056
PMB-B + 8% WEO	4.326	83.98	12.376
PB	3.323	86.022	11.655
PB + 4% WEO	2.328	91.424	6.248
PB + 8% WEO	2.117	93.571	4.312

wavenumber range of 2852–2923 cm^{-1}. The C@O stretch is linked to the peak at 1746, which indicates the existence of carboxylic acids or ketones in the samples. Moreover, the 1601 cm^{-1} absorption peak represented the existence of C@C functional groups. The tiny peaks at 1376 cm^{-1} and 1456 cm^{-1} are related to the functional groups of CH_2 and CH_3, respectively, describing the CAH bending. The authors also reported the improvement in the construction temperature, energy consumption, and rutting and fatigue resistances but the deterioration in the capacity of elastic recovery and resistance of deformation. The asphalt's high temperature categorisation was changed from 5 to 9 by the addition of 4% and 8% WEO, respectively.

WEO has been found to be able to enhance the behaviour of asphalt binders at low temperatures by reducing the time of the stress relaxation and stiffness. Qurashi and Swamy [42] reported that while the behaviour of WEO-modified asphalt deteriorated at high temperatures and the degree of deterioration depended upon the contents of WEO and the type of asphalt, the performance at low temperatures showed improvement. Hesp and Shurvell [48] presented property deterioration of WEO-modified asphalt when the use of WEO exceeded 15% because the asphaltene structure became unstable and asphalt subsequently became harder. By employing X-ray fluorescence spectroscopy technology, researchers examined the influence of WEOB on the cracking behaviour of asphalt pavement during service. Their findings revealed that the presence of WEOB led to a reduction in strain tolerance and subsequent hardening of asphalt, which are critical factors determining its performance under low temperature conditions. Meanwhile, Wang et al. [75] assessed the impact of WEOB on the base binder's rheological characteristics at high temperatures in comparison with a modified binder made with SBS. They observed that the WEOB-modified binders improved viscosity but reduced deformation resistance and elastic recoverability. However, adding WEOB to SBS binder had the opposite effect. WEOB has light components which play a key role influencing the behaviour of asphalt binder at high temperatures. These components enhance the asphaltenes' solubility, which in turn

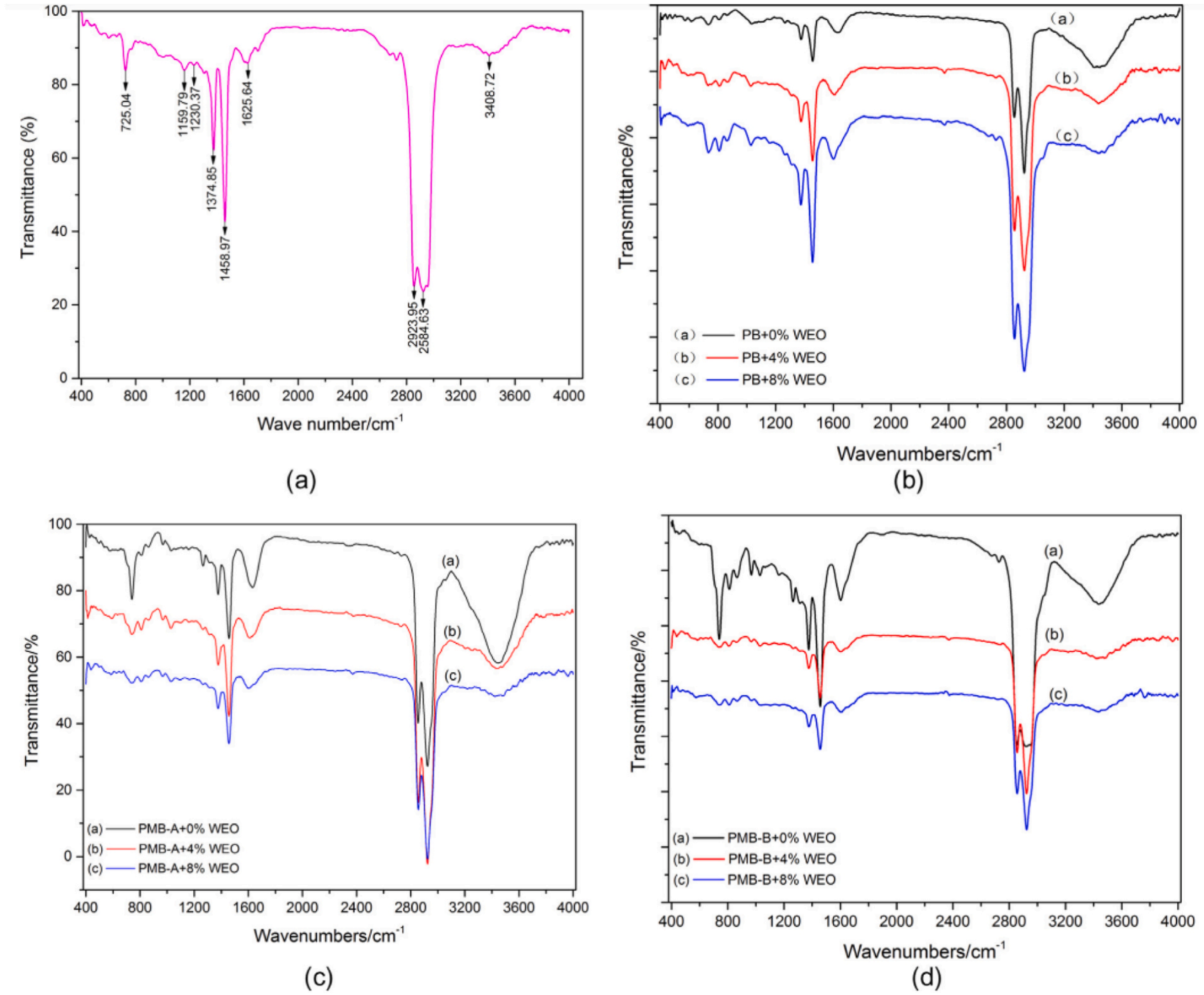


Fig. 7. Results of FTIR tests on WEO-asphalt mixtures: (a) WEO, (b) PB, (c) PMB-A, and (d) PMB-B [39].

soften the base binder. Whereas, the structural network of SBS expands due to the light components which also reduce the restriction on the thermal movement of asphalt molecules within the SBS network. Lei et al. [92] evaluated different WEOs, such as bio-based and refined ones, for their effects on the behaviour of asphalt at low temperatures. Their results in Fig. 8 demonstrate that regardless of their different types, WEOs increase the m-value but decrease the stiffness of the original asphalt binders. The modified binders have a higher rate of the stiffness reduction than the original asphalt binders, an indicator for the enhancement of the stiffness and relaxation rate of asphalt mixtures, and thereby, the pavement cracking resistance. It had been stated that the modified asphalt had the fracture energy which is more than three times that of the original asphalt binders. However, the performance at high temperatures had been noticed deteriorated.

Similarly, Lei et al. [78] carried out a separate study in which they evaluated six different types of oil additives, including refined waste motor oils, bio-based oils, and petroleum-derived oils. It was observed that all these oils resulted in a reduction in the stiffness of asphalt binders at various ranges of temperature. They found that these oil additives had a positive impact on the fatigue resistance at low temperatures but had a detrimental effect at high temperatures. Furthermore, they discovered simple linear trends for the relationship between types of oil and shear modulus or oil content and m-value.

Research has been conducted to examine the impact of oil modifiers on the performance of asphalt binder; however, further work is required to validate the trends found and increase understanding of this topic. Based on the aforementioned literature study, we can see that the majority of the studies were on WEO-modified binders, and there were few research works on WEOB-modified binders. While previous studies demonstrated that WEO can serve as a substitute for asphalt, comprehensive investigations regarding the impact of WEO on asphalt from the perspective of chemical and rheological properties are also necessary for the practical implementation of WEO-modified asphalt due to the variety of material sources and processing methods. The literature study uncovers that a limited number of articles assess the impact of oil on binder, with a focus on specific types of oil. It is vital to research how new oil extenders and modifiers affect the performance over the short and long terms, given the wide variety of new products being released on a regular basis.

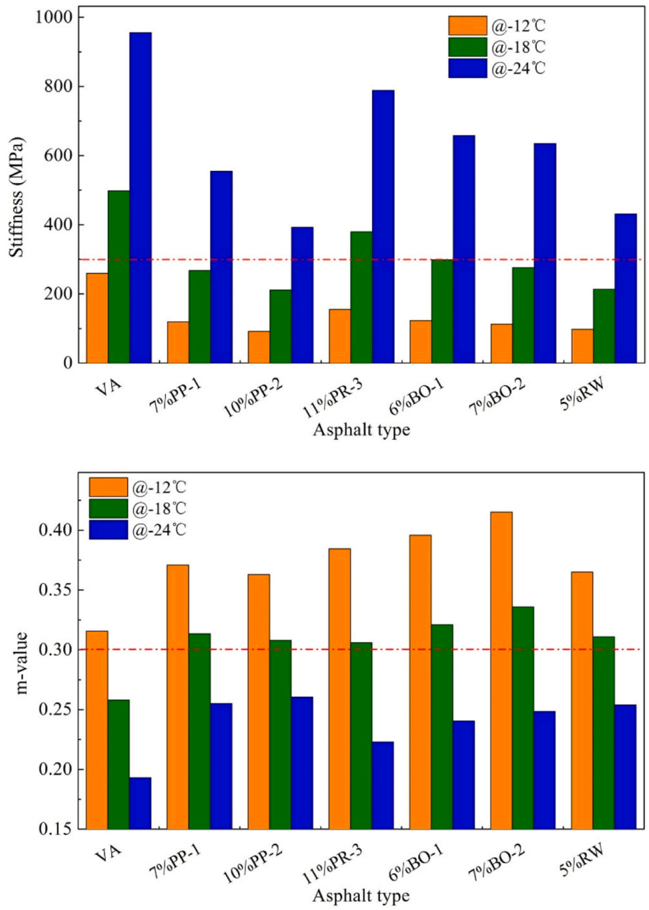


Fig. 8. Behaviour of asphalt at low temperatures in terms of stiffness and m-value [92].

5.3. Rejuvenation of aged asphalt and RAP

5.3.1. WEO used for aged asphalt

Asphalt loses its penetration grade over time when the viscosity and softening points have increased [7]. WEO can be utilised as an asphalt rejuvenator taking its ability to reduce the viscosity [63]. Asphalt aging leads to an increase in the weight ratio of asphaltene to maltene, resulting in a loss of volatility of their constituents [93,94]. Consequently, aged asphalt binders exhibit increased brittleness and stiffness. However, the use of WEO can help restore the viscoelastic properties of aged asphalt, reducing the stiffness [95] and improving the workability [39,88]. Moreover, the application of WEO has displayed benefits in improving the resistance to fatigue and cracking at low temperatures [52,96,97].

Although WEO has the effective potential to be used for asphalt rejuvenators, only a few studies had been reported on this subject until 2009 [98]. Recently, significant works have been performed using WEOs as asphalt binder rejuvenators [72,77,99–102]. According to Silva et al. [103], substituting WEO for road materials can assist in lowering the mixing temperature. Also, Shen et al. [104] mentioned that the WEO may be utilised to minimise the optimal content of commercial additives in asphalt mixtures. Moreover, DeDene and You [59] proved the potential of WEO used as a rejuvenating agent to recycle asphalt mixtures but noticed the reduction of the pavement properties. However, Peng et al. [105] employed waste polyethylene and WEO to modify asphalt. By ultraviolet aging simulation, they illustrated that WEO improves aging of asphalt. Another study by Arshad et al. [106] found enhancements in the viscosity of aged asphalt when using WEO as a rejuvenator. But, the increase in the content of WEO reduced both the viscosity and softening point. Similarly, El-Shorbagy et al. [107] utilised WCO and WEO as rejuvenator agents and resulted that the content of 4% WCO or 6% WEO improved the penetration value and softening point of rejuvenated asphalts. Zhou et al. [68] also used WCO and WEO as rejuvenating agents and concluded that at specific contents the waste oils had obvious recovering effects on the index properties including the viscosity, penetration value, ductility, and softening point. They reported a decrease in the viscosity when the contents of WCO and WEO are beyond 4%. Chemically, the light components of asphalt can be replenished by the waste oils, leading to the regeneration of asphalt.

On the other hand, Qiu et al. [80] compared the damage characteristics of WEOB-rejuvenated asphalt with those used in extracted aromatic oil (AO) for rejuvenation. According to their findings depicted in Fig. 9, when the fatigue life of asphalt binder was decreased by age, AO-modified binder had the fatigue life increase when exposed to two stains, 2.5% and 5%, while WEOB -modified binder had the fatigue life increase only at the strain state of 5% but decrease at the state of 2.5%. It implies that WEOB is more suitable for low-thickness asphalt layer pavements in terms of the fatigue performance. Fig. 10 provides the results of the creep analysis. It elucidates that after 1 h of water conditioning, both binders displace a similar behaviour. However, after conditioning for 24 h, the loss in the creep of WEOB-modified asphalt reaches up to 50%, while the loss of AO-1 almost keeps no change. It means that WEOB can be more beneficial in cold regions.

The use of two types of REOBs, called REOB-1 and REOB-2, was studied by Cai et al. [71] on three different aged asphalts, i.e. mild, moderate, and severe aging. Their results, as presented in Fig. 11, indicate effective partial recovery for both REOBs at the optimum content of 15% by the weight of asphalt binder. However, REOB-1 demonstrates a better effect, attributed to its noticeable level of aromatics and penetration than that of REOB-2. In general, the increase in REOBs content reduced the softening point and viscosity of asphalt.

Qurashi and Swamy [42] compared the viscoplastic properties of virgin and aged binders modified with WEO at different temperatures. The results, as shown in Fig. 12, exhibited the reduction in the viscosity with the increase in temperature. Below a certain temperature, the binder modified with WEO gave lower viscosity compared with the binders using only the virgin binder or their mixture. In addition, the WEO-modified binders displayed lower complex modulus and softening points, but higher phase angles across all temperatures. Overall, it was witnessed that the best performance was achieved when the WEO content ranged from 2% to 4%.

The increased stiffness brought on by using old asphalt binder can be effectively mitigated by utilising WEO as a partial substitute within the asphalt binder system. Even a partial replacement of this kind can contribute to the resource conservation, energy savings, increased recyclable content, and environmentally friendly building methods. Additionally, WEO can be used in place of additives that are sold in stores. Based on the above study, it can be concluded that using WEO for asphalt and asphalt mixture regeneration is viable; nevertheless, there are still a number of issues that need to be resolved. In conclusion, investigations on the use of WEOs as regenerants have been conducted. Unfortunately, the majority of studies concentrate exclusively on the performance of old asphalt that has been rejuvenated using a single WEO. The effect of aged asphalt on regeneration has not been thoroughly studied, and the improvement in the mixture's performance has not been adequately explained. However, WEO degrades land and water resources, thus its usage must be considered carefully in order to promote sustainable growth. In addition, WEO is a material that, if not properly treated, could contaminate the environment. Its use in asphalt pavement might lessen its detrimental impact on the environment as well as the costs associated with construction. However, prior research mostly addressed the use of WEO as a recycling agent rather than as a modifier for asphalt binder, hence the majority of studies to date have only examined viscoelastic qualities within the linear range. Extensive study on the damaging properties of regenerated asphalt binder in the non-linear range is conspicuously lacking. Furthermore, only a small number of studies carried out a thorough examination of the microstructure of regenerated asphalt binder and the combing damage features throughout the non-linear range in order to assess the regenerative effect of different types of recycling agents.

5.3.2. WEO used for RAP

In the early 20th century, significant advances have been made in the asphalt industry to reclaim asphalt and aggregate from demolished pavements [103,108–110]. However, directly using RAP results in the concrete mixtures having substantially high stiffness, making them difficult for compaction, and the constructed pavement prone to premature failure [111–115]. The high stiffness of RAP itself results from the gradual oxidation of asphalt, which alters the composition of asphalt, eroding its viscoelastic characteristics [116]. Various approaches are adopted in practice to address the challenge of reusing RAP for new pavement construction, including high amount usage of asphalt, cold or warm mix techniques, and the use of asphalt softener [117]. However, these techniques are only feasible at a limited scale but not effective for a practice involving high volume use of RAP under the increasing requirements for sustainable construction of road infrastructures, for which using rejuvenating agents has proven to be a feasible alternative [118]. So far, various commercial rejuvenators have been used for large-scale reuse of RAP and the usage of RAP is over 30% of the total materials [119–121]. Upon the rejuvenating feature of WEO for asphalt [42,122–124], a recent review by Al-Saffar et al. [125] highlighted the potential of using WEO to improve the characteristics of asphalt concrete with 30% RAP content. In accordance with Eltwati et al. [126], adding 9% WEO to asphalt mixtures that contain RAP binders greatly enhanced their performance. Also, Singhabhandhu and Tezuka [127] indicated that using WEO at 7–13% for asphalt binder containing 30–40% RAP

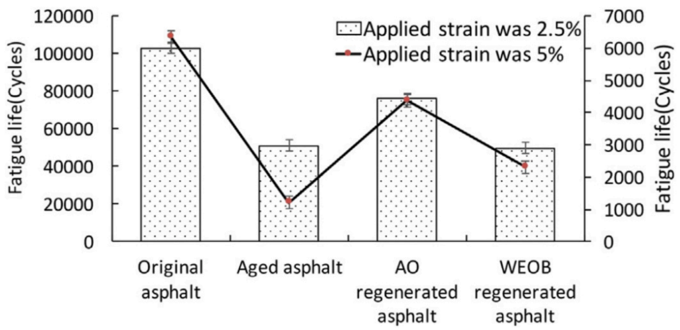


Fig. 9. Fatigue life of several asphalts at two applied stresses (application of cyclic loading in form of linearly increasing load amplitudes) [80].

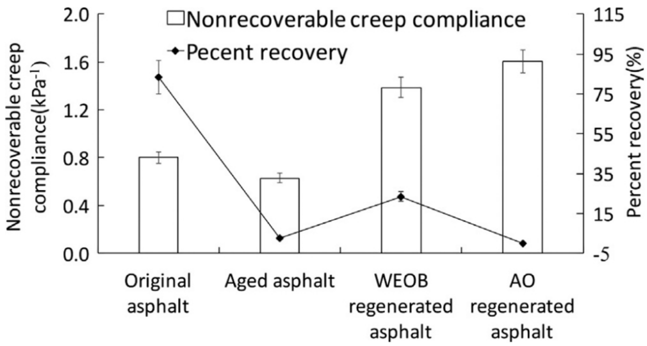


Fig. 10. Percentage of recovery and nonrecoverable creep compliance for several asphalts [80].

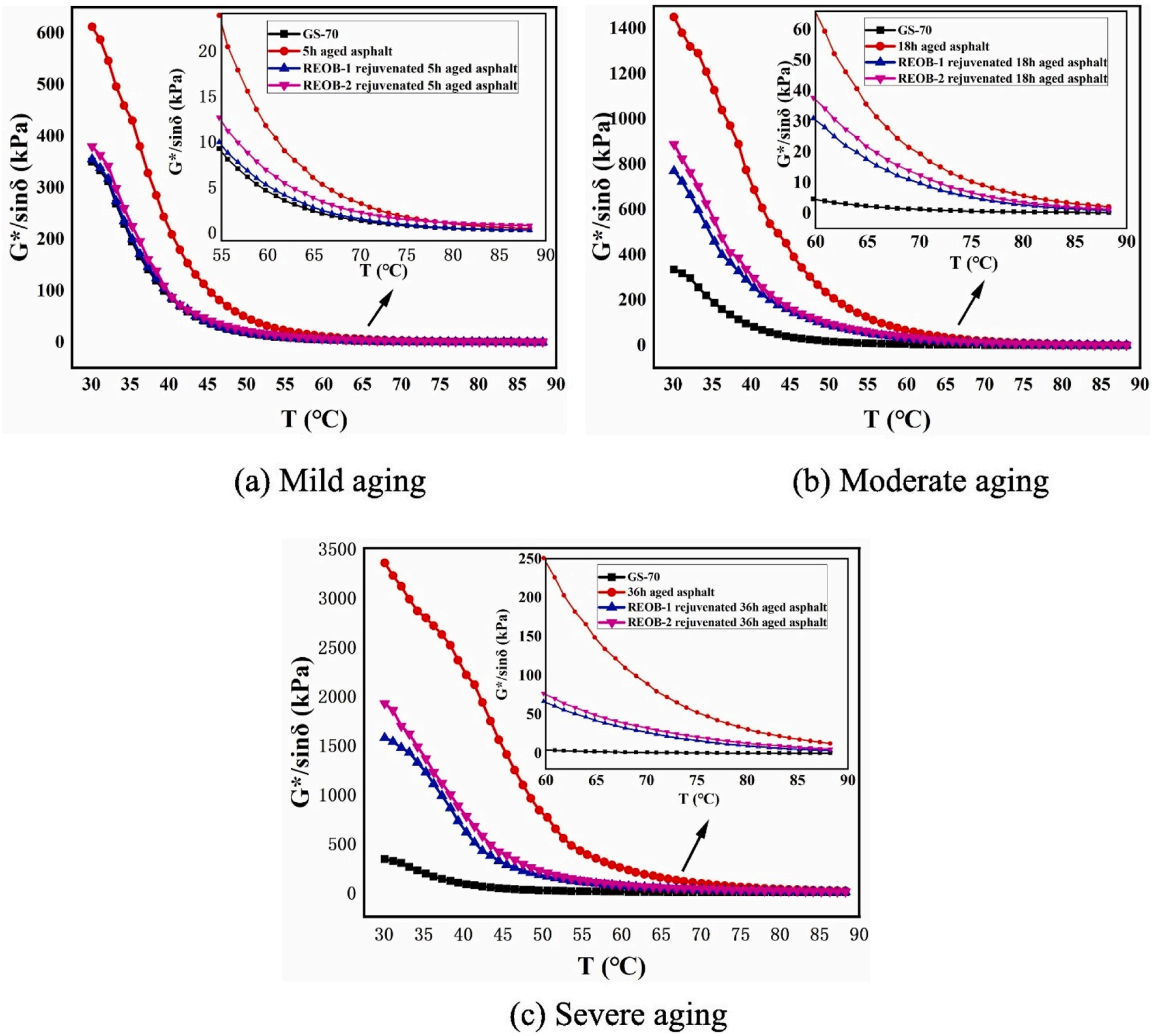


Fig. 11. G*/sinδ of various REOB rejuvenated asphalts [71].

generated similar regeneration results to those obtained from employing commercial regenerating agents. Farooq et al. [128] reported that a 100% WEO and RAP mixture met the flow value and Marshall stability requirements of binder layer design for heavy traffic and the wear layer design for medium traffic. However, when storing time increased, WEO-modified asphalt penetration rate provided a

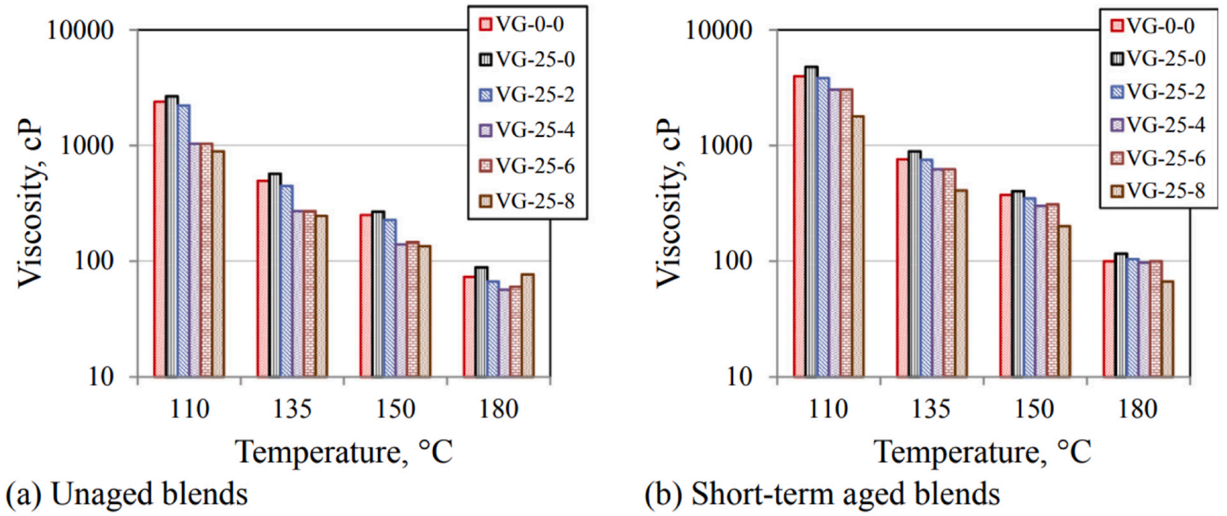


Fig. 12. Effect of temperature on viscosity of blends with different WEO contents; blends with 0%, 2%, 4%, 6%, and 8% WEO were labelled as VG-25-0, VG-25-2, VG-25-4, VG-25-6, and VG-25-8, respectively [42].

general declining trend [99].

In another study, Mamun and Al-Abdul Wahhab [129] assessed the WEO effect on the mixes of RAP up to 50% and compared it with the effect of a commercial rejuvenator. It was seen that the asphalt mixtures had an ITS of 860.94 kPa and 719.42 kPa by the use of 7% WEO with 30% and 40% of RAP, respectively. The results are similar to that using virgin asphalt binders and that rejuvenated utilising a commercial rejuvenator. When the amount of RAP was increased by over 40% and WEO by over 7%, the ITS value showed a significant decrease. Using WEO at the contents between 7–20% and RAP up to 50%, the mixtures had low moisture damage, which is 20% less than the maximum permissible value. However, when the WEO content exceeds 20%, the moisture susceptibility increases.

On the other hand, some negative impacts of using WEO on RAP were obtained by Jia, et al. [46]. They found an increase in the existence of the carbonyl functional groups that are related to the oxidation of asphalt binder. The use of WEO in 5% and 10% reduced the high temperature grade by 6 °C and 12 °C, respectively. Due to WEO, the asphalt's ability to recover elastically was weakened, which reduced its rutting resistance. The impacts on the stiffness are displayed in Fig. 13. At the reference temperature of -6 °C, the stiffness of 5% oil mixture is similar to the control asphalt, demonstrating similar stiffness properties at low temperatures. At low temperatures, the use of WEO considerably reduced the stiffness of asphalt binder, with 10% WEO having the greatest effect. This behaviour at low temperatures was largely influenced by WEO. This is because engine oils normally flow at relatively low temperatures, enabling engines to initiate at those temperatures. The authors suggested further studies to validate the findings.

Further, Joniet al. [130] compared asphalt cement (AC (60−70)) and WEO as rejuvenators at various contents, i.e.: 1%, 1.5%, 2%, 2.5% and 3%, added to RAP. The optimal content of regeneration additive (AC, 3%) had a higher value than the optimal ratio of regeneration additive (WEO, 1.5%). This phenomenon can be attributed to the influence of the low viscosity of these waste materials on the Marshall properties of the pure RAP mixture. It plays a significant role in determining the optimal content, enabling the restoration of aging binder properties and yielding results that meet the specifications for surface layer requirements at these ratios. WEO increases the Marshall stability by 20.3% while AC by 40.8%. The flow value of the WEO-1 was slightly lower than that of AC-1 but both were within the specification of standards. Both rejuvenators produced a high moisture resistance of over 80% of the specified requirements by standards [130]. Thus, WEO can reduce the stiffness of RAP and increase the RAP content, though its fatigue improvement is limited.

Recovering the flexibility of RAP binder with the addition of WEOs could be comparable to adding an asphalt rejuvenating agent. WEO may be used to asphalt paving mixtures for the aforementioned reasons, either knowingly or unknowingly to paving customers or agencies. Nevertheless, prior research fails to elucidate the degree of RAP at which WEO functions as a rejuvenating agent. Several studies have looked at how rejuvenation affects the performance of virgin binders that make up RAP binders. According to these studies, the stiffness of RAP binder can be successfully lowered by adding a rejuvenator, which improves the binder resistance to thermal cracking but decreases its resistance to rutting. Compared with a conventional single rejuvenator, RAP binder rejuvenated using a compound rejuvenator ought to exhibit superior fatigue cracking performance and rutting resistance. It would appear to reason that adding WEO will soften the old binder in RAP. However, as the performance of asphalt including RAP and WEO would be vulnerable to the combined impacts of WEO, virgin binder, and aged RAP binder, one cannot conclude that the fatigue and cracking resistances of asphalt mixtures will be improved. Therefore, creating asphalt binders with RAP binders that operate at their best is essential.

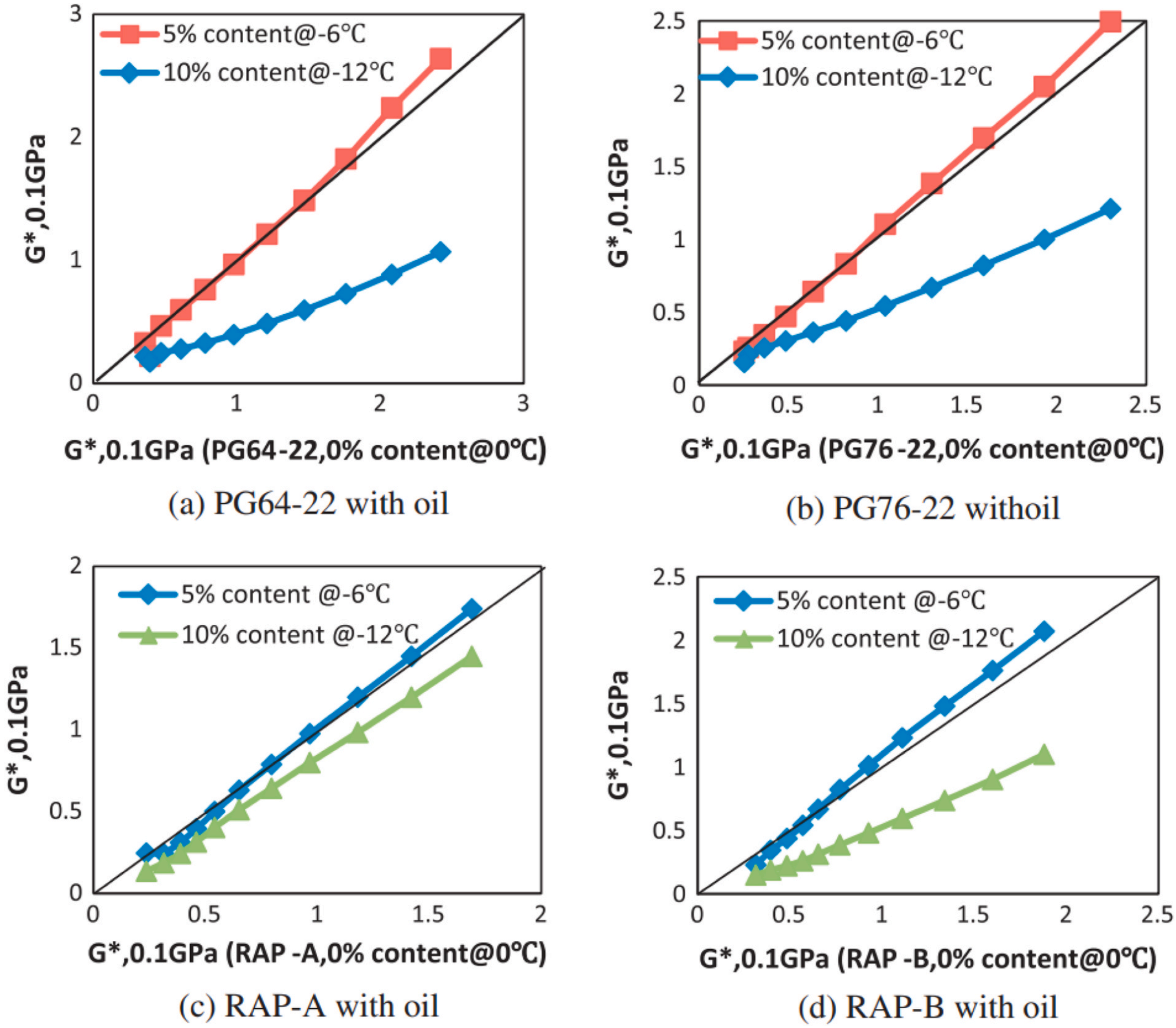


Fig. 13. Results of stiffness at low temperatures of various asphalt binders [46].

5.4. WEO Used for Asphalt Self-Healing

The self-healing capability of asphalt is important for the sustainability of pavement infrastructure [131]. In general, the flowing property of asphalt plays a key factor in asphalt's self-healing capability. However, solely depending on its inherent flowing property, asphalt is unable to fulfil self-healing for damaged pavements [132]. Taking advantage of other light materials to enhance the fluidity of asphalt has been proved an effective measure [133]. The concept of using WEO to enhance the asphalt capability of self-healing has attracted more interest. By the use of a three-point bending experiment, Yamaç et al. [134] found that WEO-modified asphalt exhibited the improved self-healing capacity. The self-healing capacity of asphalt material can be quantified in terms of the degree of fatigue damage under specific loading and climatic conditions, reflecting the fracture resistance of asphalt thereby representing a key design parameter of pavements in engineering [135]. There are two different approaches to evaluate the self-healing capacity of asphalt binders, they are the fracture-heal-fracture test and the fatigue-heal-fatigue test. For the fracture-heal-fracture test, specimens are made in a specific shape consisting of a weak section, where the specimens break up when subjected to direct tension. Afterwards, the broken specimens are assembled back at the broken sections and healed under high temperature. The healed specimens are tested again to compare the tensile strength and other parameters [136–138]. The fatigue-heal-fatigue test follows the same procedure but having different temperatures and loading modes. A dynamic shear rheometer is used to repeatedly apply oscillation shear then the shear is stopped and healing time is added. Then, the same shear load is applied again. Although samples are still failing partially even though they are in a microdamage state, the loading mode is close to the practical condition and corresponds to the optimal healing condition [139,140]. Liu et al. [83] performed a study using polyphosphoric acid (PPA) and WEO to improve the self-healing capacity of asphalt. As illustrated by Fig. 14, they compared the fatigue life ratio, which is utilised as the self-healing indicator for the fatigue-heal-fatigue test, against the contents of PPA/WEO. Their results indicated that fatigue life ratios had been substantially increased by 1000% using 2% PPA and 2% WEO, and by 1150% utilising 1% PPA and 4% WEO. The application of sole WEO or PPA can enhance the recovery of the fatigue life as well for the modified asphalt at a certain WEO content, while increasing the PPA content also increased the fatigue life. Both PPA and WEO by themselves were able to restore the original asphalt's fatigue life, modulus, and dissipated energy, but time for healing was increased too. The best performance was obtained from asphalt treated with 2% PPA and 6% WEO. In addition, with the lengthening of the healing time, original asphalt has stronger improved healing indicators than modified asphalt. This is because modified asphalt damage can generally be repaired rapidly.

Apart from traffic loading, asphalt pavement in service is meanwhile subject to various influences from the surrounding environment including humidity and temperature, which, sustaining for a long term, may initiate minor damages, such as microcracks [141]. Without timely maintenance, such damages can continue to develop, becoming more visible, until break the integrity and stability of the pavement structure [142]. Motivated by the natural and biological mechanism of recovery, encapsulation self-healing technology has been developed and proven an effective approach for pavement repairing [136,143–147]. Microcapsules containing healing binders are embedded in the pavement mixes when doing construction. Thereafter, in line with the developing microcracks under service, the microcapsules can be broken up to release the healing agents. Driven by capillary actions, the healing agents infiltrate through and fill up the cracks to prevent further cracking propagation [148].

Wang and Hao [67] studied a refined WEO-modified asphalt as the healing agent. Using a synthesized polymer for microcapsules to have adequate thermal stability to resist mixing temperature, the authors reported that WEO provided a minor impact on the penetration value and softening point though the reduced ductility of asphalt. It also increased the brittleness of the repaired pavement mix.

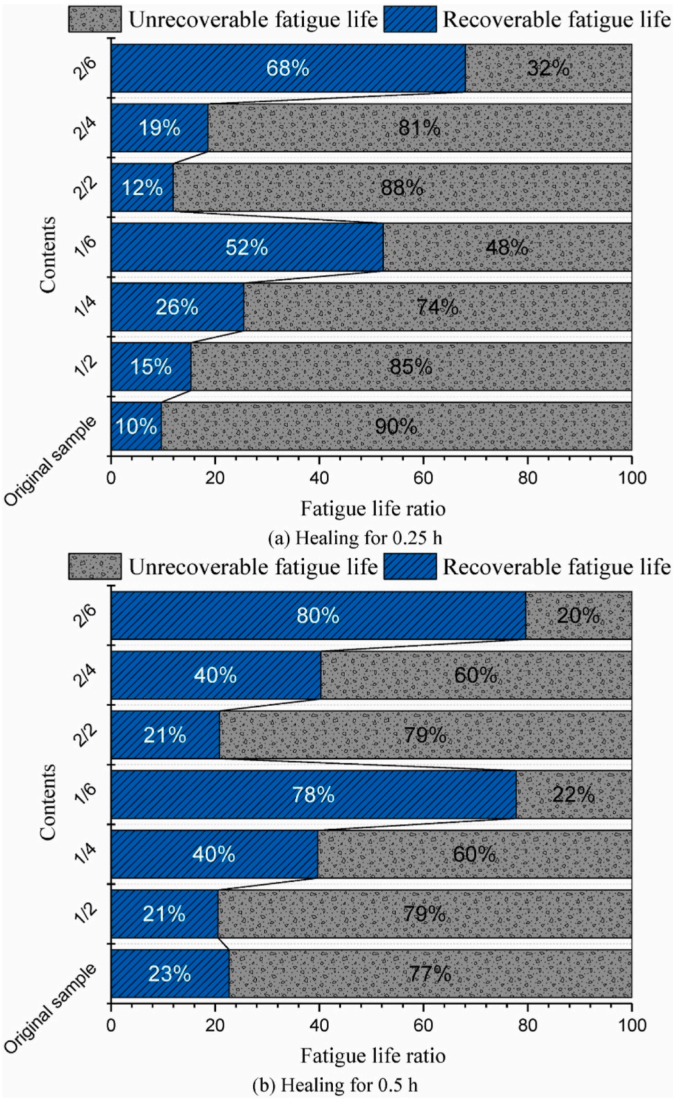


Fig. 14. Fatigue life ratio of asphalt binder [83].

However, WEO improved the resistance to fatigue under both high and low strains. The maximum service life recovery by healing was achieved when microcapsules addition was below 4 wt%. Multiple rest experiments uncovered that complex modulus recovery rapidly declined during the first few rests before stabilising at a specific level subsequently. For the microcapsule samples, complex modulus recovery accelerated. Four stages can be deduced from these tests throughout the entire process, as depicted in Fig. 15. In the beginning, shear loading is subjected to samples and microcapsules are rarely ruptured. Secondly, with the proceeding of shear, complex modulus decreases when microcracks start and the microcapsules rupture due to the shear oscillation. Thirdly, a healing agent, released from the ruptured microcapsules and driven by capillary actions or intermolecular surface forces, starts to fill the cracks. Finally, after an extended period of healing, the small molecule chains of WEO gradually diffuse into the larger molecule chain of asphalt, leading to accelerated self-diffusivity and softening of the samples. The last three stages are repeated until all the microcapsules are broken.

According to recent research attempts, the recovery impact of microcapsules can be demonstrated, and using light oil as the microcapsules' core to restore damaged materials may be a workable approach. However, prior research on the impact of microcapsules on the rheological behaviour of asphalt binder and the potential longevity of the healing effect has been few. It is vital to comprehend the healing durability offered by microcapsules, since this could potentially prolong the asphalt pavements' service life. Based on the fatigue-healing test, markers such as the fatigue life recovery, modulus recovery, and dissipated energy recovery are evaluated in order to determine the degree to which asphalt binders have healed.

5.5. WEO composite binders

The use of composite binders by various materials having WEO was investigated in several research works. Liu et al. [27] examined a composite binder modified using WEO at 2%, 4%, and 6%, and PPA at 1% and 2%. They found that PPA increased the softening point but reduced the ductility and penetration of the initially WEO-modified asphalt. However, the highest impacts were obtained by the use of 1% PPA and 6% WEO and 2% PPA and 2% WEO for the ductility, softening point, and penetration value at 172.2% and -34.8%, -14.6% and 6.3%, and 16.6% and 134.8%, respectively. Utilising PPA helps ease the adverse impact of WEO on the behaviour of

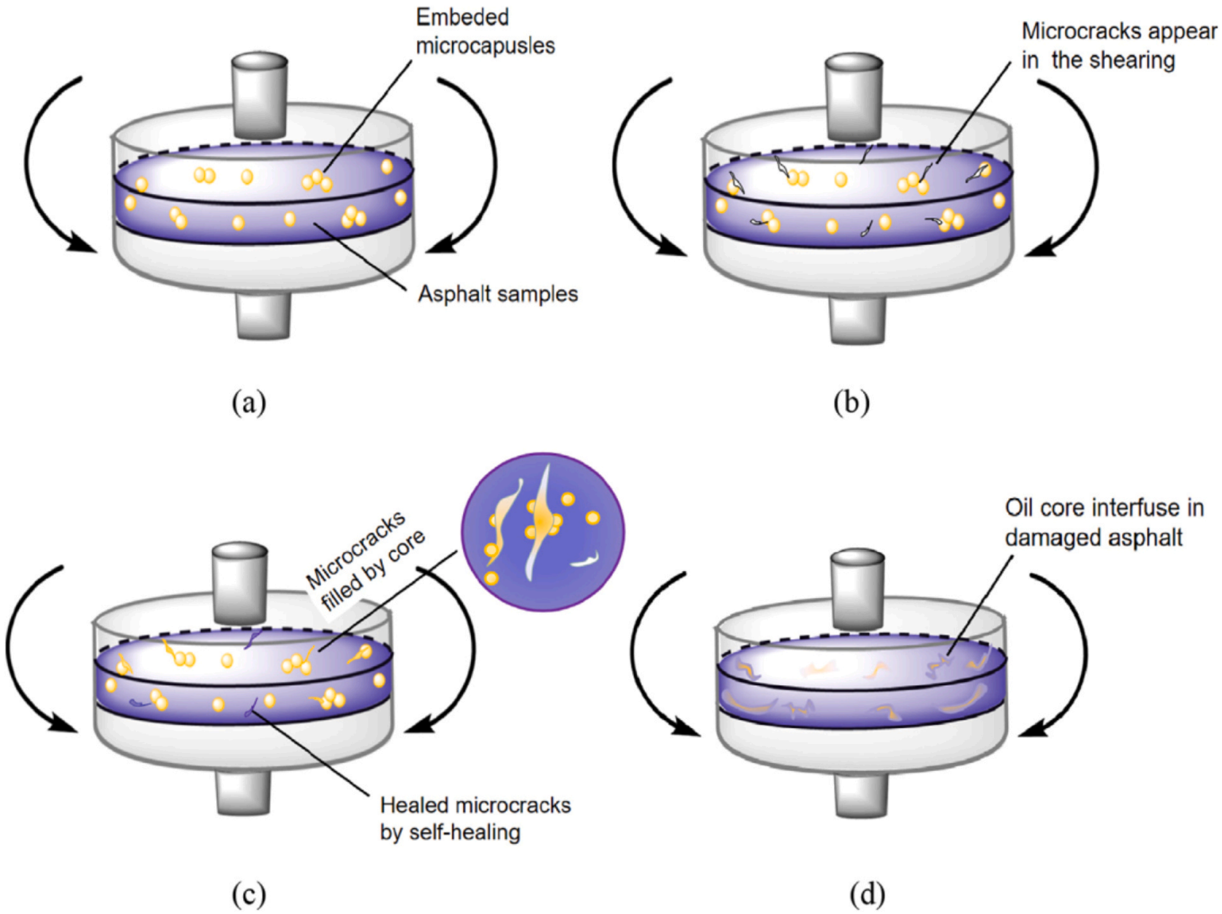


Fig. 15. An illustration of how microcracks form and heal: (a) initial shearing without microcracks, (b) shearing with microcracks, (c) microcapsules rupturing and oil core releasing and filling microcracks, and (d) asphalt microcracks distributing oil core [67].

asphalt at high temperatures. At the same WEO concentration, the PPA decreased the binder's thermal stability or temperature sensitivity. Based on the FTIR analysis, the modified and original asphalt binders had characteristic peaks between 2850 and 3000 cm^{-1}, around 1500 cm^{-1} and roughly 748 cm^{-1}. Asphalt and PPA react chemically according to the change in the FTIR curve, which obscured the PPA image in the optical microscope. The rutting factor, or index of persistent deformation, was improved by 31.2% compared with the original asphalt at the optimal content of 2% WEO/PPA. Meanwhile, Liu et al. [39] used a DSR test to assess the behaviour of various asphalts in terms of the fatigue factor. They found that PPA and WEO working together had produced superior performance over the SBS rubber and WEO composites.

On the other hand, Eltwati et al. [82] assessed the composite of WEO and SBS polymer to modify RAP binders. They resulted that the optimum contents of the WEO-SBS composite are 5% and 10%, respectively, for the binders containing 30% and 50% of RAP, in terms of the properties including the softening point, ductility, and penetration grade. In comparison with the control mixture, the regenerated asphalt binders had improvements in the low-temperature performance, increased cracking resistance, and higher tensile strength and rutting resistance. There were also enhancements in the Marshall properties, moisture susceptibility, and aggregate coating properties.

However, Fernandeset al. [79] studied a composite using WEO or REOB (as partial substitutes for bitumen) together with polymers, including waste polyethylene (HDPE), crumb rubber, and SBS. They concluded that modified binders using the composite displaced either better or similar properties in comparison with a commercial binder product. The optimum composites were identified with the composition of 6% HDPE together with 10% WEO or 15% REOB, 5% SBS together with 10% WEO or 12.5% REOB, and 20% crumb rubber together with 7.5% WEO or 15% REOB. Meanwhile, the WEO/REOB composite binders showed less thermal susceptibility than commercial binders. The WEO/REOB composite binders were more flexible at low temperatures and more rutting resistant at high temperatures. Among all the polymers, SBS demonstrated the best performance in regenerating asphalt. The combination of WEO or REOB together with polymers was not what was expected to result in an excessive hardening of the modified binders, as all the tested binders are within the specification limits in terms of the rolling thin-film oven test. However, compared with WEO, REOB can have a more significant reduction in the amount of fresh bitumen usage without compromising the binder properties because of its higher viscosity magnitude.

Furthermore, Paliukaite et al. [76] compared the ductility of the asphalt cement modified using the REOB alone and the REOB-SBS composites. REOB alone displayed a negative impact on the high-strain failure properties. However, as illustrated in Fig. 16, REOB-SBS composites provided a big improvement in the tolerance for ductile strain, which brought in the benefits of the reduction of cracking distress.

Many researchers have assessed the use of WEO together with rubbers. Li et al. [77] evaluated the use of WEO together with vehicle

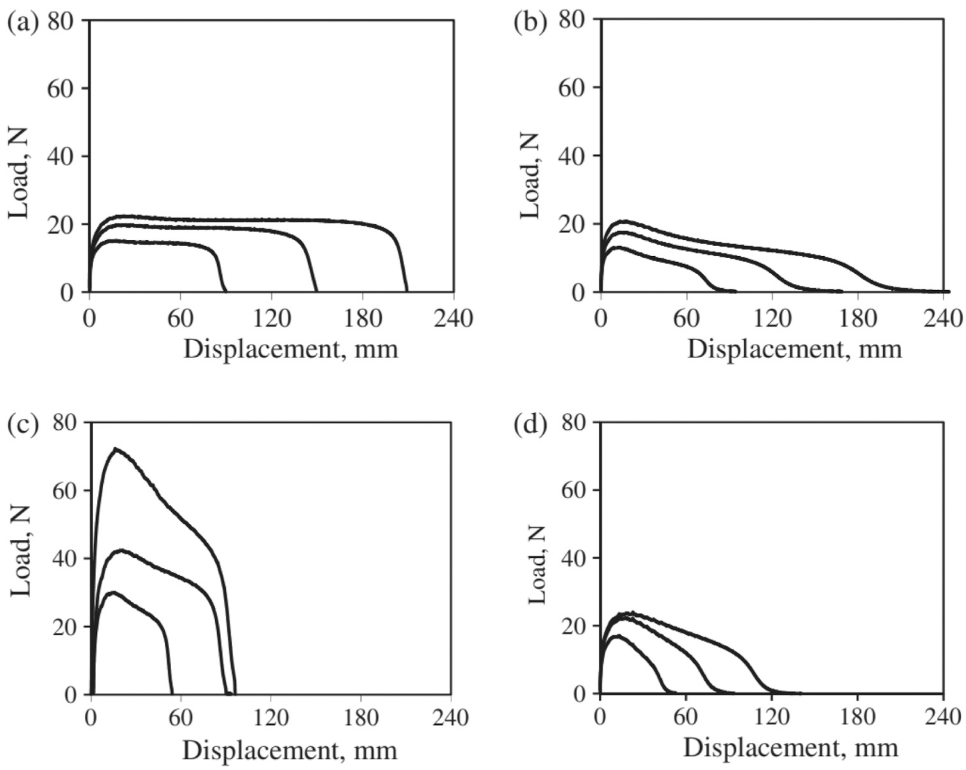


Fig. 16. Results of DENT tests on modified asphalts: (a) 5% SBS D1192, (b) 3% SBS D1192 + 8% REOB, (c) 4% SBS D1192 + 20% RAP, and (d) 2.5% SBS D1192 + 6% REOB + 20% RAP [76].

tyre rubber (GTR) at a temperature in the range of 150 °C to 280 °C, and degraded vehicle tyre rubber (DGTR) was obtained with different devulcanization degrees. The results indicated that devulcanization and temperature remarkably impacted the level of crosslinked structure and thereby the characteristics of the modified binder. The use of WEO improved the partial degradation of GTR, effectively influencing the rubber devulcanization degree. The significant content of WEO reduced the stiffness of modified asphalt and increased the processing properties including the viscosity, softening point, and ductility tests, which enhanced the cracking resistance at low temperatures. However, as WEO increased the flowability of asphalt, it adversely impacted the resistance to rutting as well as storage stability at high temperatures.

Additionally, Xu et al. [81] utilised WEO and microwave desulfurization to develop an asphalt with a significant amount of dissolved crumb rubber. The solubility of crumb rubber in asphalt increased by more than 10–20% on normal rubber asphalt. The significant content of crumb rubber improved the behaviour of asphalt at low and high temperatures in addition to its storage stability. As depicted in Fig. 17, the cumulative shear strain decreased when the rubber content increased, but at certain rubber content, it increased in a linear trend with time. Compared with that of larger rubber content, the binder of 5% rubber gave the maximum cumulative strain at high temperatures. Binders exhibited lower cumulative deformation when rubber content was more than 5%. Binders of rubber content lower than 5% had small elastic recovery as the unloading curves were flat. Also, the rubber content had a main impact on the creep deformation.

The use of lignin and WEO together as bio-additives for aged asphalt modification was investigated by Fakhri and Norouzi [70]. They found that WEO decreased the viscosity and creep stiffness, while lignin in opposite increased the viscosity and creep stiffness compared with the control binder. The stiffening effect of lignin was reduced by the application of WEO, and the lignin-modified binders were less resistant to the low-temperature cracking. In comparison with the virgin binder, utilising combined lignin and WEO increased the rutting resistance and produced superior results at low temperatures. Using both additives can strengthen the binder's resistance to aging, per the carbonyl and sulfoxide indices.

However, glass fibre has also been employed to work together with WEO to improve the RAP mixtures. Eltwati et al. [126] studied different contents of glass fibre at 0.0%, 0.1%, 0.2%, and 0.3% and WEO at 6%, 9%, and 12% to rejuvenate asphalts of high percentages of RAP at 60%, 70%, and 80%. Their results pointed out that the combination of glass fibre and WEO enhanced the resilient modulus, moisture susceptibility, rutting resistance, and ITS of asphalt. The optimum content of fibre was found to be 0.2%. Ziari et al. [149] examined the effect of low glass fibre percentages at 0.06%, 0.12%, and 0.18% on asphalt with high RAP content under three temperatures, i.e., -15 °C, 0 °C, and 15 °C, and reported improvement in the cracking resistance of the modified asphalt binders.

In a different approach, Chen et al. [69] used WEO, extracted furfural oil, and epoxy resin (WEO-RA) to rejuvenate aged asphalt. They reported no chemical reactions had occurred but only physical modification happened to the aged asphalt. The WEO-RA agent had thermal stability in the temperature range covering mixing and service, i.e., 30–200 °C, which was comparable with the original asphalt although slightly lower at high temperatures. The WEO-RA generated noticeable improvement in the rutting resistance particularly at low temperatures because of better complex modulus and phase angles under the conditions. In addition, WEO-RA also provided a similar aging resistance and storage stability as those of virgin asphalt.

It is advantageous to add WEO to asphalt in order to save the environment and crude oil. Furthermore, there are greater environmental and economic benefits when more WEO is included. However, the higher WEO component in asphalt will cause the material to perform worse at high temperatures. Therefore, compound modification is a useful technique to compensate for the drawbacks of single modification. Given that some of those issues are resolved by the use of polymers, rubbers, lignin, PPA, and glass fibres, bitumen modification with waste motor oil products and additives may provide the paving industry a viable, cost-effective, and environmentally acceptable alternative. However, there are still requirements for the extent to which such could practically be applied. Also, other bio-binders can be investigated. While bio-binders stiffen at high temperatures and increase resistance to the permanent deformation, WEO functions as a lubricant and works well at low temperatures. Consequently, they can also increase resistance to the irreversible deformation and postpone the binders aging, as well as address environmental issues brought on by their inappropriate disposal.

5.6. Economic and environmental impacts of using and producing WEO

The economic and environmental benefits of using WEO for the asphalt rejuvenation and modification are two important elements in appraisal [150]. However, so far, only a few studies have been carried out on the subject except the general concept that recycling WEO together with RAP asphalt reduces the required amount of virgin aggregates and asphalt, and accordingly the cost and greenhouse emission, as well as the corresponding energy consumption [150,151]. Wang et al. [152] found that a warm asphalt mixture using WEO decreased the mixing and compaction temperatures by 17.9 °C and 17.6 °C, respectively. However, the asphalt rejuvenation had the cost increased. Environmentally, WEO is a polluting material, which is going to contaminate water resources and ground, therefore, requires effective management. By comparison, recycling WEO has more environmental benefits than economic ones [153]. In addition, WEO recycling is also a cheaper and more effective alternative approach than incineration from economic and environmental perspectives [154]. To refine and recycle WEO, various techniques have been developed, including hydrogenation, acidic refining, distillation, and clay treatment, to remove mechanical, chemical, and physical impurities [155]. The more effective recycling process for waste oils is solvent extraction followed by adsorption [156,157]. The selection of solvents should consider having minimum solubility for carbonaceous additives but maximum solubility for the treated oil [154].

Botas et al. [158] performed a simulation for the process of refining used engine lubricating oil. As shown in Fig. 18, oil at the first step is treated by extraction to obtain the water-containing complex chemicals. The extracted complex chemicals are next heated and distilled under air pressure to remove 99% of the water content. The remaining C_3-free oil is heated and distilled at air pressure to

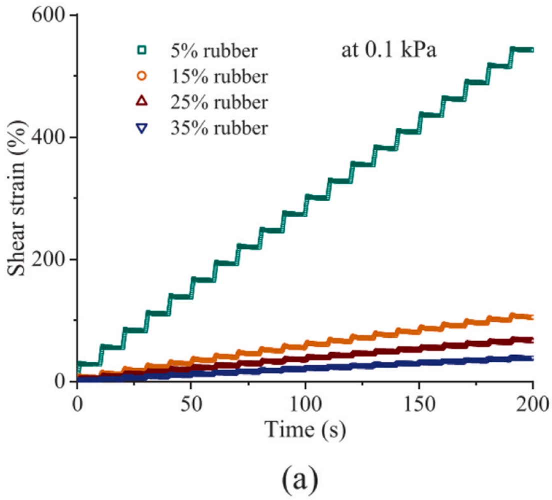


Fig. 17. MSCR test results of rubber asphalt binders at stress levels: (a) 0.1 kPa and (b) 3.2 kPa [81].

further separate up to 93% light hydrocarbons, which can be used as an extra fuel source to help compensate for the energy consumption. Finally, the last step is the vacuum distillation of the residue under atmospheric conditions to have the heavy fractions, such as base oil and gas oil, as well as various by-products, such as heavy cuts, complex compounds, and light hydrocarbons. The complex

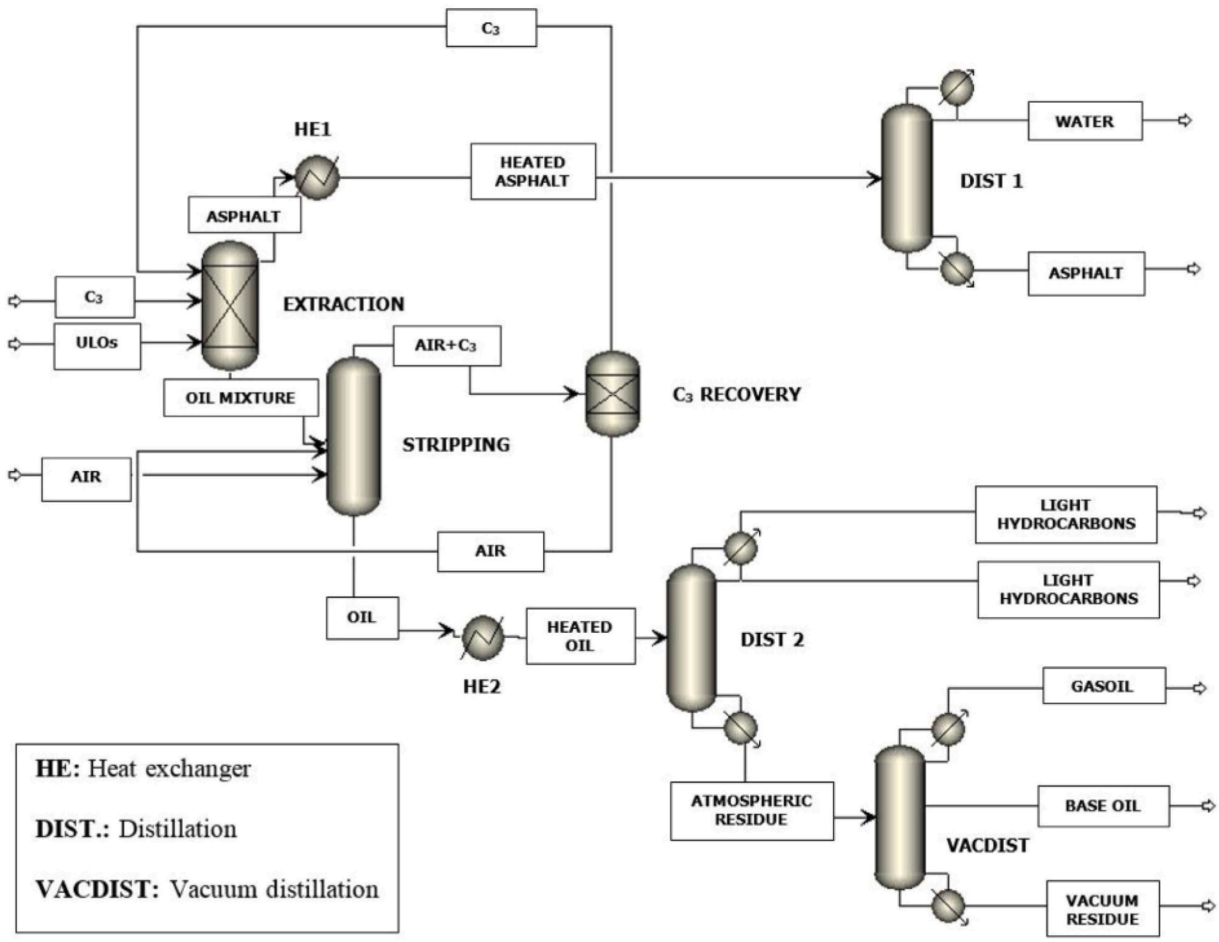


Fig. 18. Upgrading used lubricating oil by a simulated process in Aspen Plus diagram [158].

compounds and the final residue can be used for asphalt formulation at last.

For the refining process, the authors conducted a life cycle assessment (LCA). The results from various scenarios are summarised in Table 8. It was demonstrated that atmospheric distillation (50%) and vacuum distillation (28%) are the two processes with the greatest potential to contribute to global warming, mostly because of their heating requirements. Moreover, the other two by-products take 53% of the total energy demand, which adds to the energy consumption of the process. In addition, there is an environmental side effect because of acidification, a result of the large fossil fuel consumption used for power generation and the heating for distillation processes, in which vacuum distillation takes 43% of the total fuel consumption, while the second atmospheric distillation takes 30%. On the other hand, the distillation processes generate toxicity to both the human beings and the ecosystem. The vacuum distillation has the effect on each of both at the probability of 26% and 30%, respectively, while the second atmospheric distillation at the probability of 21% and 21%, respectively. Further, the transport part also contributes 29% and 21% to each of them. However, overall, the method substantially reduces the impact on the environment in terms of 90% categories for assessment. The LCA justified that oil recycling has clear environmental benefits over conventional refinery processes. It is advised to perform more research to improve the performance of the two distillation processes.

On the other hand, Duđak et al. [159] evaluated four different treatment scenarios for waste lubrication oil (WLO), a type of WEO, as outlined in Table 9. These scenarios included burning WLO in waste incinerators, re-refining used oil to recover base oil, and utilising WLO as a substitute for fossil fuels in cement kilns. The results of the LCA are compared in Table 10. The negative values in Table 10 indicate that the studied waste management methods provide a net benefit, as the total impact of waste treatment is offset by the avoided impacts resulting from the use of co-products as substitutes. The CemK process has the lowest greenhouse gas emission, which is then followed by the refining process. On average, re-refining 1000 kg of WLO can reduce the greenhouse gas emission equivalent to 516 kg CO_2. On the other hand, incineration, as expected, increases gas emissions even with the full energy recovery. For the sake of reducing fossil fuels, the refining process is the best, with an average fuel save equivalent to 1026 kg of fossil oil (ca. 43 GJ) for each metric tonne WEO treatment. The results are in good agreement with the other two studies [160,161]. The aggregated points imply that the selection for the best waste oil management is conditional, significantly depending upon the specific environmental situation. While re-refining exhibits the best for the resource conservation, CemK proves the best for the ecosystem protection, and incineration, both Inc1 and Inc2, is the best approach for the human health. However, it should be noted the results considerably relies on the assumptions made in the research, therefore, more research is obviously needed.

Applying WEO on asphalt can reduce emissions of CO_2, nitrous oxide, and methane. Additionally, the lower mixing and paving temperatures result in less energy and money being consumed. Nonetheless, the scenario including burning of WLO in cement kilns and various re-refining procedures is the better option if the preservation of fossil resources is the main priority. This is due to the possibility of substituting different fossil-based goods with the energy and/or materials recovered in the latter two processes, which would lead to a major preservation of resources. Future studies should concentrate on devising more practical and efficient methods of gathering WLO that is currently untreated and uncollected, as this contributes significantly to environmental degradation. Future models ought to incorporate a range of pre-treatment procedures that have the potential to boost treatment activities' effectiveness and raise the caliber of the co-products produced. The application of mass flow and economic value criteria for the impact allocation, which permits the distribution of environmental impacts between main system products and by-products, demonstrates that, in every case examined, producing base oil through ULO recycling is unquestionably more environmentally friendly than using traditional refinery processes. It is recommended that more research be done to optimise the vacuum distillation and second atmospheric distillation columns' operating conditions, because lowering the energy requirements of these phases will be the most effective approach to enhance the environmental performance of the ULO recycling process.

6. Conclusions

This article provides a comprehensive review of the up-to-date studies using WEO for asphalt binder improvement and

Table 8
Environmental effects related to a tonne of generated base oil under various scenarios [158].

Environmental impact	Fresh oil system[a]			ULOs system[b]		
	Total	Scenario 1	Scenario 2	Total	Scenario 1	Scenario 2
Cumulative energy demand (MJ)	79800	59850	73655	6144	4706	5960
Global warming potential (kg-eq CO_2)	1050	787	969	363	278	352
Ecotoxicity (CTUeco)	1140	855	1052	109	83.5	105
Human toxicity (CTUh)	3.54 E-4	2.66 E-4	3.27 E-4	4.19 E-5	3.21 E-5	4.06 E-5
Acidification (mol S or N eq)	3.48	2.61	3.21	0.38	0.29	0.37

Scenario 1 and 2 represent the mass flow and economic criterion, respectively.
[a] Total economic value (including product and by-product) is €2166.5. The allocation factor for base oil according to the economic criterion is calculated as 2000/2166.5, resulting in 0.923. The total outgoing mass flow (including product and by-product) is 1333 kg, and the allocation factor for base oil in accordance with the mass flow criterion is calculated as 1000/1333, which equals to 0.75 J.A.
[b] Total economic value (including product and by-product) is €2061. The allocation factor for base oil based on the economic criterion is calculated as 2000/2061, resulting in 0.97. The total outgoing mass flow (including product and by-product) is 1305 kg, and the allocation factor for base oil in accordance with the mass flow criterion is calculated as 1000/1305, which equals to 0.766 J.A.

Table 9
Different WLO treatment scenarios (actual amounts are about equivalent to treated WLO amounts for the year 2017, remainder is re-refined or burned in heating facilities without or with recovery of energy) [159].

Scenario	Burning in HWI with recovery of energy (Inc1)	Burning in HWI without recovery of energy (Inc2)	Re-refining (ReR1 to ReR5)	Burning in cement cilns (CemK)
Scenario 1 (tonne)			26,602	7777
Scenario 2 (tonne)	13,301		13,301	7777
Scenario 3 (tonne)	8867	8867	8867	7777
Scenario 4 (tonne)	9470	9470	9470	5967

Table 10
Results of treating 1000 kg of WLO at midpoint and aggregate endpoint levels [159].

	Incl	Inc2	ReR1	ReR2	ReR3	ReR4	ReR5	CemK	Unit
Midpoint impact categories									
Toxicity	-0.11	5.4×10^{-4}	0.04	0.0025	-0.0011	0.004	0.0027	-0.003	
Human non-carcinogenic	-1300	160	380	6.6	-8.2	46	-25	-69	kg 1,4-DCB
Marine ecotoxicity	-94	8.4	24	-3.6	-2.3	0.022	-6.3	-5.3	kg 1,4-DCB
Stratospheric ozone depletion	-5.5×10^{-4}	1.1×10^{-5}	-0.001	-8.9×10^{-4}	-8.6×10^{-4}	-8.8×10^{-4}	-9.1×10^{-4}	-7.0×10^{-4}	kg CFC11 eq
Freshwater eutrophication	-1.7	0.18	0.62	0.15	0.068	0.17	0.12	-0.023	kg Peq
Freshwater ecotoxicity	-72	6.1	21	-1.1	-0.36	1.5	-2.7	-2.8	kg 1,4-DCB
Water consumption	-450	180	-3600	-1400	41	-270	-2700	-620	
Human carcinogenic toxicity	-1.3	0.2	-0.24	-1.1	-0.53	-0.79	-1.2	-0.45	kg 1,4-DCB
Terrestrial acidification	-7.7	0.13	-4.3	-5	-4.7	-5.1	-4.5	-3.7	kg SO_2 eq
Land use	-4.5	0.47	-1.9	-5.4	-3.4	-5.3	-7.5	-3.8	m^2 a crop
Ecosystems									
Health	-7.2	0.9	1.1	-2.9	-1.4	-2.4	-3.3	-0.3	m^3
Ozone formation, Human	-2.2	0.22	-1.9	-1.8	-1.8	-1.9	-1.9	-1.7	kg NOx eq
Marine eutrophication	-840	5	-1100	-1000	-1000	-980	-1000	-900	kg N eq
Fossil resource scarcity	150	2800	-530	-460	-460	-540	-600	-1100	kg oil eq
Terrestrial ecotoxicity									kg 1,4-DCB
Mineral resource scarcity									kg Cueq
Fine particulate matter	-4.9	0.084	-0.6	-1.5	-1.5	-1.4	-1.3	-1.2	kg PM2.5 eq
Global warming	-57	0.78	-18	-21	-22	-22	-26	-24	kg CO_2 eq
Ionizing radiation									kBq Co-60 eq
Formation	-99	29	11	-15	-15	-12	-18	-20	
Ozone formation, Terrestrial	-2.3	0.22	-2	-2	-1.9	-2	-2	-1.8	kg NOx
Aggregated endpoint									
Categories	-3.6×10^{-3}	2.8×10^{-3}	-7.5×10^{-4}	-1.4×10^{-3}	-1.4×10^{-3}	-1.4×10^{-3}	-1.5×10^{-3}	-1.9×10^{-3}	DALY
Damage to ecosystem quality									Species x yr
Damage to resource availability	-240	1.6	-540	-460	-460	-450	-470	-410	USD
Damage to human health	-2.8×10^{-6}	8.2×10^{-6}	-2.3×10^{-6}	-2.6×10^{-6}	-2.5×10^{-6}	-2.8×10^{-6}	-2.9×10^{-6}	-4.1×10^{-6}	

rejuvenation. The impact of WEO alone and its composites on the functional characteristics of asphalt binders have been the subject of most research and investigations. Meanwhile, the economic, environmental, and eco impacts are also the research topic needing more detailed knowledge. Several important conclusions can be drawn from this study:

- Database: the number of publications grew in 2014, and between 2019–2022, while, China had the highest record.
- Asphalt binder modification: The utilisation of WEO as a modifier offers the potential to enhance the properties of asphalt binder. The addition of WEO to asphalt binder can improve the resistance to rutting in pavement. Furthermore, it enhances the performance of pavement at low temperatures, although its effectiveness at high temperatures may be compromised.
- A rejuvenated agent: WEO can restore the basic physical characteristics of aged asphalt, such as the phase angle and complex module, thereby improving the fatigue life of the pavement. WEO can enhance the content of RAP used in pavement construction, having better rutting, fatigue, temperature, moisture, and cracking resistance compared with the untreated RAP mixtures.
- As a self-healing agent: WEO can be incorporated into asphalt healing agents to repair microcracks caused by fatigue and thermal stress. This is edge-front research. Only a few studies have been reported so far.

- Composite materials: As an effective anti-aging additive, WEO can together with various polymers, such as PPA and SBS or rubbers (tyre or crumb rubber), as well as fibre glass, be incorporated into asphalt to improve the high-temperature characteristics with more comprehensive characteristics of modified asphalts.
- Environmental considerations: The utilisation of WEO in asphalt offers potential environmental benefits, including reduction of waste disposal and conservation of natural resources, thereby minimising environmental impact. However, the adverse factors of the recycling process itself, including cost, energy consumption, greenhouse gas emissions, and impact on human beings and wildlife, need further research.

7. Future directions

The use of WEO in asphalt and pavement engineering practice has many other factors in consideration, such as the type and quality of WEO, the dosage and mixing procedure, and the specific requirements for the pavement to be constructed. Further research is necessary to fully understand the long-term effect on material function, environmental implications, and economic feasibility in line with local regulations and guidelines. In terms of this study, some specific knowledge gaps are highlighted for future research as:

a. the mechanism between the rejuvenation effect of WEO and its composition. There is yet no quantifiable measure of the rejuvenating effect;
b. the field experiment and analysis for economic and environmental benefits;
c. WEO-asphalt mixture's cracking resistance after secondary age requires relevant studies to enhance its cracking resistance capability; and
d. data on the long-term impacts of rejuvenated asphalt mixtures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Z. Lin, H. Wang, S. Li, Pavement anomaly detection based on transformer and self-supervised learning, Autom. Constr. 143 (2022) 104544.
[2] S. Al-Busaltan, A. Dulaimi, H. Al-Nageim, S. Mahmood, M.A. Kadhim, M. Al-Kafaji, Y.O. Özkılıç, Improving the mechanical properties and durability of cold bitumen emulsion mixtures using waste products and microwave heating energy, Buildings 13 (2) (2023) 414.
[3] H. Wang, X. Zhang, S. Jiang, A Laboratory and field universal estimation method for tire-pavement interaction noise (TPIN) based on 3D image technology, 14 (19) (2022) 12066.
[4] I. Hakeem, M.A. Hosen, M. Alyami, S. Qaidi, Y. Özkılıc, Influence of heat–cool cyclic exposure on the performance of fiber-reinforced high-strength concrete, Sustainability 15 (2) (2023) 1433.
[5] H. Wang, X. Zhang, M. Wang, Rapid texture depth detection method considering pavement deformation calibration, Measurement 217 (2023) 113024.
[6] Y. Ma, W. Hu, P.A. Polaczyk, B. Han, R. Xiao, M. Zhang, B. Huang, Rheological and aging characteristics of the recycled asphalt binders with different rejuvenator incorporation methods, J. Clean. Prod. 262 (2020) 121249.
[7] S. Liu, A. Peng, S. Zhou, J. Wu, W. Xuan, W. Liu, Evaluation of the ageing behaviour of waste engine oil-modified asphalt binders, Constr. Build. Mater. 223 (2019) 394–408.
[8] C. Aksoylu, Y.O. Özkılıç, A. Bahrami, S.A. Yıldızel, I.Y. Hakeem, N. Özdöner, M. Karalar, Application of waste ceramic powder as a cement replacement in reinforced concrete beams toward sustainable usage in construction, Case Studies in Construction Materials 19 (2023) e02444.
[9] S. Fayed, E. Madenci, A. Bahrami, Y.O. Özkiliç, W. Mansour, Experimental study on using recycled polyethylene terephthalate and steel fibers for improving behavior of RC columns, Case Studies in Construction Materials 19 (2023) e02344.
[10] Tu, H., Wei, Z., Bahrami, A., Kahla, N. B., Ahmad, A., & Özkılıç, Y. O. (2023). Recent advancements and future trends in 3D printing concrete using waste materials. Developments in the Built Environment, 100187.
[11] S.A. Yıldızel, Y.O. Özkılıç, A. Bahrami, C. Aksoylu, B. Başaran, A. Hakamy, M.H. Arslan. Experimental investigation and analytical prediction of flexural behaviour of reinforced concrete beams with steel fibres extracted from waste tyres. Case Studies in Construction Materials, 2023 e02227.
[12] Y.O. Özkılıç, Ö. Zeybek, A. Bahrami, A.İ. Çelik, M.A.O. Mydin, M. Karalar, P. Jagadesh, Optimum usage of waste marble powder to reduce use of cement toward eco-friendly concrete, journal of materials research and technology 25 (2023) 4799–4819.
[13] M. Zahoor, S. Nizamuddin, S. Madapusi, F. Giustozzi, Sustainable asphalt rejuvenation using waste cooking oil: a comprehensive review, J. Clean. Prod. 278 (2021) 123304.
[14] A.İ. Çelik, Y.O. Özkılıç, A. Bahrami, I.Y. Hakeem, Effects of glass fiber on recycled fly ash and basalt powder based geopolymer concrete, Case Studies in Construction Materials 19 (2023) e02659.
[15] A.İ. Çelik, Y.O. Özkılıç, A. Bahrami, I.Y. Hakeem, Mechanical performance of geopolymer concrete with micro silica fume and waste steel lathe scraps, Case Studies in Construction Materials 19 (2023) e02548.
[16] J.J. Assaad, C.A. Issa, Effect of recycled acrylic-based polymers on bond stress-slip behavior in reinforced concrete structures, Journal of Materials in Civil Engineering 29 (1) (2017) 04016173.
[17] N.N. Gerges, C.A. Issa, N.J. Khalil, L. Abdul Khalek, S. Abdo, Y. Abdulwahab, Flexural capacity of eco-friendly reinforced concrete beams, Scientific Reports 13 (1) (2023) 20142.
[18] N.N. Gerges, C.A. Issa, E. Sleiman, S. Aintrazi, J. Saadeddine, R. Abboud, M. Antoun, Eco-Friendly Optimum Structural Concrete Mix Design, Sustainability 14 (14) (2022) 8660.
[19] D. Zhao, C. Li, Q. Wang, J. Yuan, Comprehensive evaluation of national electric power development based on cloud model and entropy method and TOPSIS: a case study in 11 countries, J. Clean. Prod. 277 (2020) 123190.

[20] N.N. Gerges, C.A. Issa, S.A. Fawaz, Rubber concrete: Mechanical and dynamical properties, Case Studies in Construction Materials 9 (2018) e00184.
[21] N. Gerges, C.A. Issa, E. Sleiman, M. Najjar, A. Kattouf, Experimental study of the shear behavior of RC beams strengthened with high-performance fiber-reinforced concrete, International Journal of Concrete Structures and Materials 17 (1) (2023) 17.
[22] A. Jahami, C.A. Issa, Exploring the use of mixed waste materials (MWM) in concrete for sustainable construction: a review, Construction and Building Materials 398 (2023) 132476.
[23] C.A. Issa, G. Hilal, Sustainable construction materials: Recycled aggregate concrete from known concrete strength debris, The Open Construction & Building Technology Journal 17 (1) (2023).
[24] Y. Huang, R.N. Bird, O. Heidrich, A review of the use of recycled solid waste materials in asphalt pavements, Resour. Conserv. Recycl. 52 (1) (2007) 58–73.
[25] S. Ahmad, O. Dawood, M.M. Lashin, S.U. Khattak, M.F. Javed, F. Aslam, T.M. Alaboud, Effect of coconut fiber on low-density polyethylene plastic-sand paver blocks, Ain Shams Engineering Journal 14 (8) (2023) 101982.
[26] B. Iftikhar, S.C. Alih, M. Vafaei, M.F. Javed, M.F. Rehman, S.S. Abdullaev, A.M. Hassan, Predicting compressive strength of eco-friendly plastic sand paver blocks using gene expression and artificial intelligence programming, Scientific reports 13 (1) (2023) 12149.
[27] Z. Liu, S. Li, Y. Wang, Characteristics of asphalt modified by waste engine oil / polyphosphoric acid: conventional, high-temperature rheological, and mechanism properties, J. Clean. Prod. 330 (2022) 129844.
[28] M. Antoun, C.A. Issa, G. Aouad, N. Gerges, Sustainable masonry blocks: Olive wood waste as substitute for fine aggregates, Case Studies in Construction Materials 15 (2021) e00590.
[29] N. Gerges, C.A. Issa, M. Antoun, E. Sleiman, F. Hallal, P. Shamoun, J. Hayek, Eco-friendly mortar: Optimum combination of wood ash, crumb rubber, and fine crushed glass, Case Studies in Construction Materials 15 (2021) e00588.
[30] C.A. Issa, G. Salem, Utilization of recycled crumb rubber as fine aggregates in concrete mix design, Construction and Building Materials 42 (2013) 48–52.
[31] A.M. Memon, M.H. Sutanto, M. Napiah, N.I.M. Yusoff, R.A. Memon, A.M. Al-Sabaeei, M. Ali, Physicochemical, rheological and morphological properties of bitumen incorporating petroleum sludge, Constr. Build. Mater. 297 (2021) 123738.
[32] H. Luo, X. Huang, R. Tian, J. Huang, B. Zheng, D. Wang, B. Liu, Analysis of relationship between component changes and performance degradation of Waste-Oil-Rejuvenated asphalt, Constr. Build. Mater. 297 (2021) 123777.
[33] M. Jin, Y. Ma, W. Li, J. Huang, Y. Yan, H. Zeng, C. Lu, J. Liu, Multi-scale investigation on composition-structure of C-(A)-SH with different Al/Si ratios under attack of decalcification action, Cem. Concr. Res. 172 (2023) 107251.
[34] A.A. Alola, F.V. Bekun, T.S. Adebayo, G. Uzuner, The nexus of disaggregated energy sources and cement production carbon emission in China, Energy & Environment 34 (6) (2023) 1937–1956.
[35] F.V. Bekun, A.A. Alola, B.A. Gyamfi, P.A. Kwakwa, G. Uzuner, Econometrics analysis on cement production and environmental quality in European Union countries, International Journal of Environmental Science and Technology 20 (4) (2023) 4265–4280.
[36] H.B. Abdullah, R. Irmawati, I. Ismail, N.A. Yusof, Utilization of waste engine oil for carbon nanotube aerogel production using floating catalyst chemical vapor deposition, J. Clean. Prod. 261 (2020) 121188.
[37] Z. Wang, Q. Wang, C. Jia, J. Bai, Thermal evolution of chemical structure and mechanism of oil sands bitumen, Energy 244 (2022) 123190.
[38] H. Wang, K. Derewecki, Rheological properties of asphalt binder partially substituted with wood lignin, Airfield and Highway Pavement 2013: Sustainable and Efficient Pavements. 2013, pp. 977–986.
[39] S. Liu, A. Peng, J. Wu, S.B. Zhou, Waste engine oil influences on chemical and rheological properties of different asphalt binders, Constr. Build. Mater. 191 (2018) 1210–1220.
[40] S. Arafat, N. Kumar, N.M. Wasiuddin, E.O. Owhe, J.G. Lynam, Sustainable lignin to enhance asphalt binder oxidative aging properties and mix properties, J. Clean. Prod. 217 (2019) 456–468.
[41] S. Asukar, A. Behl, P. Gundaliya, Utilization of lignin as an antioxidant in asphalt binder, Int. J. Innov. Res. Technol., IJIRT 2 (12) (2016) 198–207.
[42] I.A. Qurashi, A.K. Swamy, Viscoelastic properties of recycled asphalt binder containing waste engine oil, J. Clean. Prod. 182 (2018) 992–1000.
[43] W.P. Teoh, Z.H. Noor, C.A. Ng, Y.C. Swee, Catalyzed waste engine oil as alternative binder of roofing tiles – Chemical analysis and optimization of parameters, J. Clean. Prod. 174 (2018) 988–999.
[44] L. Feng, J. Liu, L. Hu, Rheological behavior of asphalt binder and performances of asphalt mixtures modified by waste soybean oil and lignin, Constr. Build. Mater. 362 (2023) 129735.
[45] B. Kuczenski, R. Geyer, T. Zink, A. Henderson, Material flow analysis of lubricating oil use in California, Resour. Conserv. Recycl. 93 (2014) 59–66.
[46] X. Jia, B. Huang, B.F. Bowers, S. Zhao, Infrared spectra and rheological properties of asphalt cement containing waste engine oil residues, Constr. Build. Mater. 50 (2014) 683–691.
[47] P. Herrington, P. Hamilton, Recycling of waste oil distillation bottoms in asphalt, 1998.
[48] S.A.M. Hesp, H.F. Shurvell, X-ray fluorescence detection of waste engine oil residue in asphalt and its effect on cracking in service, Int. J. Pavement Eng. 11 (6) (2010) 541–553.
[49] E.R. Brown, P.S. Kandhal, F.L. Roberts, Y.R. Kim, D.Y. Lee, T.W. Kennedy, Hot Mix Asphalt Materials, Mixture Design and Construction: Third Edition, National Asphalt Pavement Association2009.
[50] A. Institute, The Asphalt Handbook, Asphalt Institute2007.
[51] J.G. Speight, Chapter 1 - Nomenclature and Terminology, in: J.G. Speight (Ed.), Asphalt Materials Science and Technology, Butterworth-Heinemann, Boston, 2016, pp. 3–43.
[52] C.D. DeDene, Investigation of using waste engine oil blended with reclaimed asphalt materials to improve pavement recyclability, Michigan Technological University, 2011.
[53] Q. Yuan, Z. Liu, K. Zheng, C. Ma, Civil Engineering Materials: From Theory to Practice, Elsevier Science2021.
[54] N.M. Katamine, Physical and mechanical properties of bituminous mixtures containing oil shales, J. Transp. Eng. -ASCE 126 (2000) 178–184.
[55] M.S. Mamlouk, J.P. Zaniewski, Materials for Civil and Construction Engineers, Pearson Education 2016.
[56] D.E. Newcomb, B.J. Nusser, B.M. Kiggundu, D.M. Zallen, Laboratory study of the effects of recycling modifiers on aged asphalt cement, Transportation Research Record (1984).
[57] U.S.E.P.A., Managing used oil: Advice for small businesses, 1996. 〈https://archive.epa.gov/wastes/conserve/materials/usedoil/web/html/usedoil.html〉.
[58] P.D. Xiaoyang Jia, P.D. Baoshan Huang, P.E. M.ASCE, J.A. Moore, P.D.; and Sheng Zhao, Influence of waste engine oil on asphalt mixtures containing reclaimed asphalt pavement, J. Mater. Civ. Eng. (2015), 04015042-1, 04015042-9.
[59] C.D. DeDene, Z-P. You, The performance of aged asphalt materials rejuvenated with waste engine oil, Int. J. Pavement Res. Technol. 7 (2) (2014) 145–152.
[60] M.A. Al-Ghouti, L. Al-Atoum, Virgin and recycled engine oil differentiation: a spectroscopic study, J. Environ. Manag. 90 (1) (2009) 187–195.
[61] O.A. Bamiro, O.A. Osibanjo, Pilot Study of Used Oils in Nigeria, 2004.
[62] C.-Y.I. Yang, The feasibility studies onsonochemical process for treating used oil: Toxin reduction for eliminating recycle interference, University of Southern California, 2008.
[63] K.-a Johnson, S.A.M. Hesp, Effect of waste engine oil residue on quality and durability of SHRP materials reference library binders, Transp. Res. Rec. 2444 (2014) 102–109.
[64] S. Yan, C. Zhou, Y. Sun, Evaluation of rejuvenated aged-asphalt binder by waste-cooking oil with secondary agingconsidered, J. Mater. Civ. Eng. (2022).
[65] H. Li, B. Dong, W. Wang, G. Zhao, P. Guo, Q. Ma, Effect of waste engine oil and waste cooking oil on performance improvement of aged asphalt, Appl. Sci. 9 (9) (2019) 1767.
[66] X. Zhou, G. Zhao, S. Wu, S. Tighe, D. Pickel, M. Chen, S. Adhikari, Y. Gao, Effects of biochar on the chemical changes and phase separation of bio-asphalt under different aging conditions, J. Clean. Prod. 263 (2020) 121532.
[67] Y. Wang, P. Hao, Rheological and fatigue-healing durability of asphalt containing synthesized microcapsules with refined waste oil core, Constr. Build. Mater. 274 (2021) 121964.

[68] S. Zhou, C. Lu, X. Zhu, F. Li, Preparation and characterization of high-strength geopolymer based on BH-1 lunar soil simulant with low alkali content, Engineering 7 (11) (2021) 1631–1645.
[69] A. Chen, Z. Hu, M. Li, T. Bai, G. Xie, Y. Zhang, Y. Li, C. Li, Investigation on the mechanism and performance of asphalt and its mixture regenerated by waste engine oil, Constr. Build. Mater. 313 (2021) 125411.
[70] M. Fakhri, M.A. Norouzi, Rheological and ageing properties of asphalt bio-binders containing lignin and waste engine oil, Constr. Build. Mater. 321 (2022) 126364.
[71] F. Cai, Z.-g Feng, Y. Li, D. Yao, M. Lin, X. Li, Properties and mechanism of Re-refined engine oil bottom rejuvenated aged asphalt, Constr. Build. Mater. 352 (2022) 129068.
[72] H. Li, G. Liu, B. Dong, G. Zhao, P. Guo, J. Huang, Y. Sheng, Research on the development and regeneration performance of asphalt rejuvenator based on the mixed waste engine oil and waste cooking oil, Int. J. Pavement Res. Technol. 12 (3) (2019) 336–346.
[73] B. Shu, M. Zhou, T. Yang, Y. Li, Y. Ma, K. Liu, S. Bao, D.M. Barbieri, S. Wu, The properties of different healing agents considering the micro-self-healing process of asphalt with encapsulations, Materials 14 (1) (2020).
[74] H. Ding, Y. Qiu, W. Wang, X. Zhang, Adverse effect of waste engine oil bottom on asphalt performance and its mechanism, Jianzhu Cailiao Xuebao/J. Build. Mater. 20 (2017) 646–650.
[75] W. Wang, M. Jia, W. Jiang, B. Lou, W. Jiao, D. Yuan, X. Li, Z. Liu, High temperature property and modification mechanism of asphalt containing waste engine oil bottom, Constr. Build. Mater. 261 (2020) 119977.
[76] M. Paliukaite, M. Assuras, S.A.M. Hesp, Effect of recycled engine oil bottoms on the ductile failure properties of straight and polymer-modified asphalt cements, Constr. Build. Mater. 126 (2016) 190–196.
[77] Y. Li, A. Shen, Z. Lyu, S. Wang, K. Formela, G. Zhang, Ground tire rubber thermo-mechanically devulcanized in the presence of waste engine oil as asphalt modifier, Constr. Build. Mater. 222 (2019) 588–600.
[78] Z. Lei, H. Bahia, T. Yi-qiu, C. Ling, Effects of refined waste and bio-based oil modifiers on rheological properties of asphalt binders, Constr. Build. Mater. 148 (2017) 504–511.
[79] S.R.M. Fernandes, H.M.R.D. Silva, J.R.M. Oliveira, Developing enhanced modified bitumens with waste engine oil products combined with polymers, Constr. Build. Mater. 160 (2018) 714–724.
[80] Y. Qiu, H. Ding, A. Rahman, W. Wang, Damage characteristics of waste engine oil bottom rejuvenated asphalt binder in the non-linear range and its microstructure, Constr. Build. Mater. 174 (2018) 202–209.
[81] P. Xu, J. Gao, J. Pei, Z. Chen, J. Zhang, R. Li, Research on highly dissolved rubber asphalt prepared using a composite waste engine oil addition and microwave desulfurization method, Constr. Build. Mater. 282 (2021) 122641.
[82] A. Eltwati, A. Mohamed, M.R. Hainin, E. Jusli, M. Enieb, Rejuvenation of aged asphalt binders by waste engine oil and SBS blend: physical, chemical, and rheological properties of binders and mechanical evaluations of mixtures, Constr. Build. Mater. 346 (2022) 128441.
[83] Z. Liu, S. Li, Y. Wang, Waste engine oil and polyphosphoric acid enhanced the sustainable self-healing of asphalt binder and its fatigue behavior, J. Clean. Prod. 339 (2022) 130767.
[84] B. Ozarisoy, H. Altan, State-of-the-Art II: Bibliometric Review of the Last 30 Years Energy Policy in Europe. Handbook of retrofitting high density residential buildings: policy design and implications on domestic energy use in the eastern mediterranean climate of Cyprus, Springer, 2023, pp. 93–156.
[85] H.K. Shanbara, A. Dulaimi, T. Al-Mansoori, S. Al-Busaltan, M. Herez, M. Sadique, T. Abdel-Wahed, The future of eco-friendly cold mix asphalt, Renew. Sustain. Energy Rev. 149 (2021) 111318.
[86] A.A. Al-Omari, T.S. Khedaywi, M.A. Khasawneh, Laboratory characterization of asphalt binders modified with waste vegetable oil using SuperPave specifications, Int. J. Pavement Res. Technol. 11 (1) (2018) 68–76.
[87] C. Fang, M. Zhang, R. Yu, X. Liu, Effect of preparation temperature on the aging properties of waste polyethylene modified asphalt, J. Mater. Sci. Technol. 31 (3) (2015) 320–324.
[88] A. Villanueva, S. Ho, L. Zanzotto, Asphalt modification with used lubricating oil, Can. J. Civ. Eng. 35 (2008) 148–157.
[89] M.N. Borhan, F. Suja, A. Ismail, R. Rahmat, The effects of used cylinder oil on asphalt mixes, Eur. J. Sci. Res. 28 (3) (2009) 398–411.
[90] M. Zargar, E. Ahmadinia, H. Asli, M.R. Karim, Investigation of the possibility of using waste cooking oil as a rejuvenating agent for aged bitumen, J. Hazard. Mater. 233-234 (2012) 254–258.
[91] R. Maharaj, C. Maharaj, Physical properties of low density polyethylene, polyvinylchloride and used engine oil modified asphalt, Prog. Rubber Plast. Recycl. Technol. 31 (3) (2015) 173–187.
[92] Z. Lei, H. Bahia, T. Yi-qiu, Effect of bio-based and refined waste oil modifiers on low temperature performance of asphalt binders, Constr. Build. Mater. 86 (2015) 95–100.
[93] F. Handle, M. Harir, J. Füssl, A.N. Koyun, D. Grossegger, N. Hertkorn, L. Eberhardsteiner, B. Hofko, M. Hospodka, R. Blab, P. Schmitt-Kopplin, H. Grothe, Tracking ageing of bitumen and its SARA fractions using high-field FT-ICR mass spectrometry, Energy Fuels 31 (2017).
[94] M. Le Guern, E. Chailleux, F. Farcas, S. Dreessen, I. Mabille, Physico-chemical analysis of five hard bitumens: identification of chemical species and molecular organization before and after artificial aging, Fuel 89 (11) (2010) 3330–3339.
[95] J. Zhang, X. Zhang, M. Liang, H. Jiang, J. Wei, Z. Yao, Influence of different rejuvenating agents on rheological behavior and dynamic response of recycled asphalt mixtures incorporating 60% RAP dosage, Constr. Build. Mater. 238 (2020) 117778.
[96] X. Li, N. Gibson, A. Andriescu, T. S. Arnold, Performance evaluation of REOB-modified asphalt binders and mixtures, Road. Mater. Pavement Des. 18 (sup1) (2017) 128–153.
[97] T. Shoukat, P.J. Yoo, Rheology of asphalt binder modified with 5W30 viscosity grade waste engine oil, Appl. Sci. 8 (7) (2018) 1194.
[98] J.C. Ssempebwa, D.O. Carpenter, The generation, use and disposal of waste crankcase oil in developing countries: a case for Kampala district, Uganda, J. Hazard. Mater. 161 (2) (2009) 835–841.
[99] T. Bai, Z.-a Hu, X. Hu, Y. Liu, L. Fuentes, L.F. Walubita, Rejuvenation of short-term aged asphalt-binder using waste engine oil, Can. J. Civ. Eng. 47 (7) (2020) 822–832.
[100] H. Taherkhani, F. Noorian, Investigating permanent deformation of recycled asphalt concrete containing waste oils as rejuvenator using response surface methodology (RSM), Iran. J. Sci. Technol. Trans. Civ. Eng. 45 (3) (2021) 1989–2001.
[101] F. Yang, H. Li, G. Zhao, P. Guo, W. Li, Mechanical performance and durability evaluation of sandstone concrete, Adv. Mater. Sci. Eng. 2020 (2020) 1–10.
[102] H.H. Joni, R.H. Al-Rubaee, M.A. Al-zerkani, Rejuvenation of aged asphalt binder extracted from reclaimed asphalt pavement using waste vegetable and engine oils, Case Stud. Constr. Mater. 11 (2019).
[103] H.M.R.D. Silva, J.R.M. Oliveira, C.M.G. Jesus, Are totally recycled hot mix asphalts a sustainable alternative for road paving? Resour. Conserv. Recycl. 60 (2012) 38–48.
[104] J. Shen, S. Amirkhanian, J. Miller, Effects of rejuvenating agents on superpave mixtures containing reclaimed asphalt pavement, J. Mater. Civ. Eng. 19 (2007).
[105] C. Peng, C. Guo, Z. You, F. Xu, W. Ma, L. You, T. Li, L. Zhou, S. Huang, H. Ma, L. Lu, The effect of waste engine oil and waste polyethylene on UV aging resistance of asphalt, Polymers 12 (3) (2020) 602.
[106] A.K. Arshad, N.A. Kamaluddin, W. Hashim, S.R. Ahmad Roslan, Physical and rheological properties of aged bitumen rejuvenated with waste engine oil, Appl. Mech. Mater. 802 (2015) 363–368.
[107] A.M. El-Shorbagy, S.M. El-Badawy, A.R. Gabr, Investigation of waste oils as rejuvenators of aged bitumen for sustainable pavement, Constr. Build. Mater. 220 (2019) 228–237.
[108] F. Xiao, S.N. Amirkhanian, Resilient modulus behavior of rubberized asphalt concrete mixtures containing reclaimed asphalt pavement, Road. Mater. Pavement Des. 9 (4) (2008) 633–649.
[109] X. Shu, B. Huang, E.D. Shrum, X. Jia, Laboratory evaluation of moisture susceptibility of foamed warm mix asphalt containing high percentages of RAP, Constr. Build. Mater. 35 (2012) 125–130.

[110] F. Moghadas Nejad, A. Azarhoosh, G.H. Hamedi, H. Roshani, Rutting performance prediction of warm mix asphalt containing reclaimed asphalt pavements, Road. Mater. Pavement Des. 15 (1) (2014) 207–219.
[111] W. Mogawer, T. Bennert, J.S. Daniel, R. Bonaquist, A. Austerman, A. Booshehrian, Performance characteristics of plant produced high RAP mixtures, Road. Mater. Pavement Des. 13 (sup1) (2012) 183–208.
[112] I.L. Al-Qadi, Q. Aurangzeb, S.H. Carpenter, W.J. Pine, J.S. Trepanier, Impact of high RAP contents on structural and performance properties of asphalt mixtures, Civil Engineering Studies, Illinois Center for Transportation Series (2012).
[113] A.W. Ali, Y.A. Mehta, A. Nolan, C. Purdy, T. Bennert, Investigation of the impacts of aging and RAP percentages on effectiveness of asphalt binder rejuvenators, Constr. Build. Mater. 110 (2016) 211–217.
[114] A. Moniri, H. Ziari, M.R.M. Aliha, Y. Saghafi, Laboratory study of the effect of oil-based recycling agents on high RAP asphalt mixtures, Int. J. Pavement Eng. 22 (11) (2021) 1423–1434.
[115] S. Debbarma, G.D. Ransinchung, R.N. S. Singh, S.K. Sahdeo, Utilization of industrial and agricultural wastes for productions of sustainable roller compacted concrete pavement mixes containing reclaimed asphalt pavement aggregates, Resour., Conserv. Recycl. 152 (2020) 104504.
[116] A.A. Mamun, M. Arifuzzaman, Nano-scale moisture damage evaluation of carbon nanotube-modified asphalt, Constr. Build. Mater. 193 (2018) 268–275.
[117] S. Im, P. Karki, F. Zhou, Development of new mix design method for asphalt mixtures containing RAP and rejuvenators, Constr. Build. Mater. 115 (2016) 727–734.
[118] M. Elkashef, J.H. Podolsky, R.C. Williams, E.W. Cochran, Preliminary examination of soybean oil derived material as a potential rejuvenator through Superpave criteria and asphalt bitumen rheology, Constr. Build. Mater. 149 (2017) 826–836.
[119] G. Mazzoni, E. Bocci, F. Canestrari, Influence of rejuvenators on bitumen ageing in hot recycled asphalt mixtures, J. Traffic Transp. Eng. 5 (3) (2018) 157–168.
[120] F. Moghadas Nejad, A. Azarhoosh, G. Hamedi, Laboratory evaluation of using recycled marble aggregates on the mechanical properties of hot mix asphalt, J. Mater. Civ. Eng. 25 (2013) 741–746.
[121] M. Zaumanis, M.C. Cavalli, L.D. Poulikakos, Effect of rejuvenator addition location in plant on mechanical and chemical properties of RAP binder, Int. J. Pavement Eng. 21 (4) (2020) 507–515.
[122] S. Fernandes, J. Peralta, J.R.M. Oliveira, R.C. Williams, H.M.R.D. Silva, Improving asphalt mixture performance by partially replacing bitumen with waste motor oil and elastomer modifiers, Appl. Sci. (2017).
[123] F. Wang, Y. Fang, Z. Chen, H. Wei, Effect of waste engine oil on asphalt reclaimed properties, AIP Conf. Proc. 1973 (1) (2018).
[124] L. Devulapalli, S. Kothandaraman, G. Sarang, Microstructural characterisation of reclaimed asphalt pavement with rejuvenators, Int. J. Pavement Eng. 23 (4) (2022) 1038–1049.
[125] Z.H. Al-Saffar, H. Yaacob, M.K.I.M. Satar, S.N.N. Kamarudin, M.Z.H. Mahmud, C.R. Ismail, S.A. Hassan, N. Mashros, A review on the usage of waste engine oil with aged asphalt as a rejuvenating agent, Mater. Today.: Proc. 42 (2021) 2374–2380.
[126] A.S. Eltwati, M. Enieb, Z.H. Al-Saffar, A. Mohamed, Effect of glass fibers and waste engine oil on the properties of RAP asphalt concretes, Int. J. Pavement Eng. 23 (14) (2022) 5227–5238.
[127] A. Singhabhandhu, T. Tezuka, The waste-to-energy framework for integrated multi-waste utilization: waste cooking oil, waste lubricating oil, and waste plastics, Energy 35 (6) (2010) 2544–2551.
[128] M.A. Farooq, M.S. Mir, A. Sharma, Laboratory study on use of RAP in WMA pavements using rejuvenator, Constr. Build. Mater. 168 (2018) 61–72.
[129] A.A. Mamun, H. Al-Abdul Wahhab, Evaluation of waste engine oil-rejuvenated asphalt concrete mixtures with high RAP content, Adv. Mater. Sci. Eng. 2018 (2018) 1–8.
[130] H. Joni, R. Al-Rubaee, M. Shams, Assessment of durability properties of reclaimed asphalt pavement using two rejuvenators: Waste engine oil and asphalt cement (60-70) penetration grade, IOP Conf. Ser.: Mater. Sci. Eng. 1090 (2021) 012001.
[131] A. Bhasin, D.N. Little, R. Bommavaram, K. Vasconcelos, A framework to quantify the effect of healing in bituminous materials using material properties, Road. Mater. Pavement Des. 9 (sup1) (2008) 219–242.
[132] M.R.M. Aliha, A. Razmi, A. Mansourian, The influence of natural and synthetic fibers on low temperature mixed mode I+II fracture behavior of warm mix asphalt (WMA) materials, Eng. Fract. Mech. 182 (2017) 322–336.
[133] B. Liang, F. Lan, K. Shi, G. Qian, Z. Liu, J. Zheng, Review on the self-healing of asphalt materials: mechanism, affecting factors, assessments and improvements, Constr. Build. Mater. 266 (2021) 120453.
[134] Ö.E. Yamaç, M. Yilmaz, E. Yalçın, B.V. Kök, J. Norambuena-Contreras, A. Garcia, Self-healing of asphalt mastic using capsules containing waste oils, Constr. Build. Mater. 270 (2021) 121417.
[135] S. Shen, X. Lu, Y. Zhang, R. Lytton, Fracture and viscoelastic properties of asphalt binders during fatigue and rest periods, J. Test. Eval. 42 (2014) 20130030.
[136] D. Sun, Q. Pang, Z. Xingyi, Y. Tian, T. Lu, Y. Yang, Enhanced self-healing process of sustainable asphalt materials containing microcapsules, ACS Sustain. Chem. Eng. 5 (2017).
[137] J. Qiu, M.F.C. van de Ven, S. Wu, J. Yu, A.A.A. Molenaar, Evaluating self healing capability of bituminous mastics, Exp. Mech. 52 (2011) 1163–1171.
[138] S. Maillard, C. Roche, F. Hammoum, L. Gaillet, C. Such, Experimental investigation of fracture and healing of bitumen at pseudo-contact of two aggregates, Eurobitume (2004) 1291.
[139] L. Shan, Y. Tan, Y. Richard Kim, Establishment of a universal healing evaluation index for asphalt binder, Constr. Build. Mater. 48 (2013) 74–79.
[140] Y. Tan, L. Shan, Y. Richard Kim, B.S. Underwood, Healing characteristics of asphalt binder, Constr. Build. Mater. 27 (1) (2012) 570–577.
[141] F. Canestrari, A. Virgili, A. Graziani, A. Stimilli, Modeling and assessment of self-healing and thixotropy properties for modified binders, Int. J. Fatigue 70 (2015) 351–360.
[142] D.N. Little, A. Bhasin, M.K. Darabi, 7 - Damage healing in asphalt pavements: theory, mechanisms, measurement, and modeling, in: S.-C. Huang, H. Di Benedetto (Eds.), Advances in Asphalt Materials, Woodhead Publishing, Oxford, 2015, pp. 205–242.
[143] M. Aguirre, M. Hassan, S. Shirzad, L. Mohammad, S. Cooper, I. Negulesco, Laboratory testing of self-healing microcapsules in asphalt mixtures prepared with recycled asphalt shingles, J. Mater. Civ. Eng. 29 (2017) 04017099.
[144] A. García, C. Austin, J. Jelfs, Mechanical properties of asphalt mixture containing sunflower oil capsules, 2016.
[145] T. Al-Mansoori, J. Norambuena-Contreras, R. Micaelo, A. Garcia, Self-healing of asphalt mastic by the action of polymeric capsules containing rejuvenators, Constr. Build. Mater. 161 (2018) 330–339.
[146] B. Shu, S. Wu, L. Dong, Q. Wang, Q. Liu, Microfluidic synthesis of ca-alginate microcapsules for self-healing of bituminous binder, Materials (2018).
[147] S. Xu, A. Tabaković, X. Liu, E. Schlangen, Calcium alginate capsules encapsulating rejuvenator as healing system for asphalt mastic, Constr. Build. Mater. 169 (2018) 379–387.
[148] J.-F. Su, P. Yang, Y.-Y. Wang, S. Han, N.-X. Han, W. li, Investigation of the self-healing behaviors of bitumen/microcapsules composites by a repetitive direct tension test, Materials 9 (2016) 600.
[149] H. Ziari, M.R.M. Aliha, A. Moniri, Y. Saghafi, Crack resistance of hot mix asphalt containing different percentages of reclaimed asphalt pavement and glass fiber, Constr. Build. Mater. 230 (2020) 117015.
[150] M. Zaumanis, R.B. Mallick, R. Frank, 100% recycled hot mix asphalt: a review and analysis, Resour., Conserv. Recycl. 92 (2014) 230–245.
[151] Y. Huang, R. Bird, O. Heidrich, Development of a life cycle assessment tool for construction and maintenance of asphalt pavements, J. Clean. Prod. 17 (2) (2009) 283–296.
[152] Z. Wang, J. Li, Z. Zhang, M. Jia, J. Yang, Formulation of a new warm-mix recycling agent and its rejuvenating effect on aged asphalt, Constr. Build. Mater. 262 (2020) 120804.
[153] I. vasiliadou, Waste Engine Oil Recycling, Adv. Recycl. Waste Manag. 6 (6) (2021).
[154] T. Bhaskar, M.A. Uddin, A. Muto, Y. Sakata, Y. Omura, K. Kimura, Y. Kawakami, Recycling of waste lubricant oil into chemical feedstock or fuel oil over supported iron oxide catalysts, Fuel 83 (1) (2004) 9–15.
[155] D.I. Osman, S.K. Attia, A.R. Taman, Recycling of used engine oil by different solvent, Egypt. J. Pet. 27 (2) (2018) 221–225.

[156] A. Kamal, F. Khan, Effect of extraction and adsorption on re-refining of used lubricating oil, Oil Gas. Sci. Technol. -Rev. De. l'IFP 64 (2) (2009) 191–197.
[157] M. Jamshidnezhad, Predicting asphaltene precipitation by simple algorithm using solubility parameter calculated based on Peng-Robinson equation of state, J. Jpn. Pet. Inst. 51 (4) (2008) 217–224.
[158] J.A. Botas, J. Moreno, J.J. Espada, D.P. Serrano, J. Dufour, Recycling of used lubricating oil: evaluation of environmental and energy performance by LCA, Resour. Conserv. Recycl. 125 (2017) 315–323.
[159] L. Duđak, S. Milisavljevic, M. Jocanović, F. Kiss, J. Mitar, V. Karanovic, M. Orošnjak, Life cycle assessment of different waste lubrication oil management options in Serbia, Appl. Sci. 11 (2021) 1–20.
[160] A. Pires, G. Martinho, Life cycle assessment of a waste lubricant oil management system, Int. J. Life Cycle Assess. 18 (1) (2013) 102–112.
[161] H. Fehrenbach, Ecological and energetic assessment of re-refining used oils to base oils: Substitution of primarily produced base oils including semi-synthetic and synthetic compounds; Institute for Energy and Environmental Research (IFEU): Heidelberg, Germany, 2005.