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# Ageing influence in rejuvenated reclaimed asphalt binder incorporating waste cooking oil: A review

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# Ageing influence in rejuvenated reclaimed asphalt binder incorporating waste cooking oil: A review

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**Abstract**

Mixing Recycled Asphalt Binder (RAP) with fresh asphalt mixture offers both environmental and economic advantages. However, the aged asphalt binder in RAP presents a significant challenge in sustainable asphalt pavement construction. One of sustainable approach is by using Waste Cooking Oil (WCO) to bring back the original properties of aged asphalt. Although, WCO ability to soften the aged binder is already established, its ability to improve the binder ability to resist the ageing is remain unknown. Researchers have recently explored the potential of using WCO as a sustainable rejuvenator for RAP, aiming to improve the binder's resistance to ageing. This review covers important topics such the oxidative ageing mechanism in asphalt binders, ageing simulation techniques, the effectiveness of WCO in restoring the RAP properties, and WCO performance to increase asphalt ageing resistance. Through a comprehensive analysis of numerous prior studies, this review sheds light on the impact of WCO on the rheological characteristics, ageing resistance, and mechanical performance of the rejuvenated asphalt binder. The results from the examined literature are that WCO can be utilized as a sustainable rejuvenator in RAP by increase the durability and ageing resistance of binder. This review also points out some of the asphalt binder ageing factors are remains unknown which can be investigate for future research in this field. Ultimately, this review can be referred as a guidance to index and track the ageing factors in rejuvenated RAP by evaluates its characteristics and properties.

*Keywords: Waste Cooking Oil, Recycle Asphalt Binder, Oxidative Ageing, Construction Waste Management.*

## 1. Introduction

The most utilized materials for roads construction worldwide are asphalt (also known as bitumen), but conventional asphalt production and construction processes have left a significant environmental and economic impacts. The conventional asphalt mixture production is involving mixing the fresh binder and aggregates only. By replacing fresh aggregate and binder with Recycled Asphalt Pavement (RAP) in the fresh mixture will benefit environmentally and economically. RAP is a practical and sustainable option because it reduces Greenhouse Gas Emissions (GHG) and lowers energy consumption [1]. One of the key benefits of utilizing RAP is the reduction in the need for valuable dumping sites required for disposing of unwanted pavements [2]. By reducing the amount of waste material, RAP contributes to more efficient use of resources and reduces the environmental burden associated with conventional asphalt production. Research conducted by Bizarro et al. [3] found that one ton of asphalt mix with 93% of RAP produced in 105ºC has the potential to reduce carbon footprint up to 64% compared to virgin mix with 0% RAP contains. Furthermore, a study conducted by Wei et al. [4] found that adding RAP will reduce the Volatile Organic Compound (VOCs) up to 94.82% in mixing stage. While Zaumanis et al. [5] found that in cooperating 100% of RAP will save 50% to 70% construction cost compared to virgin mixture. Rafiq et al. [6] conduct a study at Lahore–Islamabad motorway (M-2) discovered a 57% cost reduction at the manufacturing plant and a 14% cost reduction at life cycle costing as compared to the regular asphalt mixture. Therefore, the utilization of RAP in fresh asphalt mixtures has been proposed as a sustainable solution to address these issues and decrease the negative environmental and financial impacts of asphalt materials.

Alternatively, the aged binder in RAP undergoes degradation over time, resulting in reduced performance and increased susceptibility to cracking. To overcome the negative effects of ageing and boost RAP's functionality, researchers and industry practitioners have recently investigated a variety of rejuvenation techniques. One possibility is to use Waste Cooking Oil (WCO) as a sustainable and affordable rejuvenator for the aged binder.

WCO, a byproduct of cooking activity, has proven potential as a sustainable and renewable resource that can restore the aged asphalt binder in RAP, restoring its original properties and enhancing performance. WCO encompass varieties such as plant based, animal derived, or synthetic fat. WCO can come from various sources, such as households, restaurants, and food processing plants. The variety of WCO differs depending on geographical area. There are various types of WCO, including mahua oil, sunflower oil, soybean oil, palmolein oil, cotton seed oil, canola oil, tung oil, animal manure and chicken fat oil [7]. Consequently, before utilizing WCO as a rejuvenator in asphalt binder, its qualities and properties need to be carefully examined. Without proper disposal method, WCO can pollute land resources and water [8]. Hence, with correct and proper technique, cooperating WCO in asphalt pavement can help reduce the pollution also.

However, according to research made by Elahi et al. [9], the utilization of WCO in asphalt binder is still in empirical stage. That means there is still a limitation on information about WCO which may be due to lack of study and combination of results and recommendation. Notably the ageing resistance of rejuvenated asphalt binder incorporated WCO require a future investigation. According to Yan et al. [10], many researchers are focusing on evaluating the ageing resistance on the properties of asphalt binder. However, the performance of asphalt mixtures after ageing also needs to be explored. In addition, the study of asphalt ageing should not rely solely on a single scale but needs to incorporate multiple scales for future investigation [11].

The objective of this review article is to provide a comprehensive overview of the most recent developments in techniques and methods that have been discovered in ageing resistance of RAP incorporated with WCO. By reviewing recent literature, this paper seeks to evaluate the effectiveness and ability of WCO as a sustainable and affordable rejuvenator and its impact on the rheological characteristic, ageing resistance, and antioxidant of the rejuvenated binder. This review article gives information about RAP rejuvenation methods and suggestions for creating long-lasting, sustainable asphalt pavements.

## 2. Reclaimed Asphalt Pavement (RAP)

RAP is one of the most reusable and recyclable construction waste materials globally. RAP is a byproduct of road maintenance, where the road surface is removed throughout a milling or grinding process. The milling process involves using rotary cutters to grind, cut, press, or crush the asphalt mixture. RAP is considered 100% recyclable using several methods, including cold or hot, in-plant or in-situ [12]. The usage of RAP can be traced back to 1917, but it gained significant attention in the 1970s, particularly during the Arab oil embargo when oil prices skyrocketed [13]. This prompted scientists to develop an economical and environmentally friendly method to reduce dependency on asphalt binders, leading to the widespread use of RAP. Notably, in the past 20 years, the use of RAP has become increasingly significant. It should be noted that the properties and qualities of RAP are not solely depending on its physical, rheological, and chemical properties but also on the milling process itself [14].

Currently, RAP in the US is usually only allowed to be 20 percent in each mix design. This is wasteful despite RAP being utilized up to 100 percent [15]. Precautionary measures must be adopted because the aged binder in the RAP has potential to induce early fatigue and low temperature cracking failures, potentially affecting pavement performance beyond the acceptance service period. The stiff binder in the RAP is a result of ageing, which is why government and local authorities impose limits on the RAP percentage in the asphalt mixture. Rejuvenators have been developed to address this issue and restore the binder's original characteristics.

RAP is typically one of the construction solid wastes that is used directly in the production of new asphalt mix. The quality of RAP must be carefully checked and determined through proper testing and quality control that meets the desired specifications and quality standards before it can be fully utilized. RAP binder is typically stiffer than virgin asphalt. The quality of the mix may be impacted when RAP is added to virgin mix, so it is important to determine the right binder and rejuvenator content. The quality of the mix can be impacted by the mixing temperature. Research conducted by Balik et al. [16] found that mixing performance (stability, Marshall quotient, indirect tensile strength and fatigue life) decrease as the temperature decreases. Hence, the temperature should be adjusted as needed. The optimum mixing temperature, rejuvenator dosage and compaction can be achieved by following standard operation procedure.

The source of RAP is the most significant of the several elements that influence the quality of RAP. The RAP's quality should be good if it originates from a high-quality road surface. Guthrie et al. [17] conducted an experiment to find out how RAP affects the mechanical characteristics of recycled base materials in Northern Utah, USA. The study revealed that RAP quality and source can affect the mechanical performance of recycled base materials for roadways. The California Bearing Ratio (CBR) was found to decrease between 13% and 29% at 25% of different 5 RAP source. Hence, it is essential that the testing method can be carried out efficiently to suit the dynamic environment of asphalt production since the properties of RAP vary according to the age and origin of the millings.

Due to the differences between virgin and RAP aggregate, the size and distribution of RAP particles can have a considerable impact on the mix's quality. Properties including angularity, specific gravity, and abrasion value must be taken into consideration in stage design [18]. According to Zaumanis et al. [19], the milling process can affect the quality of RAP by generating 4.8% additional dust in RAP, but it does not affect the aggregate angularity. By using a high milling depth and increasing the milling machine's movement speed, larger RAP chunks are generated, and the larger chunks are then used to create filler. Zaumanis et al. [14] also discovered that the temperature of the milling tools did not age the binder, indicating that the mix's quality was not severely impacted.

### *2.1. Asphalt binder ageing*

In general, asphalt ages in the final two stages: during manufacture and throughout its service lifetime as illustrates in Fig. 1. The production stage of asphalt mixture at the quarry and the lay-down procedure on the construction site constitute the first stage, also known as short-term ageing. Short-term ageing is brought on by heating and immediate oxidation. While, long-term ageing, or the second stage, develops gradually over the road's service life. Long-term ageing is a complicated phenomenon that results from several factors.

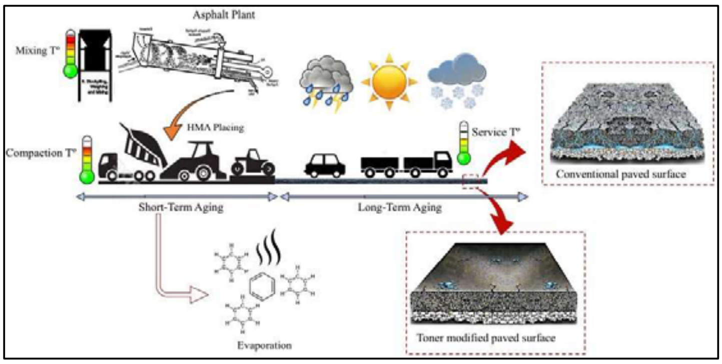


Fig. 1 Asphalt binder ageing stages [20]

During the service time asphalt ageing is caused due to oxidation, UV radiation from sunlight, temperature fluctuations, moisture, and traffic loading [21]. Ageing is a normal occurrence in asphalt mixtures over time, leading to various issues such as cracking, rutting, and surface deterioration. Asphalt mix consists of course and fine aggregates with asphalt serving as the binder. Ageing can occur from these six factors, which are oxidation, volatilization, polymerization, thixotropy, syneresis and separation. Most of the factors occur during the service time except volatilization factor [15]. According to Hamzah et al. [22] oxidation is a process of asphalt binder reacting with atmospheric oxygen. This reaction increases the polarity, acidity, and condensation of molecules. Oxidative ageing can be classified in two categories, thermal oxidative and photo-oxidative ageing [11]. Most of previous study only focusing on thermal oxidative, which simulate the ageing under high temperature. Photo-oxidative ageing is a more recent method that was under development and the standard for simulating the ageing is currently unavailable. It is important to investigate how sunlight affects the ageing of asphalt binder. This occurs because the sunlight gives energy to the molecules in the binder, causing them to react more quickly with the oxygen in the air [11].

According to Das et al. [23] the oxidation process depends on the type and source of the bitumen. Many reactive hydrocarbons may participate in the reaction process during oxidation. During the process, there are three separate processes that take place: fragmentation, oxygen addition, and condensation or carbonization. Fragmentation involves breaking down molecules into smaller fragments, which generates by-products such as water, carbon dioxide, acetic acid, and methane [24] Since these by-products are naturally volatile, the bitumen eventually loses its presence. Fig.2 illustrates Carbonyl (C=O) and sulfoxide (S=O) that produced in the bitumen because of the oxygen addition event [25] During the oxidation process asphaltene content of asphalt binder also increases [26]. Not to mention, the condensation or carbonization process produces molecules with a larger molecular weight and aromatic properties [24].



3

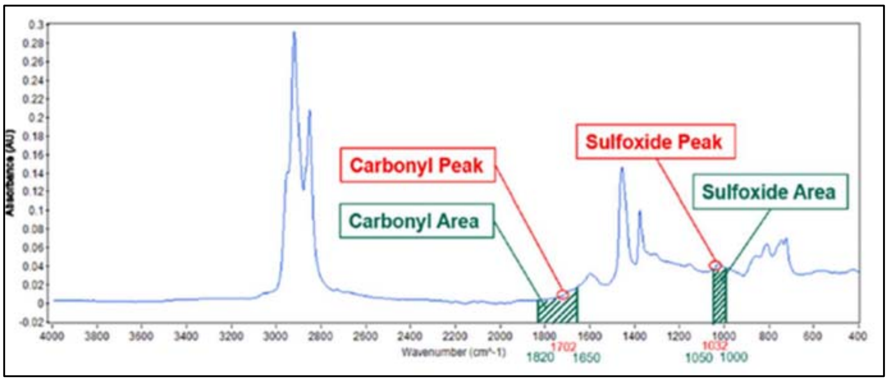


Fig. 2 Carbonyl and sulfoxide that produce during oxidation [27]

Volatilization is the process by which lighter or volatile components in the asphalt binder evaporate into the atmosphere. It usually occurs during the mixing process, where the asphalt binder is exposed to the high temperature. Polymerization is the combination of small particles to form a larger particle. However, there is no scientific evidence that this is one of the significant factors during low-temperature ageing. Thixotropy or steric hardening is defined as progressive hardening due to the formation of new structure in the asphalt binder over period, due to the reheating and remolding. According to Cháves-Pabón et al. [28] this process includes reorientation of molecules and crystallization of certain chemical compounds in the asphalt binder. In the other hand, syneresis is the hardening process of asphalt binder by eliminating lighter or oily component to the atmosphere from the surface of asphalt binder. Lastly, separation is known as removal of oil constituents, asphaltenes and resins by absorptive porous aggregate.

## 3. Performance of WCO as rejuvenator

After being exposed to traffic loads and UV radiation from sunlight, RAP usually becomes stiffer and more brittle than virgin asphalt. To address this issue, a rejuvenator is added to the RAP. Rejuvenators are additives or substances used in RAP to improve its performance before it can be reused or mixed with virgin asphalt. Rejuvenators have been used since the 1970s, and several commercial rejuvenators have been available in the market over the past decades. Numerous additives, including polymers, chemical modifiers, extenders, oxidants, antioxidants, hydrocarbons, and anti-stripping additives, have been developed to enhance RAP performance [29]. WCO was introduced as a modifier in 2012 and is known for its affordability and accessibility. Since then, WCO has been utilized as a binder modifier, rejuvenator, solvent for ground tire rubber pre-treatment [30], and most recently in self-healing alginate-based capsules. Typically, WCO was added to RAP mixture by using a dry method as illustrates in Fig.3 [31]. WCO was initially filtered to remove the dirt in the oil. While, the fresh aggregate and RAP mixture were initially heated to 164°C before being mixed with virgin asphalt binder and WCO.

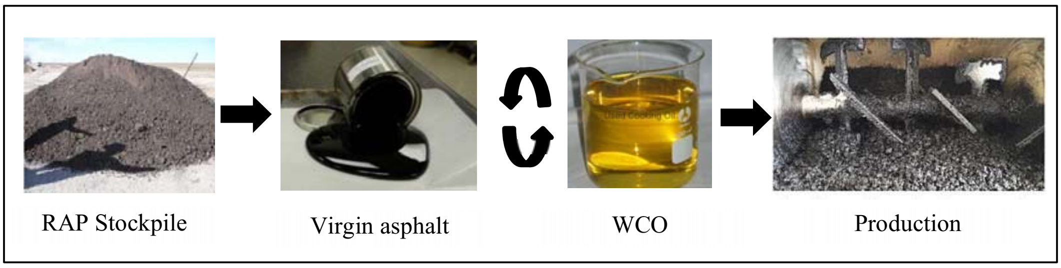


Fig. 3 Dry method to rejuvenate RAP mixture

Regarding the application of WCO to age-hardened bitumen as an antioxidant and rejuvenator, several conclusions have been noted. It has been shown that WCO can rehabilate the physical characteristic of aged binders. One of the key findings is that WCO has the capability to soften the binder, causing the softening point to reduce and the penetration value to rise. Additionally, the rotational viscosity of the asphalt is reduced when WCO is utilized [32]. Furthermore, it was noted that increasing the amount of added WCO raised both the flash and fire points. This implies that increasing the amount of WCO in the binder could decrease the temperature at which the binder becomes prone to ignition [33]. The optimal dosage of WCO for achieving a specific penetration value varies based on the initial penetration of the aged binder. For example, Asli et al. [34] found that a target penetration value of 80/100 required a dosage of 4-5% WCO for 30/40 penetration, while 3-4% WCO was needed for 40/50 penetration, and 2-3% WCO for 50/60 penetration. Rejuvenation with WCO results in greater penetration value, attributed to a reduction in the asphaltenes-to-maltenes ratio, while also reducing the tendency for short-term ageing compared to virgin binder [35]. WCO also improves the coating and adhesion potential with aggregates, which facilitates the creation of high-strength Hot Mix Asphalt (HMA). When WCO and Waste Engine Oil (WEO) were compared for performance, WCO demonstrated a greater ability to soften the binder in the past studies [36].

It has been observed that applying WCO significantly affects the performance of asphalt binders at both high and low temperatures. However, the application of WCO into the aged asphalt binder also has some drawbacks. It has been noted that adding WCO tends to reduce the asphalt's resistance to rutting, making it more prone to deformations from traffic loads [37]. Adding additional WCO to the asphalt binder also results in a higher m-value, suggesting that the binder is more resistant to cracking [38]. Thus, the usage of WCO can have a severe impact on the asphalt mixture overall performance, even though it can have certain advantages in terms of binder softening and viscosity reduction, particularly in terms of rutting resistance. To address this issue, crumb rubber was introduced by Yi et al. [35] to improve high-temperature rutting resistance. However, O'Rear et al. [39] found, 10% of WCO is still satisfied with the cracking and rutting resistance according to super pave grading. El-Shorbagy et al. [40] also discovered that, despite a decrease in rutting resistance, 3.5% of WCO exhibit virgin binder performance. Additionally, the finding of Zhang et al. [41] discovered that WCO with a lower acid value exhibited enhanced rejuvenation capability.

Based on the chemical properties of asphalt binder, Fourier Transform Infrared Spectroscopy (FTIR) shows that adding WCO decreases the carbonyl index in RAP binder, indicating a reduction in the level of oxidation [42]. The sulfoxide index may be more applicable, as not all carbonyl indices are suitable for assessing the degree of rejuvenation in aged asphalt [43]. This is because the Chicken Fat Oil (CFO) contains many carbonyls groups, which are derived from unsaturated fatty acids. Therefore, determination of chemical component of WCO is very important to track the ageing in the binder.

## 4. Ageing resistance performance of rejuvenated binder in cooperated WCO

The ageing performance of RAP incorporating WCO is a critical aspect of evaluating the effectiveness and sustainability of using WCO as a rejuvenator in asphalt pavement systems. Rheological properties are closely related to how well asphalt resists aged [44]. When evaluating asphalt's suitability for pavement applications, ageing resistance is an important element. In the case of rejuvenated asphalt, the focus is on secondary ageing resistance, this relates to the rejuvenated binder's resistance to further ageing processes throughout time [10]. In addition, the asphalt binder ageing performance is also subjected to determine the rejuvenator optimal dosage [45].

A study conducted by Xinxin et al. [46] investigated the mass loss of binder in RTFO to determine its ageing characteristics led to the discovery that the presence of light components (aromatics compound) in WCO causes the asphalt mass loss to increase with increasing WCO dosage. In contrast, Langa et al. [47] found that after RTFO the binder gained weight, this due to oxidation process had occurred during the heating. The mass loss or gain after heating can be a benchmark to determine volatilization or oxidation factor. After RTFO the rejuvenated binder shows a lower reduction in penetration value and complex shear modulus, illustrates higher ageing resistance when compared virgin asphalt binder [35]. This result was find similar to the result of Suo et al. [48], who discovered that after RTFOT, the viscosity of the rejuvenated asphalt binder increased, indicating that the binder became harder after heating. Comparing to the WEO, Joni et al. [49] discovered that after TFOT, the rejuvenated binders incorporated with WCO exhibited higher retained penetration and ductility values. This suggests that the asphalt binder with incorporated WCO possessed superior ageing resistance.

Mills-Beale et al. [50] evaluated the rheological properties of asphalt binder from Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) by utilizing fatigue resistance (G*/sin) and stiffness (S) as parameters. They found that short-term ageing was increased from these two parameters. Azahar et al. [51] revealed that when the Ageing Index Properties (AIP) was determined using fatigue resistance parameters (G*/sin), the modified binder with both untreated and treated WCO obtained a lower AIP than the control sample (60/70). This indicates the modified binder has lower ageing susceptibility to the virgin binder, due to the antioxidant content of the oil. These findings were confirmed by Mohi Ud Din et al. [52]. They found that base binder had higher ageing index (rutting parameters) than rejuvenated binder due to higher loss from loss of volatiles. Ji et al. [53] aged the asphalt binder to evaluate the fatigue resistance factor ($G^*/\sin\delta$), compared to base binder, the rejuvenated asphalt binder exhibits greater fatigue resistance with optimum dosage of WCO. However, El-Shorbagy et al. [40] conducted tests based on the Superpave method with 5.5 percent of WCO and observed that the rutting resistance after RTFO exhibited a lower value compared to the control binder, indicating WCO can be used in low volume road. Yi et al. [54] developed a novel rejuvenator, Waste Rubber Oil (WRO) from Crum Tire Rubber (CTR) and WCO. They found that WRO enhanced the aged binder's low temperature properties in terms of low temperature continuous grading, due to the presence of CTR in the rejuvenator. Yan et al. [55] combine WCO with European Rock Asphalt (ERA) to form novel rejuvenator. They discovered that increasing the dosage of WCO will increase the ageing resistance (G* ratio) of asphalt binder by reducing the creep strength and creep rate. Abdalla et al. [42] found that from Glow-rower (G-R) parameter, comparing to all examined aged binders and RAP, WCO is more efficient at increasing the resistance to cracking at intermediate temperatures due to the ability to reduce the oxidation in the rejuvenator.

Zargar et al. [35] found the asphaltenes to maltenes ratio decreased with the adding of WCO. Indicate that reduction in heavy component of asphalt. Santos et al. [56] simulate the rejuvenated asphalt binder with soybean oil by using RTFO and PAV, reported that, the carbonyl index increase as the ageing extend, indicates that the oxidation in asphalt binder can be determine from the FTIR analysis. While Lyu et al. [57] discovered that the synergistic impact of WCO and Crum Rubber improves the ageing resistance of the binder by lowering the carbonyl and sulfoxide indices. However, Luo et al. [58] found that inconsistence results from the sulfoxide index indicating not every oil can use sulfoxide index as indicator to oxidation. Finally, Ziari et al. [56] conduct a mechanical test to track ageing due to WCO, found that asphalt mixture in cooperated WCO is become more sensitive to moisture and show a poor performance on fatigue and cracking after ageing. This is because adding rejuvenator in the mixture led to less adhesion in the RAP aggregate.

## 5. Ageing Index Properties (AIPs) to Track oxidative ageing.

AIPs is used in assessing the ageing degree of asphalt binder by considering a combination of physical, rheological, and chemical properties. Various factors, such as changes in physical, rheological and chemical characteristics, are considered when measuring these ageing indices. Basically, AIPs can be explained as the ratio of a specific binder property's value before and after ageing [59]. These AIPs can help engineers and researchers develop more resilient and long-lasting road surfaces by providing valuable insights regarding the performance and durability of asphalt over time. The DSR is an extremely powerful tool for evaluating and characterizing the rheological properties of asphalt binders. Sweep temperature and sweep frequency are the two primary test modes that it is able of using. In contrast to the sweep temperature test, which subjects the binder to varying temperatures, the sweep frequency test places the binder under a variety of loading circumstances.

The research conducted by Rad et al. [27], chemical AIPs were identified to monitor oxidation levels in asphalt binder. Fourier Transform Infrared Attenuated Total Reflectance (FTIR-ATR) spectrometry was utilized to measure the chemical AIPs, with a focus on two specific indicators: the carbonyl area (calculated between 1850-1650 cm-1) and the sulfoxide area (calculated between 1000-1050 cm-1) in the infrared spectrum of the asphalt (see Fig. 2). The trapezoidal rule was applied to accurately estimate the areas within the specified wave number ranges. Cavalli et al. [60] evaluating the surface roughness or morphology of the binder by employing Atomic Force Microscopy (AFM) imaging device. To differentiate between different main domains, present in photographs of the bitumen phase, the AFM images was converted to an 8-bit greyscale representation. In this greyscale representation, the areas belonging to white and black represented two distinct domains known as the catana and paraphase within the asphalt. To quantify the area occupied by each of these domains, the ImageJ/Fiji software was used to perform black and white binary picture area calculations.

It is important to recognize that not all parameters can effectively track the factors influencing asphalt ageing. Table 1 provides an overview of numerous tests used to monitor ageing factors in asphalt binder. However, it should be noted that indexing values from AFM, UV-visible absorption spectroscopy, and Gel Permeation Chromatography (GPC) have not been established through research, making the accuracy of these parameters uncertain and speculative. Mass loss after heating, FTIR, and GPC have shown promise in tracking thermal oxidative ageing in binders. When it comes to ageing caused by sunlight, UV-visible spectroscopy and GPC are helpful methods. In the case of tracking volatilization, only mass loss after heating can provide a confirmation. However, Saturates, Aromatics, Resins, and Asphaltenes (SARA) fraction and GPC remain uncertain due to their inability to differentiate between volatilized molecules and broken-down particles. Furthermore, there is a lack of information in the past literature to effectively track polymerization, thixotropy, syneresis, and separation as ageing factors in asphalt. Despite the challenges in tracking these factors, ongoing research is necessary to develop comprehensive and reliable methods for monitoring and understanding the ageing process in asphalt binders.

Table 1 Parameters to index and tracking ageing factor

| Test | Ageing Index (AI) | Ageing factor tracking | | | |
|---|---|---|---|---|---|
| | | Thermal oxidative | Photo-oxidative | volatilization | Polymerization, Thixotropy, Syneresis and Separation |
| Mass loss | Yes | Yes | Maybe | Yes | Undiscover |
| Penetration | Yes | No | No | No | Undiscover |
| Softening | Yes | No | No | No | Undiscover |
| Viscosity | Yes | No | No | No | Undiscover |
| DSR | Yes | No | No | No | Undiscover |
| BBR | Yes | No | No | No | Undiscover |
| FTIR | Yes | Yes | Maybe | No | Undiscover |
| SARA fraction | Yes | Maybe | Maybe | Maybe | Undiscover |
| AFM | Maybe | No | No | No | Undiscover |
| UV-visible | Maybe | No | Yes | No | Undiscover |
| GPC | Undiscover | Yes | Yes | Maybe | Undiscover |

## 6. Conclusions

In conclusion, the utilization of RAP in road construction offers a cost-effective and eco-friendly solution, contingent upon rigorous quality evaluation and testing prior to implementation. Adjusting binder content to achieve optimal mix quality is vital for RAP due to its origin from recycled road surfaces, resulting in higher stiffness compared to virgin asphalt. Maintaining uniform temperature control during mixing and compaction is crucial for producing high-quality results. RAP source significantly impacts quality, with better outcomes seen from high-quality road surfaces. Disparities between virgin and RAP aggregates should be considered, highlighting the benefits of a well-graded mix for enhanced performance. Overall, with diligent testing, monitoring, and consideration of all factors, RAP supports sustainable road construction practices.

The efficacy of WCO as an asphalt pavement rejuvenator is well-established. Assessing the ageing performance of RAP rejuvenated with WCO is crucial for understanding its potential. Asphalt binder's ageing resistance, particularly in rejuvenated asphalt, hold significance. Through a comprehensive review of prior research, the impact of WCO on various ageing indices, encompassing physical, chemical, and rheological properties post-secondary ageing, is elucidated. Optimal dosage and binder characteristics post-rejuvenation are vital aspects highlighted. The review also covers past ageing evaluation methodologies, ageing resistance assessment, and oxidation tracking techniques. These findings deepen our understanding of oxidative ageing in rejuvenated asphalt, aiding further development of WCO rejuvenation techniques.

In essence, incorporating RAP into asphalt mixes aligns with sustainable strategies for addressing environmental and economic concerns. WCO, as a RAP binder rejuvenator, holds promise in enhancing asphalt pavement performance and sustainability. Its capacity to soften binders, decrease viscosity, and restore physical properties of aged binders is pivotal. Positive results are evident in rejuvenated binder characteristics, ageing resistance, and mechanical performance. However, precise WCO dosage is crucial to maintain rutting resistance. Future studies should explore prolonged performance and durability of WCO-incorporated RAP, further enhancing asphalt pavement sustainability. Additionally, while existing literature focuses mainly on thermal oxidative ageing and volatilization, limited attention is given to simulating photo-oxidative ageing. Therefore, research should address other ageing factors to fully comprehend the behaviour of rejuvenated recycled binders.

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