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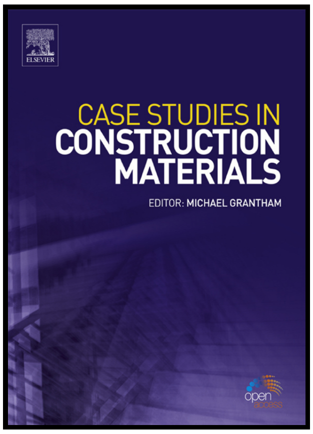

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Analytical Review on Potential Use of Waste Engine Oil in Asphalt and Pavement Engineering

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Abstract

The article provides a comprehensive overview of the research utilizing 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 the 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 work on the economic and environmental appraisal associated with a wide WEO utilization. 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, enhances the overall performance of aged asphalt. The integration of WEO and the reclaimed asphalt binders can enhance crack resistance, which however highly relies on the added WEO quantity. Future research should be prioritized to understand the comprehensive impact of WEO on reclaimed asphalt binder for the compatibility between the rejuvenator compound and the reclaimed aged asphalt, and the effect of WEO on the durability of the modified asphalt mixes. In addition, field investigation and analyse are also required for a bigger, inclusive and more detailed picture of the economic and environmental impacts.

Keywords: Asphalt binders, asphalt pavement, performance improvement, sustainable recycling, waste engine oil.

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, 7], which has generated adverse impacts on the natural environment and has also constantly been raising the cost of construction [8]. Approximately, 1.5 billion tons of construction waste are generated annually, which is still keeping a trend of increase. Storing, handling, and transportation of these wastes represent a huge challenge [9]. So far, the most commonly used measures for handling the wastes are landfilling and burning, which has not only consumed previously available land but also produced irreversible contamination of the environment [10]. Thus, it is vital to find innovative solutions for waste management [11]. Using waste materials to replace the 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 [12]. Meanwhile, it helps reduce the emission of carbon dioxide (CO_2) [13, 14].

Significant amounts of oil wastes, such as waste plastic oil (WPO), waste cooking oil (WCO), and waste engine oil (WEO), are being produced worldwide every day [15, 16], which, the 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 [17]. The major generation of the 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. [15, 18].

WEO contains significant amounts of heavy metals including zinc, calcium, barium, lead and magnesium, which pose a potential danger to living organisms [19], including human beings and all wide ecosystems [20]. According to the report by the U.S. Department of Energy, most of WEO is recycled for fuel [14], such as diesel [15], lubricant oil after additional processing treatment [21], or roofing tiles [22]. Meanwhile, being approximately similar to petroleum asphalt in terms of physical and chemical properties, researchers have investigated the use of WEO in pavement engineering [23], particularly, in conjunction with asphalt binders [24, 25], such as directly using WEO in asphalt binders [21, 26, 27].

2. Research Significance

The 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 road surface's quality and endurance. Utilizing 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 use 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 isn't 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 paper discusses recent study publications that were just released and were not discussed in earlier review articles. A systematic literature review strategy was used to review and assemble a significant body of literature that was published in the last 20 years. There were several research databases used for this, including Scopus, Web of Science, and Google Scholar

The impacts of 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 the suggested solutions. The review consists of several subsections. The first subsection introduces the topic and general information about asphalt concrete and its production. The 2nd subsection focuses on the properties of WEO preparation of WEO-asphalt binders. The 3rd section describes the previous results and the main findings for the impact of using WEO in the 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 have been discussed. In the end, the current knowledge gap has been highlighted for future research directions.

3. Asphalt Concrete

Asphalt as a historical building material initially used in Sumeria in 6,000 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 [28]. 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 1876. USA using sediment in lakes [29]. The discovery of petroleum refinement in the 1900s has led to the modern asphalt that is widely used today [28].

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 (CMA), warm mix asphalt (WMA), and hot mix asphalt (HMA). 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 [30]. The 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 strength but also have sufficient softness for dissipating stresses within the matrix [31, 32].

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 the asphalt binder. On the other hand, maltenes are a mixture of resins and oils that disperse and stabilize the asphaltenes [33, 34]. The maltenes can be further divided into non-polar and polar saturated aromatics, which contribute to different adsorption characteristics. However, advanced technology, such as modified Clay-Gel absorption chromatography and advanced solubility test, is required to break down maltenes [35]. The relationship between asphaltenes and maltenes can be compared with that between the aggregate and the asphalt binder of the asphalt concrete by the analogy that the maltenes for asphaltenes are like the asphalt binder itself for aggregates. The size of maltenes is much smaller than that of asphaltenes. It is the asphaltenes which provide the structure and the final form of asphalt binders, while the resin composites in the maltenes peptizes the asphaltenes and the oil composites to deliver the homogeneity of the final asphalt binder [28, 34].

4. Waste Engine Oil

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 [31]. Therefore, WEO is not suitable for original purposes and requires replacement for a period of time [36]. These non-degradable substances are difficult to decompose, however, from a recycling perspective point of view, WEO can be used to modify asphalt binders or in reclaimed asphalt pavement (RAP), etc. [37, 38].

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 [39-41]. 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 summarises the contents of SARA and metal components of WEO from various references. The SARA components can impact 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 [13, 42]. Using conventional tests for WEO, Yan et al. [43] found that all the WEO components have closely similar solubility. Different composite test approaches may bring in errors due to poor separation. Among them, the thin layer chromatography-flame ionization detector (TLC-FID) technique has been proved of fast separation speed and high sensitivity. As well as requiring a small sampling volume, this approach has been widely used for detecting the components of WEO [44, 45].

Table 1. Physical properties of WEO from different studies.

Property	Ref. [13, 43]	Ref. [11]	Ref. [46]	Ref. [18]	Ref. [47]	Ref. [48]	Ref. [49]	Ref. [50]
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. [13]	Ref. [51]	Ref. [52]	Ref. [53]	Ref. [49]	Ref. [31]
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

While, Abdullah et al. [15] 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 (CNC) 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. In addition, the gas chromatography-mass spectrometry (GC-MS) analysis reveals that the 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 the hydrocarbons are aliphatic alcohol, trimethyl benzene, cyclohexylmethylhexylester, 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.

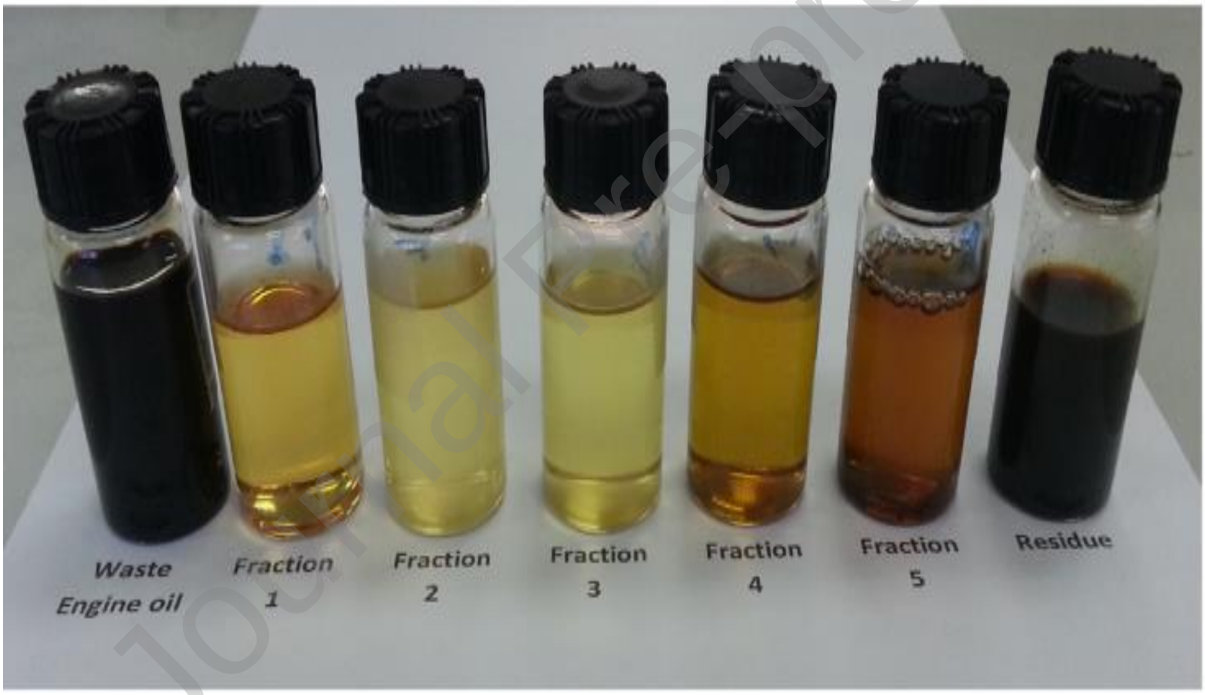


Figure 1. WEO fractions, following fractional distillation, were heated to 400 ^{o}C and then treated for 3 hours. Fraction 1 (F1) 0.9% distilled at 100-150 ^{o}C, fraction 2 (F2) 1.9% distilled at 150-200 ^{o}C, fraction 3 (F3) 4.4% distilled at 200-250 ^{o}C, fraction 4 (F4) 11% distilled at 250-300 ^{o}C, and fraction 5 (F5) 43% distilled at 300-400 ^{o}C [15].

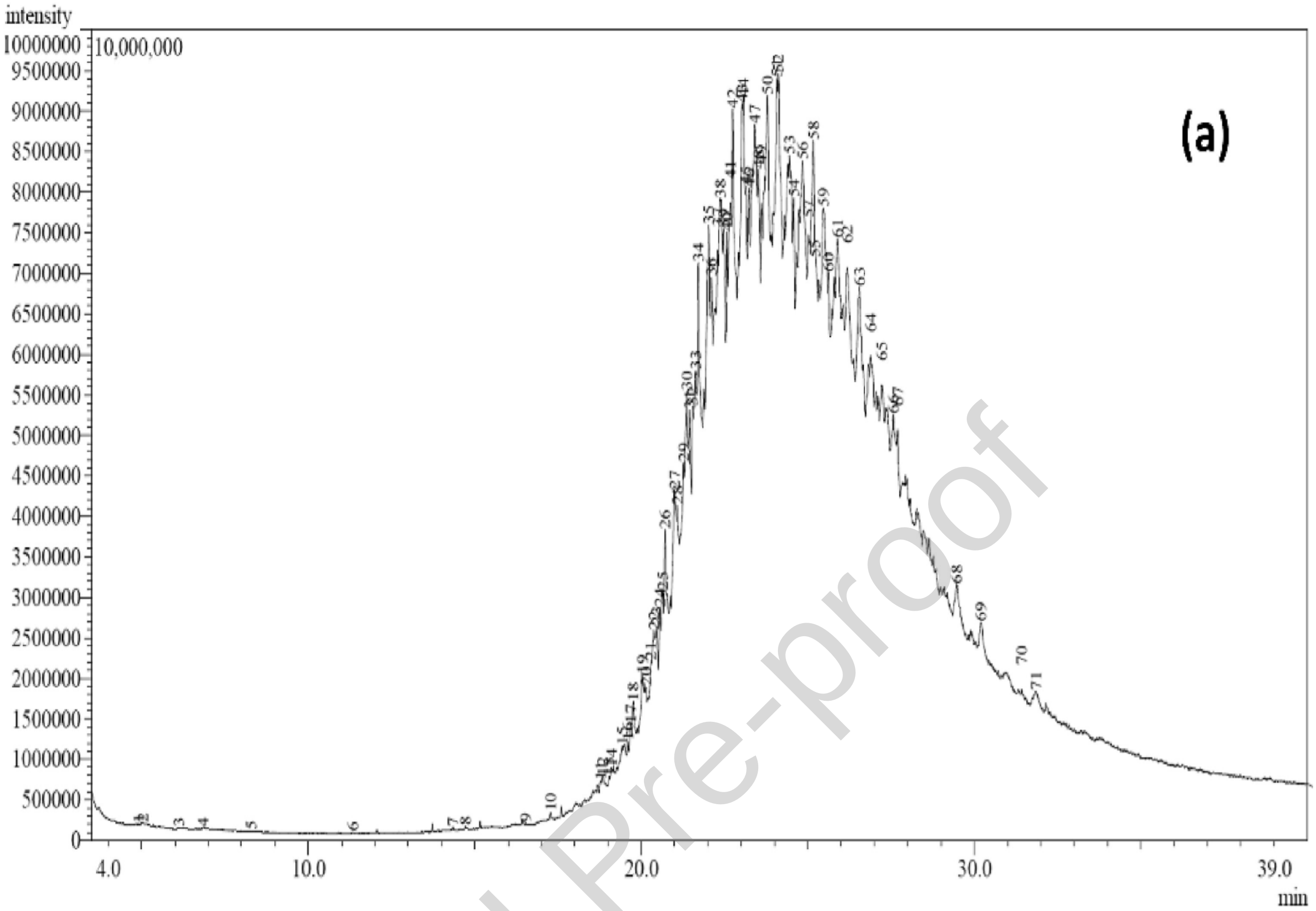


Figure 2. GC-MS results of WEO [15].

Table 3. WEO compounds from GC-MS test [15].

Peak	Compounds	Formula
WEO 1, 2	Dimethylbenzene	C8H10
3, 4	1,2,3-Trimethyl benzene	C9H12
5	1-Ethyl-2,4-dimethylbenzene	C10H14
6	2,4,4,6,6,8,8-Heptamethyl-1-nonene	C16H32
8	2-Ethylisohexanol	C8H18O
7, 9	Sulphurous acid, cyclohexyl methyl hexyl ester	C13H26O3S
10	2-Thiopheneacetic acid, decyl ester	C16H26O2S
11	n-Eicosane	C20H42
13	n-Pentatriacontane	C35H72
12, 14	n-Heneicosane	C21H44
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	C54H110

15, 17, 23, 24, 25, 27, 34, 36, 50, 56, 57	n-Tetratetracontane	C44H90
28	Octacosane	C28H58
18, 19, 29, 65	n-Tetracontane	C40H82
20	Sulphurous acid, cyclohexyl methyl octadecyl ester	C25H50O3S
45	n-Hexatriacontane	C36H74
33, 44, 69	Hexacontane	C60H122
51, 55, 60	8-Hexylpentadecane	C21H44
48, 71	Dodecahydrosqualene	C30H62
61, 66	9-Octylhexacosane	C34H70
67	9-Dodecyltetradecahydroanthracene	C26H48
70	2-Heptylthiophene	C11H18S

Similarly, Liu et al. [18] used GC–MS chromatograms of WEO and found that the chemical components of WEO have lower than 200 g/mol of molecular weights. It suggests that WEO's main components have low molecular weights. Table 4 and Fig. 3 provide an overview of their findings and show that polyolefin oil, paraffin oil, and aromatic solvents are the main components. These elements resemble the aromatics in asphalt. Alkylbenzene and alkanes in the C9–C12 range make up the majority of the aromatics.

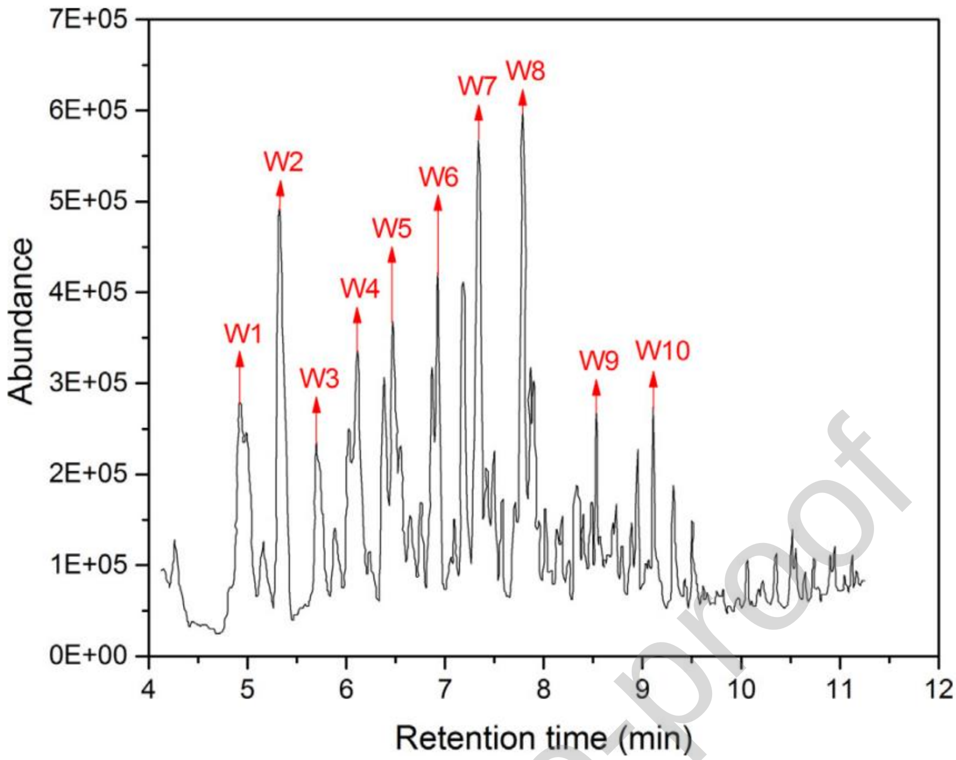
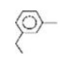
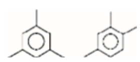
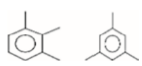
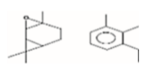
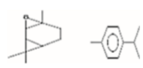
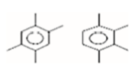
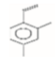
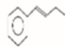
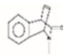
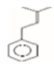
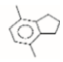
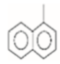


Figure 3. GC/MS chromatogram of WEO [18].

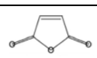
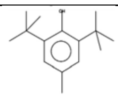
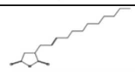
Table 4. GC-MS analysis results show the chemical composition of WEO [18].

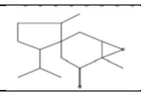
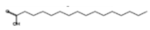
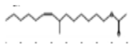
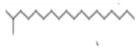
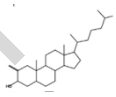
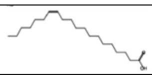
Label	Retention time (min)	Synonyms	Formula	CAS	Molecular weight	Structure
W1	4.929	Benzene, 1-ethyl-3-methyl-	C_9H_{12}	620-14-4	120.19200	
W2	5.329	Benzene, 1,3,5-trimethyl- Benzene, 1,2,4-trimethyl-	C_9H_{12}	108-67-8; 95-63-6	120.19200	
W3	5.704	Benzene, 1,2,3-trimethyl- Benzene, 1,3,5-trimethyl-	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	 

On the other hand, Wang et al. [54] studied the chemical compositions of the WEO bottom (WEOB), a common type of WEO. Their findings are shown in Table 5, which shows that linear alkanes with a carbon number range from C4 to C28 and an alkylbenzene structure are the main components of the WEOB. Therefore, it may be inferred that the WEOB primarily constitutes similarly aromatic solvents, namely paraffin oils and polyolefin, which are identical to the aromatics found in asphalt. Downstream and maleic anhydride compounds, such as 2-Dodecen-1-yl succinic anhydride, were also found, showing that there were chemical reactions taking place with the additives while they were being used.

Table 5. Composition of WOEB as determined from GC–MS analysis [54].

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-isopropy	$C_{15}H_{24}O_2$	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, 5ὰ)-	$C_{28}H_{48}O$	400	
14.87	*cis*-13-Eicosenoicacid	$C_{20}H_{38}O_2$	310	

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 [11, 18, 55, 56]. Asphalt is at first oven heated up to a temperature in the range of 130-190 ^{o}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 the WEO is added along with or with other additional additives. When used together with other additives, the mixing WEO asphalt first needs to last for 10 to 30 min followed by another 22-40 min extra mixing with the other added-in additives. WEO along the mixing time usually ranges between 30 to 90 min. For the WEO asphalt mixture, the WEO content ranges between 2 to 10% by the weight of the asphalt binder. Figure 4 provides an example of the shear mixing procedure for the type of WEOB when mixed with SBS-modified asphalt [54].

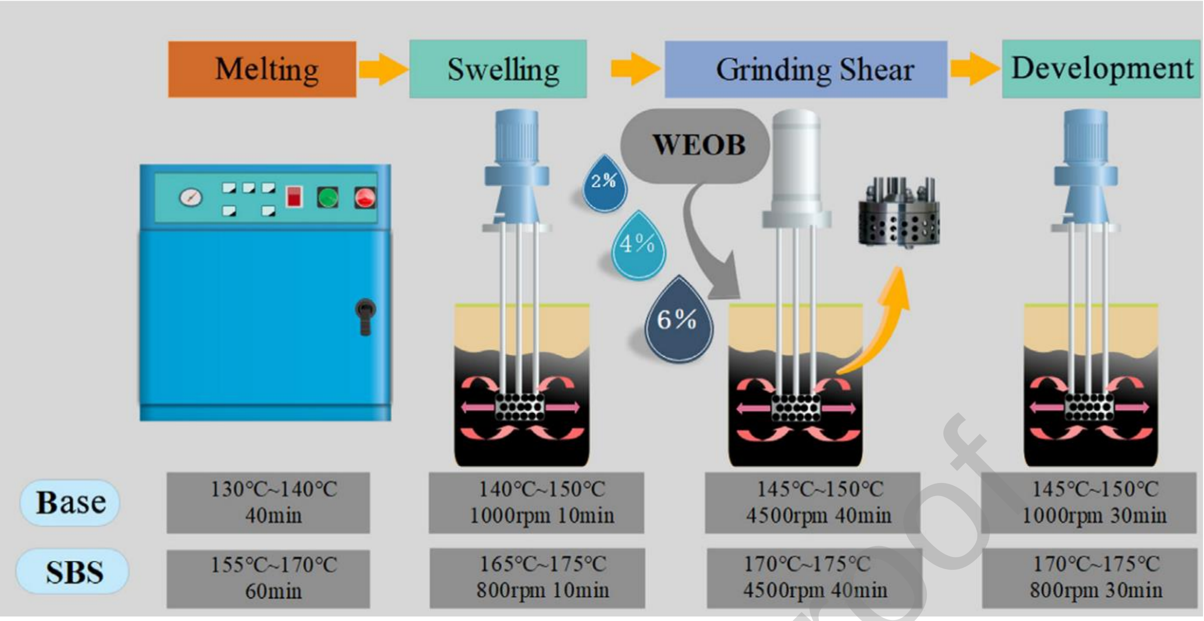


Figure 4. Steps involved in the preparation process of WEOB and WEOB/SBS modified asphalt binders [54].

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

Ref.	WEO	Asphalt	Mix	temperature	stirring time	Test	Standard
[11]	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	-
						FTIR spectroscopy	AASHTO (2006)
						Dynamic shear Rheological (DSR) tests	T0625-JTG E20-2011 in China (2011)
						Brookfield viscosity test	-
[25]	local auto repair shop	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	-
[55]	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

[57]	Refine waste oil Motor oil (RW)	Wisconsin asphalt	RW (5%)	-	-	Aging procedures	AASHTO T 240 and AASHTO R 28
						Linear amplitude sweep (LAS) test	AASHTO M320
						Bending beam rheometer (BBR) test	AASHTO T 313
						Multiple stress creep recovery (MSCR) tests	AASTO T350
						Rheological properties of the binder	ASTM D6373 and AASHTO M 320
[58]	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 ºC	40 min	Basic properties	EN 1426 standard, EN
						Multiple Stress Creep Recovery (MSCR) tests	AASHTO TP 70-11
						Rheological properties	1427 standard EN 14770 standard
[59]	WEOB (petroleum refinery)	styrene-butadiene-styrene copolymer (SBS) three-block polymer asphalts	WEO (8%)	-	-	Double-edge notched tension (DENT) test	-
						Linear amplitude sweep (LAS) test	AASHTO T 315 (DSR)
						Multiple stress creep and recovery (MSCR) tests	AASHTO T315(DSR)
[18]	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 ºC, 160 ºC	30 min	Rotational viscosity Dynamic shear rheometer (DSR)	-
						Fourier transform infrared (FTIR) spectroscopy	-
						Gel-permeation chromatography (GPC)	-
						Gas chromatograph mass spectrometry (GC–MS)	-
[56]	WEO (from vehicle service station)	Base asphalt (AH-50)	WEO (25%, 35%, 45%) + Ground tire rubber (GTR) (20%, 30%, 40%)	170 ºC	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)
						Fourier transforms infrared (FTIR)	-
						Thermogravimetric analysis	-
						Morphological analysis	-
						Dynamic mechanical analysis	-
						Dynamic shear rheological property test	-
[54]	WEOB (Waste engine oil bottom)	Base binder (60/80) and SBS binder (SBS, 4.3%)	WEOB (2%, 4% and 6%)	140-175 ºC	10-40 min	GC–MS test FTIR test	-
						Rotational viscosity test	ASTM 4402

						Temperature sweep test	ASTM D7175
						MSCR test	ASTM D7405-15
						Fluorescence microscopy	-
[47]	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)	(ASTM D5, ASTM D36, ASTM D113 and ASTM D4402)
						Aging test	JTG E20 T0609
[60]	WEO	Esso #90 base asphalt, rubber asphalt containing waste engine oil (ERA), microwave treated rubber asphalt (WRA), conventional rubber asphalt (RA), and highly dissolved rubber asphalt using WEO and microwave desulfurization method (WERA)	40 mesh crumb rubber (5%, 15%, 25%, and 35%) polyethylene (3%) WEO (25%)	185 ºC	90 min	Storage stability test and corresponding indicators	ASTM D7173
						Rheological indices at low temperatures	-
						Rheological indices of multiple stress creep recovery (MSCR) test at high temperatures	AASTO TP70-09
						Solubility test and corresponding index	-
[48]	WEO (from cars after 5000–6000 km of service mile)	a road petroleum asphalt (Pen60/80)	WEO rejuvenator (WEO 4.5%, furfural extraction oil 5.0%, and epoxy resin 0.5%) water-borne epoxy resin and the water-borne curing agent (2:1)	130 ◦C	30 min	High temperature rheological properties	-
						Fatigue test	-
						Semi-circular bending test	ASTM D3497
						Hamburg wheel tracking test	AASHTO T324
						Dynamic uniaxial compression test	-
						Freeze-thaw split test	-
						Molecular weight test	-
						Thermogravimetric (TG) test	-
						Chemical structure test	-
						physical properties (penetration, ductility, and softening point)	(ASTM D5, ASTM D113, ASTM D36)
						Low-temperature rheological properties	-
[61]	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 (30R+WS, and (50R+WS),	140 ◦C	15 min	Accelerated rutting test	AASHTO T324-11
						Bending beam rheometer (BBR) test	ASTM D6648
						Aggregate coating test	AASHTO T195
						RTFO, PAV, and dynamic shear rheometer (DSR) tests	-
						Indirect tensile strength (ITS) test	ASTM D6931-2017

			The SBS/WEO (10/90, 20/80, and 30/70)			SARA analysis	ASTM D4124
						Marshall stability-flow test	ASTM D6927
						Thermal gravimetric analysis (TGA)	ASTM E1131
						FTIR test	-
[50]	REOB (Re-refined engine oil bottom)	base asphalt (GS-70)	REOB with different contents (5, 10, 15, 20, 25, 30) wt. %	150℃	30 min	Dynamic shear rheometer (DSR) test	ASTM D7175
						Physical property test (penetration, ductility, softening point and viscosity)	(ASTM D5, ASTM D113, ASTM D36 and ASTM D4402)
						Fourier transform infrared (FTIR) test	-
						Thin-layer chromatography with flame ionization detection (TLC-FID) test	-
						Bending beam rheometer (BBR) test	ASTM D6648
[21]	WEO (a petrol vehicle stationed in a local auto repair shop)	VG-30 grade asphalt binder RAP material (damaged pavements)	WEO (0, 2, 4, 6, and 8%) RAP (0, 25%)	160 ºC	30 min	dynamic shear rheometer	ASTM D 7175-08
						FTIR	
						softening point	AASHTO T53
						Viscosity	ASTM D4402
[62]	WEO	80/100 asphalt	WEO (2%, 4% and 6% mass of asphalt) PPA (1% and 2%)	135 ◦C	30 min	Fatigue-healing test	-
						Radar chart method	-
						Differential scanning calorimetry (DSC) test	ASTM D3418
						Linear amplitude sweep (LAS) test	ASHTO TP 101-14

5. Functional Roles or Applications of WEO

5.1 Database

Scopus database was used as it represents a main international, recognized, and prominent peer-reviewed database [63, 64]. The used keywords included “waste” And “engine” And “oil” And + “asphalt” OR “bitumen”; “Waste engine oil” + “asphalt” OR “bitumen”, applied to probe articles, titles, abstracts, and keywords. In order to obtain extensive literature on the subject and cover regional preferences, bitumen and asphalt were used as synonyms.

The analysis identified 189 papers from the period 2002 to 2023. Figures 5 and 6 illustrate the Scopus database and their authorship countries respectively. It can be seen that the period of 2014, and between 2019 to 2022 shows 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 the year. Figure 6 shows the distribution of publications across the globe, with China having the highest authorship of more than 60 publications. Next came India with 20 publications, followed by Malaysia, the United States, Iraq, and Iran with more than 10 publications. Overall, the database analysis indicated that the topic is a recent and innovative subject in asphalt pavements.

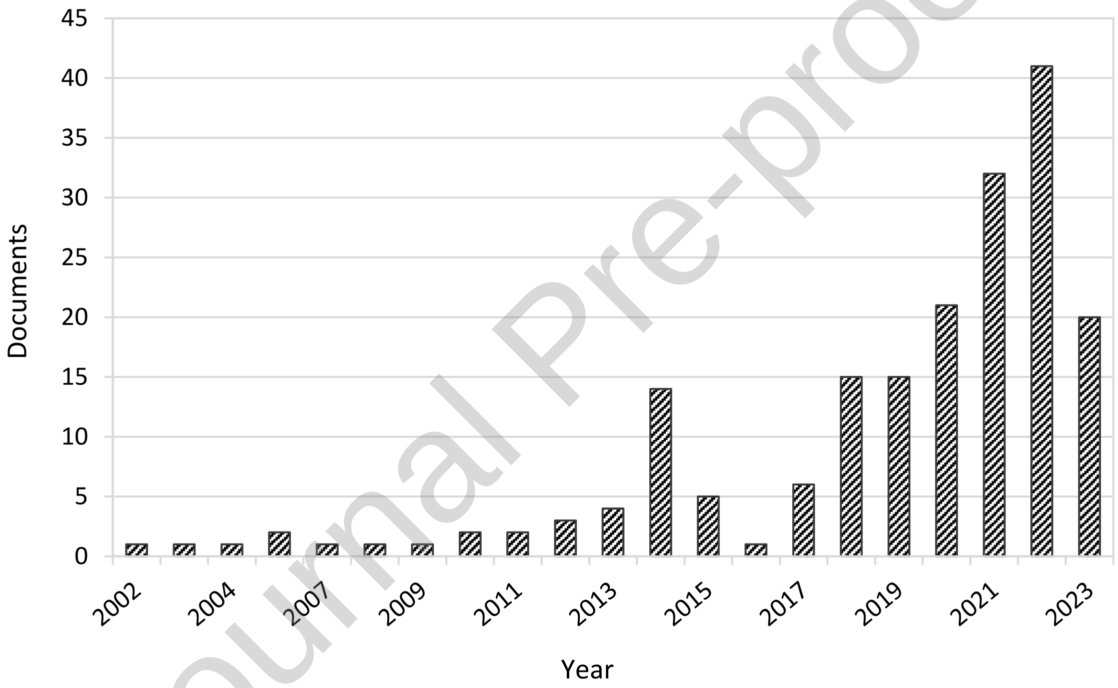


Figure 5. Number of scientific publications per year from Scopus.

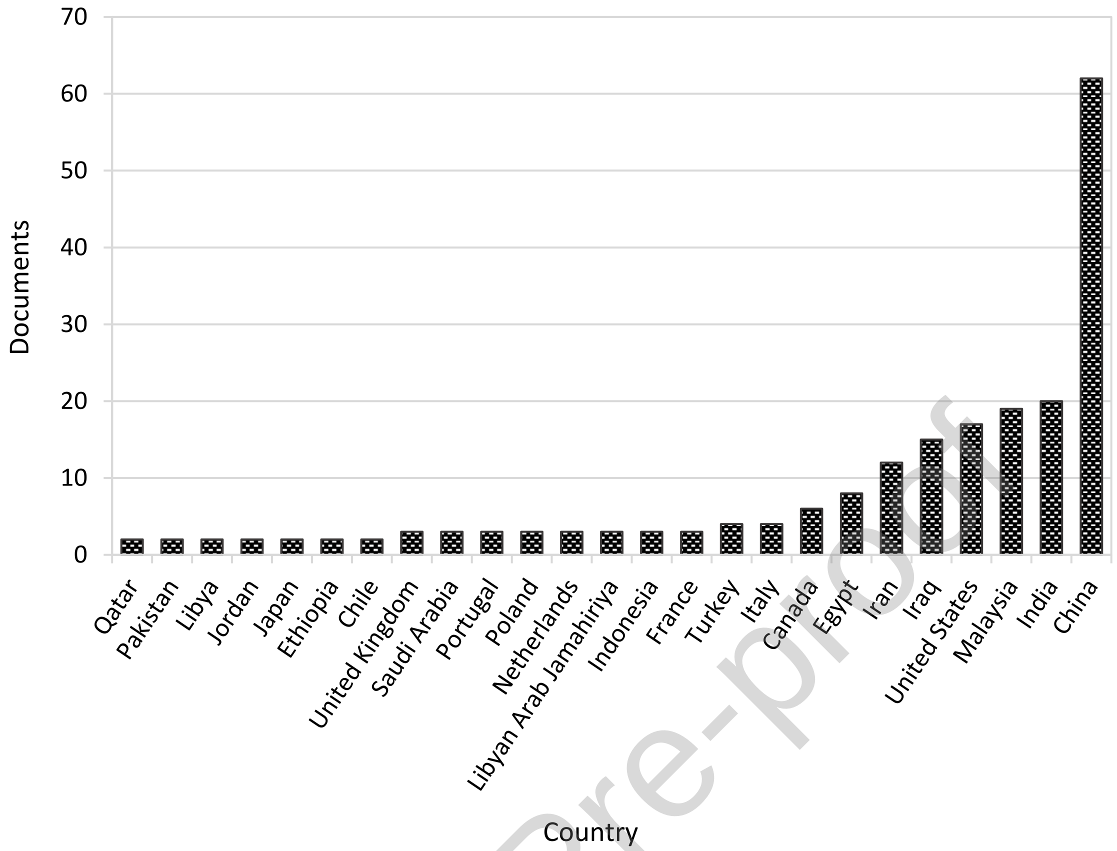


Figure 6. Number of scientific publications per country from Scopus.

5.2 Modification of Asphalt Binders

Due to having similar molecular components as that of asphalt, WEO was utilized to modify asphalt binders [65, 66]. Villanueva et al. [67] found that the use of WEO caused a reduction of the softening point of asphalt binders. They also found that using lubricating oil had minor enhancement on the behaviour of modified asphalt at low temperatures through the use of a bending beam rheometer (BBR) test. In another study conducted by Borhan, Suja, Ismail and Rahmat [68], it was observed that the modified binders experienced a decrease in ductility and specific gravity. However, Zargar, Ahmadinia, Asli and Karim [69] found 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. There were reports that increasing the amount of WEO reduced the fatigue and rutting of asphalt [38, 70]. Nevertheless, Fernandes et al. [68] reported increased fatigue resistance of WEO-modified asphalt in comparison with SBS-modified asphalt.

On the other hand, Liu, Peng, Wu and Zhou [18] investigated 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 are 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 the LMS and MMS but an increase in the SMS as illustrated in Table 7. The infrared spectra illustrated in Fig.7 show that WEO modified binders consist of similar functional groups as that 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 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 CH2 and CH3, respectively, describing the CAH bending. The authors also reported the improvement in construction temperature, energy consumption, rutting and fatigue resistance but meanwhile the deterioration in the capacity of elastic recovery and resistance of deformation. The asphalt's high temperature categorization was changed from 5 to 9, respectively, by the addition of 4% and 8% WEO.

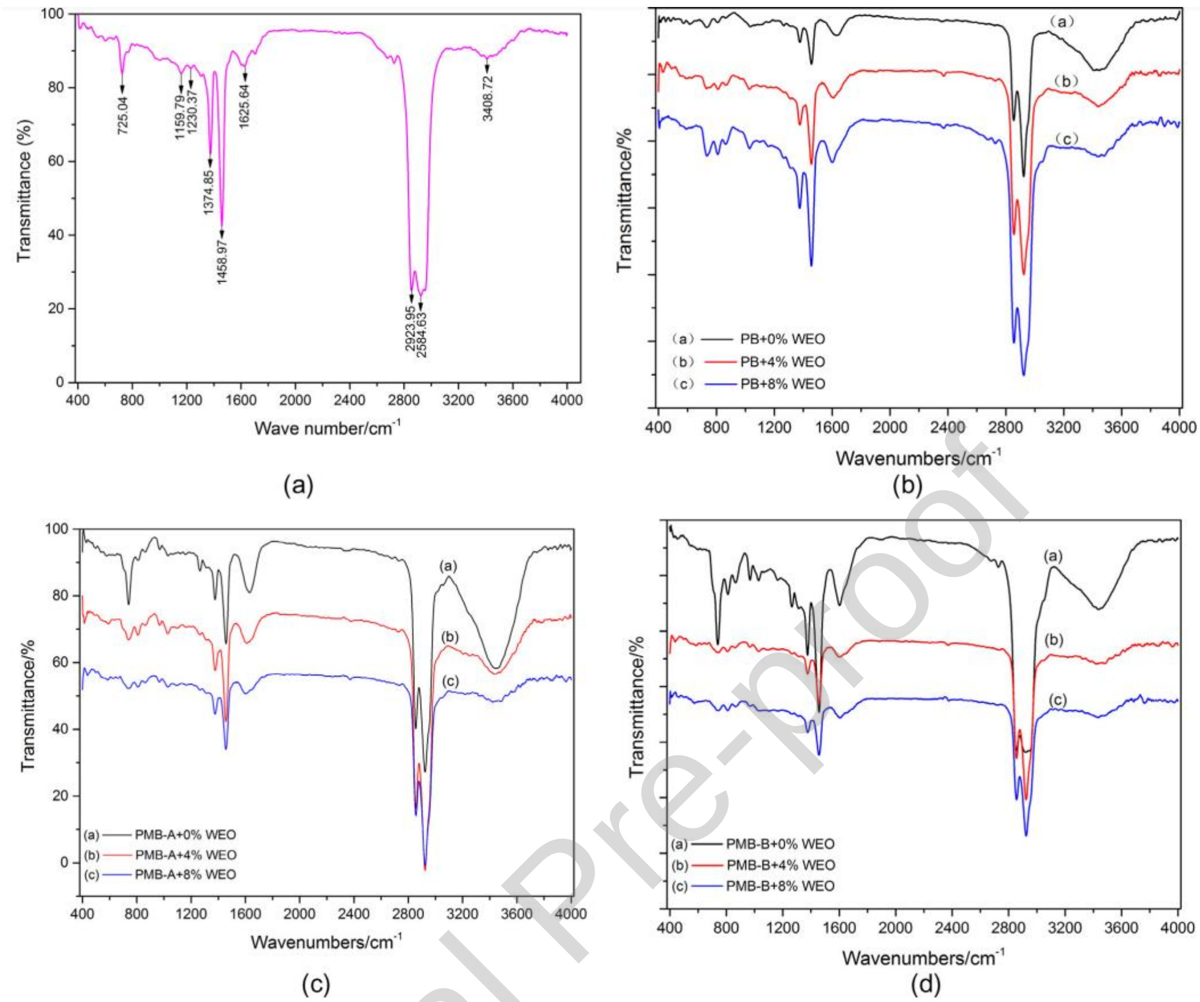


Figure 7. Results of FTIR test of WEO-asphalt mixtures: (a) WEO, (b) PB, (c) PMB-A, and (d) PMB-B [18].

Table 7. Sizes of molecules in WEO- asphalt mixtures [18].

Asphalt types	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

WEO has been found able to enhance the behaviour of asphalt binders at low temperatures by reducing the time of stress relaxation and stiffness. Qurashi and Swamy [21] showed that while the behaviour of WEO modified asphalt deteriorated at high temperatures, the degree of deterioration depended upon the contents of the WEO and the type of asphalt, the performance at low temperatures showed improvement. While Hesp and Shurvell et al. [27] reported property deterioration of WEO asphalt when the use of WEO exceeds 15% because the asphaltene structure became unstable and the asphalt subsequently became harder. By employing X-ray fluorescence (XRF) spectroscopy technology, researchers investigated the influence of waste engine oil bottom (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 the asphalt, which are critical factors determining its performance under low temperature conditions. Meanwhile, Wang et al. [54] investigated the impact of WEOB on the base binder's rheological characteristics at high temperatures in comparison to a modified binder made with SBS. They observed that the WEOB-modified binders had improved viscosity but reduced deformation resistance and elastic recoverability. However, adding WEOB to the SBS binder has the opposite effect. WEOB has light components which play a key role influencing the behaviour of asphalt binder at high temperature. These components enhance the asphaltenes' solubility, which in turn soften the base binder. Whereas, the structural network of the SBS expand due to the light components which also reduce the restriction on the thermal movement of asphalt molecules within the SBS network. In another study, Lei et al. [71] investigated different WEOs, such as bio-based and refined ones, for their effect on the behaviour of asphalt at low temperatures. Their results in Fig. 8 have shown that, regardless of their different types, the WEOs increase the m-value but decrease the stiffness of the original asphalt binders. The modified binders have a higher rate of stiffness reduction than the original asphalt binders, an indicator for the enhancement of stiffness and relaxation rate of asphalt mixtures, and thereby, the pavement cracking resistance. It had been claimed that the modified asphalt had the fracture energy which is more than three times than that of the original asphalt binders. However, the performance at high temperature had been noticed deteriorated.

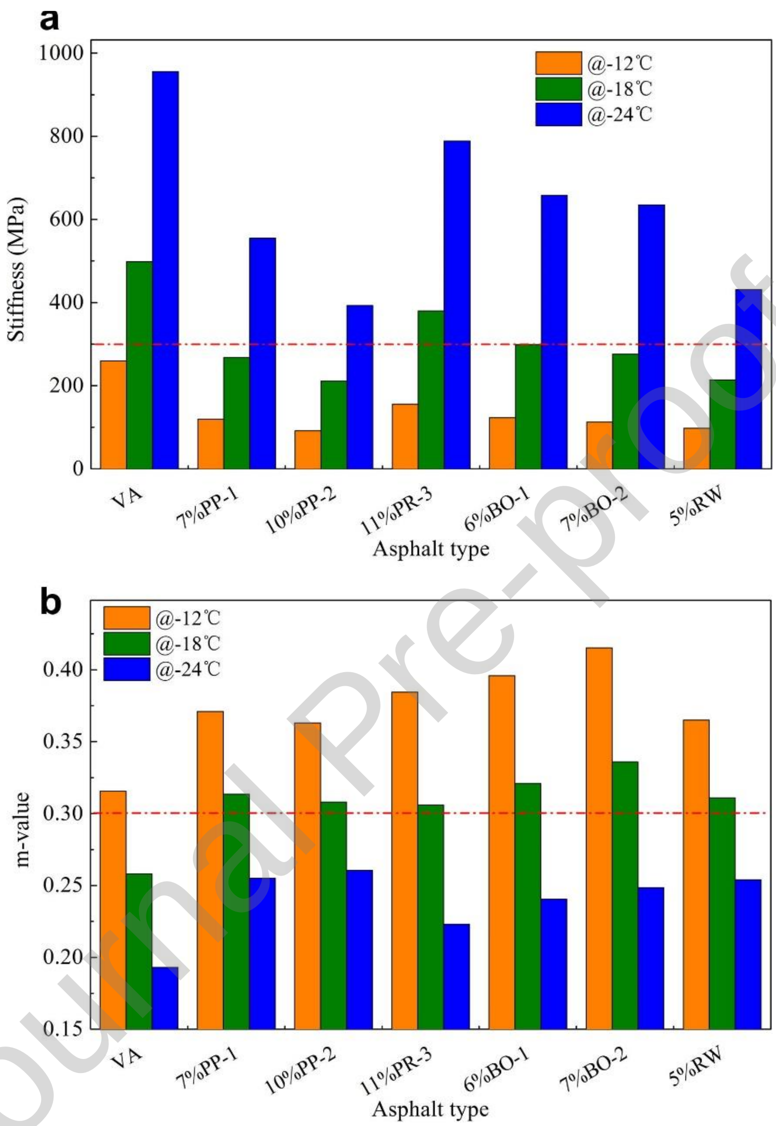


Figure 8. The behaviour of asphalt at low temperatures in terms of stiffness and m-value [71].

Similarly, Lei, Bahia, Yi-qiu and Ling [57] conducted a separate study in which they examined six different types of oil additives, including refined waste motor oil, bio-based oils, and petroleum-derived oils. The researchers observed that all of these oils resulted in a reduction in the stiffness of the asphalt binders at various ranges of temperature. They found that these oil additives had a positive impact on fatigue resistance at low temperatures but had a detrimental effect at high temperatures. Furthermore, they discovered simple linear trends for the relationship between the types of oil and shear modulus or oil content and m-value.

Research has been conducted to investigate the impact of oil modifiers on asphalt binder performance; however, further work is required to validate the trends found and increase our understanding of this topic. Based on the aforementioned literature study, we can see that: (i) the majority of the studies were on WEO modified binders, and there was less research on WEOB modified binders. While previous research has demonstrated that waste engine oil (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 reveals that a limited number of articles examine 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 performance over the short and long terms, given the wide variety of new products being released on a regular basis.

5.3 Rejuvenation of Aged Asphalt and Reclaimed Asphalt Pavement

5.3.1 Used for aged asphalt

Asphalt loses its penetration grade over time when the viscosity and softening points have increased [7]. WEO can be utilized as an asphalt rejuvenator taking its ability to reduce the viscosity [42]. Asphalt aging leads to an increase in the weight ratio of asphaltene to maltene, resulting in a loss of volatility of their constituents [72, 73]. Consequently, aged asphalt binders exhibit increased brittleness and stiffness. However, the use of waste engine oil (WEO) can help restore the viscoelastic properties of aged asphalt, reducing stiffness [74], and improving workability [18, 67]. Moreover, the application of WEO has shown benefits in enhancing the resistance to fatigue and cracking at low temperatures [31, 75, 76].

Although WEO has the effective potential to be used for asphalt rejuvenators, only a few studies had been reported on this subject until 2009 [77]. Recently, significant works have been performed using WEOs as asphalt binder rejuvenators [51, 56, 78-81]. According to Silva [82], substituting WEO for road materials can assist in lowering the mixing temperature. Also, Shen [83] demonstrated that the WEO may be utilized to minimize the optimal content of commercial additives in asphalt mixtures. Meanwhile, Dedene [38] proved the potential WEO utilized as a rejuvenating agent to recycle asphalt mixtures but noticed the reduction of the pavement properties. While Peng et al. [84] used waste polyethylene (WPE) and WEO to modify asphalt. By ultraviolet aging simulation, they demonstrated that WEO improves the aging of the asphalt. Another study by Arshad et al. [85] found improvement in the viscosity of aged asphalt when using WEO as a rejuvenator. However, the increase in the content of WEO reduced both the viscosity and softening point. Similarly, El-Shorbagy et al. [86] used WCO and WEO as rejuvenator agents and found that the content of 4% WCO or 6% WEO improved the penetration value and softening point of rejuvenated asphalts. Li et al. [47] also used WCO and WEO as rejuvenating agents and found 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 content of the WCO and WEO is 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. [59] compared the damage characteristics of WEOB-rejuvenated asphalt with those used in extracted aromatic oil (AO) for rejuvenation. According to their findings illustrated in Fig. 9, when the fatigue life of asphalt binder was decreased by age, the AO modified binder had the fatigue life increase when exposed to two stains, 2.5% and 5%, while the WEOB modified binder had 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 fatigue performance. Figure 10 provides the results of the creep analysis. It shows that after 1 hr of water conditioning, both binders displace a similar behaviour. However, after conditioning for 24 hr, the loss in creep of the WEOB modified asphalt reaches up to 50% while the loss of the AO one almost keeps no change. It means that the WEOB can be more beneficial in cold regions.

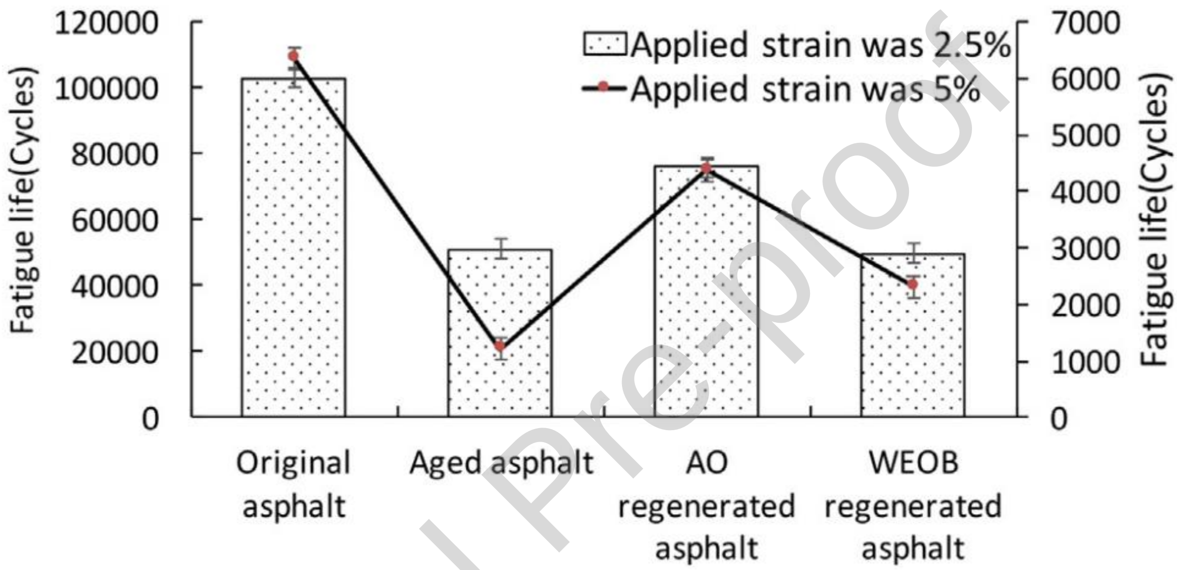


Figure 9. The fatigue life of several asphalts at two applied stresses, application of cyclic loading in the form of linearly increasing load amplitudes [59].

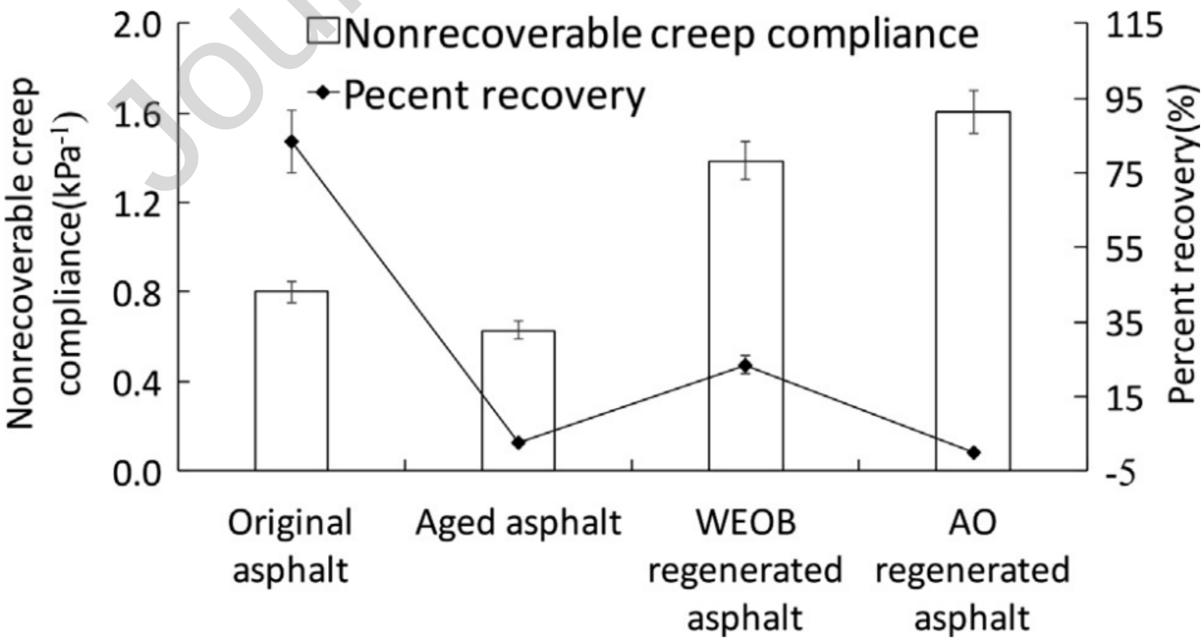


Figure 10. Percentage of recovery and nonrecoverable creep compliance for several asphalts [59].

The use of two types of re-refined engine oil bottom, called REOB-1 and REOB-2 was studied by Cai et al. [50] on three different aged asphalts, i.e. mild, moderate and severe ageing. Their results, as shown in Fig. 11, indicate effective partial recovery for both REOBs at the optimum content of 15% by the weight of the asphalt binder. However, the REOB-1 demonstrates a better effect, attributed to its significant level of aromatics and penetration than that of the REOB-2. In general, the increase in REOBs content reduced the softening point and viscosity of asphalt.

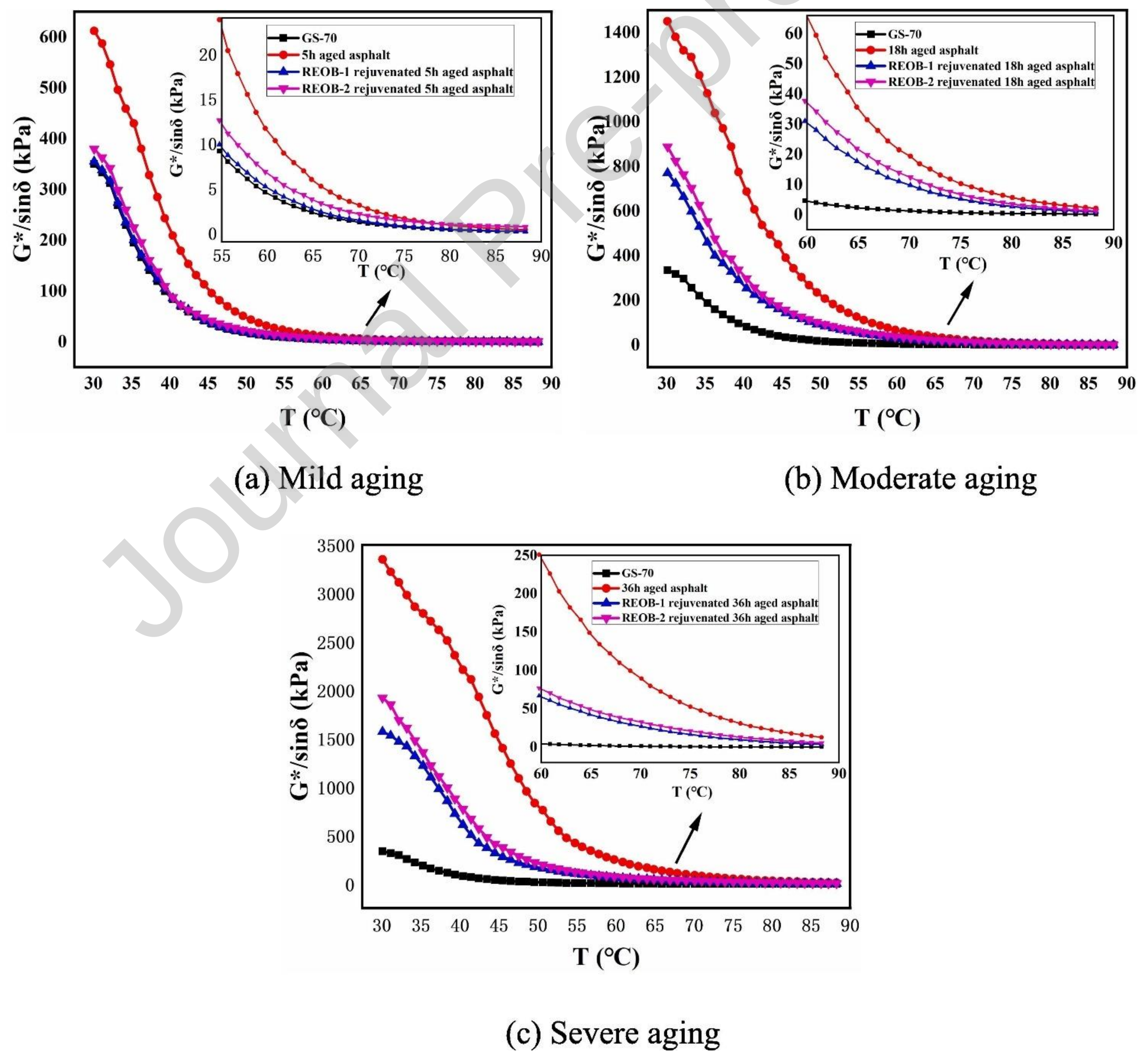


Figure 11. G*/sinδ of various REOB rejuvenated asphalts [50].

Similarly, Qurashi and Swamy [21] conducted a comparison of the viscoplastic properties of virgin and aged binders modified with WEO at different temperatures. The results, as depicted in Fig. 12, indicated the reduction in viscosity with the increase in temperature. Below a certain temperature, the binder modified with WEO exhibits lower viscosity compared to the binders using only the virgin binder or their mixture. Additionally, the WEO-modified binders display lower complex modulus and softening points, but higher phase angles across all temperatures. Overall, the study observed that the best performance was achieved when the WEO content ranged from 2% to 4%.

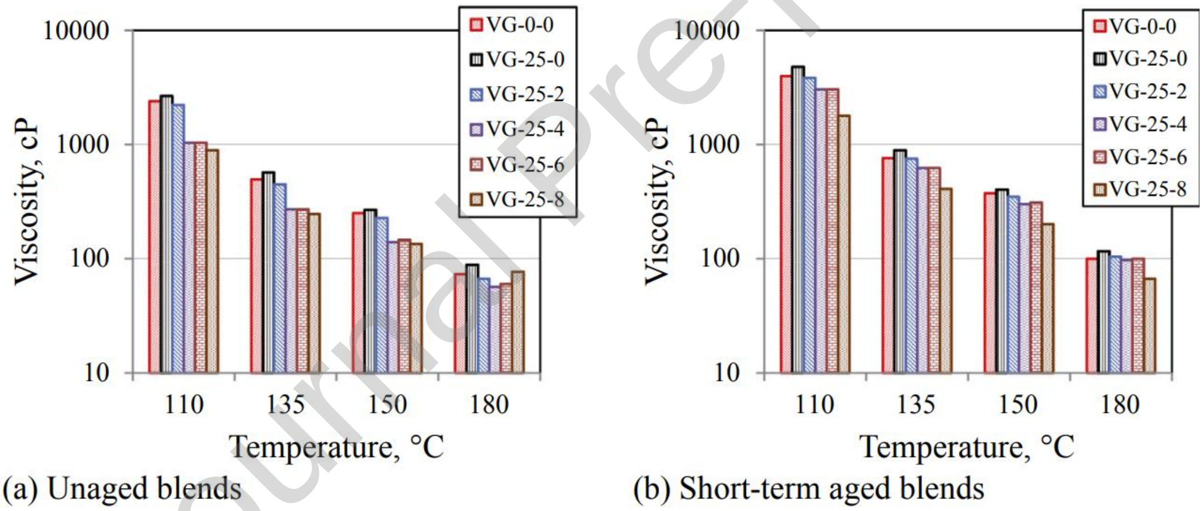


Figure 12. Temperature and WEO content influence viscosity; blends with 0, 2, 4, 6, and 8% WEO were labelled VG-25-0, VG-25-2, VG-25-4, VG-25-6, and VG-25-8, respectively [21].

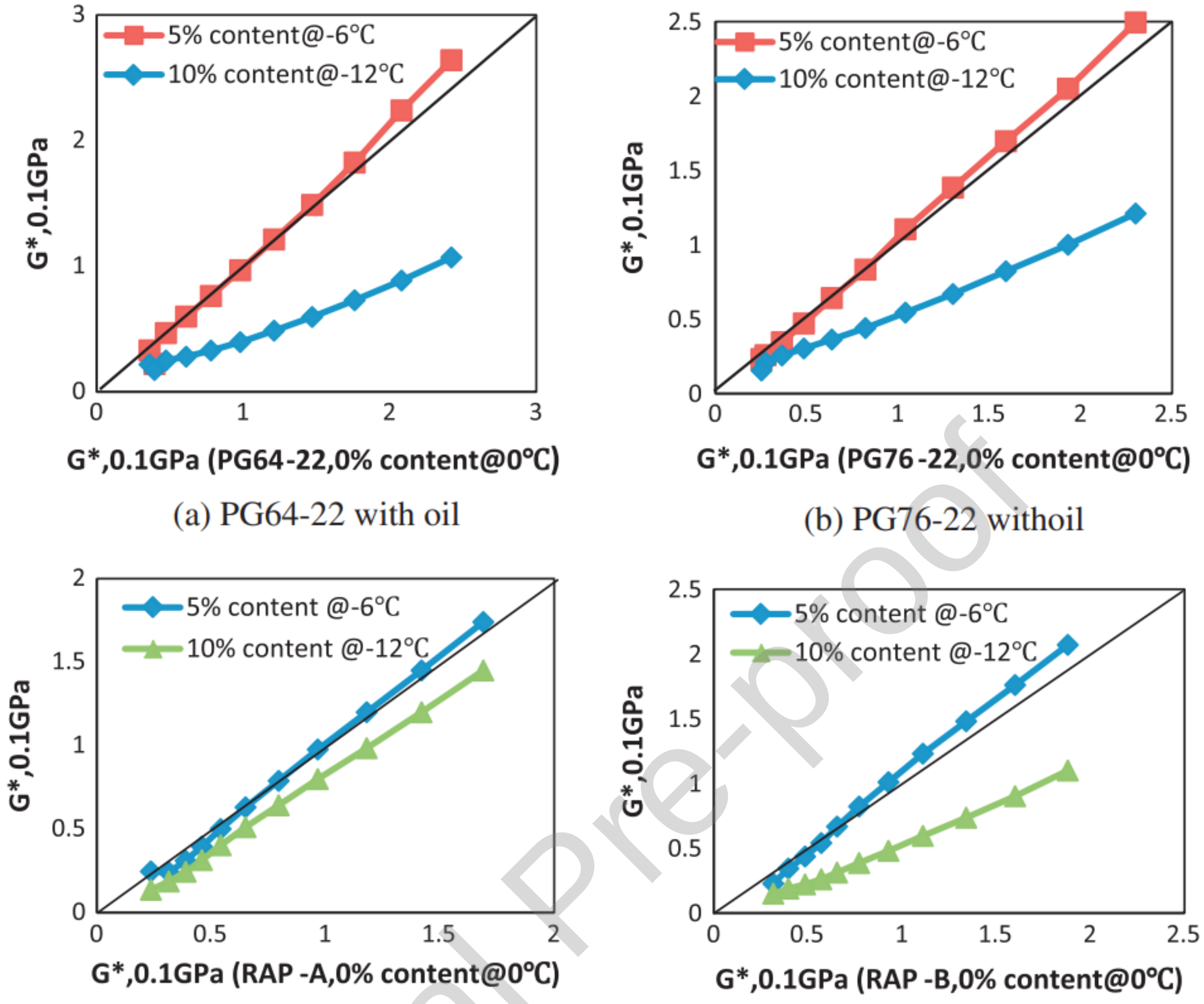
The increased stiffness brought on by using old asphalt binder can be effectively mitigated by using WEO as a partial substitute within the asphalt binder system. Even a partial replacement of this kind can contribute to resource conservation, energy savings, increased recyclable content, and environmentally friendly building methods. Additionally, WEO can be used in place of additives that are sold in stores. Based on the study above, 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, studies on the use of waste oils as regenerants have been conducted. Unfortunately, the majority of studies concentrate exclusively on the performance of the old asphalt that has been rejuvenated using a single waste oil. 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, waste oil degrades land and water resources, thus its usage must be considered carefully in order to promote sustainable growth. In addition, waste engine oil 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 conducted 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 Used for Reclaimed Asphalt Pavement (RAP)

In the early 20th century, significant advances have been made in the asphalt industry to reclaim asphalt and aggregate from demolished pavements [82, 87-89]. 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 [90-94]. The high stiffness of RAP itself results from the gradual oxidation of asphalt, which alters the composition of asphalt, eroding its viscoelastic characteristics [95]. 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 [96]. 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 for road infrastructures, for which using rejuvenating agents has proven to be a feasible alternative [97]. So far, various commercial rejuvenators have already been used for large-scale reuse of RAP, the usage of the RAP is over 30% of the total materials [98-100]. Upon the rejuvenating feature of WEO for asphalt [21, 101-103], a recent review by Al-Saffar et al. [104] highlighted the potential of using WEO to improve the characteristics of asphalt concrete of as high as 30% RAP content. According to Eltwati et al. [105], adding 9% WEO to asphalt mixtures that contain RAP binders greatly improved their performance. Also, a study by Singhabhandhu and Tezuka [106] indicated that using WEO at 7-13% for the asphalt binder containing 30-40% RAP generated similar regeneration results to those obtained from employing commercial regenerating agents. Farooq, Mir and Sharma [107] reported that a 100% WEO and RAP mixture met the flow value and Marshall stability requirements for binder layer design for heavy traffic and the wear layer design for medium traffic. However, when storing time increased, the WEO asphalt penetration rate showed a general declining trend [78].

In another study, Mamun and Al-Abdul Wahhab [108] evaluated the WEO effect on the mixes of RAP up to 50% and compared it with the effect of a commercial rejuvenator. The study indicated that the asphalt mixtures had an indirect tensile strength 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 using 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 WEO content exceeds 20% the moisture susceptibility increases.

On the other hand, some negative impacts of using WEO on RAP were obtained in the study by Jia, Huang, Bowers and Zhao [25]. They found an increase in the existence of the carbonyl functional groups that are related to the oxidation of the 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 stiffness are shown in Fig. 13. At the reference temperature of -6 OC, the stiffness of the 5% oil mixture is similar to the control asphalt, demonstrating similar stiffness properties at low temperatures. At low temperatures, the use of WEO significantly reduced the stiffness of the asphalt binder, with 10% WEO having the greatest effect. This behaviour at low temperatures was significantly influenced by the 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.



(a) PG64-22 with oil (b) PG76-22 withoil

(c) RAP-A with oil (d) RAP-B with oil

Figure 13. Results of stiffness at low temperatures of various asphalt binders [25].

On the other hand, Joni, Al-Rubaee and Shams [109] compared Asphalt Cement (AC (60-70)) and WEO as rejuvenators at various contents, i.e.: 1, 1.5, 2, 2.5 and 3%, added into RAP. The optimal content of regeneration additive (AC, 3%) had a higher value than the optimal ratio of regeneration additive content (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 reclaimed asphalt pavement (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. The WEO increases the Marshall Stability by 20.3% while the AC by 40.8%. The flow value of the WEO one was slightly lower than that of the AC one but both were within the specification of standards. Both rejuvenators produced a high moisture resistance of over 80% of the specified requirement by standards [109]. 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 engine oil residues could be comparable to adding an asphalt rejuvenating agent. Waste engine oil 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 the 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 to a conventional single rejuvenator, the RAP binder rejuvenated using a compound rejuvenator ought to exhibit superior fatigue cracking performance and rutting resistance. It would appear to reason that adding waste oil will soften the old binder in RAP. However, as the performance of asphalt including RAP and waste oil would be vulnerable to the combined impacts of waste oil, virgin binder, and aged RAP binder, one cannot conclude that the fatigue and cracking resistance of asphalt mixtures will be improved. Therefore, creating asphalt binders with RAP binders that operate at their best is essential.

5.4 Used for Asphalt Self-healing

The self-healing capability of asphalt is important for the sustainability of pavement infrastructure [110]. 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 [111]. Taking advantage of other light materials to enhance the fluidity of asphalt has been proved an effective measure [112]. The concept of using WEO to enhance the asphalt capability of self-healing has attracted more and more interest. By an assessment with the use of a three-point bending experiment, Yamaç, Yilmaz, Yalçın, Kök, Norambuena-Contreras and Garcia [113] found that asphalt modified using WEO showed 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 pavement in engineering [114]. There are two different approaches to evaluating 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 will be tested again to compare the tensile strength and other parameters [115-117]. The Fatigue-heal-fatigue test follows the same procedure but having different temperature 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, 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 [118, 119]. Liu et al. [62] performed a study using Polyphosphoric acid (PPA) and WEO to improve the self-healing capacity of asphalt. As shown by Figure 14, they compared the fatigue life ratio, which is used 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% using 1% PPA and 4% WEO. The application of sole WEO or PPA can enhance the recovery of fatigue life as well for the modified asphalt at a certain WEO content, increasing the PPA content also increased 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 is also increased. 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.

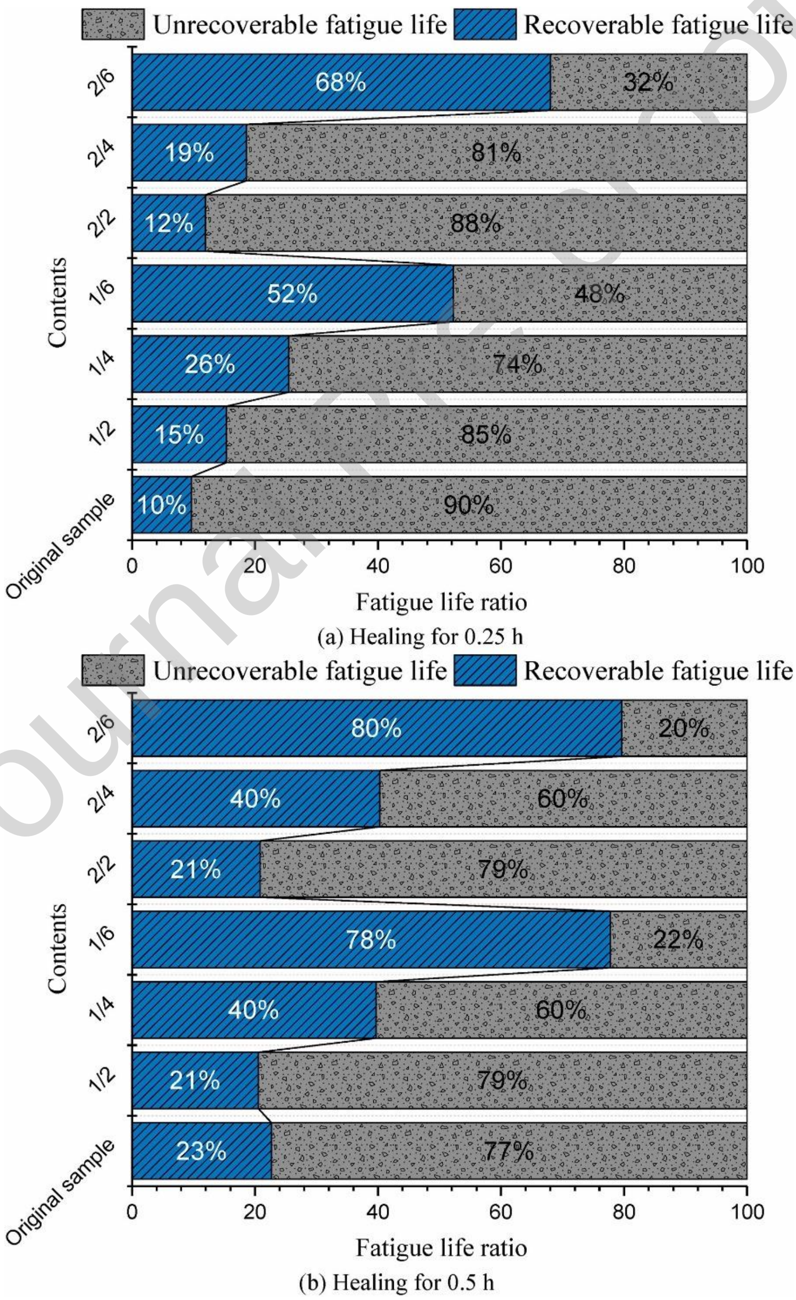


Figure 14. Fatigue life ratio of asphalt binder [62].

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 micro-cracks [120]. Without timely maintenance, such damages can continue to develop, becoming more visible, until break the integrity and stability of the pavement structure [121]. Motivated by the natural and biological mechanism of recovery, encapsulation self-healing technology has been developed and proven an effective approach for pavement repairing [115, 122-126]. 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 will infiltrate through and fill up the cracks to prevent further cracking propagation [127].

Using a refined WEO modified asphalt as the healing agent was studied by Wang and Hao [46]. Using a synthesized polymer for the microcapsules to have adequate thermal stability to resist mixing temperature, the authors reported that the WEO provided a minor impact on the penetration value and softening point though reduced the ductility of asphalt. It also increased the brittleness of the repaired pavement mix. However, WEO improved the resistance to fatigue under both high and low strains. The maximum service life recovery by the healing was achieved when microcapsules addition is below 4 wt.%. Multiple rest experiments revealed that complex modulus recovery rapidly declined during the first few rests before stabilizing at a specific level subsequently. For the microcapsule samples, complex modulus recovery accelerated. Four stages can be deduced from these tests, as illustrated in Fig. 15, throughout the entire process. In the beginning, shear loading is subjected to samples and microcapsules are rarely ruptured. Secondly, with the proceeding of shear, complex modulus deceases when microcracks start and the microcapsules rupture due to the shear oscillation. Thirdly, a healing agent, released from 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 of the microcapsules are broken.

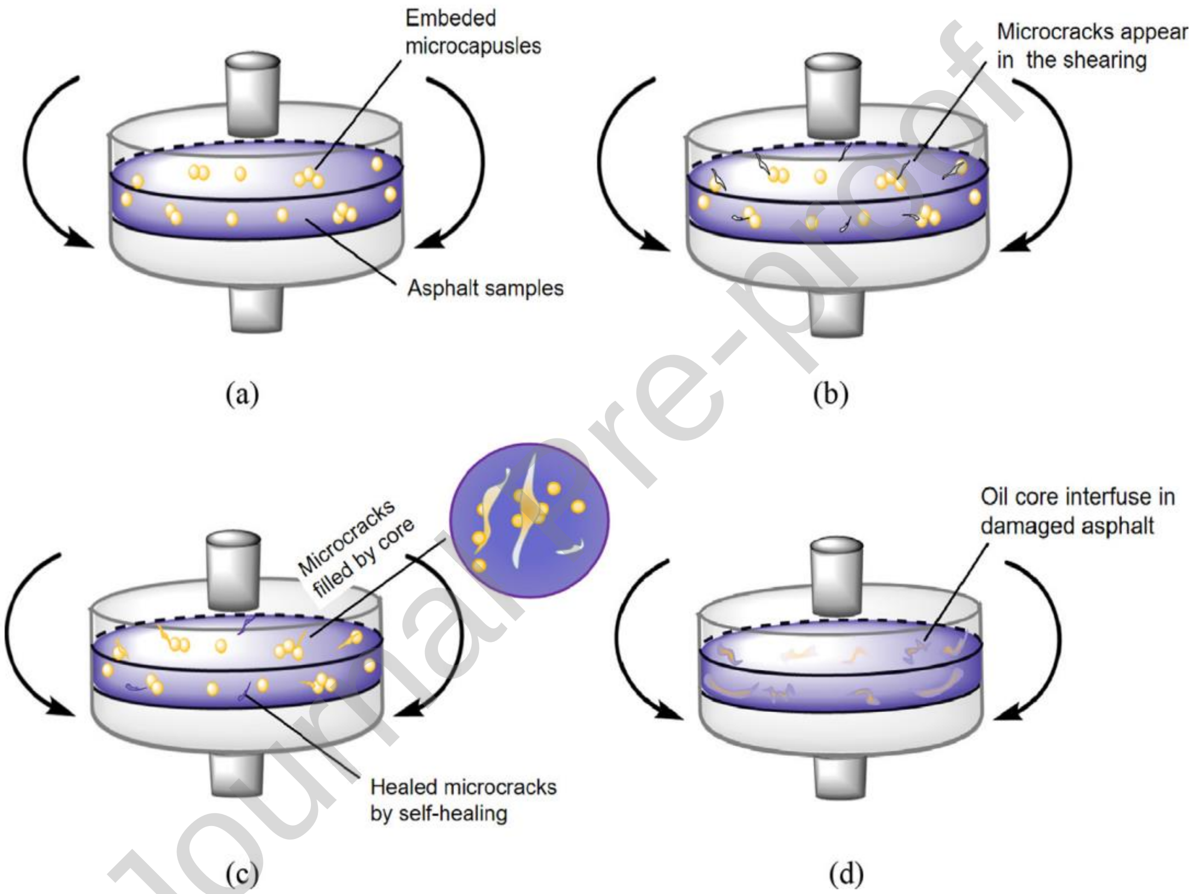


Figure 15. An illustration of how microcrack forms and heals: (a) initial shearing without microcracks; (b) shearing with microcracks; (c) microcapsules rupturing and oil core releasing and filling the cracks; and (d) asphalt cracks distributing oil core [46].

According to recent research, 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 behavior 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 pavement's service life. Based on the fatigue-healing test, markers such as 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 with WEO was investigated in several research. Liu et al. [11] investigated 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 ductility, softening point, and penetration value at 172.2% and – 34.8%, − 14.6% and 6.3%, and 16.6% and 134.8%, respectively. Using PPA helps ease the adverse impact of WEO on the behaviour of asphalt at high temperatures. At the same WEO concentration, the PPA decreased the binder's thermal stability or temperature sensitivity. According to 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, improved by 31.2% compared to the original asphalt at the optimal content of 2% WEO/PPA. Meanwhile, Liu et al. [18] used a dynamic shear rheometer (DSR) test to assess the behaviour of various asphalts in terms of the fatigue factor. They found that the PPA and WEO working together had produced superior performance over the SBS rubber and WEO composites.

On the other hand, Eltwati et al. [61] assessed the composite of WEO and SBS polymer to modify the RAP binders. They found 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 improvement in low-temperature performance, increased cracking resistance, and a higher tensile strength and rutting resistance. There were also improvements in the Marshall properties, moisture susceptibility and aggregate coating properties.

However, Fernandes, Silva and Oliveira [58] studied a composite using WEO or REOB (as partial substitutes for bitumen) together with polymers, including waste polyethylene (HDPE), crumb rubber (CR) and styrene-butadiene styrene (SBS). They found 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% CR 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 showed 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 (RTFOT). However, compared with WEO, REOB can have a more significant reduction in the amount of fresh bitumen usage without compromising on the binder properties because of its higher viscosity magnitude.

While Paliukaite et al. [55] compared the ductility of the asphalt cement modified using the REOB alone and the REOB-SBS composites. REOB alone showed a negative impact on the high-strain failure properties. However, as indicated in Fig. 16, REOB-SBS composites generated a big improvement in the tolerance for ductile strain, which brings in the benefits of the reduction of cracking distress.

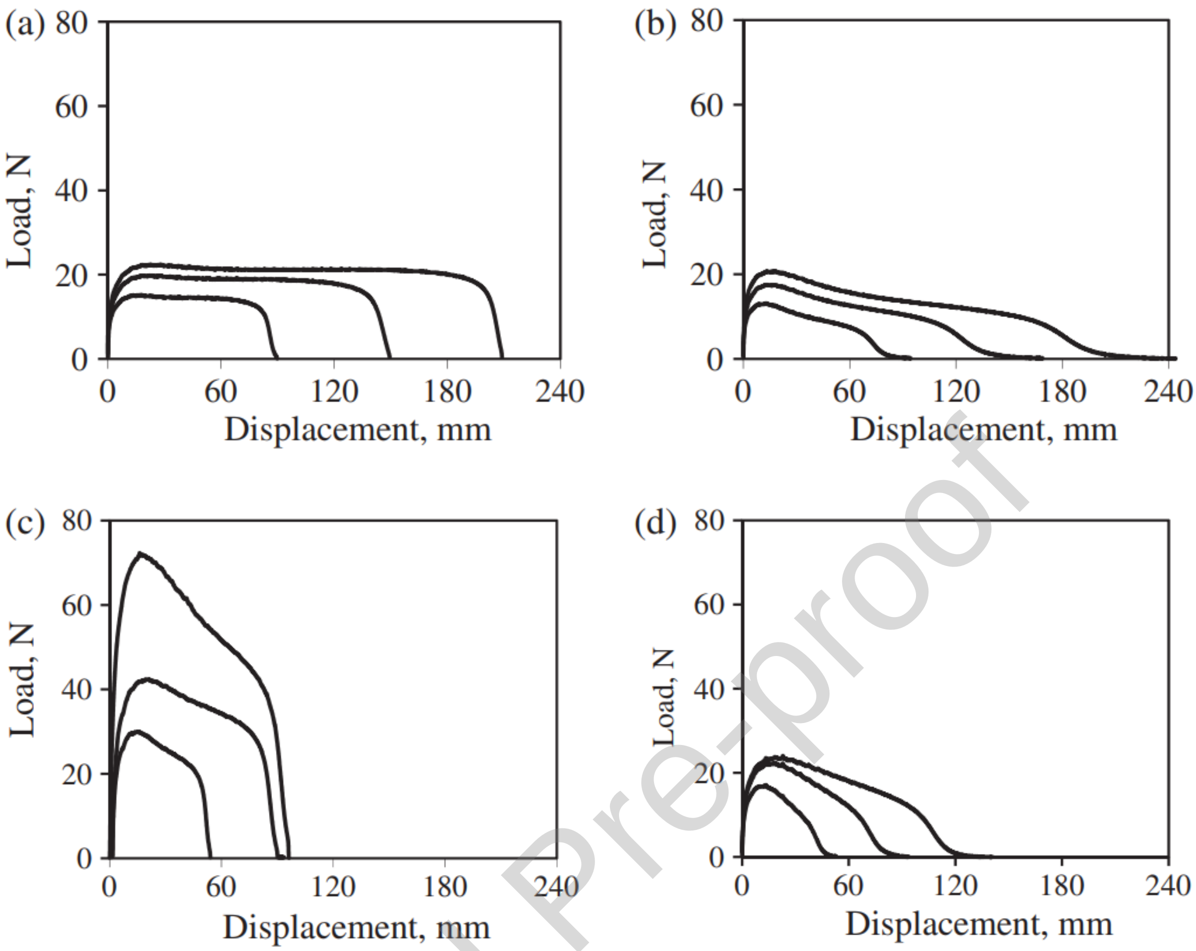


Figure 16. Results of DENT tests of modified asphalts: (a) 5% SBS D1192, (b) 3% SBS D1192 + 8% REOB, (c) 4% SBS D1192 + 20% RAP, and (d) 2.5% SBS D1192 + 6% REOB + 20% RAP [55].

Many researchers have investigated the use of WEO together with rubbers. Li et al. [56] studied the use of WEO together with vehicle tyre rubber (GTR) At a temperature in the range of 150 to 280 °C, and degraded vehicle tyre rubber (DGTR) was obtained with different devulcanization degrees. The results indicated that devulcanization and temperature significantly impact 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 viscosity, softening point and ductility tests, which improve cracking resistance at low temperatures.

However, as WEO increases the flowability of asphalt, it adversely impacts the resistance to rutting as well as storage stability at high temperatures.

Similarly, Xu et al. [60] used 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 indicated in Fig. 17, the cumulative shear strain decreases when rubber content increases, but, meanwhile, at certain rubber content, it increases in a linear trend with time. Compared with that of larger rubber content, the binder of 5% rubber showed the maximum cumulative strain at high temperatures. Binders showed lower cumulative deformation when rubber content is more than 5%. Binders of rubber content lower than 5% have small elastic recovery as the unloading curves were flat. Also, the rubber content had a main impact on the creep deformation.

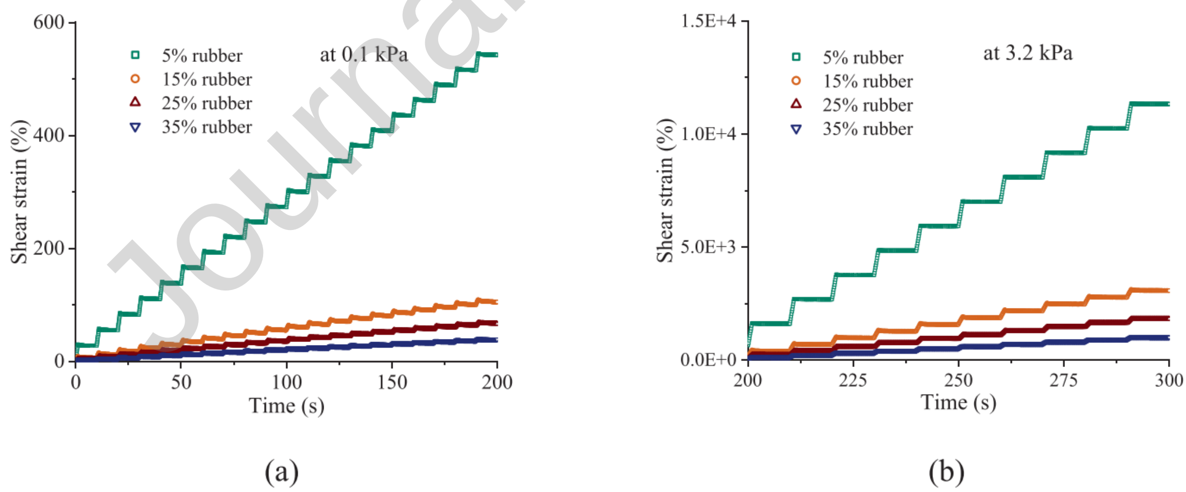


Figure 17. MSCR test results of rubber asphalt binders at stress levels: (a) 0.1 kPa; and (b) 3.2 kPa [60].

The use of lignin and WEO together as bio-additives for aged asphalt modification was investigated by Fakhri and Norouzi [49]. They found that WEO decreased the viscosity and creep stiffness while lignin in opposite increased the viscosity and creep stiffness compared to the control binder. The stiffening effect of lignin was reduced by the application of WEO, and the lignin-modified binders were less resistant to low-temperature cracking. In comparison to the virgin binder, using lignin and WEO combined increased 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.

While glass fiber has also been employed to work together with WEO to improve the RAP mixtures. Eltwati et al. [105] investigated different contents of glass fiber 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 indicated that the combination of glass fibre and WEO improved the resilient modulus, moisture susceptibility, rutting resistance, and indirect tensile strength of asphalt. The optimum content of fibers was found to be 0.2%. Ziari et al. [128] studied the effect of low glass fibre percentages at 0.06, 0.12, and 0.18% on the asphalt of high RAP content under three temperatures, i.e.: −15, 0, and 15°C, and reported improvement in cracking resistance of the modified asphalt binders.

In a different approach, Chen et al. [48] used WEO, extracted furfural oil and epoxy resin (WEO-RA) to rejuvenate aged asphalt. They reported no chemical reactions had taken place but only physical modification happened on the aged asphalt. The WEO-RA agent has thermal stability in the temperature range covering mixing and service, i.e.: 30~200°C, which is comparable with the original asphalt although slightly lower at high temperatures. The WEO-RA generated noticeable improvement in rutting resistance particularly at low temperatures because of better complex modulus and phase angles under the conditions. In addition, WEO-RA also generated a similar aging resistance and storage stability as that of virgin asphalt.

It is advantageous to add WEO to asphalt in order to save the environment and save crude oil. Furthermore, there are greater environmental and economic benefits the more WEO that 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 fibers, bitumen modification with waste motor oil products and additives may provide the paving industry a viable, cost-effective, and environmentally acceptable alternative. However, there is 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 permanent deformation, WEO functions as a lubricant and works well at low temperatures. Consequently, they can also increase resistance to 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 Production of WEO

The economic and environmental benefits of using WEO for asphalt rejuvenation and modification are two important elements in appraisal [129]. 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 [129, 130]. Wang et al. [131] found that a warm asphalt mixture using WEO reduced 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, so requires effective management. By comparison, recycling WEO has more environmental benefits than economic ones [132]. In addition, WEO recycling is also a cheaper and more effective alternative approach than incineration from economic and environmental perspectives [133]. 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 [134]. The more effective recycling process for waste oils is solvent extraction followed by adsorption [135, 136]. The selection of solvents should consider having minimum solubility for carbonaceous additives but maximum solubility for the treated oil [133].

Botas et al. [137] performed a simulation for the process of refining used engine lubricating oil. As shown in Fig. 18, The 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 C3-free oil is heated and distilled at air pressure to further separate up to 93% light hydrocarbons, which can be used as an extra fuel source to help compensate for 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 compounds and the final residue can be used for asphalt formulation at last.

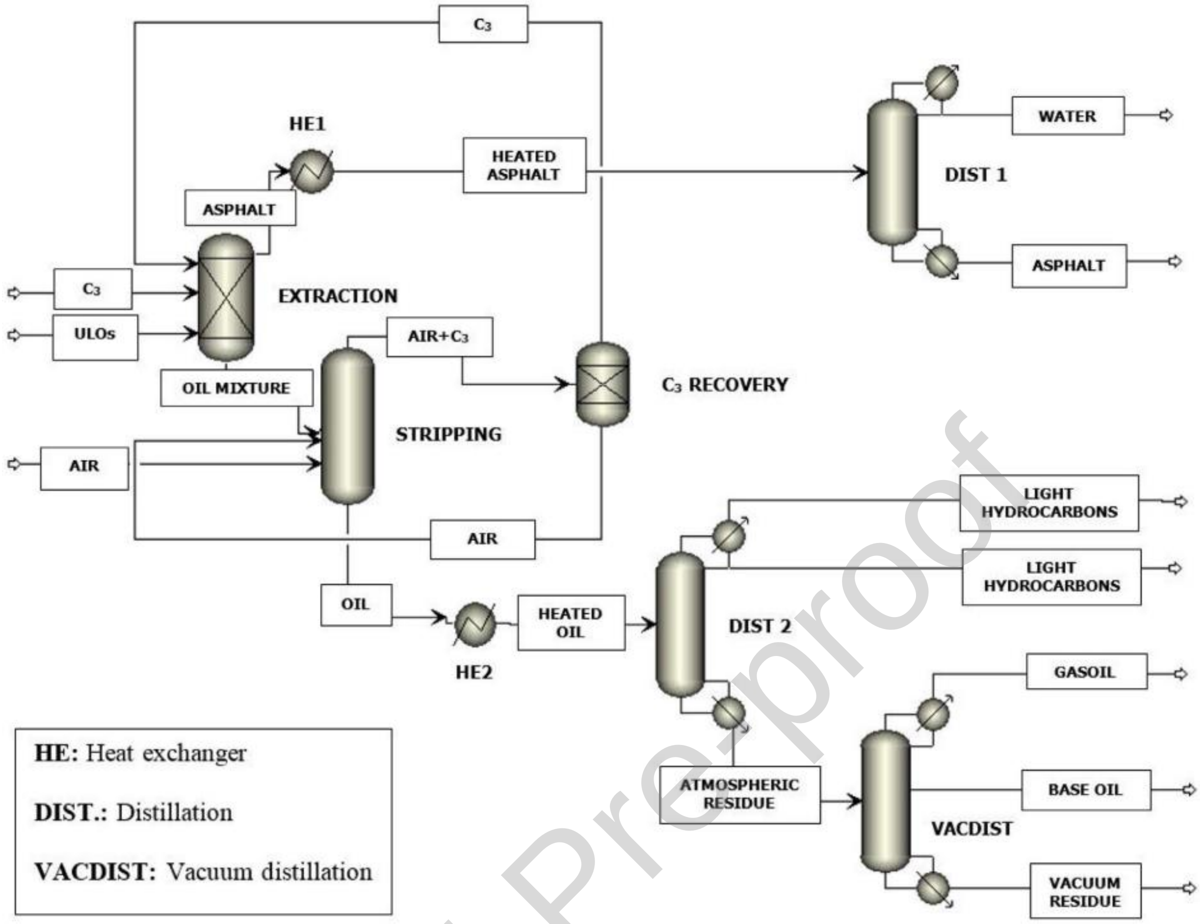


Figure 18. Upgrading used lubricating oil by a simulated process in the Aspen Plus diagram [137].

For the refining process, the authors carried out a life cycle assessment (LCA). The results from various scenarios are summarized in Table 8. They 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 total fuel consumption, while the second atmospheric distillation takes 30%. On the other hand, the distillation processes generate toxicity to both 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). In addition, 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 the 90% categories for assessment. The LCA justified that oil recycling has clear environmental benefits over conventional refinery processes. It is advised to conduct more research to improve the performance of the two distillation processes.

Table 8. Environmental effects related to a ton of generated base oil under various scenarios [137].

Environmental impacts	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 CO2)	1050	787	969	363	278	352
Ecotoxicity (CTUeco)	1140	855	1052	109	83.5	105
Human toxicity (CTUh)	3.54E-4	2.66E-4	3.27E-4	4.19E-5	3.21E-5	4.06E-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.
Botas et al. Resources, Conservation & Recycling 125 (2017) 315–323 32.
[a] Total economic value (including product and by-product) is €2166.5. The allocation factor for base oil based on 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 based on the mass flow criterion is calculated as 1000/1333, which equals 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 based on the mass flow criterion is calculated as 1000/1305, which equals 0.766.

On the other hand, Duđak et al. [138] investigated four different treatment scenarios for waste lubrication oil (WLO), a type of waste engine oil (WEO), as outlined in Table 9. These scenarios included burning WLO in waste incinerators, re-refining used oil to recover base oil, and utilizing WLO as a substitute for fossil fuels in cement kilns. The results of the life cycle evaluation 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 the 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 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 ton WEO treatment. The results are in good agreement with the other two studies [139, 140]. The aggregated points indicate that the selection for the best waste oil management is conditional, significantly depending upon the specific environmental situation. While re-refining shows the best for resource conservation, the CemK proves the best for ecosystem protection, and incineration, both Inc1 and Inc2, is the best approach for human health. However, it should be noted the results significantly relies on the assumptions made in the research, therefore more research is obviously needed.

Table 9. Different WLO treatment scenarios (actual amounts are about equivalent to treated WLO amounts for the year 2017, the remainder is re-refined or burned in heating facilities without or with recovery of energy) [138].

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 Kilns (CemK)
Scenario 1 (ton)			26,602	7777
Scenario 2 (ton)	13,301		13,301	7777
Scenario 3 (ton)	8867	8867	8867	7777
Scenario 4 (ton)	9470	9470	9470	5967

Table 10. Results of treating 1000 kg of WLO at the midpoint and aggregate endpoint levels [138].

	Incl	Inc2	ReR1	ReR2	ReR3	ReR4	ReR5	CemK	Unit
Midpoint impact categories									
toxicity	-0.11	5.4 X 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 x 10-4	1.1 x 10-5	-0.001	-8.9 x 10-4	-8.6 x 10-4	-8.8 x 10-4	-9.1 x 10-4	-7.0 x 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 SO2 eq
Land use	-4.5	0.47	-1.9	-5.4	-3.4	-5.3	-7.5	-3.8	m² a crop
ecosystems									
health	-7.2	0.9	1.1	-2.9	-1.4	-2.4	-3.3	-0.3	m³
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 CO2 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 x 10-3	2.8 x 10-3	-7.5 X 10-4	-1.4 x 10-3	-1.4 x 10-3	-1.4 X 10-3	-1.5 X 10-3	-1.9 X 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 x 10-6	8.2 x 10-6	-2.3 X 10-6	-2.6 x 10-6	-2.5 X 10-6	-2.8 X 10-6	-2.9 X 10-6	-4.1 X 10-6	

Applying WEO on asphalt can reduce emissions of carbon dioxide, nitrous oxide, and methane. Additionally, the lower mixing and paving temperatures result in less energy and money being consumed. Nonetheless, the scenario including the 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 result in a major preservation of resources. Future studies should concentrate on devising more practical and efficient methods of gathering the 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 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 advised that more research be done to optimize 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 ULO recycling process's environmental performance.

6. Conclusions

This article provides a comprehensive review of the up-to-date studies using WEO for asphalt binder improvement and rejuvenation. The impact of the WEO alone and its composites on the functional characteristics of asphalt binders have been the subject of most research and investigation. 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, China had the highest record.
- Asphalt Binder Modification: The utilization of waste engine oil 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 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 (tire or crumb rubber), as well as fiber glass, be incorporated into asphalt to improve the high-temperature characteristics with more comprehensive characteristics of modified asphalts.
- Environmental Considerations: The utilization of WEO in asphalt offers potential environmental benefits, including reduction of waste disposal and conservation of natural resources, thereby minimizing environmental impact. However, the adverse factors of the recycling process itself, including cost, energy consumption, greenhouse gas emission and impact on human beings and wildlife, need further research study.

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 the WEO, the dosage and mixing procedure, and the specific requirement 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.

Conflict of interest

The authors affirm that they do not have any known financial interests or personal relationships that could have potentially influenced the findings presented in this article.

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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.