Sustainable Asphalt Rejuvenation by Using Waste Tire Rubber Mixed with Waste Oils

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Abstract: Waste materials such as waste tire rubber (WTR), waste cooking oil (WCO), bio-oils, waste engine oil (WEO), and other waste oils have been the subject of various scientific studies in the sustainable and waste research field. The current environmental concerns have been identified to protect natural resources and reuse waste materials. Accordingly, this work reviews the use of recycled waste tire rubber mixed with waste oils (waste cooking oil, waste engine oil) and bio-oils that can be extracted from waste oils to rejuvenate asphalt in reclaimed pavements. This new solution may reduce the massive amounts of WTR and waste oils and produce a more environmentally sustainable material. Reclaimed, aged asphalt has been rejuvenated to achieve various penetration capabilities and properties by blending asphalt with one or more waste materials to evaluate the binder using standard tests. Many solutions with promising results in improving the properties of asphalt mixtures have been selected for further characterization. This review highlights that the addition of WTR and waste materials to rejuvenated asphalt binders improves stability, enhances the viscoelastic properties, provides better fatigue and crack resistance performance, and enhances the compatibility of the rejuvenated rubber oil asphalt. Moreover, the flashing point, softening point, ductility, and penetration of aged asphalt and Poly(styrene-butadiene-styrene)-rubber-rejuvenated and waste-rubber-oil-rejuvenated asphalt were enhanced after applying the rejuvenator compound. On the other hand, adding waste oil to WTR and asphalt reduces the viscosity and enhances the storage stability compared to the asphalt rubber binder.

Keywords: waste tire rubber; waste engine oil; waste cooking oil; waste oil; rejuvenated asphalt; bio-oil

1. Introduction

This study aims to assess devulcanized waste tire rubber (WTR) mixed with waste oils to rejuvenate asphalt binders and compare various types of waste oil mixed with WTR. Waste disposal (e.g., WTR and oils) has become an environmental concern in many parts of the world. As automobile manufacturing grows, the amount of waste tires and engine oil (WEO) has increased. Tire production worldwide exceeds 1.5 billion tires annually, while 1,089,000 tons, or more than 66 million tires, have been transferred into the milled rubber market. [1–4]. Moreover, the amount of wasted vehicle engine oil exceeded 10 million barrels. In the United States alone, more than 1.3 billion gallons of motor oil are wasted annually. Furthermore, the U.S. Environmental Protection Agency (EPA) reports that more than 757,082 L are illegally wasted annually [5,6]. On the basis of global data, vegetable oil used in cooking exceeds 284.88 million metric tons, with a yearly increment of 4% [7]. In addition, waste cooking oil (WCO) is widely produced and damages the environment worldwide [8]. The European Union produces approximately 700,000–1,000,000 tons of WCO annually, including snack food and French fry oils. An estimated 40,000 tons of WCO are produced every year in Asian countries alone [9,10].
The reuse of waste tire rubber has been a hot subject due to the enormous number of waste tires, and scholars have started to consider waste tire rubber as an asphalt binder rejuvenator. Numerous scholars [10–34] have studied the rejuvenation of asphalt with rubber and the resulting properties, including chemical, physical, rheological, and viscoelastic properties, as well as their low-temperature performance and high-temperature performance. Furthermore, various literature reviews [17,20–22,31] have summarized the effects of asphalt rejuvenated with rubber.

While many studies related to waste materials have indicated the importance of reusing them as a rejuvenator agent for asphalt, in this context, the vast amounts of waste cooking oils (e.g., rapeseed oil, soybean oil, and all waste vegetable oils), as well as waste tires, have stimulated researchers to reuse waste tire rubber as a rejuvenator of asphalt binders. Several researchers have examined the effect of using WCO with aged or non-aged asphalt [35,36] on its rheological and chemical properties [33,37–44] and physical properties [41,43–45]. WTR has also been investigated in several studies [46–58]. Moreover, various researchers have reviewed the effects of waste cooking oil on asphalt rejuvenation. Some of these researchers adopted the systematic literature review technique [38], while others conducted comprehensive reviews [27,59]. Both methods had extensive differences in the results reported. Furthermore, others still have investigated the effect of using waste bio-oils as a rejuvenator material on asphalt binders [60].

Using waste tire rubber with waste oils as recycled material in the design of substructures has been gaining popularity as a new research field. Researchers are investigating sustainable options, particularly designing asphalt mixtures to produce sustainable materials as an alternative to road materials. The increased demand for sustainable alternatives has accelerated investigations and produced numerous studies in this field. Even though the use of waste oils in asphalt offers numerous advantages, such as the influence on the environment, paving methods, workers’ physical and mental health, workers’ well-being and safety, effective economic costs, energy savings, paving and manufacturing benefits, and considerable reductions in emissions and pollutants, deficiencies are also apparent in certain properties of asphalt.

The addition of WTR to aged or virgin asphalt produces rejuvenated asphalt with WTR, which improves the rutting resistance and fatigue performance [61]. However, the addition of WTR is accompanied by an increase in viscosity. Therefore, it is necessary to incorporate waste oils into the rubber-rejuvenated asphalt binder to minimize the binder’s viscosity. Moreover, adding more waste oil decreased the impact of aging on asphalt. However, none of these previous researchers summarized the implications of using WCO with WTR as a rejuvenator and mixing it with asphalt, WEO, or other liquid media. This paper will discuss the implications of using waste oils to devulcanize WTR and its effect on asphalt binders.

2. Methodology

The literature survey was carried out by exploring five databases, notably Scopus, Web of Science, Google Scholar, PubMed, and Transport Research International Documentation (TRID), which comprises the most extensive online database for the transportation engineering field.

For each of the search engines, the following phrase strings and keywords were used: Waste tire rubber; waste tyre; crumb tire rubber; waste cooking oil; used frying oil; waste cooking vegetable oils; waste edible animal oil; waste vegetable oil; waste edible vegetable oil; waste engine oil; swill-cooked dirty oil; cooked dirty oil; illegal waste cooking oil; waste bio-oil; rejuvenator; rejuvenation; rejuvenating; asphalt; bitumen; recycling agents; softening additives; softening agents.

Articles that included the treatment of WCO, WTR, WEO, and WRCO (transesterification) before introduction into asphalt are also included.
However, studies accompanied by the separate components of treated WCO or WTR such as grease/glycerin for bitumen rejuvenation were not included as the present research focuses purely on WCO, WTR, WEO, and WRCO.

Mainly, this paper evaluates the following:
1. Use of rejuvenators in asphalt mixes with RAP compared to virgin bitumen.
2. WTR rejuvenator and its chemical composition with the presence of waste oils.
3. Changes in the physical properties of the binder due to the addition of WTR, WCO, and WEO.
4. Changes in the rheological properties of the binder due to the addition of WTR, WCO, and WEO.
5. Changes in the chemical properties of the binder due to WTR, WCO, and WEO.
6. Difference between a rejuvenator and a softener, to identify the advantages and shortcomings of the utilization of WCO. (see Figure 1).

Figure 1. Methodology of the review paper.

3. Applicable Waste Materials on Rejuvenated Asphalt

One of the best methods to use waste materials (WTR, WCO, and other liquid media) is incorporating them into asphalt binders as a rejuvenator. Figure 2 illustrates that researchers preferred to use binders with WTR and WCO or another liquid medium; many researchers [62–72] preferred to use binders of performance grade (PG 64-22) with WTR and WCO or another liquid medium. Ren et al. used virgin and aged asphalt to study the effect of devulcanized rubber for different periods [73]. Fernandes et al. used base 35/50 asphalt [74,75]. Dong et al. used (PG 64-24) as the base asphalt [76]. Other researchers have used 60/70 [77–81], 60/80 [53], or 80/100 [81] penetration grades. Zhou et al. adopted virgin asphalt type 90 penetration grade for heavy traffic pavement in domestic use [82]. Some researchers [83] have used two types of neat binder penetration grades: 60/70 (PG 64-16) and 85/100 (PG 58-22) [56,70,84]. Xingyu et al. selected PG 82-16 [85].
3.1. Waste Tire Rubber (WTR)

The use of WTR will pave the way for a new generation of sustainable road construction. Moreover, it will also reduce the natural resources humans use and the waste-produced materials that destroy the environment. Authors [68,76,86,87] studied the main chemical compositions of WTR. They observed that ash, acetone extract, carbon black, and rubber hydrocarbons were under the technical requirement of WTR, as listed in Table 1. Figure 3 displays the mesh percentage of WTR used in previous studies and the percentage of the waste tire rubber pretreatment process adopted in previous studies. Many reviews have been conducted on WTR recycling and processing methods [88–91]. Various pretreatment methods for WTR have been proposed, such as the wet grinding process, which was explained by McDonald in the 1960s. As a restoration technique for maintaining asphalt pavements [31,92], the cryogenic grinding process uses nitrogen to freeze WTR, utilizing microbially devulcanized rubber to produce rejuvenated asphalt [93], and Asaro et al. proposed that supercritical CO₂ can be used to improve thermomechanical devulcanization [94]. Then, an impact mill is utilized to produce tiny particle sizes of WTR scrap from the frozen waste tire rubber [10,95]. However, the cost of this method is higher than that of other preprocess treatments [96]. Many researchers [54,76,84,87,97,98] prefer the radial grinding reducing treatment of WTR, in which mechanical forces are used to break down waste tire rubber at an ambient temperature. In the asphalt–rubber–oil-rejuvenated binder, the WTR used was a 40-crum rubber mesh, i.e., its size ranged from 0.0075 mm to 4.75 mm [56,62,65,68,75,76,79,87,99]. Lei et al. used a particle size of 100 WTR crumb mesh [81,84]. Kabir et al. used a 60-crum WTR mesh [63,67]. Per ASTM D6114, Duan et al. selected a particle size of 100-crum rubber mesh to produce an asphalt-rejuvenated binder with WTR. This specification recommends that all WTR particles must pass through sieve no. 8 (2.36 mm) [80]. Moreover, the physical properties are affected by the WTR gradation and performance of the asphalt–rubber–oil-hot mixture [20]. However, some researchers have used other types of rubber [53,73,74,80], such as (SBR), which refers to styrene-butadiene rubber. Some researchers used two types of WTR: 80 meshes [84] and 20 meshes, respectively [67,81,82]. Cao and Wang passed WTR through 50 mesh (0.297 mm) [69]. Ahmed et al. studied bio-oil liquid yield and quality by using WTR to obtain a uniform particle size between 0.6 mm and 1.8 mm with sugarcane bagasse [99]. Mansourkhaki et al. used polybutadiene rubber (PBR 1220) and 11 blended and non-blended binders [83]. The combination of WTR and asphalt binder had been studied previously without WCO or other waste oils. They deduced that the effect of the addition of WTR to rejuvenate the asphalt mixture improves the resistance to permanent deformation [100] and increases the mix’s fatigue and thermal cracking capabilities [101], as well as its mechanical properties and rutting resistance [102]. However, more rejuvenators are required to increase the mix’s rutting resistance even more. The increase in Carbon black content of the oil, as well as its metal content, has a negative impact on the quality of
the rejuvenated asphalt. For rejuvenated asphalt mixtures, the increase in WTR amount increases the thermal cracking resistance. However, it also results in a reduction in the rutting resistance and affects the fatigue and moisture resistance of the rejuvenated asphalt [38].

Table 1. Main chemical compositions of WTR [68,76,86,87].

| Test Items          | Unit | Test Result | Technical Requirement |
|---------------------|------|-------------|-----------------------|
| Ash                 | %    | 7.39        | ≤8                    |
| Acetone extract     | %    | 8.98        | ≤16                   |
| Carbon black        | %    | 30.22       | ≥28                   |
| Rubber hydrocarbon  | %    | 53.42       | ≥48                   |
| Carbon C            | %    | 72.52       | -                     |
| Oxygen O            | %    | 10.68       | -                     |
| Nitrogen N          | %    | 3.58        | -                     |
| Silicone Si         | %    | 1.84        | -                     |
| Sulfur S            | %    | 1.61        | -                     |
| Metal element       | %    | 9.76        | -                     |

![Figure 3.](image)

**Figure 3.** (a) Percentage of rubber mesh used in previous studies. (b) Percentage of rubber pretreatment process adopted in previous studies.

3.2. Waste Cooking Oil (WCO)

To devulcanize WTR, researchers started to search for new waste materials, such as WCO, to be used in sustainable road construction. Reducing the number of waste materials that destroy the environment can be achieved by utilizing waste materials such as the devulcanization of WTR. One of the most widely produced oil wastes is WCO, which is obtained from various kitchen sources after frying or cooking. The significant utilization of the two sources is as follows: (i) Raw materials for the refining and petrochemical industries and (ii) civil engineering materials [44]. The properties of WCO depend on many factors, such as the degradation process, impurities, and operation temperature [44,103]. The main physical and chemical properties of WCO studied by Dong et al. and Zhao [86,87] indicated that the physical properties of actual waste cooking oil, waste rapeseed oil, and waste soybean oil are different from each other (see Table 2).

Many researchers [62,68,69,75,76,79,85,87] preferred to collect WCO from local restaurants. However, some authors collected WCO from environmental companies [78,79]. The fatty acid structure of WCO has been determined in some studies [78] through gas chromatography–mass spectrometry (GM-MC) to compare different chemicals contained inside a test sample or Fourier transform infrared spectroscopy (FTIR) [104]. The combination of WCO and base asphalt binder has previously been tested without the inclusion of WTR, and it was discovered that the use of WCO to rejuvenate asphalt enhances the thermal cracking [105] and fatigue resistance properties of the mix [106], but requires effort regarding the rutting resistance or applying more rejuvenation to polymers to increase the rutting resistance [36,107]. The high acid value of waste cooking oil affects the regenerative
properties of asphalt; meanwhile, a high moisture content affects the regenerative properties of asphalt [108]. An increase in the amount of waste cooking oil (WCO) used in asphalt mixtures results in enhanced resistance of rejuvenated asphalt to thermal cracking [109]. However, it has a harmful influence on the pavement’s rutting, fatigue, and moisture resistance [59].

Table 2. Main physical and chemical properties of WCO [68,76,86,87].

| Performance                        | Actual Waste Cooking Oil | Waste Rapeseed Oil | Waste Soybean Oil |
|------------------------------------|--------------------------|--------------------|-------------------|
| Acid value (mg(KOH)/g)             | 0.7                      | 6.4                | 2.0               |
| Flash point (°C)                   | 304                      | 298                | 301               |
| Tetradecanolic acid (wt%)          | 1.41                     | -                  | -                 |
| Hexadecanoic acid (wt%)            | 1.34                     | 0.49               | 0.71              |
| Hexadecenoic acid (wt%)            | 17.04                    | 5.38               | 10.04             |
| Octadecenoic acid (wt%)            | 80.21                    | 90.98              | 88.36             |
| Seventeen carbonic acids (wt%)     | -                        | 3.15               | 0.69              |
| Total Fatty Acids                  |                          |                    |                   |
| Saturated fatty acid (wt%)         | 18.45                    | 8.53               | 10.93             |
| Unsaturated fatty acid (wt%)       | 81.55                    | 91.47              | 89.07             |

3.3. Waste Engine Oil (WEO) and Other Liquid Media

Given the increase in the number of engines globally, whether in motorbikes, cars, large vehicles, or other machines, the amount of WEO has also increased, causing harm to the environment. Therefore, the need to use these waste materials in engineering operations has arisen. Research on waste engine materials remains scarce compared to other waste oil materials. The main physical and chemical properties of WEO were studied by various scholars [56,86,110] who observed that the flash point was 146 °C, the viscosity index was 2.5991 KV40 °C cSt (mm²/s), torque was 1.41%, and the acid value was 1.34 mgKOH/g. Several scholars studied the effect of using WEO with WTR to prepare a rubber asphalt binder [54,56,70,74] by using WEO collected from small carports, vehicle service stations, or local auto repair shops. The combination of WEO and asphalt had been studied previously without WTR or other waste oils and deduced in rejuvenated asphalt. A higher percentage of WEO decreases the percentage of large-sized molecules and the carbonyl (C=O) functional group amount, as well as the ratio of small molecules. Meanwhile, WEO has been shown to dramatically lower the viscosity of binders as well as the temperature of the construction site. At any given frequency, the complex modulus values fall, while the phase angle values increase, as a result of the incorporation of WEO into the asphalt. Aside from that, waste engine oil could cause a harmful influence on rejuvenated asphalt rutting resistance performance while having a beneficial impact on the fatigue performance of rejuvenated asphalt [50,56]; furthermore, it demonstrated excellent performance in terms of low-temperature characteristics. In conclusion, the proposed composite treatment method for waste engine oil demonstrated that the rejuvenated binder has the ability to improve the performance of rejuvenated asphalt with WTR, hence encouraging the use of rejuvenated asphalt with WTR in the construction of asphalt pavements [56].

Some researchers have studied other types of waste oil, such as bio-oils that are extracted from waste vegetable oil and other vegetable oils. Yin et al. investigated rejuvenated asphalt’s anti-aging performance by using WTR impregnated into epoxidized soybean oil (ESO) [77]. Rahman et al. focused on the influence of adding WCO, WTR, and palm oil fuel ash (POFA) to decrease virgin asphalt dosage. Moreover, they used POFA as an additive [78]. Duan et al. studied microalgae acidified oil added to devulcanize poly(styrene-butadiene-styrene) (WTR/SBS) rejuvenated asphalt [80]. Hong et al. investigated virgin asphalt after long-term aging and SBS-rejuvenated asphalt binders by utilizing 77% aromatic oil and 23% SBS polymer as asphalt rejuvenators [53]. Lei et al. examined WTR-rejuvenated asphalt effects with bio-oil as a devulcanization agent to investigate its high-temperature
performance [81]. Zhou et al. used fatty acid residue bio-oil and, before using it, the authors filtered the residue and dehydrated it [67]. Zhou et al. used 3% slurry oil with 6% WTR to produce asphalt as rejuvenated emulsion [82]. The combination of waste engine oil and the asphalt binder has been studied previously without WTR or other waste oils, and it was deduced that the bio-asphalt mix performance and its characteristics were better than traditional blends because of the often improved workability and, as a result, better compaction that can be accomplished through their use. Reduced asphalt aging occurs due to the reduced production temperature, which not only leads to increased thermal resistance but also fatigue cracking resistance during the manufacturing process. (see Figure 4).

![Figure 4. Percentage of waste oils used in previous studies.](image)

### 4. Effect of Waste Oils on the Characterization Properties of Rejuvenated Asphalt

#### 4.1. Solubility

Solubility is an essential property for evaluating WTR and the dissolution rate of waste oils to produce a new mixture. WTR solubility depends on the interaction condition with a waste oil–asphalt binder. The optimum WTR pre-swelling condition is defined using a waste oil–asphalt binder.

As shown in Figure 5, Dong et al. used WCO, WTR, and an asphalt binder. They observed that the rubber’s hydrocarbon content was reduced by 18.5%. Meanwhile, the carbon black (CB) content increased by 219% and the mineral filler also increased by 125.8%, indicating a massive amount of chain scission and depolymerization in WTR molecules [76]. Dong et al. studied the residues of WTR and the pyrolysis product. They noticed that the rubber hydrocarbon content was reduced by 6%, CB content was increased by 65.4%, and the mineral filler increased by 37.5%, which was a massive amount due to the macromolecules in rubber. Moreover, co-pyrolysis technology can be used to devulcanize and degrade rubber [87]. Ma et al. experimented with WTR and WCO to study the mixture’s solubility. The rubber hydrocarbon content was reduced by 80.9% between WTR-P and WTR-O and 88% between WTR-P and WTR. CB content increased by 129%, which was a massive amount due to the chain scission and devulcanization of WTR molecules. The mineral filler also increased by 126–216%, and a conclusion was drawn that the solubility of WTR was influenced by the WCO molecular content, treatment process, such as curing time, and effective temperature [65]. However, an increase in WTR-released content from decomposed WTR is attributed to WTR insolubility in toluene [71,76]. After treating WTR solubility in virgin asphalt and WCO, a significant rise of up to 60% compared with untreated WTR solubility was observed after pyrolysis, leading to a more than 25%
increase in WCO content, which remains constant [87]. Therefore, WCO content has a critical value that must not exceed the percentage that makes WTR solubility constant. WTR solubility exerted a negligible effect during the swelling process from the curing time.

![Figure 5](image_url)

Figure 5. Redraw major components of WTR samples from previous studies [62,65,76,83,87]. (a) Operating oil (%), (b) Rubber hydrocarbon (%), (c) Carbon black (%), (d) Mineral filler (%).

Moreover, given that WCO consists of lightweight molecules, the authors recognized that the light fraction in the rejuvenated asphalt has a molecular weight of 280–360 g/mol, which is similar to virgin asphalt. To determine the gel content, in the absence of the base asphalt, Dong and Zhao conducted a Soxhlet extraction experiment for 48 h. Furthermore, the soluble linear molecules caused a decrease in residual rubber hydrocarbon content, particularly in a noteworthy part of the chain, such as rubber hydrocarbon molecules. This action led to energy accumulation, which caused CB content to increase gradually, peeling the rubber hydrocarbon molecules until the surrounding CB was released [62]. Mansourkhaki et al. noticed that as the dosage of aromatic oil increased, the asphalt binder solubility at a low temperature with a softer binder in the binder colloidal system improved, enhancing colloidal stability [83].

From previous studies, an increase in WCO or WEO led to a rise in carbon black content, leading to an increase in elastic modulus and a decrease in viscosity. Moreover, the maximum service temperature of asphalt was increased. Similar to carbon black, the mineral filler increased with the rise in waste oil amount, enhancing the stiffness of the
asphalt matrix and the rutting resistance of the binder. Rubber hydrocarbon is easy to decompose. It releases lightweight components, affecting the asphalt viscosity performance. The corresponding high-temperature performance may be reduced (e.g., plural modulus reduction), but it also exerts a positive effect on rejuvenated asphalt aging performance, supplementing the lightweight component of rejuvenated asphalt loss and improving aging performance.

4.2. Effect of Waste Oils on Functional Groups of Rejuvenated Asphalt

Fourier-transform infrared (FTIR) analysis was conducted to characterize the distribution of present within the organic matter [111,112]. Furthermore, the effect of the chemical reaction of water and waste oil on the properties of the produced binder was explored [113]. Figure 6 summarizes the research that considered the FTIR of various base asphalts, rubber asphalts, waste oil-rejuvenated asphalts with WTR, aged asphalts, and waste oil-rejuvenated asphalts with WTR binders. The aging and rejuvenation degrees can be established by analyzing the strengths of carbonyl (C=O) and sulphoxide (S=O) peaks [59]. Figure 6 clearly shows that all studied binders along with WTR, WCO, WEO, and other liquid media had resemblance bonds in two bonds (C–C and C–H) based on their alkaline elements.

In the base asphalt samples from several studies [65,68,73,85,114], sulphoxide (S=O), carbonyl (C=O), and aliphatic group peaks appeared in all the samples. However, O–H and C–H peaks appeared in only some of the samples [73,85]. In WTR, carbonyl (C=O) always appears in the analysis; however, carbonyl (C=O) disappears in the presence of WCO. In some asphalt binders, carbonyl (C=O) disappears but reappears in the mixture after adding SBS to the oscillating disk rheometer (waste cooking oil waste tire rubber rejuvenator (ODR)); the ODR causes the –C=O in the ester to stretch and vibrate [68]. Ma et al. selected WTR, base asphalt, and WCO for analysis under different conditions [65]. The carbonyl (C=O) absorption peak between 1097 and 1741 cm$^{-1}$ stretches and vibrates C=O in the ester of waste cooking oil. The absorption peak at 1535 cm$^{-1}$ dissolves in WTR-P compared to WTR peaks. Li et al. analyzed WTR, base asphalt, and WEO under different conditions and observed ester molecules and sulphoxide (S=O) bonds in the absorption peaks at 1262–1030 cm$^{-1}$ for WTR-rejuvenated asphalt (WTRMA) and pretreated WTR rejuvenated asphalt (PWTRMA) with extruded rubber [98]. Dong et al. deduced that the strong absorption peak that appeared in WTR was due to the C–H in M-xylene, which was attributed to the volatilization of small molecules of benzene, proving that natural rubber was released from cross-linking WTR rejuvenated asphalt chains [76]. When asphalt ages, it loses some of its lightweight oil combinations, and the reactions of oxidation affect the carbonyl (C=O) and sulphoxide (S=O) groups. This process is correlated with an increase in polar components (asphaltene). When asphalt was rejuvenated with waste oils, new absorption peaks between 600 cm$^{-1}$ and 1400 cm$^{-1}$ can be observed, which are connected to alkyl (C–O) and ester carbonyl groups, respectively. Ma et al. analyzed functional groups within the range of 600–1800 cm$^{-1}$. For the hot storage-stable rubber asphalt rejuvenator (HSSRA) and rejuvenated asphalt with WTR (WTR-AR), an increase in aging degree resulted in an increase in absorption peak intensity due to the thermal oxidative process. Furthermore, the aging indices of the virgin asphalt rubber, asphalt rubber-PAV, and asphalt rubber-RTFOT samples increased [79]. The aging susceptibility of hot storage-stable rubber-rejuvenated asphalt is relatively small compared to that in rejuvenated asphalt with WTR, and WTR-AR, particularly for long-term aging samples. Duan et al. studied microalgae acidified oil added to devulcanize SBS-AR. They determined that amide chains reformed in microalgae biodiesel (MB). Moreover, compared with WTR/SBS, microalgae biodiesel with WTR mixed with SBS (MBCR/SBS-2) presented O–H absorption peaks at 3355 cm$^{-1}$ and 3187 cm$^{-1}$ on account of the primary amide bond in MB [80]. Ren, Liu, and Fan et al. used waste oils (WCO and WEO) and SBR with aged asphalt to improve its properties. WCO/SBR exhibited additional characteristic peaks of C–H and C=H. Meanwhile, WEO/SBR had an S=O absorption peak at 966 cm$^{-1}$, signifying the presence
of SBR content [73]. Dong and Zhao observed that soluble molecules generated after linear long-chain large molecules were broken into smaller molecular weights. Meanwhile, the chemical reactions between WTR and WCO caused the disintegration of components in the WTR functional groups [62]. Hong et al. noticed that after long-term aging, C=O and S=O were 0.9%, 4.0%, 1.4%, and 2.9% for aged polymer-modified asphalt PMA-BA. IPB/PS, which is equal to (polybutadiene Area to Area polystyrene) reduction, was due to polybutadiene (PB) degradation and adding more than 15% AR diluted SBS content, weakening the polymer network [53]. Zhou et al. reported that the adsorption of ester biomolecules improved WTR and asphalt cross-linking connections, where biomolecules interact with asphalt molecules [67]. From previous studies and Figure 6, S=O, the aliphatic group 1350–1525 cm$^{-1}$ and C–H appeared in all types of waste oil. Moreover, the S=O group appeared in all base asphalt results. All rubber–asphalt–oil rejuvenator asphalts with or without long/short-term aging indicated that C–O, C=O, S=O, and the aliphatic group 1350–1525 cm$^{-1}$ were present in all the binders. According to the above investigations, the carbonyl (C=O) peak increases with the polar compounds in the aged asphalt binder. The presence of waste oil-based alkyl groups and ester functional groups in the asphaltenes reduces the carbonyl (C–O) peak, which reduces the aging effect but does not completely recover the carbonyl (C–O) peak to the levels found in virgin asphalt.

4.3. Effect of Waste Oils on Elastic and Viscous Rejuvenated Asphalt

It is possible to describe the elastic and viscous rejuvenated asphalt binders at various temperatures using the dynamic shear rheometer DSR using the AASHTO TP-70 standard. DSR conducts MSCR tests at various temperatures [68]. Dong and Zhao noticed that WTR recovered its plasticity after pyrolysis; however, its elasticity decreased. The zero shear viscosity results were obtained from DSR, proving that the waste rubber/oil WRO flowability was ameliorated with the addition of a high interaction temperature, and noticed that the WCO-WTR rejuvenator (ODR) composite-rejuvenated asphalt indicated that the rejuvenated asphalt had a more elastic binder than the virgin asphalt [62]. Most notably, not only at high-temperature values but also at low temperatures values, the mixes containing ODR and 4 wt% of SBS gave rise to more elasticity than SBS-rejuvenated asphalt [68]. Ma et al. concluded that the waste cooking oil-assisted swelling of WTR improved the compatibility of WTR-rejuvenated asphalt by increasing the time period during which WTR releases components, notably virgin rubber, into the asphalt matrix. In the asphalt binders rejuvenated by WTR, the authors observed that an improved elastic response mainly was attributed to the inclusion of WTR particles, regardless of whether or not waste cooking oil rubber was also included [79]. Lei et al. deduced that according to the results of the dynamic shear rheometer, both WTR and bio-oil are renewable resources that can be used as an asphalt rejuvenator binder to enhance the performance of aged asphalt mixes and the high-temperature performance of aged asphalt binders by increasing the asphalt binder’s elasticity and viscosity [81]. As a result of the viscoelastic behavior, Ren et al. deduced that waste oil has not only a negative impact on the elasticity but also decreased deformation resistance of the rejuvenated aged asphalt binder. They also deduced that mixes with a higher content of SBR and lower content of waste oil are advantageous for increasing the flow resistance of rejuvenated asphalt [73]. Zhou et al. observed that WTR pre-swelling had a significant influence on the asphalt’s increased elastic recovery behavior, which increased the asphalt’s resistance to permanent deformation, commonly known as rutting resistance [67]. When comparing the elastic recovery (rutting resistance) with asphalt containing non-swelled WTR, a WTR-to-waste oil ratio of 1:1 was used, and the elastic recovery rose by 156 percent. With creep stiffness falling by 39 percent and with the increase in the m-value of up to 17 percent, rubber pre-swelling was also shown to be beneficial for the cracking resistance of the mixes at low temperatures, according to the study. Overall, adding WCO or other liquid media to rejuvenated asphalt increases the elastic recovery of the asphalt more than it does with virgin asphalt and decreases the viscosity of the asphalt.
4.3. Effect of Waste Oils on Elastic and Viscous Rejuvenated Asphalt

... macrobiomolecules improved WTR and asphalt cross-linking connections, where biomolecules chemical reactions between WTR and WCO caused the disintegration of components in long-chain large molecules were broken into smaller molecular weights. Meanwhile, the SBR content... 

4.4. Effect of Waste Oils on Stiffness and Relaxation Characteristics of Rejuvenated Asphalt

The bending beam rheometer or BBR test measures asphalt binders’ stiffness and relaxation characteristics at low temperatures. These characteristics illustrate the asphalt binder’s resistance to low temperatures that cause cracking. Ma et al. deduced that the hot storage-stable rubber asphalt (HSSAR) thermal cracking resistance improved with the...
addition of WCO because WCO recompensed the absorbed lightweight fraction in the asphalt binder and improved the low-temperature relaxation capability of rejuvenated rubber asphalt. Moreover, WCO decreased the stiffness and improved the viscous component of rubber asphalt [79]. Zhao and Dong found that using SBS/0.4S with increased SBS content exerted a combined influence and slightly enhanced low-temperature asphalt binder properties. When compared to the base asphalt and asphalt binders rejuvenated by SBS, the sample WTR: SBS: sulfur (WRO/4SBS/0.4S) demonstrated strong cracking resistance at 28 °C and extreme low-temperature performance, as evidenced by the reduced stiffness and increased m-value. It follows that the WCO-WTR rejuvenator (ODR) is extremely important in promoting the ability of low-temperature deformation and stress relaxation in rubber [68]. Tao Zhou et al. determined that mixtures demonstrated a promising deformation capability under load due to the deflection of the increase in test examples for SAR-M and pre-swelled WTR at 1 min and 4 min. The pre-swelled WTR decreased by 39%, and the m-value increased by 17% more than that of rubber asphalt, showing a better improvement in bio-oil physisorption to WTR particles [67].

Wei Hong et al. deduced that the increase in the aged asphalt rejuvenated binder caused a noticeable decrease in creep stiffness and improved the m-curve value. The softening effect was pronounced for asphalt rubber. Creep stiffness was excessively low with aged polymer-rejuvenated asphalt after rejuvenation with polymer-rejuvenated aromatic rejuvenator. The addition of SBS helped preclude the over-softening effect of aromatic oil [53]. Mansourkhaki et al. studied 11 samples by using the BBR test; the m-value criterion for low temperature was identified as the determinative factor [83].

Moreover, a slight drop in low temperature was observed when adding PBR to modify the binders. However, the addition of PBR affected the creep stiffness and rate negatively because rubber caused the asphalt to stiffen [83]. Ren et al. noticed that the low-temperature cracking resistance of asphalt could be affected by the aging degree. When the temperature decreases, the stiffness value of asphalt increases; similarly, when the temperature decreases, the m-value decreases, and therefore it was deduced that the rejuvenated asphalt stiffness value decreases with aged asphalt [73].

4.5. Effect of Waste Oils on Molecular Weight of Rejuvenated Asphalt

GPC, or size-exclusion chromatography, is used to study the size of molecules and the distribution of molecular weight [116]. It is also used to determine the rejuvenated binder’s reaction mechanism, the asphalt binder’s aging mechanism, and the aged asphalt’s rejuvenation mechanism [117]. The results of Dong et al. illustrated that WTR absorbed heat energy and C–C bonds at rubber hydrocarbon molecules in the primary chain after devulcanization cross-linking started to fracture and reform the structure of a molecule into a small-weight molecule [62]. Zhao and Dong noted that the average molecular number (Mn) and molecular weight (Mw) were inversely proportional to the polydispersity index (PDI), which is the ratio of Mw to Mn and GPC time as Sulphur content increases. These authors deduced that Sulphur reinforces WCO devulcanized WTR and virgin asphalt binder combination. Furthermore, the influence of Sulphur on SBS is noteworthy in WCO devulcanized WTR rejuvenated asphalt due to cross-linking reactions amongst SBS, WCO devulcanized WTR (i.e., waste rubber oil or WRO), and the base asphalt [68]. Ma et al. found that an increase in aging degree may cause a decrease in the amount of small molecular size (SMS%) of HSSRA. The rubber rejuvenated asphalt binder also decreased. However, the large molecular size (LMS%) of all the asphalt mixes increased due to the complex mechanism of component exchange between WTR scraps and the asphalt binder phase. No noticeable difference was observed between asphalt rubber and HSSRA [79]. Peng et al. verified after using GPC that the molecular weight distribution of the asphalt binder containing 4 wt% waste tire rubber + 6 wt% waste engine oil is very similar to the rejuvenated asphalt mix [48].
4.6. Effect of Waste Oils on Thermal Behavior

Thermalgravimetric analysis (TGA) provides essential numerical information, such as the initial decomposition temperature (T_i), the maximum weight loss rate temperature (T_{max}), and the final decomposition temperature (T_f) [80]. Dong et al. obtained the chemical structure contents of pyrolysis product residues and WTR through TGA and observed an increasing soluble linear rubber chain as a consequence of the devulcanization of a cross-linked network structure. Duan et al. studied microalgae acidified oil added as a rejuvenator to devulcanize WTR/SBS rejuvenated asphalt via TGA [87]. The temperature of microalgae acidified oil (345 °C) was lower than that of virgin asphalt and higher than the experimental producing temperature (165 °C). Consequently, all binders remained stable throughout the preparation process of the mixes [80].

In previous studies, TGA was utilized to characterize exchanges in the chemical compositions of the waste tire rubber crosslinking before and after devulcanization. These studies found that binders with WCO exhibited loose rubber hydrocarbon decomposition. Moreover, WTR dissolved in the asphalt binder at specific temperate degrees in the presence of bio-oil. Therefore, differential scanning calorimetry (DSC) is also a thermos-analytical measurement technique to study the difference in heat amount that is required to raise the sample temperature and reference as a function of temperature and is also used to study thermal behavior performance. Dong et al. determined that WTR has two clear weight loss peaks, which are present in rubber hydrocarbon decomposition and WTR decomposition. Meanwhile, WRO has three pronounced weight loss peaks: From the extended release of natural rubber (NR) and the decomposition of synthetic rubber (SR) and WTR. Moreover, DSC curves significantly changed after the heat was increased, proving that the heating rate affected WRO decomposition [76].

5. Effect of Waste Oils on The Properties of Rejuvenated Asphalt

5.1. Effect of Waste oils on Conventional Physical Properties

5.1.1. Effect of Waste Oils on Penetration, Softening Point, and Ductility

The characteristics of conventional binders include the following: Penetration, which is commonly used to test the sensitivity for temperature, rheology, and diffusion properties of asphalt materials. Ductility is used to measure the braking distance of a standard asphalt sample under typical testing conditions. The softening point of asphalt is determined as the temperature at which two disks of a piece fail to hold the weight of a steel ball. It should be noted that all these tests are analyzed following ASTM specifications. Mansourkhaki conducted penetration and softening point tests and found that with rejuvenated asphalt binder at various dosages, penetration increased as the dosage sufficiently increased. Moreover, the acceptable dosage range was 7.2–7.7%, and 7.2% was selected to decrease the rejuvenation cost [83]. Duan et al. observed that microalgae biodiesel (MB) content above 2% decreased the softening point of the rejuvenated asphalt–WTR–SBS-rejuvenated asphalt (MBWTR/SBS) binder due to an increase in lightweight MB contents [80]. From the experimental results, Hong et al. concluded that the softening point and ductility of aged asphalt and SBS-rejuvenated asphalt samples were enhanced after applying the rejuvenator compound [53]. Dong et al. asserted that using WCO is safer because the WCO flash point is higher than that of virgin asphalt [87].

From Figure 7, a conclusion can be drawn that the penetration of asphalt–rubber-rejuvenated asphalt was enhanced with increased WCO content. However, the penetration value decreased in the asphalt binder after long-term aging BA-LAT [53], although it was also enhanced in all the WEO samples. Moreover, the softening point results meet the T0606 and ASTM D-36 standards, and an increase in the softening point results enhances the asphalt binder.
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5.1.2. Effect of Waste Oils on Flashing Point

The flashing point is used to determine the temperature at which binder fumes may flash first. All these tests are analyzed in accordance with ASTM specifications. Dong et al. studied the influence of rejuvenated asphalt with WTR devulcanized by the WCO flashing point and deduced that it is convenient to use waste cooking oil WCO, which has a higher flash point than neat asphalt by approximately 20 degrees and was therefore utilized in this study. Moreover, the authors deduced that the co-pyrolysis of rubber oil at mild-temperature mixes is smaller than the flashpoint of WCO in normal status < 300 °C, and the flashpoint of neat asphalt is 278 °C [87]. Kamoto et al. noticed that the higher flashpoint, the higher the temperatures required, and this temperature increase is due to ignition and the production of vapor. As long as the heating is maintained above the flashpoint, the vapors ignite in the presence of a flame and continue to burn, showing the fire point temperature, which results in a safe sample being produced due to the lower fire hazard [54].
shortage of researchers studying the effect of the flashpoint on devulcanized WTR for use as an asphalt rejuvenator, this review did not find a brief explanation of its effect, and it is recommended to do more research on the flashpoint effect.

5.1.3. Effect of Waste Oils on Viscosity of Rejuvenated Asphalt

Viscosity is an essential factor for studying and demonstrating rubber–asphalt workability [118]. The viscosity ratio can reflect the aging degree, which is influenced by high temperatures on elastic–viscous proportion component changes in virgin asphalt. A low viscosity ratio indicates a small proportion change or high aging resistance of rejuvenated asphalt [77]. Ma et al. noticed a slight decrease in the viscosity of HSSRA and WTR asphalt rejuvenators with an increase in test temperature. The comprehensive rotary viscosity of the solution was decreased by the introduction of WCO into the rejuvenated asphalt by WTR. This finding can be attributed to the WCO increase, leading to the proportion of the lubricant phase and decreasing asphalt and WTR interaction. [65,79].

Furthermore, the blending and compaction temperatures of HSSRA were decreased compared with those of WTR rejuvenated asphalt. Duan et al. reported that viscosity decreased when temperature increased in each sample. Moreover, MB decreased the viscosity of rejuvenated asphalt by WTR/SBS. After adding 2% MB, the viscosity sharply decreased due to the lubricating effect of MB on WTR and SBS [80]. These authors observed a gentler decrease after increasing the amount of MB from 4% to 6% due to the adsorption of MB onto the surfaces of WTR and SBS [119]. Dong and Zhao noticed that WRO viscosity exhibited an inverse relationship with an increased interaction temperature. WRO decreased due to the temperature enhancement of heat energy growth in a reaction system. When the large rubber molecules in WTR absorb a sufficient amount of energy, the devulcanization degree becomes more complicated [62]. Kamoto et al. found that Sample 2, which had a composition of 1 asphalt:2.5 WTR:1.5 WEO and lower viscosity, was the best sample. The authors also determined that lower viscosity means additional WTR, affecting asphalt performance during temperature increases [54]. Xingyu et al. observed that WRO viscosity notably increased, proving that WCO viscosification in WRO increased WRO viscosity at 260 °C after 70 min [85]. Yu et al. found that bio-oil asphalt rubber (bio-AR) and asphalt rubber rejuvenated with a warm mix of additives exhibited approximate viscosity values due to the workability enhancement [46]. Li et al. reported that adding more WEO caused decay in asphalt viscosity due to the increase in the lightweight components of asphalt [98]. Moreover, these authors noticed that vessel temperature augmentation led to analogical shrinkage in viscosity after comparing the samples. However, the degraded WTR rejuvenated asphalt binder sample no. 180 (DRMA180) was excluded due to precipitated hydrocarbon molecule mobility in waste engine oil at high temperatures, which influenced WTR swelling. Ren, Liu, and Fan et al. used aged and rejuvenated asphalt samples at various heat degrees (120 °C, 135 °C, 150 °C, and 160 °C) to study the viscosity values. The authors reported that WCO rejuvenated asphalt with WTR, while WEO achieved superior viscosity [73].

Meanwhile, the viscosity of rejuvenated asphalt was lower than that of aged asphalt in the binders. Li et al. studied the influence of WEO and WCO on the viscosity of aged asphalt at 135 °C. They determined that all viscosity values decreased as WEO or WCO content increased [120]. Li et al. studied various asphalt binders. All the other binders presented lower viscosity values than that of asphalt styrene-butadiene rubber with waste oil SBRMA at 120 °C, 135 °C, and 150 °C, proving that the additives may exert a high-grade viscosity reduction influence on SBRMA. However, Sasobit reduced the binder’s viscosity value by extending the proportion of lightweight molecular components in the asphalt matrix [115]. Rahman et al. found that asphalt 60/70 was sensitive to a change in temperature with a viscosity ratio of 3.33 compared to the other binder with a viscosity ratio of <3.00 [78].

Moreover, the authors determined that rejuvenated binders are less sensitive to temperature changes. As shown in Figure 8, the viscosity decreased in nearly all the binders
with an increase in temperature because the content of ground asphaltene was high in the asphalt. However, the viscosity increased in waste rubber oil asphalt and WCO with an increase in temperature due to the deficiency in ground asphaltene content of the samples.

![Figure 8. Relationship between viscosity and time for different samples](image)

### 5.2. Effect of Waste Oils on High-Temperature Properties of Rejuvenated Asphalt

The complex modulus and phase angle are utilized to analyze the performance-related criteria under the specifications of D6373 [85], AASHTO Standard M320, and ASTM D7175-15 [121]. The phase angle is used to illustrate a binder’s viscoelastic ratio. The materials that have a lower phase angle exhibit higher elasticity and deformation recovery capability. Dong and Zhao investigated the influence of WRO temperature by using rheological properties. They observed that $G^\ast$ decreased when temperature increased due to WTR deformation resistance, elasticity weakness, and plasticity improvement [62]. However, $\delta^\circ$ increased with temperature, indicating that the deformation capability of the system had a weakness. Rahman et al. studied seven samples in a DSR test and found that the samples exhibited temperature change sensitivity. They deduced that the rejuvenated binders demonstrated weak rutting resistance and better fatigue resistance [78]. Lei et al. determined that the 80-mesh rubber rejuvenated asphalt (RMA) phase angle was directly proportional to the bio-oil content increase due to the influence of bio-oil on asphalt viscosity characteristics [81]. However, the phase angle of the 20-mesh RMA exerted less influence on the bio-oil content than the 80-mesh RMA. Moreover, the bio-oil improved rubber asphalt viscosity, and the effect magnitude depended on the WTR mesh. Zhao and Dong observed that WCO pre-desulphurization with WTR 1(WRO)/4 SBS/0.4 Sulphur SMA achieved the most significant complex modulus amongst all samples of WCO-devulcanized WTR (WRO) composite-rejuvenated asphalt, confirming the high rutting resistance, except in SBS-rejuvenated asphalt (SBSMA) [68]. All phase angle $\delta^\circ$ values decreased with an increase in conversion frequency. Furthermore, WRO with SBS composite-rejuvenated asphalt binders with Sulphur demonstrated better performance than non-Sulphur binders. Increasing the SBS content enhanced the rutting resistance at high temperatures. Moreover, the SBS/0.4S binder exhibited better high-temperature rutting resistance and cracking resistance at a low temperature compared with the conventional SBS rejuvenated asphalt. After drawing the $G^\ast$ and $\delta^\circ$ master curves for the two samples, Ma et al. found that the phase angle was reduced with an increment in the loading frequency [79]. The incorporation of WCO into rubber-rejuvenated asphalt prevented WTR particles from cross-linking. Moreover, various aging degrees increased with the loading increment. In the hot mix, the $G^\ast$ of HSSRA was lower than that of rubber asphalt at low-high frequencies due to the weakening influence of WCO. Duan et al. studied microalgae acidified oil added as a rejuvenator with
WTR/SBS-rejuvenated asphalt via DRS. They suggested that $\delta^o$ increased below 30 $^\circ$C, and the $\delta$ of MBCR/SBS-2 was smaller compared with that of the other samples. Moreover, the $\delta^o$ of 5% SBS-rejuvenated asphalt exhibited better elastic properties than the other samples. In the high-frequency region, the highest $G^*$ value was from MBCR/SBS-2-rejuvenated asphalt. The addition of 2% MB enhanced the viscoelastic properties due to the lightweight components. By contrast, a higher MB content resulted in a small $G^*$ value because of the supersaturation and cross-linking of rubber, which reduced the effect of MB, decreasing the rejuvenated asphalt’s elasticity. Duan et al. also suggested a >5% SBS-rejuvenated asphalt binder to increase the stress and high-temperature rutting resistance. They concluded that the MBCR/SBS-2 sample achieved the smallest non-recoverable creep compliance ($J_{nr}$) at various stress levels [80]. Yi et al. found that the phase angle of the artificially aged binder with WRO demonstrated a low reduction because the effective oil content of WRO was 8% by artificially aged binder weight. The 10% WRO binder contained less lightweight oil components than the 10% WCO-based binder after high-temperature preparation. The complex modulus was reduced with a temperature rise, and the highest decrease in complex modulus was recorded in the 10% WRO binder. Furthermore, WTR absorbed the lightweight components of the WRO rejuvenator and released them gradually along with the aging process. Therefore, the 10% WRO rejuvenated asphalt binder exhibited good RTFO-aging resistance [85]. Hong et al. presented the master curves of $G^*$ and $\delta^o$ for virgin, aged, and rejuvenated asphalt binders by polymer rejuvenator. Long-term aging resulted in higher $G^*$ and lower $\delta^o$. The addition of 15% aromatic oil appeared to over-rejuvenate the aged mixture due to higher $G^*$ and lower $\delta^o$ [53]. Zhou et al. used three samples, i.e., waste tire rubber aromatic oil-modified asphalt WRMA-0, WRMA, and WRMA-3, to study $G^*$ and $\delta^o$. Visco-elastic analysis was conducted to investigate the differences in their performance. All the WRMA samples included 6% WTR. This percentage was reported in the relevant literature. The $G^*/\sin \delta^o$ of the controlled WRMA had a high value in low-frequency regions, confirming the enhancement of high-temperature rutting resistance [82].

As shown in Figure 9a,b, the frequency rise caused a rise in the complex shear modulus and a decrease in the phase angle, causing an improvement in rutting resistance. In Figure 9c,d, a temperature rise caused a reduction in rutting factor $G^*/\sin \delta^o$ and a rise in the phase angle, causing a decrease in the rutting performance. In general, waste oils significantly affect the rutting performance of rubber–asphalt rejuvenators, depending on the type and content of waste oil. In contrast with the decrease in the phase angle and the rise in frequency, the phase angle increased with a rise in temperature, attributable to the elastic behavior of the rubber–asphalt–oil mixture.

5.3. Effect of Waste Oils on Anti-Permanent Deformation Capability of Rejuvenated Asphalt

Researchers typically use multiple stress creep recovery (MSCR) tests to evaluate the anti-permanent deformation capability of an asphalt binder with regard to the effect of damage. Zhao and Dong compared the MSCR results among four samples. They noticed that the SHB of sample 1 stemmed from castor, the bio-oil of sample 2 was the remnant of the biodiesel refining procedure, and 20 wt% WTR was dissolved in the asphalt binder at 260 $^\circ$C for 6 h through the preparation of sample 3. The binder with waste cooking oil waste tire rubber rejuvenator (ODR) and 4 wt% SBS provided a more crucial elastic behavior than the SBS-rejuvenated asphalt at high and low temperatures [68]. Due to the shortage of research studying the use of multiple stress creep recovery (MSCR) tests on devulcanized WTR to use as an asphalt rejuvenator, this review did not find a brief explanation of its effect, and it is recommended to conduct more research on the MSCR test.
5.4. Effect of Waste Oils on Low-Temperature Properties of Rejuvenated Asphalt

The low-temperature performance of rejuvenated asphalt plays a significant role in the thermal cracking mechanism of asphalt pavements. Ma et al. [79] deduced that HSSAR thermal cracking resistance improved with the addition of WCO because WCO recompensed the absorbed lightweight fraction in the asphalt binder and improved the low-temperature relaxation capability of rejuvenated asphalt with WTR. Moreover, WCO decreased the stiffness and improved the viscous component of rubber asphalt. Zhao and Dong found that using SBS/0.4S with increased SBS content exerted a combined influence and slight enhancement on the low-temperature properties of asphalt. The sample WRO/4SBS/0.4S exhibited high cracking resistance at 28 °C and extreme low-temperature performance [68]. Mansourkhaki et al. studied 11 samples using the BBR test. The m-value criterion for low temperature was identified as the determinative factor. Moreover, a slight drop in low temperature was observed while adding PBR to modify binders [83]. However, the addition of PBR affected the creep stiffness and was negatively rated because rubber caused the asphalt to stiffen (see Figure 10a,b). Moreover, the authors deduced that the low temperature decreases the binder’s cracking resistance. Li et al.’s results demonstrate that compared to sasobit and ESO, the sasobit/ESO composite not only lowered the mix’s preparation temperature better but can also compensate for unfavorable effects when sasobit or ESO is added individually and improve SBR-rejuvenated asphalt binder’s low-temperature performance [115]. In conclusion, from previous studies, the
thermal cracking resistance improved with waste oils due to recompensing the absorbed lightweight fraction in the asphalt binder. It improved the low-temperature relaxation capability of rejuvenated asphalt with WTR.

Figure 10. (a) Creep stiffness and (b) m-value of various binders from several studies [53,67,68,79,83].

5.5. Effect of Waste Oils on Aging Resistant

The mixture of rubber–asphalt–waste oil is frequently aged via RTFOT and tested to simulate short-term effects in accordance with ASTM D2872. Ma et al. conducted an orthogonal test and simulated short-term aging effects. They found that the rubber particle size in WRO was smaller than that in asphalt rubber due to the effect of WCO on asphalt during preparation. Furthermore, slight rubber particle cross-linking occurred in rubber asphalt with thermal oxidative aging [79]. Li et al. studied the capability to improve short-term aging resistance for SBS in the presence of soybean oil. Compared
with that of Sasobit, a better decreasing effect on the binder preparation temperature was achieved. Moreover, the high- and low-temperature performance of the mixture was concurrently enhanced [115]. Lei et al. found 20-mesh rubber-rejuvenated asphalt rutting factors were better for unaged asphalt than 80-mesh rubber-rejuvenated asphalt rutting factors, proving that the particle size of WTR affected the high-temperature performance of the asphalt mixture [81]. At high temperatures, the 20-mesh WTR improved the asphalt binder’s anti-deformation capability and maintained its elastic nature. In terms of low/high-temperature durability and ductility, Yin et al. determined that the ESO cross-linked asphalt rubber binder outperformed microwave radiated-rubber rejuvenated asphalt because of the following reasons. (1) The polarity oil found in epoxidized soybean oil permeated to the asphalt mixture and produced oil in aged asphalt binder attributable to oxidation. (2) A compound was formed due to the reaction of the opening ring between the epoxy bond in epoxidized soybean oil and the unsaturated bond in asphalt [77]. In regard to improving the performance of old asphalt, Ren Liu and Fan et al. examined the impacts of utilizing WCO, WEO, and SBR and deduced that waste oil had a negative impact on the anti-aging performance of asphalt as well as the aging resistance to rutting. Moreover, the viscosity of asphalt improved sufficiently after aging. However, an increment in WCO and WEO negatively affected aged asphalt’s viscosity, and this effect was enhanced by adding SBR [73]. Xingyu et al. used a WRO rejuvenator with an artificially aged binder and mixed it slowly with aromatic oil and WCO at a dosage of 10%. They concluded that the waste rubber oil asphalt rejuvenator considerably enhanced low-temperature aging properties under the effect of low-temperature continuous grading [85].

The mixture of rubber–asphalt–waste oil is frequently aged using the pressure aging vessel test to simulate long-term aging effects in accordance with ASTM D6521. Hong et al. investigated base asphalt aging under long-term aging conditions mixed with SBS-rejuvenated asphalt binders to rejuvenate and modify the binder using 77% aromatic oil and 23% SBS polymer. MAR enhanced the performance of aged and polymer-rejuvenated asphalt [53]. Mansourkhaki et al. deduced that using additives in binder colloidal systems altered the aged binder’s chemical composition and reduced the Gaestel index (IC) while enhancing physical and rheological properties [83]. Rahman et al. found that asphalt properties are influenced by aging, affecting the hardening of the mixture. The POFA percentage in Samples 3 and 5 was 10%, improving the binder for hardening. Sample 6 contained 7.5% POFA and 10% WTR to enhance binder complications after aging [78]. From previous studies, in conclusion, the mixture’s high- and low-temperature performance was concurrently enhanced with the addition of waste oils to rejuvenate asphalt with WTR.

5.6. Effect of Waste Oils on Storage Stability of Rejuvenated Asphalt

The segregation test is also called a cigar tube test and is used to appraise WTR compatibility with asphalt before and after devulcanization according to the specifications of the Standard Test Methods of Asphalt and Bituminous Mixtures for Highway Engineering T0661-200 and ASTM D7173. Dong and Zhao asserted that WCO-pyrolyzed WTR-rejuvenated asphalt’s storage stability is more significant than ordinary WTR-rejuvenated asphalt [62]. Kabir et al. found that surface-activated WTR caused a considerable gain of up to 203% in the recovery rate compared with untreated WTR [63]. Amongst surface-activated WTR particles, the maximum recovery percentage reached up to 40% in corn stover oil. Zhou et al. determined that the surface activation and pre-swelling of WTR enhanced storage stability by up to 41% and 20%, respectively [67]. Moreover, the chemical adsorption process of both binders is more effective than molecular physical bonding with regard to phase separation reduction. In conclusion, the storage stability was improved. From previous studies, the storage stability is naturally improved compared to the asphalt rubber binder and adding oil to WTR asphalt enhances the compatibility of the binder, (see Figure 11).
Amongst surface-activated WTR particles, the maximum recovery percentage reached up to 40% in corn stover oil. Zhou et al. determined that the surface activation and pre-swelling of WTR enhanced storage stability by up to 41% and 20%, respectively [67]. Moreover, the chemical adsorption process of both binders is more effective than molecular physical bonding with regard to phase separation reduction. In conclusion, the storage stability was improved. From previous studies, the storage stability is naturally improved compared to the asphalt rubber binder and adding oil to WTR asphalt enhances the compatibility of the binder, (see Figure 11).

### Figure 11

Redrawn non-recoverable creep compliance value and percentage recovery of several binders under (a) 0.1 kPa, (b) 3.2 kPa, and (c) 0.1 kPa and 3.2 kPa stress [53,73,77–79,81,83,85,115].
5.7. Effect of Waste Oils on Compatibility and Morphology of Rejuvenated Asphalt

The incompatibility issue of rejuvenated asphalt using WTR was essentially caused by the great differences in chemical nature (molecular size and polarity) and physical features (density and solubility) between WTR and the asphalt matrix. However, mixing WTR with waste oils had a sufficient influence on compatibility [122]. Dong and Zhao reported that the segregation indices of asphalt rubber and the waste cooking oil WTR rejuvenator (ODR) were 7.2 °C and 0.5 °C, respectively, because the compatibility of the WCO pyrolysis of WTR with virgin asphalt in WCO was improved sufficiently [62]. Ren, Liu, and Fan et al. asserted that investigating the compatibility between aged and rejuvenated asphalts is essential to ensuring the stability of rejuvenated asphalt. Such compatibility decreased with the waste oil dosage increment due to the difference in components between aged asphalt and oil rejuvenators. Adding more SBR also helped enhance rejuvenated asphalt compatibility, absorbing light compounds, and reinforcing the stability of the micellar structure of rejuvenated asphalt [73]. Yin et al. concluded that the compatibility between WTR particles and the asphalt binder was improved through a compound with a solid network structure, affecting the stability of asphalt and further enhancing asphalt aging resistance [77]. Ma et al. suggested that before preparing rejuvenated asphalt with WTR, pre-swelling WTR with WCO is preferable to improve the compatibility of the rejuvenated asphalt with WTR. However, the lowest separation tendency was observed in rubber asphalt due to storage stability. Moreover, rubber asphalt compatibility was the best [65]. Dong et al. studied the surface morphology and observed that WTR swelled after absorbing light oil, producing a sticky, fluffy binder. Moreover, the carbon black CB weight loss was minimal compared with rubber hydrocarbon, and thus, a large amount of CB remained in the residues. Furthermore, the linear rubber molecule chains separated from the dissolved cross-linked chain during WTR devulcanization [87]. From previous studies, the compatibility is naturally improved compared to the asphalt rubber binder and adding oil to WTR asphalt enhances the morphology of the asphalt binder.

6. Conclusions

The addition of waste tire rubber (WTR) to asphalt in conjunction with waste cooking oils (WCO), waste engine oil (WEO), or other waste oil has the potential to significantly improve the characteristics of asphalt binders. The following points summarize the major conclusions.

Mixing WTR with waste oils to rejuvenate asphalt is possible. The solubility of WTR depends on the amount of waste oil and asphalt binder, and it increases with an increase in WCO or WEO and asphalt. When the rubber hydrocarbon content is reduced, carbon black CB content is inversely increased. By contrast, the residue of the pyrolysis product of WTR yields the opposite results. Moreover, the use of aromatic oil improves colloidal stability. Overall, using waste oil with WTR improves the stability of rejuvenated waste tire rubber-oil asphalts.

FTIR spectra demonstrated that the major components of waste oil are alkanes and aromatics, which are similar to the saturated and aromatic components of asphalt binders. The S=O bond appears in all WTR samples.

The Mn, PDI, and GPC time with Sulphur content quantities or the addition of more compounds affect the result of GPC. In the aged binder, the aging degree of small-sized molecules decreases and the aging degree of large-sized molecules increases.

Adding waste oils reduces viscosity by increasing shear time, and the viscosity reduction influence of binders with waste oils is highly evident. Moreover, the viscosity increases when the rubber content reaches up to 40% with the presence of waste engine oil in asphalt rubber molecules, leading to poorer processing.

The thermal behavior (TGA) results indicated that the heating rate affects the decomposition of WRO. Besides, microalgae acidified oil added to SBS and asphalt binders requires a stable preparation process. The DSC tests showed that zero shear viscosity appears because
WRO flowability is ameliorated with an increase in the interaction temperature. Meanwhile, the MSCR results indicated that WTR dissolves in asphalt at high temperatures.

In high-temperature properties, the higher the $G^\ast$ value, the stronger the deformation resistance of the material. The lower the $\delta^\circ$ value, the higher the deformation recovery capability of the material. The higher the $G^\ast$ value, the smaller the $\delta^\circ$ value. Rejuvenating asphalt with WTR and waste oils enhances the viscoelastic properties of the asphalt binder due to its lightweight components. Long-term aging results in higher $G^\ast$ and lower $\delta^\circ$.

Adding waste oils to rejuvenated asphalt rubber increases the stress binder and high-temperature rutting resistance. Moreover, waste oils add Sulphur to SBS-rejuvenated asphalt, resulting in better rutting resistance performance than non-Sulphur binders.

The short-term and long-term aging processes improve the elastic stability of WTR-rejuvenated asphalt. Moreover, the short-term treatment of asphalt improves the swelling and absorption processes of WTR in the heated, rejuvenated rubber–oil–asphalt binder. The segregation test results indicate that adding waste oil to WTR and asphalt enhanced the storage stability compared with that of the asphalt rubber binder. In corn stover oil, the maximum percentage recovery increases sufficiently after the surface-activated WTR process. However, the surface activation of the WTR function and pre-swelling improve storage stability.

The WTR with WCO or WEO is preferable for use in improving the compatibility of rejuvenated asphalt with WTR. However, the lowest separation tendency was observed in rubber oil asphalt due to the storage stability; meanwhile, the compatibility of rubber oil with asphalt was the best.

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