ESCUELA DE CONSTRUCCIÓN CIVIL
FACULTAD DE INGENIERÍA

Revista de la Construcción
Journal of Construction

Research Article

Effects of waste engine oil and cooking oil on the chemical, rheological, and permanent deformation of bitumen and asphalt mixtures

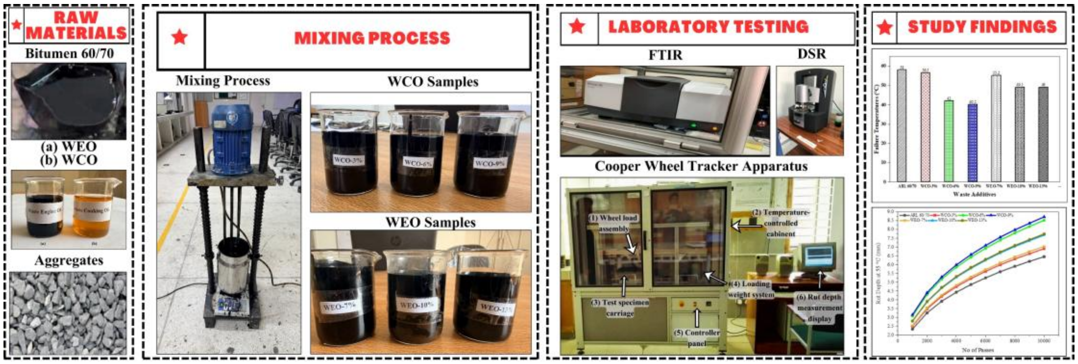
Yasir Rafique [1], Jawad Hussain [2], Waqas Haroon [3]*, and Rana Muhammad Shahid [4]

[1] Department of Civil Engineering, University of Engineering and Technology Taxila, Taxila (Pakistan); yasir.rafique@students.uettaxila.edu.pk
[2] Department of Civil Engineering, University of Engineering and Technology Taxila, Taxila (Pakistan); jawad.hussain@uettaxila.edu.pk
[3] Department of Civil Engineering, International Islamic University, Islamabad (Pakistan); waqas.haroon@iiu.edu.pk
[4] Department of Civil Engineering, International Islamic University, Islamabad (Pakistan); muhammad.shahid@iiu.edu.pk
*Correspondence: waqas.haroon@iiu.edu.pk

Received: 20.08.24; **Accepted:** 05.02.26; **Published:** 10.03.26

Citation: Rafique, Y., Hussain, J., Haroon, W. and Shahid, R. M. (2026). Effects of waste engine oil and cooking oil on the chemical, rheological, and permanent deformation of bitumen and asphalt mixtures. Revista de la Construcción. Journal of Construction, 25(1), 74-109. https://doi.org/10.7764/RDLC.25.1.74

Graphical abstract:



Highlights:

- Waste oils modify bitumen properties for improved road construction.
- Optimal dosages of WCO and WEO soften bitumen while maintaining performance.
- WCO enhances ductility; WEO impacts flexibility in modified asphalt.
- Rheological tests show stable high-temperature performance with low waste oil dosages.
- Recycling waste oils in asphalt offers sustainable and cost-effective solutions.

Abstract: In recent decades, the production of waste engine oil (WEO) and waste cooking oil (WCO) has risen, primarily attributed to shifts in human lifestyles and advancements within the automotive industry. In light of growing environmental concerns and efforts to enhance asphalt mixtures, researchers have investigated integrating these waste materials into traditional bitumen formulations. Thus, this study examines the laboratory investigation of varying proportions of WCO and WEO on the rejuvenation effect, including chemical, rheological, performance grading (PG), and resistance to permanent deformation of asphalt. A total of 7 blends were prepared, consisting of the base bitumen and different proportions of WEO (7%, 10%, and 13%) and WCO (3%, 6%, and 9%) by weight of bitumen. The rheological properties of high-temperature PG bitumen and the rutting depth of asphalt mixtures were evaluated using the Dynamic Shear Rheometer and Cooper Wheel Tracker Test. The research outcomes confirm that incorporating an appropriate dosage of WCO and WEO meets the criteria for conventional bitumen physical properties. Furthermore, the lower dosage of the WCO blend exhibited adequate tensile properties, thermal susceptibility, PG, and resistance to permanent deformation compared to WEO blends. Meanwhile, introducing WCO and WEO does not trigger additional chemical changes. However, excessive incorporation of waste oil can result in an undesirable reduction in the bitumen phase angle, thereby prolonging the construction timeframe. Therefore, based on rigorous statistical analyses, it is recommended that WCO and WEO be incorporated at dosages of 3% and 7%, respectively. This study highlights the potential of recycling WEO and WCO by incorporating them into bitumen for use in the asphalt pavement sector, thereby expanding the utilization of waste oils.

Keywords: Waste engine oil, waste cooking oil, thermal susceptibility, dynamic shear rheometer, wheel tracker test.

Abbreviation:

WEO: Waste engine oil

WCO: Waste cooking oil

PG: Performance grading

DSR: Dynamic shear rheometer

CWTT: Cooper wheel tracker test

FTIR: Fourier transform infrared spectroscopy

PI: Penetration index

VMA: Voids in mineral aggregates

Va: Air voids

VFA: Voids filled with asphalt

G*: Complex modulus

1. Introduction

The maintenance of asphalt pavements has substantial adverse effects on the economy, the environment, society, and energy use due to their vast area (Guesmi, Nafa and Bordjiba, 2023). However, as a country's population grows, traffic on its roadways further weakens them. Additionally, the issues with high axle loads, severe channelization, large-scale vehicles, and overload are increasingly important. Naturally, most pavements will likely need to be repaved when substantial flaws are discovered. However, this conventional method is more expensive and generates more waste. With improvements in people's living standards worldwide, especially in developed countries such as China and Australia, domestic and commercial waste has increased significantly (Li, Dong, et al., 2019). These wastes are collected from vehicle waste cooking oil (WCO) and engine oil (WEO). As the world population grows, so does the need for food. Cooking oil is obtained from various sources, including animal fats and plants, and is used to prepare or fry different types of food. Global animal-origin oil is about 189 million metric tons annually in the US and Canada to meet the requirements. China produces 15.9 million tons of cooking oil annually. Pakistan produces 88,000 barrels daily and imports 140,000 barrels per day. Improper treatment of these waste oils can have detrimental consequences for the environment and public health (Li, Liu, et al., 2019).

WCO is typically used in the production of soap, paints, and other chemical products, while WEO is customarily discarded or reused in the manufacture of new oil (Li et al., 2021). It is essential to highlight that used cooking oil can yield 40%-60% of WCO, with a recoverable fraction as low as 18.5%. Numerous research endeavors have been undertaken to explore the utilization of used cooking oils. These efforts encompass a range of applications, including, but not limited to, soap production, softening aged bitumen, and converting used cooking oil into biodiesel. In a 2014 study by Chen et al., 51% of households disposed of WCO into drainage systems, 17% deposited it in the soil, and an additional 15% entrusted its disposal to hired assistants. A mere 20-30% of the total WCO usage is estimated to be recycled or reused (Chen et al., 2014).

The potential for generating WCO is substantial, as evidenced by the Central Statistics Agency data in 2021. This data reveals that average per capita cooking oil consumption has increased significantly to 11.58 litres per capita per year, a notable 12.1% rise from the 10.3 liters per capita per year recorded in 2015. Several countries, including but not limited to China, Malaysia, the United States, Europe, Taiwan, Canada, and Japan, exhibit high levels of cooking oil consumption. Collectively, these nations generate an annual total of 16.54 million tons (Mt) of WCO. The primary sources of this WCO can be categorized into two main categories: commercial WCO from establishments such as hotels, restaurants, and catering services, and domestic WCO originating from households (Loizides et al., 2019).

WCO is predominantly composed of fatty acids and represents the residual oil-based by-product generated from domestic kitchens, commercial food outlets, and recycling facilities. It is defined as edible oil that has been repeatedly used for frying or heating and is consequently rendered unsuitable for further culinary use due to its harmful effects on human health (Chirani et al., 2021). WCO is typically derived from diverse vegetable and animal oils, and prolonged thermal exposure during frying initiates a series of chemical transformations, including hydrolysis, oxidation, and polymerization. These reactions give rise to a range of volatile and non-volatile compounds. The volatile fraction is released into the atmosphere, whereas the non-volatile fraction undergoes significant alterations in its physicochemical characteristics due to compositional degradation (Li, Liu, et al., 2019). Beyond its health risks, the indiscriminate disposal of WCO into natural systems poses serious environmental concerns, including soil contamination, deterioration of water quality, and disruption of aquatic ecosystems (Chirani et al., 2021).

In many countries, used cooking oil is disposed of in the sea or buried in landfills. Either way, it harms many lives, as aquatic life receives insufficient sunlight due to the thin oil layer on the sea's surface. Additionally, on land, the oil mixes with underground water, polluting it. Many countries use this waste to make biodiesel fuel for transportation (Khan et al., 2021). The amount of used cooking oil produced annually in our nation is enormous, and it is evident that not recycling it will harm the environment. One ton of waste oil can potentially contaminate 1 million tons of water. Mishandling of WCO can pose a significant risk to human and environmental health. Therefore, it is recommended to properly process and handle WCO before disposal in garbage cans, sewers, storm drains, or any similar locations to prevent environmental harm (Kabir, Yacob and Radam, 2014).

Residual oil can precipitate deposits along the inner surfaces of pipelines, resulting in a constricted cross-sectional area within the channel. It, in turn, reduces the wastewater flow rate and accelerates the occurrence of blockages. Furthermore, it has a detrimental impact on water quality, ultimately leading to adverse consequences for aquatic ecosystems, including fish, other fauna, and flora. WCO also causes several detrimental effects on soil. It induces soil compaction, reduces the rate of soil absorption, and disrupts the essential microorganisms and worms vital to soil fertility. Additionally, it retards germination. This oil can further alter the morphology and introduce toxic plant components (Irsyad et al., 2023).

Waste engine oil (WEO) is a byproduct of the automotive industry, collected annually from various automobiles. Zinc, lead, potassium, and magnesium are the most common contaminants in firewood. Due to the global population increase, approximately 11 billion tons of waste are produced annually, indicating that each person generates more than 1 ton on average, a trend expected to continue. According to estimates, waste generation is expected to double by 2025 compared to 2000. Modern societies rely on cars, which cannot operate without lubricants. The quantity of waste oil has increased in tandem with population growth and the rise in vehicle numbers. As the population increases, so does waste, leading to greater landfill space requirements and health issues (Counts, 2023). Massive volumes of garbage, including blast furnace slag, glass, steel slag, scrap tyres, plastics, WEO, and building and demolition waste, are being dumped in landfills and stockpiles worldwide, posing environmental and economic risks (Abukhettala, 2016).

About 40 million metric tonnes of lubricating oil are required globally each year. More than 60% of utilized lubricants are waste-produced oils. As a result, waste oils, which amount to 24 million metric tons annually, are among the more prevalent pollutants produced today (Qurashi and Swamy, 2018). Around 60,000 tons of oil are dumped in Pakistan, and some private companies illegally import 80,000 tons of toxic oil waste. Regarding ranking, pollution ranks 4th due to poor waste management and inadequate disposal practices. There are many techniques worldwide for disposing of used engine oil. Some of them are disposed of in the sea, on land, or by incineration. However, these techniques generate significant pollution, including land pollution. In Pakistan, used engine oil is recycled; people mostly make money by buying waste oil and recycling it. The transportation section relies on the consumption of large quantities of engine oil. The engine oil's properties deteriorated over time or with specific usage, and it was then discarded (Azam et al., 2020).

WEO is discarded oil obtained from vehicle engines (Qurashi and Swamy, 2018). The massive amount of waste oil results from millions of people worldwide using vehicles for both routine and commercial purposes, producing millions of tons of waste lubricating oil. The chemical composition of WEO varies among samples due to contaminants originating from the wear of engine components and from the heating and oxidation of lubricating oil during engine operation (Javed, Zaidi and Haroon, 2024). A substantial quantity of heavy metals in WEO has been carelessly disposed of, endangering the water and soil, harming the environment, and posing a risk to human health. The surplus of WEO is primarily disposed of through incineration or utilized as a fuel in combustion processes (Kupareva, Mäki-Arvela and Murzin, 2013). These oils create severe environmental concerns; it is essential to recycle or reclaim them. Modification of asphalt by various types of oils has also been reported. For example, mineral-oil-based oils, tall oil pitch, and high-viscosity oils have improved the low-temperature properties of base bitumen.

The WEO expansion has a relaxing effect, further enhances flexibility, and restores the properties of the base black-top. As a rejuvenating specialist, waste motor oil (WEO) is used to restore aged black-tops of varying maturity levels—the WEO blending ratio increases with maturity. For the black-top example, which matured for 5 hours, 2% of the blend can restore the infiltration, relaxation point, and malleability. For the black-top example, which matured for 7.5 hours and 10 hours, 4% of the blending sum can restore the entrance, relaxation point, and flexibility of the mature black-top. In contrast to a unique blacktop, the recovery temperature of blacktop increases only marginally. WEO impacts bond capacity among total and black-top, and stripping materials should be utilized (Kamoto et al., 2020).

Asphalt modification is not a new technique in the pavement construction industry, specifically in the United States of America (USA). It has been modified for the last twenty years. In the 1843s, the USA used asphalt modification through natural and artificial polymers (Rizvi, Khattak and Gallo, 2014). The European pavement construction industry began using asphalt modifiers in the 1930s, and North America adopted neoprene latex as a modifier in the 1950s. European contractors implemented more significant modifications than American states in the late 1970s by providing warranties and sureties to clients, thereby reducing pavement life-cycle costs. The American construction industry used polymers sparingly due to their high initial cost. Europeans discovered more polymers to modify asphalt in the mid-1980s, which were later used by the US industry. France took the initiative to develop modified bitumen across different bitumen classes in the early 1970s (Brûlé and Brule, 1996). Researchers (Bahia, Perdomo and Turner, 1997) surveyed 50 states and concluded that 47 states used modified bitumen in the 1997s. Thirty states added in a report that the quantity of modified bitumen would be more significant in the future. The research findings indicated that, based on pavement performance, numerous modifiers were used to enhance the service life of highways. Researchers (Awolusi et al., 2023) concluded that polymer modification would improve the engineering and rheological characteristics, which are directly influenced by the type and content of the polymer. Enhancing rheological properties would improve pavement performance, particularly in rutting resistance, fatigue, and high-temperature cracking.

WEO and WCO exhibit a chemical composition that closely resembles bitumen, primarily because both are derived from crude oil (Qurashi and Swamy, 2018; Li, Dong, et al., 2019). The utilization of such waste oils in asphalt mixtures has received considerable attention in recent years, both as a strategy to enhance the engineering properties of conventional asphalt and as a sustainable approach to reducing virgin bitumen consumption and alleviating associated environmental burdens. Consequently, the systematic investigation of WEO and WCO as recycling agents within asphalt technology has become a research priority. Several experimental studies have demonstrated the feasibility of incorporating WEO into bitumen. Researchers (Fernandes, Silva and Oliveira, 2018), for example, investigated the thermochemical characterization of bitumen modified with different proportions of WEO and recycled engine oil residues, combined with polymers. The modified bitumen was evaluated through conventional tests, including penetration, softening point, and viscosity. Findings indicated that, while penetration values remained comparable to those of commercially modified bitumen, the softening point temperature increased, suggesting improved high-temperature stability. Similarly, researchers (Liu et al., 2018) examined the rheological behavior of WEO-modified asphalt. They observed reductions in elasticity, heat sensitivity, and zero-shear viscosity, accompanied by enhancements in fatigue resistance and temperature sensitivity. Nonetheless, the modification was associated with a decrease in rutting resistance compared to the unmodified bitumen. Complementary results were reported by Jia et al. (2024) (Jia et al., 2014), who utilized a dynamic shear rheometer to evaluate aged asphalt modified with up to 5% WEO, showing a marked improvement in rheological performance.

In contrast, the findings of (Hesp and Shurvell, 2010) indicated that incorporating WEO at levels exceeding 15% adversely affected the low-temperature performance of rejuvenated asphalt, thereby limiting its applicability in colder climates. Complementary investigations by Hallizza Asili and colleagues (Nayak and Sahoo, 2017) examined the physicochemical behavior of rejuvenated asphalt, underscoring its practical viability and highlighting the potential economic benefits of valorizing WEO as a bitumen modifier. Extending this line of inquiry, (Zhang et al., 2017) evaluated the effects of WCO properties—particularly viscosity and acid value—on the fundamental, rheological, and chemical performance of rejuvenated asphalt. Their results confirmed that the intrinsic qualities of WCO play a decisive role in governing the efficiency of the rejuvenation process and the resultant mechanical behavior of aged bitumen.

Furthermore, it has been observed that higher-quality WCO tends to produce more effective rejuvenation outcomes, particularly in mitigating fatigue cracking and enhancing the mechanical performance of warm-mix asphalt (WMA) block pavements (Amigun, Sigamoney and von Blottnitz, 2008). (Zargar et al., 2012) extended this investigation by assessing the role of natural oils, including WCO and recycled motor oils, as rejuvenating agents. Their results showed that adding only 3–4% WCO was sufficient to restore the fundamental physical properties of bitumen, in contrast to the substantially higher proportion—approximately 20%—required with recycled oil. In parallel, (Caputo et al., 2019) investigated the rejuvenating efficiency of an oleic acid-based additive (HR rejuvenator) using advanced techniques such as Powder X-ray Diffraction (XRD) and 2D NMR spectroscopy. Their findings demonstrated that the HR rejuvenator effectively re-established the balance between asphaltenes and maltenes, thereby promoting the formation of a stable colloidal network within the bitumen. Similarly, (Asli et al., 2012) examined the microstructural and chemical alterations in asphalt rejuvenated with WCO and WEO. The study reported a marked reduction in sulfoxide (S=O) and carbonyl (C=O) functional groups, both of which are commonly associated with asphalt ageing. Collectively, these studies indicate that judicious incorporation of WCO or WEO at appropriate concentrations can restore aged asphalt to properties comparable to those of virgin bitumen, thereby meeting essential physical and rheological requirements.

With the increasing emphasis on sustainable construction practices and the growing need for cost-effective road maintenance, the application of rejuvenators in asphalt technology has gained significant attention. Rejuvenators are additives incorporated into pavement mixtures during production to restore the aged properties of the bitumen, thereby improving both physical performance and durability (Ren et al., 2022). Empirical evidence suggests that their use can significantly enhance pavement characteristics, resulting in an extended service life and reduced maintenance costs (Dinh, Park and Le, 2018). Among the various types, rejuvenating emulsions—rejuvenating agents dispersed in water-based formulations—are commonly used due to their ease of application and effectiveness. The performance of rejuvenators, however, is strongly influenced by several variables, including the type and dosage of the agent and the pavement material's intrinsic properties. In this context, WCO, a renewable by-product generated in large quantities from the food service industry, has emerged as a promising candidate for use as a rejuvenating agent (Irsyad et al., 2023).

Pakistan is a developing country, and its population continues to grow annually (Pakistan, 2017). However, this increase has also led to greater daily waste, with millions of tons of WCO and WEO vehicles produced annually (Khan et al., 2021). Both of these wastes create severe environmental problems, along with pollution of drinking water and soil. Further, despite numerous proposed procedures to evaluate the potential effectiveness of various rejuvenators in asphalt mixtures, no universally accepted standard protocol has yet been established. The haphazard disposal of WCO into municipal landfills and drainage systems, coupled with its reuse in restaurants after detrimental chemical treatments, has raised significant ecological, environmental, and health concerns. Consequently, over the past decade, several strategies have been devised to address these issues and promote the sustainable utilization of WCO. One notable approach involves producing biodiesel as a renewable energy source (Zhang, Ding and Zhao, 2012).

Recently, considerable emphasis has been placed on exploring the potential of WCO for asphalt modification. WCO has been found to have applications as rejuvenating agents, additives for hot-mix asphalt, and raw materials for producing bio-oils and bio-asphalts (Cao et al., 2018). Due to its lubricating properties, WCO can reduce asphalt viscosity. This reduction in viscosity contributes to lower consumption of fossil fuels. It mitigates the release of greenhouse gases (GHG) throughout the entire manufacturing and construction processes involved in producing bituminous pavement. Furthermore, integrating WCO with asphalt technologies offers several advantages, including extended hauling distances, improved working conditions, an expanded paving window, faster return to traffic, enhanced compaction efficiency, and increased workability for road construction projects (Rubio et al., 2012).

The recycling and reutilization of oils in modified asphalt materials can serve as a means to transform waste material properties into environmentally friendly materials. The effects of various rejuvenators, such as WCO- and WEO-modified asphalt mixture characteristics, vary due to differences in their sources and regional conditions (Eriskin et al., 2017; Pelitli, Dogan and Koroglu, 2017; Liu et al., 2018; Li et al., 2021). Thus, according to the author's best knowledge, very few studies have been published to date for Pakistan. The purpose of this study is to develop waste-oil recycling technology for use in asphalt pavements. It would not only resolve the disposal problem of waste oils but also reduce crude oil consumption in the form of asphalt binder (i.e., bitumen). The disposal issue pollutes the environment and poses a hazard to marine species. Hence, this study would not only resolve the issue of waste oil disposal but also reduce crude oil consumption. Therefore, it would reduce economic costs and promote a greener environment. For this purpose, WEO and WCO additives were incorporated into base bitumen (pen grade 60/70), and their impact on asphalt performance was evaluated. The experimental design was deliberately structured to include both bitumen-level and mixture-level analyses at multiple oil concentrations, ensuring that the distinct influence of each waste oil on chemical, rheological, and pavement performance characteristics could be comprehensively assessed.

Thus, according to the author's best knowledge, prior studies have examined the use of waste engine oil (WEO) and waste cooking oil (WCO) as rejuvenators/modifiers for asphalt binders; however, the available evidence remains fragmentary.

Therefore, most investigations emphasize either conventional binder tests or rheological characterization alone. At the same time, integrated validation linking chemical fingerprints (e.g., FTIR), viscoelastic response (DSR-based PG and frequency sweep/master curves), and mixture-level rutting performance remains limited. Moreover, direct, performance-based comparisons of WEO versus WCO under identical materials, mixing protocols, and dosage frameworks are scarce, and region-specific evidence for Pakistan, where high pavement temperatures and heavy axle loads govern permanent deformation, is particularly limited. To address this gap, the present study establishes a controlled comparative framework by incorporating graded dosages of WEO and WCO into 60/70 penetration-grade bitumen and evaluating their effects through a multi-scale program comprising conventional physical indices, FTIR, DSR-based PG, and frequency sweep rheology, and mixture rutting resistance using the Cooper Wheel Tracker Test, supported by statistical analysis.

This developed method has the potential to enhance bitumen's properties and to restore its usability using waste oil. In this study, the engineering properties of the modified bitumen were evaluated using a penetrometer, a ring-and-ball apparatus, and a ductilometer. Furthermore, Fourier Transform Infrared spectroscopy was used to confirm the dispersion of waste oils in the bitumen. Then, the temperature susceptibility of the modified bitumen and its performance grading (PG) were evaluated. Lastly, the rutting performance of modified waste oil asphalt mixtures was evaluated using the Cooper Wheel Tracker Test (CWTT). The remainder of this study is organized as follows: Section 2 presents the materials and experimental program (binder preparation and testing plan); Section 3 presents and discusses the binder and mixture performance results; Section 4 summarizes the main conclusions; and Section 5 outlines the practical implications and recommendations for pavement design and implementation.

2. Materials and methods

2.1. Aggregates

The coarse and fine aggregates were sourced from a limestone quarry in Taxila (Margalla), which is naturally rich in limestone. Their mechanical and physical properties were evaluated in accordance with AASHTO, BS, and ASTM standards, and the results are presented in Table 1. The National Highway Authority (NHA) of the Government of Pakistan (GOP) specified a coarser aggregate gradation for wearing coarse, namely, class "B" (National Highway Authority, 1998), as illustrated in Figure 1.

Table 1. Physical properties of aggregates.

Sr. No	Test description	Specification reference	Results	Recommended values (NHA General specification) (National Highway Authority, 1998)
1	Flakiness index (FI)	ASTM D 4791-99	5 %	15 (Max)
2	Elongation index (EI)	ASTM D 4791-99	4.9 %	15 (Max)
3	Aggregate absorption	AASHTO T 166	0.91 %	-
4	Sand equivalent	AASHTO T 176	74	45 (Min)
5	Los Angeles abrasion value (LAA)	AASHTO T 96,	25 %	30 (Max)
6	Sodium sulphate soundness value	AASHTO T 104,	3.51 %	12 (Max)
7	Deleterious material	Asphalt Institute, SP-2	0.9	0.2-10

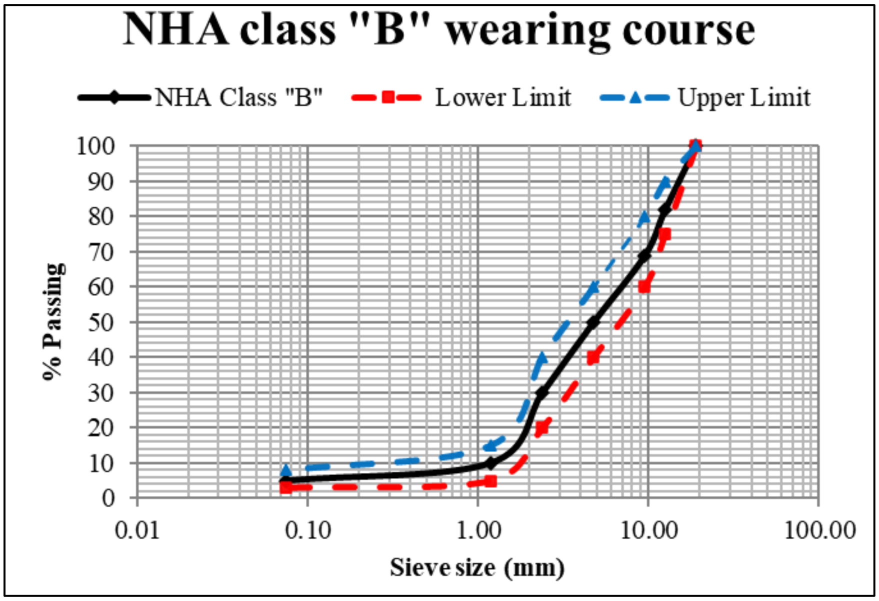


Figure 1. NHA Class B gradation.

2.2. Bitumen

For this study, penetration grade 60/70 bitumen was obtained from Attock Refinery Limited (ARL) in Rawalpindi, Pakistan.

2.3. Waste engine oil

The minimum dosage of WEO, i.e., 7% by weight of bitumen, was selected based on the previous studies (Mamun and Al-Abdul Wahhab, 2018; Mamun, Al-Abdul Wahhab and Dalhat, 2020). Still, the selection of high doses varies across sources and geographic locations. The maximum dosages of WEO recommended by various researchers range from 0% to 13% by weight of the bitumen (Eltwati et al., 2022). Therefore, three WEO percentages (7%, 10%, and 13%) were selected based on a previous study that aimed to determine the effect of varying WEO levels in the mixes (Mamun and Al-Abdul Wahhab, 2018). The WEO utilized in this research was gathered from nearby auto repair shops in the National Market of Chandni Chowk in Rawalpindi, Punjab, Pakistan, as illustrated in **Error! Reference source not found.**(a).

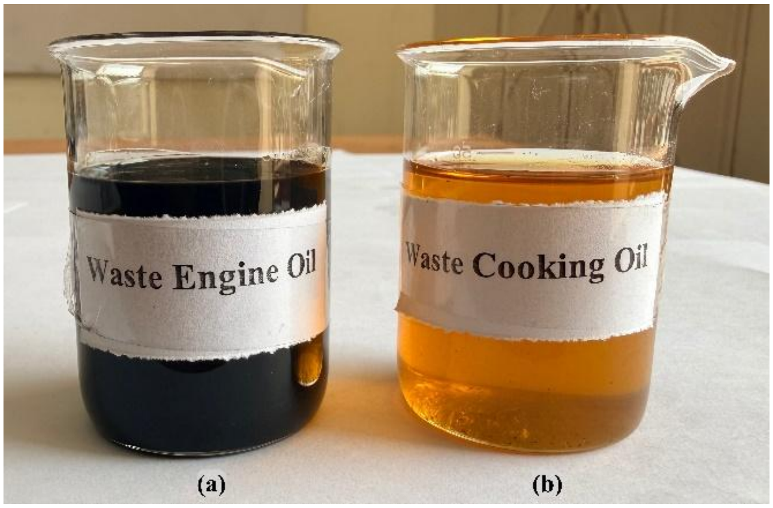


Figure 2. (a) Waste engine oil (WEO); (b) waste cooking oil (WCO).

2.4. Waste cooking oil

WCO is "waste cooking oil," a byproduct of several cooking processes. Its lightweight components are used to revitalize ageing bitumen since they are similar to the original bitumen. The minimum dosages of WCO 3% by weight of bitumen and maximum dosages up to 9% by weight of bitumen were selected in light of the previous findings (Ma et al., 2020). Thus, WCO was tested at 3%, 6%, and 9% in various blends throughout this investigation. The rejuvenator chosen was WCO, obtained from a nearby eatery, as illustrated in **Error! Reference source not found.**(b). Many fried pieces were collected in the oil samples and sorted using a standard physical method. A fine screener removes larger, unwanted particles from the oil. After filtration, the oil was so clean and clear that it was suitable for use in experiments. The chemical characteristics of WCO are crucial in regulating asphalt behavior. Figure 3 illustrates the study's roadmap, and the details are discussed in the methodology section.

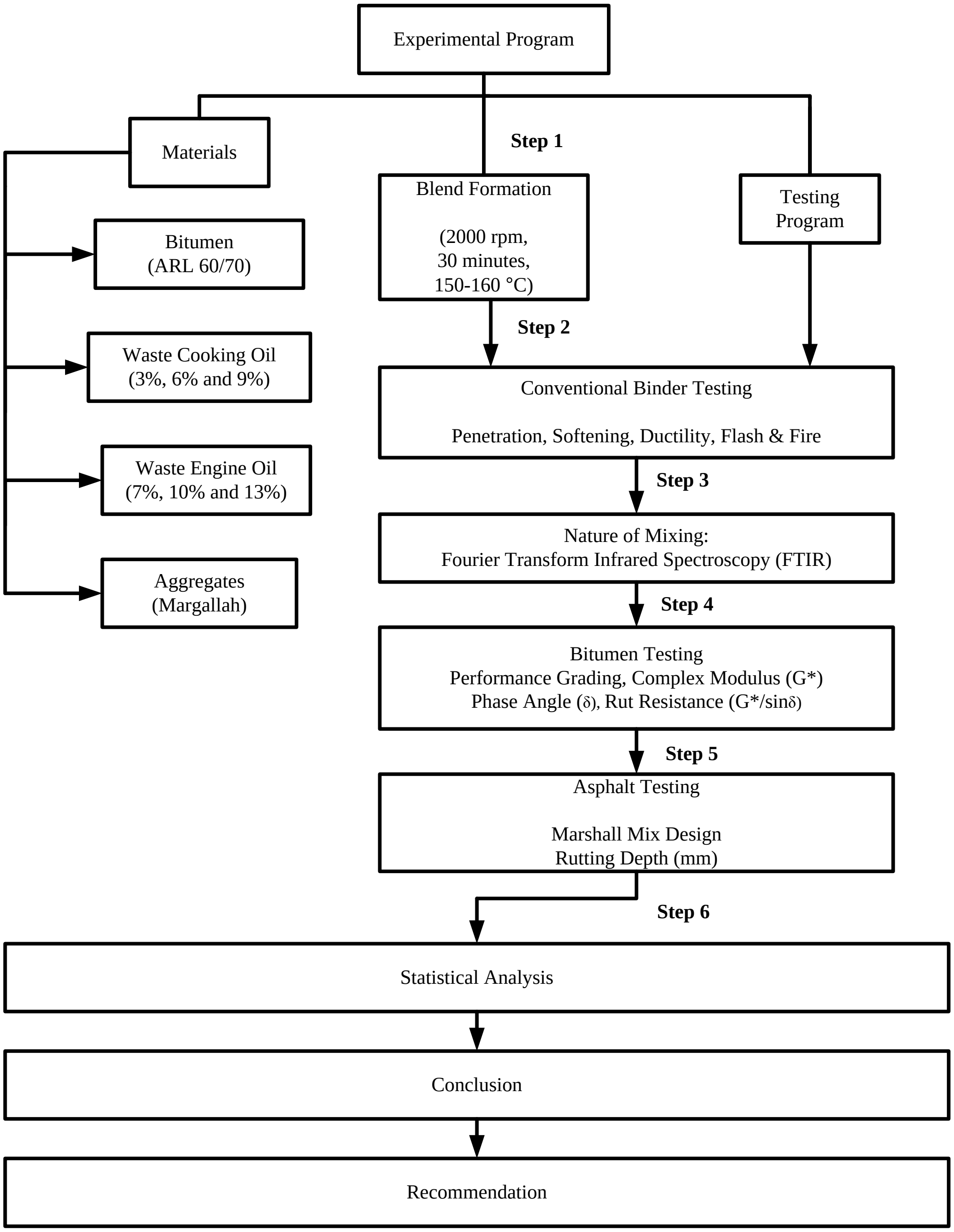


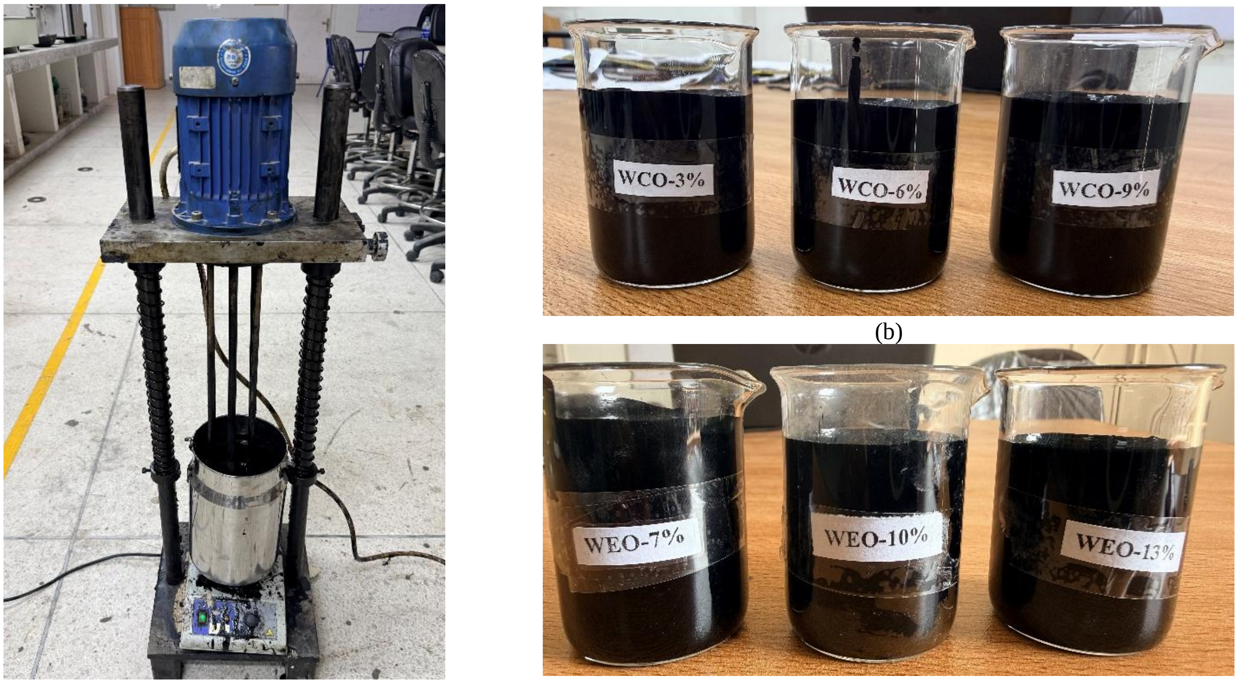
Figure 3. Roadmap of the study.

3. Methodology

The experimental program for this study was structured into sequential stages to ensure systematic evaluation of the modified bitumen and asphalt mixtures. The initial stage involved preparing modified bitumen from waste engine oil (WEO) and waste cooking oil (WCO). A total of seven samples were produced with a high-shear mixer, comprising three specimens incorporating WEO, three incorporating WCO, and one unmodified reference. In the second stage, conventional qualitative tests were conducted on the modified bitumen to examine the influence of WEO and WCO on fundamental bitumen properties. The third stage focused on confirming the chemical interaction and blending characteristics through Fourier Transform Infrared Spectroscopy (FTIR). Rheological characterization comprised the fourth stage, during which a Dynamic Shear Rheometer (DSR) was used to determine the high-temperature performance grade (PG). Master curves of the complex modulus (G*), phase angle (δ), and rutting parameter (G*/sinδ) were constructed to evaluate viscoelastic behaviour and rutting resistance. The fifth stage addressed mixture performance. Using the Marshall mix design procedure, the optimum bitumen content (OBC) was first established for the control mixture. This OBC was subsequently applied to prepare wheel-tracking slabs, enabling the measurement of rutting depth under simulated loading. Finally, the statistical robustness of the findings was verified in the sixth stage using Tukey's post hoc test to evaluate the significance of the DSR and wheel-tracking results. A schematic roadmap of the entire methodology is presented in Figure 3. The experimental framework was designed to evaluate the effects of both WCO and WEO at varying concentrations on bitumen and asphalt mixtures. This comprehensive design ensured that the influence of each oil type on chemical, rheological, and mechanical performance could be precisely identified.

3.1. Sample preparation

Firstly, 300g of untreated bitumen was heated in an oven at 100 °C, resulting in melting. Physical tests were conducted on base ARL bitumen 60/70 to verify its qualitative properties. Later, dosages of WCO (3%, 6%, and 9% by weight of bitumen) were blended with bitumen, and three samples were prepared. The combined process was formulated using a homogenizer, as illustrated in Figure 4(a).



(b)

(a)

(c)

Figure 4. (a) Mixing of WEO in bitumen using a homogenizer; (b) prepared samples containing 3%, 6%, and 9% WCO; (c) prepared samples containing 7%, 10%, and 13% WEO.

The modified samples were heated at 150-160 °C and agitated at 2000 rpm for 30 minutes (Li, Dong, et al., 2019; Li, Liu, et al., 2019). Likewise, WEO was added to the bitumen at 7%, 10%, and 13% of the total bitumen weight. Each sample was stored in a separate container with a unique marking. Figure 4 (b and c) illustrates the six prepared specimens.

3.2. Engineering tests

Penetration tests were performed to determine the effect of WEO and WCO on the bitumen stiffness, as per ASTM D 5. Bitumen was heated in an oven until it became fluid. Then, it was poured into a container up to its level. The container was then left to cool to room temperature for 40 minutes, while the water bath was maintained at 25°C, with the container remaining immersed for the same duration. Figure 5(a) shows a needle attached to a penetrometer. The container was removed from the water bath and placed on a machine. Then, its needle was lowered until its tip touched the top surface of the container. Scale and time were adjusted by setting their values to zero and 5 seconds, respectively. The machine was run, and the reading was noted down.

(a) (b)

(c)

Figure 5. (a) Penetrometer; (b) ring and ball apparatus; (c) ductilometer.

As illustrated in Figure 5(b), the ring-and-ball apparatus was used to determine bitumen consistency in accordance with ASTM D-36. In the first stage, bitumen was heated to 70-100 °C, just above its conditioning point. The glycerin and Dexedrine blend was applied to the outer surface of the glass plate to prevent bitumen from adhering to it. The ring was placed on the glass surface and covered with bitumen, allowing it to cool for 30 minutes in the air. The excess bitumen from the ring was eliminated from the upper part. The purified water in the measuring container was filled at 5 °C. The container was filled to such an extent that its surface, approximately 50 millimeters above the sample, was over the sample. The ring and ball guide were collected and placed on the center plate of the metallic casing, where they were left for 15 minutes. The heating base plate maintained a unit temperature of 50 °C until the bitumen melted and contacted the lower part of the metal plate. The temperature was noted when the ball alongside the bitumen reached the lower plate.

Ductility tests were performed on the Ductilometer (Figure 5(c)) to estimate the impact of WEO and ECO on the tensile behaviour and flexibility of bitumen, as per ASTM D113. The same penetrometer procedure was used to fill and condition the Ductilometer moulds. The moulds were immersed in a water bath for 40 minutes (the temperature should be 25 °C). The test was conducted at 25 °C, and the reading was recorded when the bitumen thread began to break or its diameter became too thin.

3.3. Thermal susceptibility

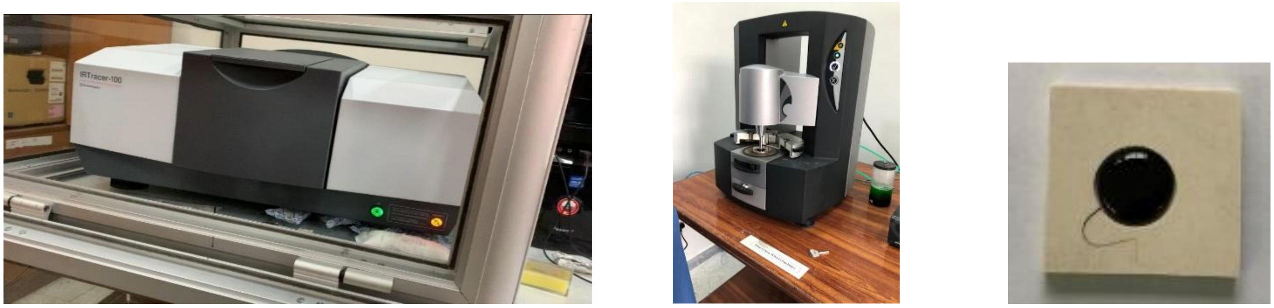
The PI (Penetration index) values were estimated using equation (1), which accounts for the effects of penetration and softening temperature (Felode, Jonathan and Ohinola, 2012; Haroon, Ahmad and Mashaan, 2022).

$$\mathrm{PI} = \frac{20-500\mathrm{A}}{1+50\ \mathrm{A}} \quad \text{where } \mathrm{A} = \frac{\log(800)-\log(\text{Pen at T})}{\mathrm{SP}-25} \qquad (1)$$

where 't' indicates the temperature, i.e., 25 °C, at which the penetration test was performed. "Pen at T" refers to the recorded penetration value at the specified temperature.

3.4. Fourier transform infrared spectroscopy

The FTIR test was performed according to ASTM E1252-98 to evaluate the chemical composition of virgin and modified bitumen samples, as illustrated in Figure 6(a). The scan ranged from 800 to 4000 cm^{-1}, and the analysis was performed at a four (4) cm^{-1} resolution. Fourier measures the absorption of infrared light as a function of wavelength, using transform infrared spectroscopy (FTIR) to determine the chemical composition of molecules.



(a) (b) (c)

Figure 6. (a) Fourier transform infrared spectroscopy; (b) kinexus dynamic shear rheometer; (c) 25 mm silicon mould.

3.5. Performance grading

The Superpave grading system was developed by the Strategic Highway Research Program (SHRP) to create a grading system based on the latest specifications and best engineering practices, meeting extreme climatic and loading conditions while accounting for the latest pavement failure analysis. The vital breakthrough for SHRP was the development of a bitumen grading technique known as a performance grading system. It aimed to develop a grading system based on the average maximum and minimum annual daily temperatures of an area. For example, 76-16 means this bitumen can be used in a locality where the maximum seven-day temperature is 76 °C and the lowest seven-day pavement temperature is -16 °C.

Therefore, the bitumen's high-performance Grading (PG) was determined using the Malvern Kinexus Dynamic Shear Rheometer (DSR), as illustrated in Figure 6(b). The apparatuses used for this test were Kinexus D.S.R., trimming tools, 'rspace' set up in PC, and silicon molds, as illustrated in Figure 6(c). Firstly, the original/modified bitumen was heated in an oven until it flowed. The modified/original bitumen was then poured into silicon molds. The filled molds were then allowed to cool to room temperature. The temperature was raised to 58 °C via a PC connected to the apparatus for executing the performance-grade test. DSR automatically noted the failure temperature when the parameter rut resistance ($G^*/\sin\delta$) fell below 1 kPa.

3.6. Frequency sweep test

The mechanical characterization of bitumen was carried out using a Kinexus dynamic shear rheometer (DSR) in accordance with AASHTO T315-19. For testing at temperatures exceeding 46 °C, 25 mm parallel plates with a 1 mm air gap were employed, whereas 8 mm plates with a 2 mm gap were used for temperatures below 40 °C. The performance grade (PG) classification was determined using 25 mm plates at 10 Hz, with failure temperature identified at a rutting factor of $G^*/\sin\delta = 1$ kPa. Frequency sweep tests were performed under controlled stress conditions across a frequency range of 0.1–100 rad/s for both unmodified and waste oil-modified bitumen at test temperatures of 22 °C, 34 °C, 46 °C, 58 °C, 70 °C, and 82 °C. The complex modulus ($|G^*|$) was determined using the time–temperature superposition principle, enabling the development of master curves across the tested frequency–temperature domain. Optimization of the shift factors and construction of smoothed $|G^*|$ master curves were achieved using Microsoft Excel's solver function, following the approach reported by (Fareed et al., 2020; Haroon and Ahmad, 2024b).

The apparatus used for this test was the KINEXUS DSR, trimming tools, a Rheoplus setup on a PC, and silicon molds. The original/modified bitumen was heated at 150 °C. The modified and original bitumen were subsequently poured into silicone molds. The filled molds were then allowed to cool to room temperature. The temperature was raised to 58 °C using the software attached to the apparatus for executing the performance-grade test. The temperature was initially set at 25 °C for the frequency sweep, and modified/original bitumen was placed between the two DSR plates (parallel plates). Then, the G* (modulus) as well as "δ (Phase angle)" were determined after completing the necessary steps with the software.

3.7. Preparation of asphalt mixtures

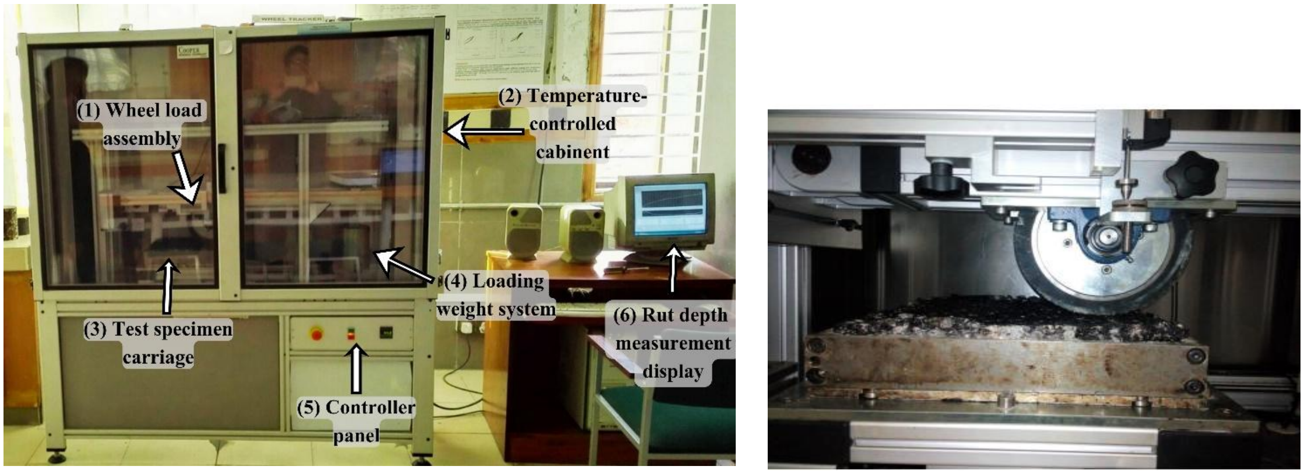
A Marshall mix design was used to determine the gradation of coarse and fine aggregates combined with selected optimum bitumen content (%) to determine the suitable percentages of air voids and voids in mineral aggregates (Guesmi, Nafa and Bordjiba, 2023; Haroon and Ahmad, 2024a). An asphalt mix was designed to ensure its stability and durability conditions (Chakravarthi, Rajkumar and Shankar, 2023). The materials and techniques used in preparing the mix are in accordance with the Asphalt Institute Manual "MS-2" (The Asphalt Institute, 1984). The primary objective of the mix design is to ensure that the asphalt has sufficient durability and stability when loaded, with no failure after traffic passes. Selecting a suitable void percentage in the asphalt mix enables targeted compaction during loading. It will enable the molecules to expand without bleeding or loss of stability. Selection of the highest value of void content that resists the harmful air and moisture entering an asphalt mix.

The asphalt mixtures were designed in accordance with the Marshall Method of mix design as specified in the Asphalt Institute Manual (MS-2) (The Asphalt Institute, 1984). Standard cylindrical specimens with dimensions of 75 mm in height (3 in.) and 102 mm in diameter (4 in.) were prepared, with careful control of mixing temperature, blending, and compaction to ensure the production of representative, dense-graded asphalt mixtures. The Marshall method primarily evaluates two critical parameters: (i) stability and flow, which measure the load-bearing capacity and deformation characteristics of the mix, and (ii) density–voids analysis, which assesses volumetric properties of the compacted specimens to ensure optimum performance.

The Marshall mix design method defines stability as the maximum load resistance of the trial sample at 60 °C (140 °F) in Newtons (N) or pounds (lb). The flow value measures the strain or displacement in increments of 0.25 millimeters (1/100 in.) during the stability test, from no load to maximum load. Stability loss is determined by comparing the stability measured after submersion of the sample in water at 60 °C for 1 day with that measured after 20 minutes of immersion in water at the same temperature. Additionally, the stiffness index is based on an empirical relationship and considers the stability ratio of the mixes at 60 °C.

3.8. Cooper wheel tracker test (CWTT)

The rutting performance of asphalt mixtures was evaluated using the Cooper Wheel Tracker Test (CWTT), following the procedure described by Eswan (2021), as shown in Figure 7(a). In accordance with the standard protocol, the applied load on the specimen can be varied between 520 N and 720 N, providing flexibility for simulating traffic conditions. The test can also be conducted within a temperature range of 30–60 °C, selected to reflect typical pavement surface temperatures during daytime conditions in Pakistan. For this study, the wheel tracking test was performed at two critical temperatures, 40 °C and 55 °C, under a constant applied load of 720 N, as illustrated in Figure 7(b). The test specimens were prepared using a roller compactor under a controlled temperature regime. The compaction procedure comprised four sequential stages: an initial 10 passes at 2 bar, followed by 10 passes at 5 bar, another 10 passes at 4 bar, and a final 5 passes at 3 bar. Upon completion of compaction, the specimens were conditioned at the designated test temperature before being subjected to the wheel tracking machine. Rut depth was measured continuously using a mechanical displacement transducer as the loaded wheel traversed the specimen surface. Data acquisition was automated, with rut depth readings transmitted to a computer every 100 loading cycles. Each test was continued up to 10,000 cycles or until the rut depth reached the failure criterion of 12.5 mm, consistent with the procedure outlined by Rasekh et al. (2023).



(a) (b)

Figure 7. (a) Cooper wheel tracking apparatus used for permanent deformation testing: (1) wheel load assembly; (2) temperature-controlled cabinet; (3) test specimen carriage; (4) loading weight system; (5) controller panel; (6) rut depth measurement display; (b) wheel passing on the slab.

4. Results and discussion

The results and discussion of bitumen modification with WCO and WEO are given below:

4.1. Penetration test results

A penetration test aims to determine the degree of hardness of the base and modified bitumen using the WEO and WCO methods. Figure 8 shows that untreated WCO exhibits greater penetration as the dosage of added WCO increases.

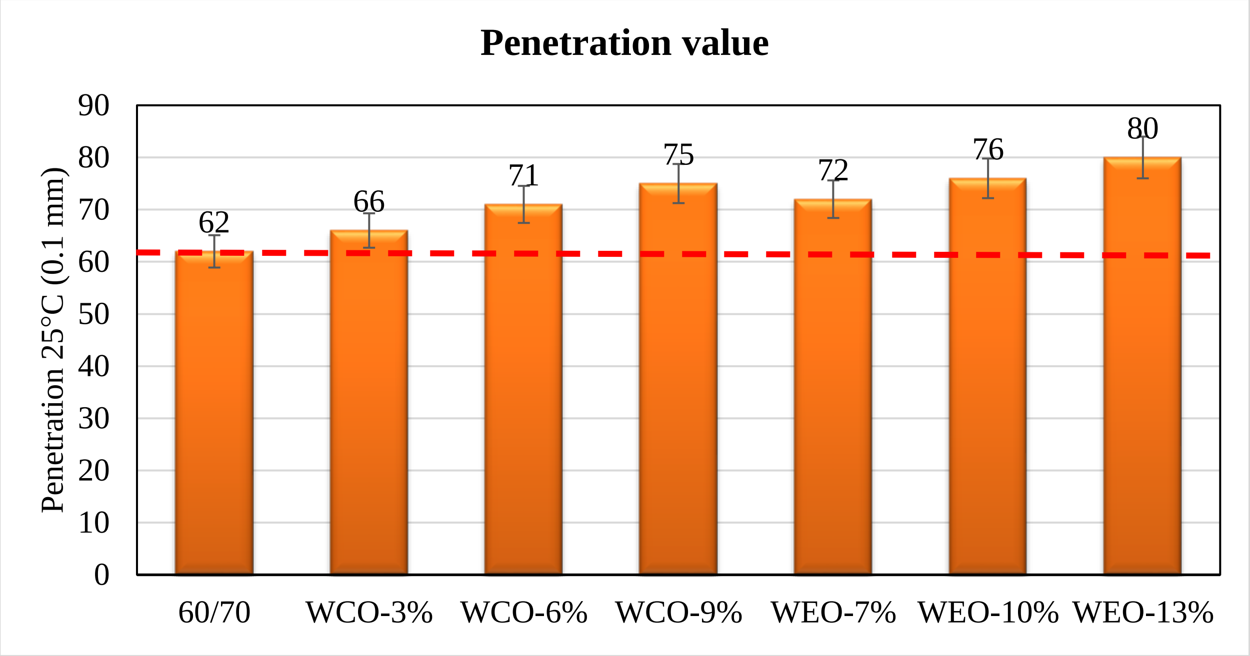


Figure 8. Effect of WEO and WCO on penetration values.

Specifically, the penetration values are as follows: for the control bitumen, it stands at 62 dmm; when 3% of WCO is added, it rises to 66 dmm; with 6% WCO addition, it further increases to 71 dmm; and finally, at 9% WCO addition, it reaches 75 dmm. This upward trend in penetration values indicates that bitumen becomes progressively softer as a greater volume of WCO is incorporated. Similar WEO penetration values were observed: 72 dmm for 7% WEO, 76 dmm for 10% WEO, and 80 dmm for 13% WEO. The negative impact on penetration values for WCO is notable, with increments of 6%, 15%, and 21% observed for 3%, 6%, and 9% replacement of WCO, respectively. Likewise, the adverse effect on WEO penetration values is significant, with an increase of 16%, 23%, and 29% recorded for 7%, 10%, and 13% replacement of WEO, respectively. The bar chart shows that the hardness values of all the modified bitumens by WEO and WCO decreased with increasing oil dosage, regardless of the type of modification. The rise in penetration trend can be attributed to a decrease in the asphaltenes-to-maltenes ratio. The change in penetrating values is more pronounced in WEOs than in WCOs. The pattern of the results is similar to that of the previous findings (Bilema et al., 2021).

4.2. Softening test results

Figure 9 shows that WEO had a lower softening point (SP) than WCO, resulting in softer bitumen. The softening point value obtained for base bitumen is 49 °C, and the softening point for WCO was measured at 46 °C for 3% replacement, 45 °C for 6% replacement, and 43 °C for 9% replacement with WCO. Likewise, altering the bitumen with WEO reduced the asphalt's softening point. The recorded values are as follows: 7% replacement yielded a softening point of 45 °C; 10% replacement, 44 °C; and 13% replacement, 42 °C. The findings indicated a noteworthy reduction in the softening point. This implies that introducing WEO and WCO into the bitumen decreased its viscosity relative to the softening point of unaltered bitumen, which was recorded at 49 °C. The incorporation of rejuvenators reduced the proportion of high-molecular-weight asphaltenes, thereby softening the bitumen. This property is crucial in liquefying bitumen, a key component in road construction. The SPs for lower dosages of WCO and WEO are acceptable and within the range (National Highway Authority, 1998). However, the high WCO and WEO contents reduced the softening points to 43°C and 42°C, respectively. The findings reflect that the penetration results incorporating WEO and WCO tend to soften the bitumen. Similar trends have been reported in a past study (Khurshid and Kumar, 2021).

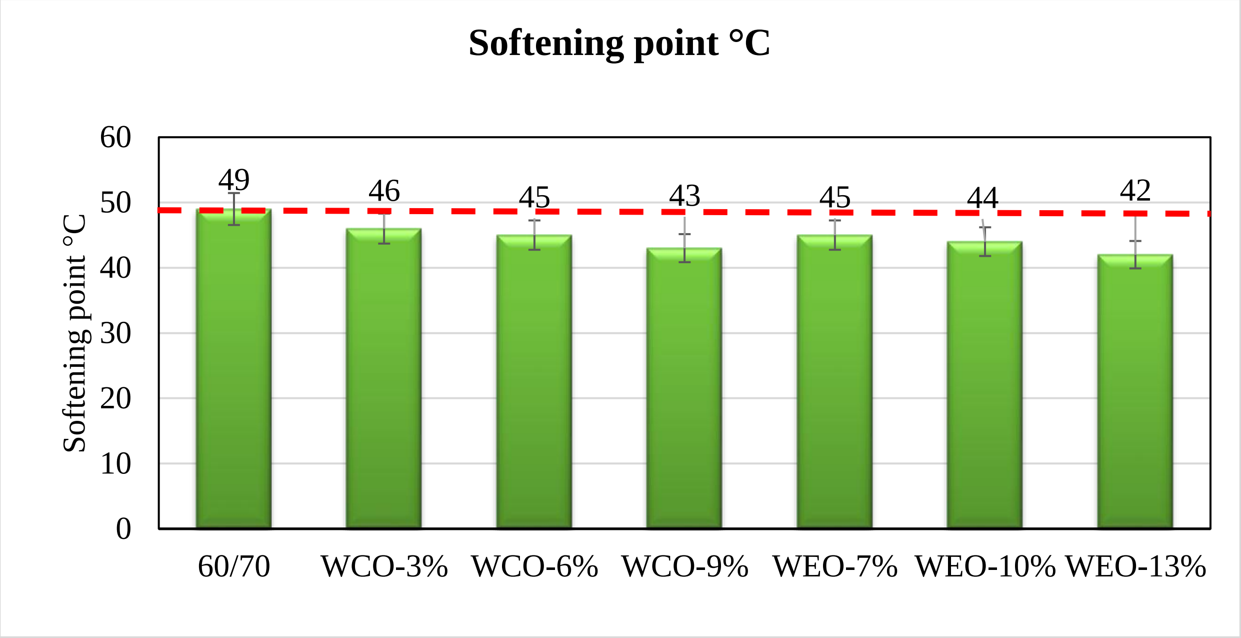


Figure 9. Effect of WEO and WCO on softening values.

4.3. Ductility test results

This parameter indicates the bitumen's stiffness, specifically its capacity to elongate in response to traffic loads during road construction without cracking. The ductility of the original bitumen was assessed and subsequently compared with the ductility values obtained from various trials involving different proportions of WCO and WEO. Figure 10 illustrates the ductility test results of the base bitumen ARL 60/70 and WEO and WCO-modified bitumen. Specimens prepared with varying ratios of WCO and WEO were tested for ductility.

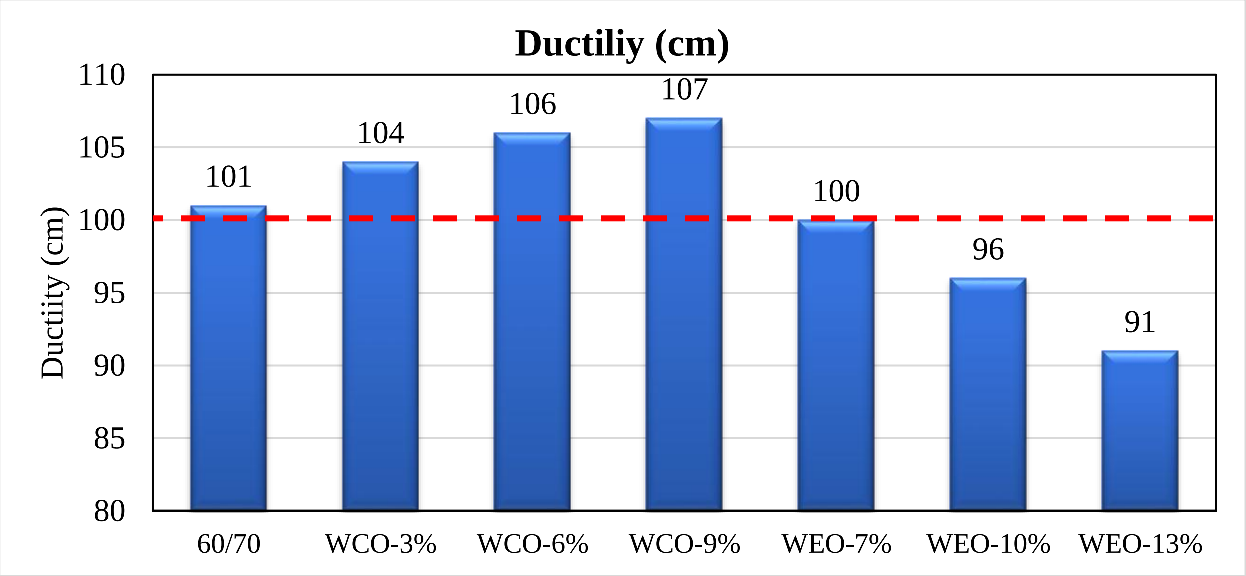
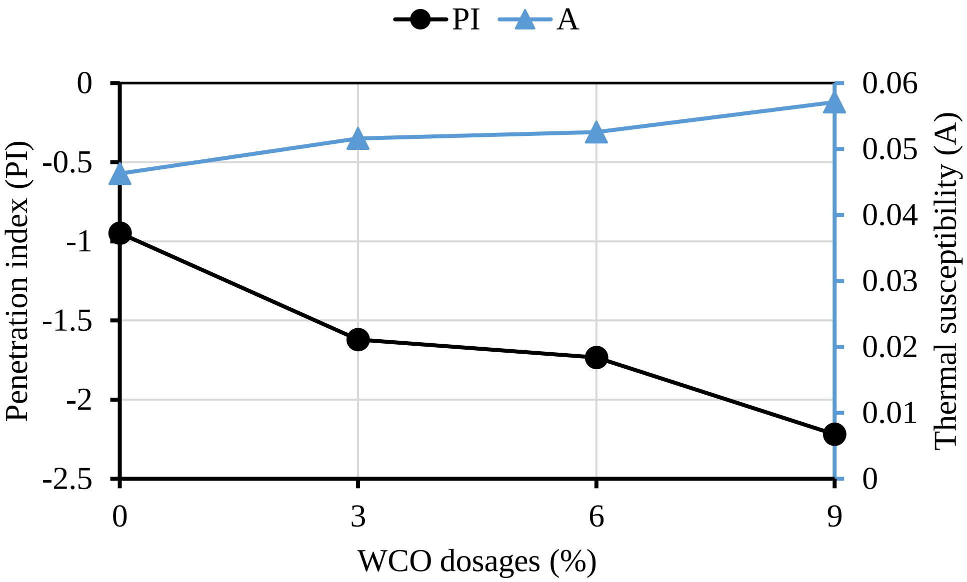


Figure 10. Effect of WEO and WCO on ductility values.

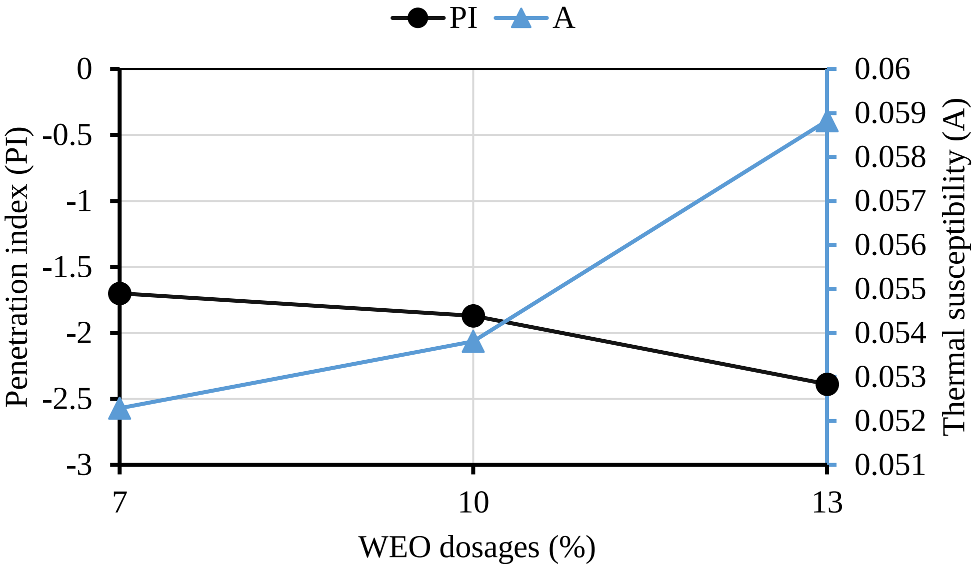
It was noted that the percentage of bitumen replaced by WCO increased to 3%, 5%, and 6%, whereas the percentage of bitumen replaced by WEO decreased to 1%, 5%, and 10%. The WCO ductility values correspondingly increased to 104 cm, 106 cm, and 107 cm, while the WEO decreased to 102 cm, 104 cm, and 10c3 mm, respectively. The modified bitumen with high WEO concentrations did not meet the ductility requirement, i.e., more than 100 cm at 25 °C. The WCO exhibited a more flexible and tensile deformation value of bitumen, i.e., more than 100 cm, which increased with the dosage of WCO up to 6%. However, a smaller increment was observed at higher dosages due to the blend's non-homogeneity. The results revealed a substantial increase in ductility compared to the unaltered bitumen, which stood at 101 cm. After a comprehensive evaluation of the ductility performance, it was concluded that an increased dosage of WCO could enhance the bitumen performance at moderate temperatures compared to WEO. Still, an excessive amount of WEO content was deemed unfavorable. Therefore, it suggests that increasing the WCO content in bitumen enhances its ability to withstand higher traffic loads before cracking. The ductility findings of WCO and WEO agree with those of a similar previous study (Bilema et al., 2021).

4.4. Effect of WEO and WCO on thermal susceptibility

An index was computed from measured penetrations and softening point temperatures, yielding Penetration Index values. A higher Penetration Index signifies a reduction in temperature sensitivity but an increase in hardness. Figure 11 (a and b) illustrates the thermal susceptibility and penetration index (PI) of base bitumen ARL 60/70 and modified bitumen with waste oils, i.e., WCO and WEO. The results of WCO demonstrate that penetration index (PI) values continuously reduced after incorporating WCO into the base bitumen. It predicts that the effect of WCO has compromised the bitumen's "A" values. Similarly, the WEO reduced the PI values, reducing the bitumen's thermal susceptibility (A). The thermal susceptibility characteristics of WCO show better results than those of WEO modification. It is commonly accepted that bituminous materials with a penetration index (PI) value lower than -2 exhibit high-temperature sensitivity (Bilema et al., 2021; Banerji et al., 2022). Therefore, high WCO-9% and WEO-13% dosages tend to become more brittle at lower temperatures. All the modified bitumen samples incorporating WCO and WEO fell within the Penetration Index (PI) range and were comparable to conventional bitumen. The recorded results are in agreement with the previous findings (Banerji et al., 2022).



(a)



(b)

Figure 11. Thermal susceptibility of (a) waste cooking oil and (b) waste engine oil.

4.5. Fourier transform infrared spectroscopy

The primary objective of the FTIR analysis was to elucidate the chemical structure modifications in bitumen induced by the incorporation of WCO and WEO. The spectra obtained for all modified samples are presented in Figure 12. Both WCO- and WEO-modified bitumen displayed a broad O–H stretching absorption band, observed at approximately 3563 cm^{-1} for WCO and 3750 cm^{-1} for WEO. In the case of WEO, additional absorption bands corresponding to aliphatic C–H groups were identified at 2904 cm^{-1}. It is important to note that the absorption peak near 2362 cm^{-1} is attributable to atmospheric CO_2 and should not be misinterpreted as evidence of a chemical interaction between the bitumen and the waste oils (Shoukat and Yoo, 2018). The characteristic stretching vibration of the carbonyl (C=O) bond typically appears between 1650 and 1735 cm^{-1}, confirming the presence of carbonyl functionalities. Similarly, absorption bands associated with C=C stretching were identified at 1600 cm^{-1}, which are indicative of aromatic compounds. Furthermore, minor peaks observed near 1540 cm^{-1} in the WEO-modified spectrum suggest the presence of polycyclic aromatic hydrocarbons (PAHs), compounds generally absent in fresh oils (Shoukat and Yoo, 2018). The band near 1470 cm^{-1} is linked to the asymmetric C–H stretching vibrations of methylene (CH_2) and methyl (CH_3) groups.

The absorption band at approximately 1050 cm^{-1} in the FTIR spectrum is generally attributed to sulfate (SO_4) groups rather than sulfoxide (S=O) functionalities, which typically appear in the 1100–1200 cm^{-1} range. In addition, the presence of carboxylic acid esters (CAO) within rejuvenating agents can be inferred from a characteristic peak around 1030 cm^{-1}. The spectral region between 680 and 940 cm^{-1} corresponds to the vibrational modes of the C–H bonds in benzene rings. For WEO-modified bitumen, additional intense absorption bands were observed within the 500–1000 cm^{-1} range. These bands are commonly associated with metallic residues generated by the high thermal stress and frictional processes that occur during engine operation (El-Shorbagy, El-Badawy and Gabr, 2019). The interpretations presented herein are consistent with previous findings reported in the literature (Haq *et al.*, 2018). Overall, the spectra exhibited reproducible patterns across all analyzed samples.

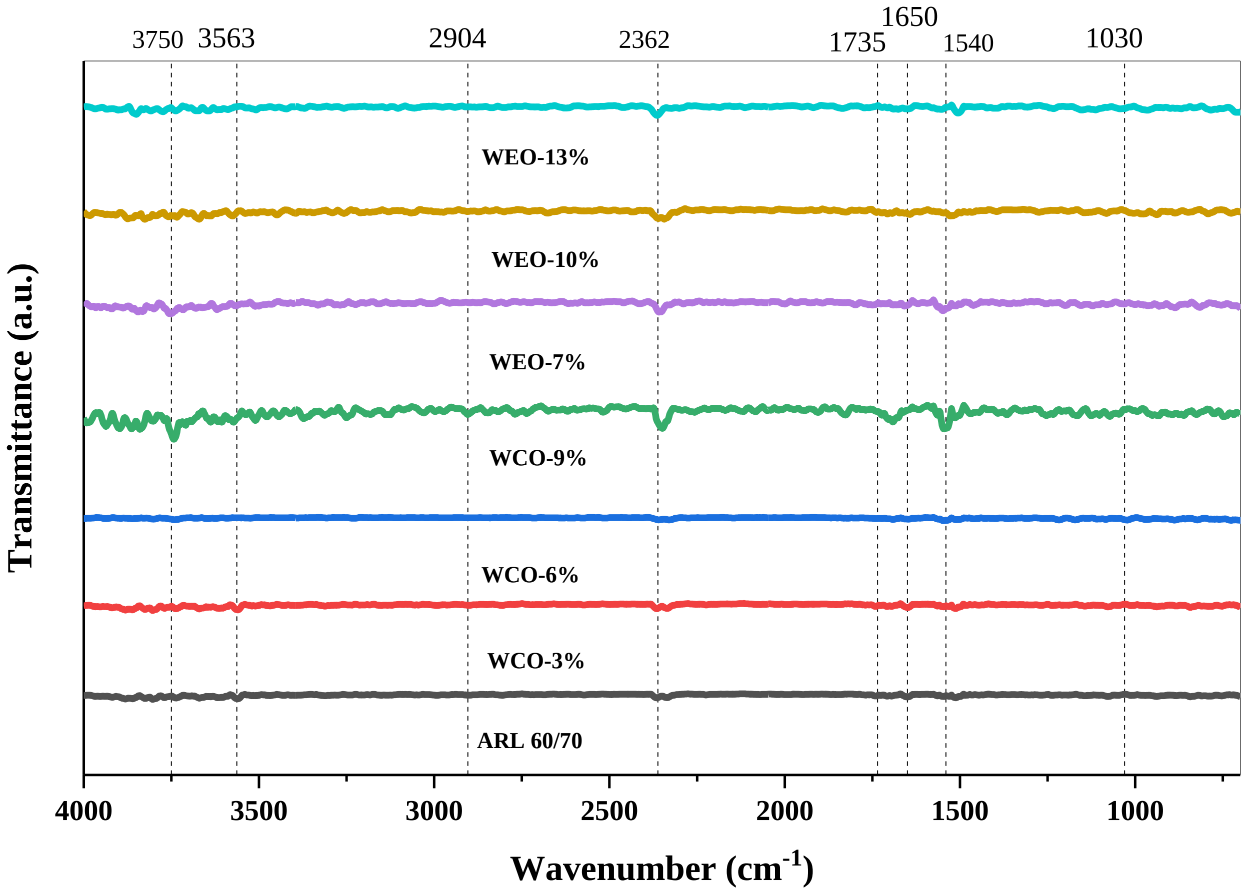


Figure 12. FTIR Analysis of WCO (3%, 6%, and 9%) and WEO (7%, 10%, and 13%) modified bitumen.

In summary, the incorporation of WCO or WEO into base bitumen enhances the conjugated system associated with the carbonyl (C=O) functional group, which in turn produces a slight reduction in the stretching frequency of C=C bonds. This reduction suggests a possible decrease in asphaltene content within the modified bitumen. Importantly, the blending of WCO and WEO with bitumen does not result in the formation of new chemical compounds, as no chemical reaction occurs between the bitumen and the waste oils (Liu et al., 2019). The influence of altered asphaltene content on the performance of WCO- and WEO-modified bitumen, as well as on corresponding asphalt mixtures, was further substantiated through advanced characterization techniques, including dynamic shear rheometer (DSR) testing and wheel tracking analysis. The outcomes of these evaluations are elaborated in the subsequent sections.

4.6. Effect of WEO and WCO on performance grading

Figure 13 illustrates that a base bitumen ARL 60/70 PG has a viscosity of 58. It was calculated based on failure temperatures deduced from G*/sinδ values exceeding 1 kPa. The incorporation of WCO and WEO reduced PG, with WCO showing a greater reduction. As shown in Figure 13, the failure temperature decreases with the addition of WCO and WEO. A small dosage of WCO reduced the PG from 58 to 52, while dosages greater than 3% by weight of bitumen reduced the PG from 58 to 40. Similarly, the small concentration of WEO, up to 7% by weight of bitumen, also reduced the PG from 58 to 52. This trend continues with an increase in WEO concentration to 13% and PG changing from 58 to 46. Thus, increasing the WEO dosage beyond 7% didn't affect the PG. Therefore, it is confirmed that small doses of WCO-3% and WEO-7% may be used in bitumen for moderate climatic conditions to pave roads with average loading and traffic capacity. Based on the failure-temperature results, the optimum dosages of WCO and WEO are 3% and 7% by weight of the bitumen, respectively. The findings agree with previous results (Bilema et al., 2021).

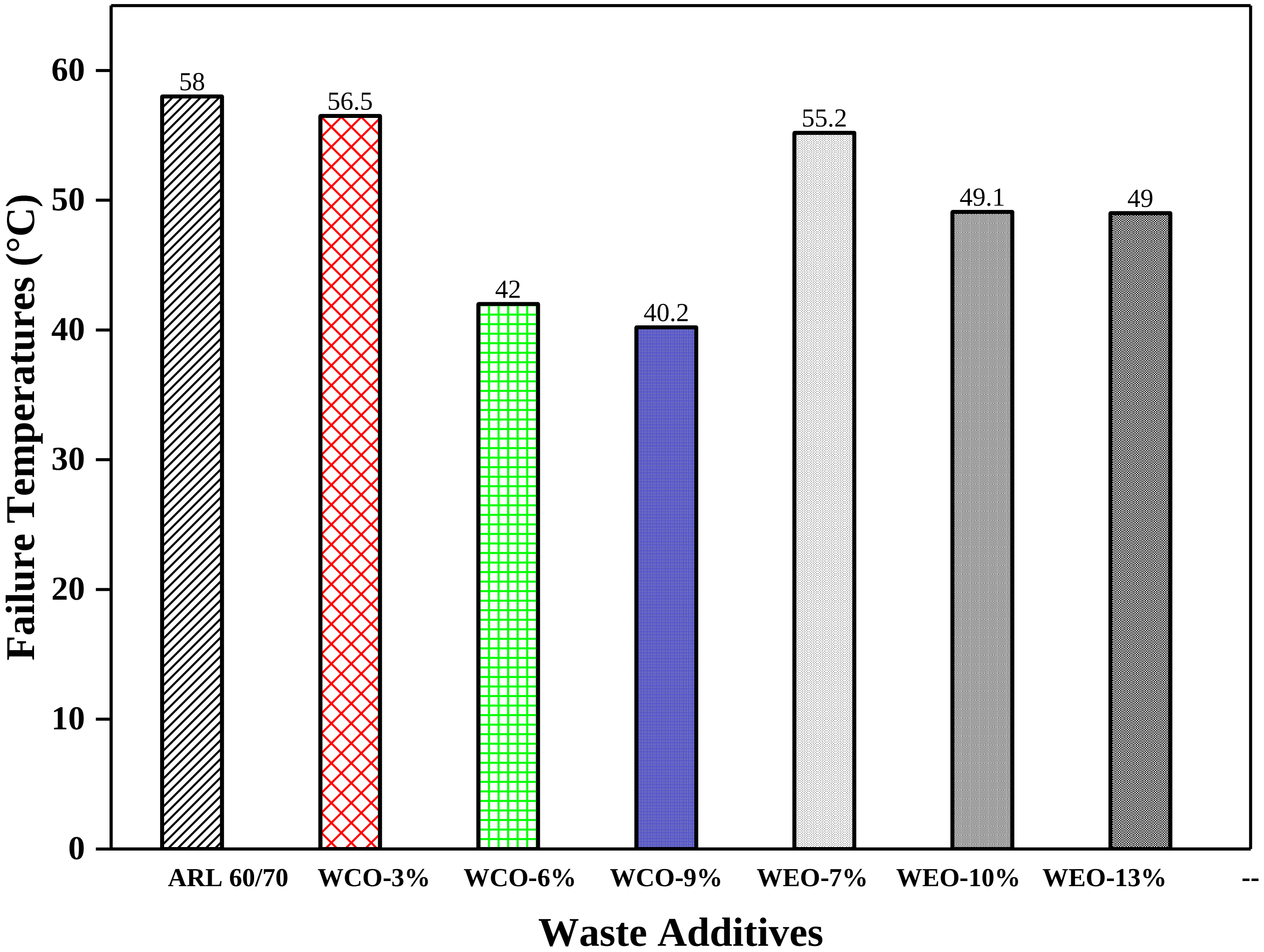
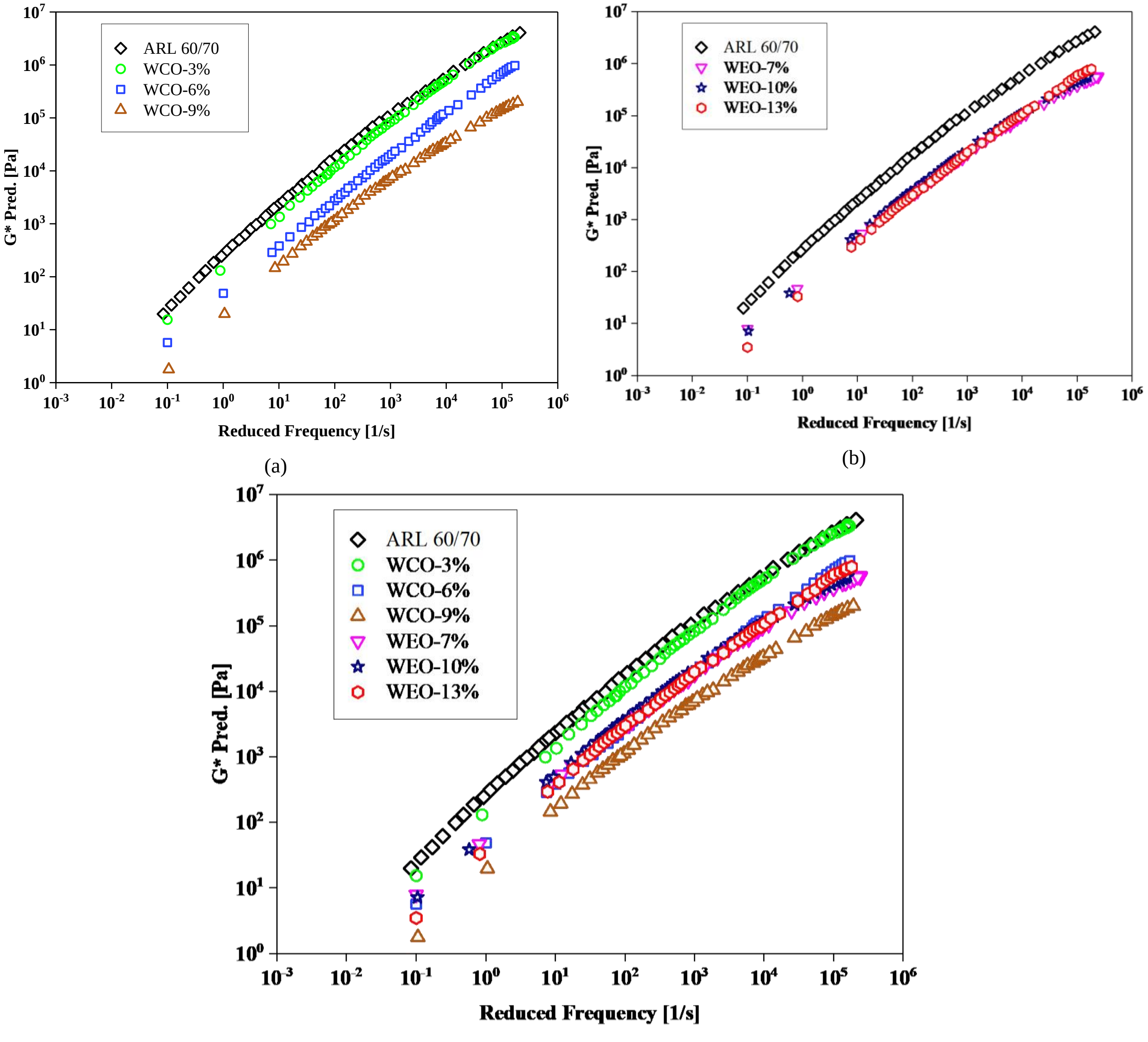


Figure 13. Effect of WEO and WCO on performance grading.

4.7. Frequency sweep test results

The primary objective of this investigation was to examine the influence of elevated temperatures on the rheological parameters of bitumen, specifically the complex shear modulus (G*), phase angle (δ), and rutting resistance (G*/sinδ), for both unmodified bitumen and modified bitumen with WCO and WEO. The frequency sweep test was employed to characterize the temperature- and time-dependent behavior of laboratory-prepared bitumen specimens incorporating these waste oils. Testing was conducted across a frequency range of 0.1 to 100 Hz, enabling the construction of master curves for each modified bitumen. The master curves were generated using a sigmoidal function, as recommended for modelling bitumen's viscoelastic response (Günay, 2022). Figure 14(a–c) illustrates the master curves of G* plotted against reduced frequency for modified bitumen with WCO, WEO, and a combination of both oils, providing a comparative assessment of their rheological performance relative to the base bitumen.

The complex modulus (G*) represents the stiffness of bitumen under varying temperature and loading conditions. It is defined as the ratio of maximum stress to maximum strain (Oner and Sengoz, 2018). As shown in Figure 14(a), the incorporation of WCO reduced G* values at elevated temperatures, with the effect becoming more pronounced at higher WCO dosages.

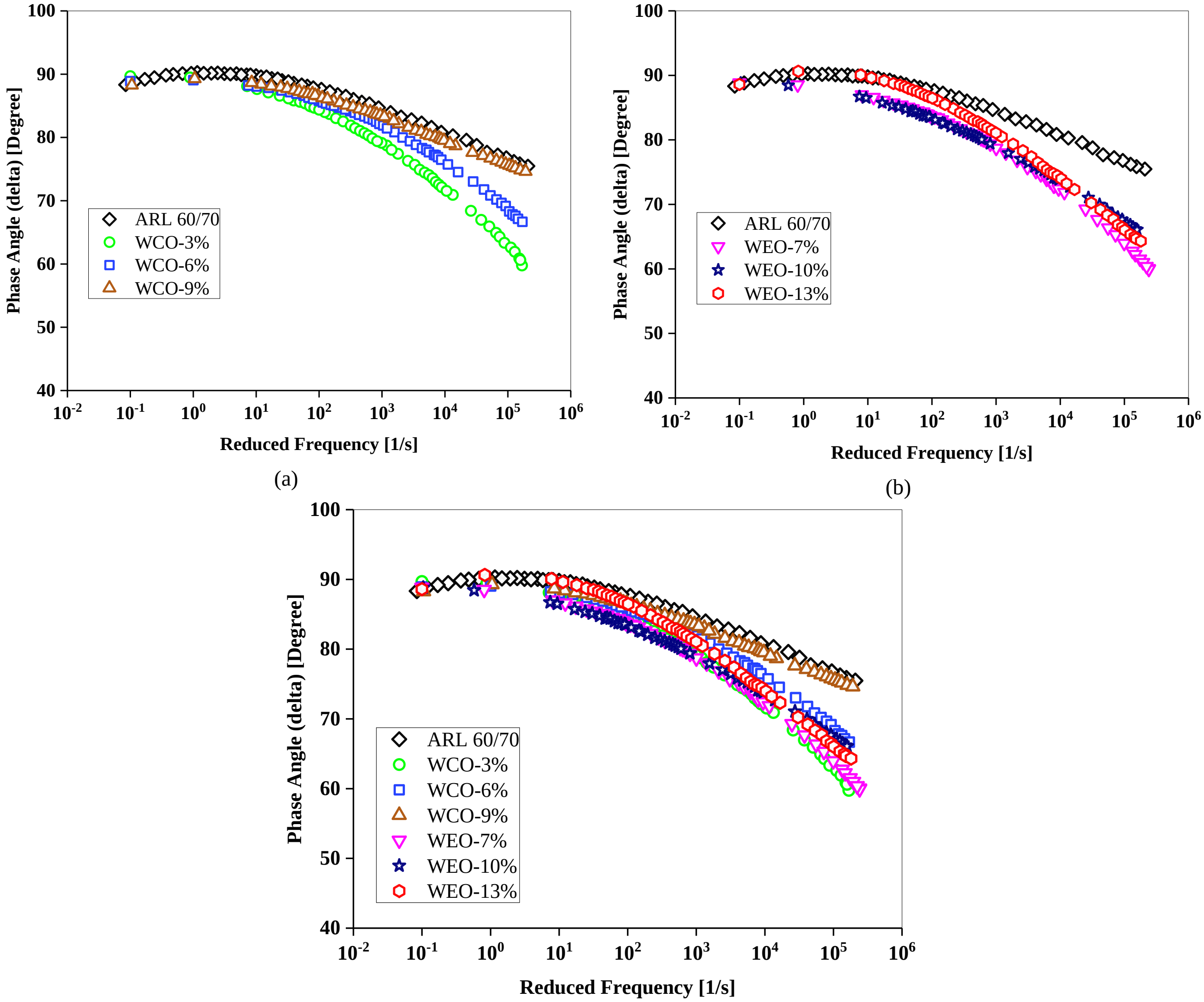


(a) (b)

(c)

Figure 14. Complex modulus master curves at 58 °C for (a) WCO-modified binder; (b) WEO-modified binder; and (c) WCO- and WEO-modified binders.

This behavior indicates that increasing WCO content decreases bitumen stiffness and consequently reduces rutting resistance under high-temperature conditions. A similar trend was observed for WEO-modified bitumen. Figure 14(b) illustrates a notable decrease in G* values with increasing WEO content, particularly within the low-frequency range, where bitumen stiffness and rutting resistance are more significantly diminished. Comparative results presented in Figure 14(c) further demonstrate that the reduction in G* with WEO addition is more substantial than with WCO at equivalent dosages, underscoring WEO's greater softening effect on the bitumen matrix at elevated temperatures. However, with the low dosage of WCO, i.e., 3%, G* values increase compared to all the waste oils and are more pronounced in all frequency ranges, which enhances the stiffness in bitumen and reduces rutting parameters. According to prior research, the introduction of waste oils decreased the complex shear modulus, findings that align with those of this study (Bilema *et al.*, 2021).



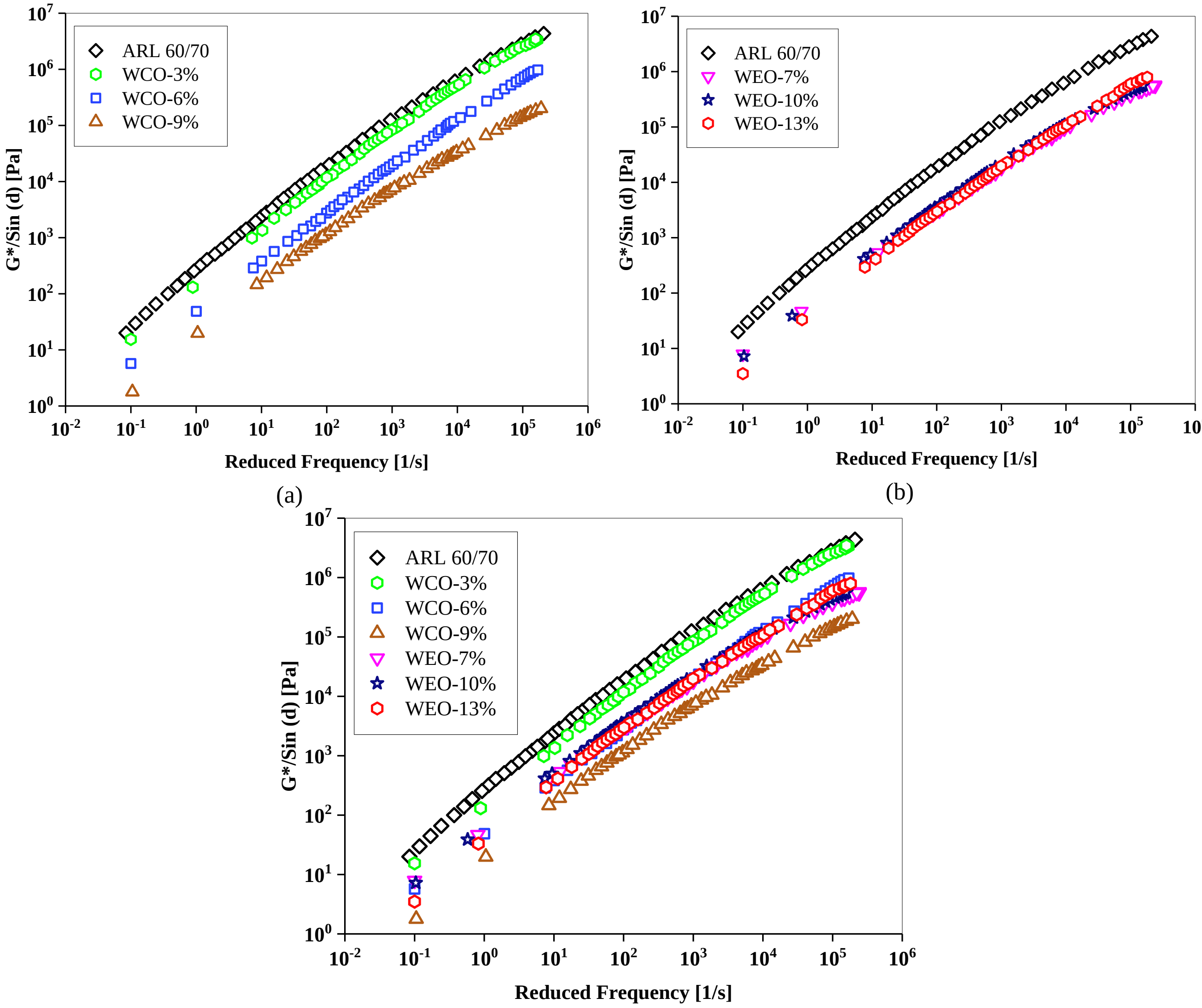
(a)

(b)

(c)

Figure 15. Phase angle master curves at 58 °C for (a) WCO-modified binder; (b) WEO-modified binder; and (c) WCO- and WEO-modified binders.

Figure 15 (a, b, and c) illustrates the master curves drawn between the phase angle and reduced angular frequency after the bitumen modification with WCO, WEO, and combined WEO and WCO. The results indicate that incorporating waste oils generally reduced the bitumen's phase angle, thereby enhancing its viscoelastic response.



(a)

(b)

(c)

Figure 16. Rutting resistance master curves at 58 °C for (a) WCO-modified binder; (b) WEO-modified binder; and (c) WCO- and WEO-modified binders.

As shown in Figure 15(a), the addition of WCO modified the phase angle behavior, with the 3% dosage producing a marked reduction compared to the control. In contrast, a higher dosage of 9% WCO exhibited a phase angle pattern comparable to that of the base bitumen, suggesting that phase angle values tend to increase as WCO content rises. This reduction at lower dosages can be attributed to the presence of polar and unsaturated compounds in WCO, which interact with the bitumen matrix, strengthening intermolecular bonding and promoting a more elastic, flexible material. These observations are consistent with the findings of (Fernandes et al., 2017). Figure 15(b) illustrates the phase angle–frequency relationship for WEO. Similar to WCO, WEO-modified bitumen exhibited lower phase angles at lower frequencies or elevated temperatures, indicating enhanced elastic behavior. This effect was particularly pronounced at lower dosages, notably WCO-3% and WEO-7%, aligning with previous research outcomes (Li, Dong, et al., 2019). Figure 15(c) presents the combined phase angle behavior of both oils, further confirming that lower dosages (WCO-3% and WEO-7%) consistently reduced phase angle values and improved the elastic characteristics of the modified bitumen. These results corroborate earlier studies that reported comparable improvements in viscoelastic properties with waste oil modification (Chen et al., 2014; Bilema et al., 2021).

Rutting resistance, expressed as the rutting factor (G*/sinδ), is a critical indicator of bitumen performance at elevated temperatures under reduced frequency loading (Akpolat, 2022). The master curves revealed a pronounced reduction in rutting resistance for WEO-modified bitumen compared to WCO. As illustrated in Figure 16(a–c), the inclusion of WCO, WEO, and their combined application improved the high-temperature performance of the modified bitumen relative to the base bitumen. Figure 16(a) shows that a 3% WCO dosage yields the highest rutting resistance among the WCO-modified samples, outperforming those with higher WCO contents. A similar trend was observed for WEO, with the 7% dosage demonstrating superior rutting resistance compared to higher concentrations (Figure 16b). When considering the combined effect of waste oils, WCO at 3% consistently provided the most significant enhancement, as indicated by the elevated G*/sinδ values across the tested samples (Figure 16c). These outcomes suggest that lower dosages of WCO and WEO optimize bitumen stiffness and resistance to permanent deformation, in line with earlier findings reported by (Chen et al., 2014; Bilema et al., 2021). The outcomes of the frequency sweep test, which characterize the viscoelastic behavior of bitumen through the complex shear modulus (G*) and phase angle (δ), are presented in Figure 17 as a Black Space diagram.

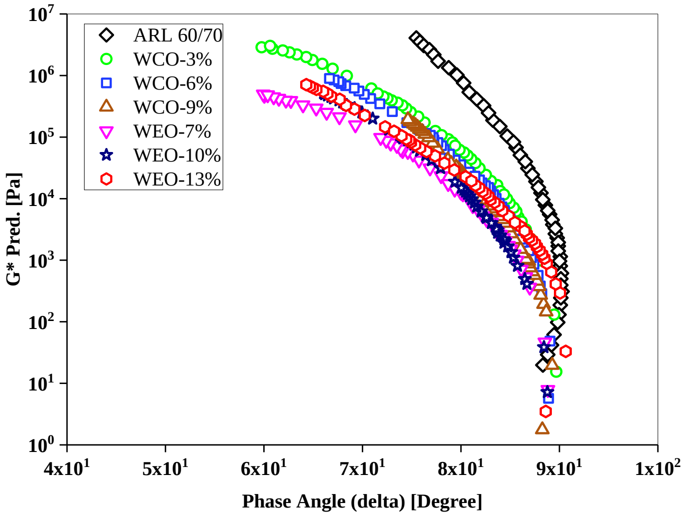


Figure 17. Black diagram showing the relationship between complex modulus (|G|) and phase angle (δ) for the tested binders.

This representation, which is both frequency- and temperature-independent, facilitates the direct comparison of all datasets on a single chart. The incorporation of WCO and WEO produced a pronounced influence on the viscoelastic response of the bitumen, as evident from the distinct deviations in the plots relative to the control bitumen. The results further revealed that increasing temperature led to a rise in phase angle, accompanied by a reduction in G* values, reflecting the expected softening of the bitumen under thermal loading. Notably, Figure 17 highlights a transition point beyond which the phase angle of WCO- and WEO-modified bitumen decreases at low frequencies and elevated temperatures. This behavior indicates a shift towards enhanced elasticity in the modified bitumen at these conditions, particularly at the specified dosages of WCO and WEO.

4.8. Marshall test results

The Marshall mix design method was adopted to determine the optimum bitumen content (OBC) of the base asphalt mixture (Chakravarthi, Rajkumar and Shankar, 2023). For this purpose, five percentages of the bitumen content, i.e., 3%, 3.5%, 4%, 4.5%, and 5%, were selected to determine the optimum bitumen content of ARL 60/70. Bitumen percentages are represented as "Bc," the measured unit weights are presented in Table 2, and the unit weight (Gmb) results are illustrated in Figure 18(a).

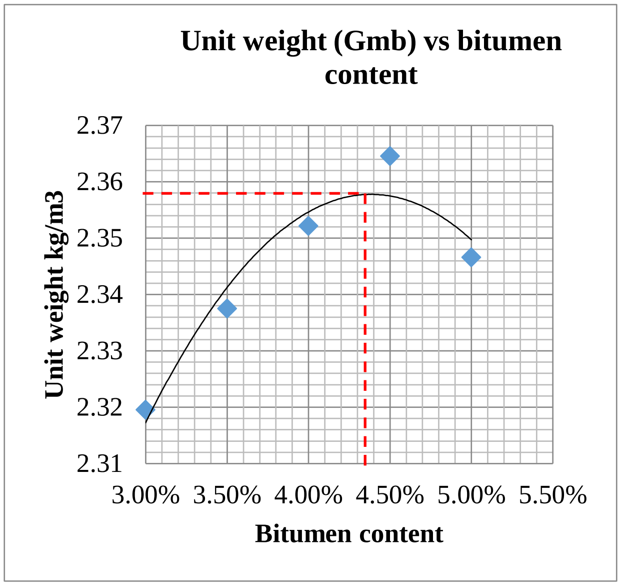
Table 2. The bulk specific gravity of compacted asphalt mixtures (ARL 60/70).

Bc (%)	Sample No.	A (g)	B (g)	C (g)	G_{mb} = A/(C-B)	Unit weight (kg/m^3)
3	1	1238	720.3	1254	2.32	2319.66

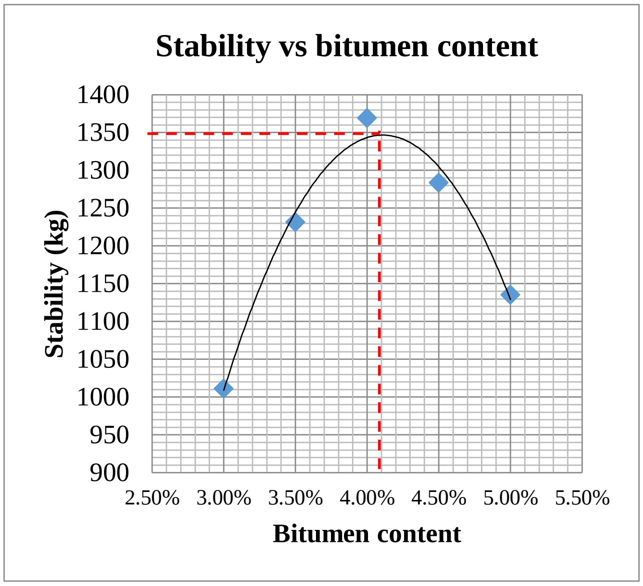
3	2	1232	717.9	1248	2.32	2324.09
3	3	1232	716.8	1249	2.31	2314.92
		Average			2.32	2320
3.5	1	1243	719	1251.2	2.34	2336
3.5	2	1237	722.6	1251.4	2.34	2339
3.5	3	1242	720.9	1252.2	2.34	2338
		Average			2.34	2337
4	1	1239	714.8	1242	2.35	2350
4	2	1241	716.4	1244	2.35	2352
4	3	1243	718	1246	2.35	2354
		Average			2.35	2351
4.5	1	1246.1	724.9	1251.2	2.37	2368
4.5	2	1245.3	719.9	1247.2	2.36	2362
4.5	3	1245.1	720.4	1247	2.36	2364
		Average			2.36	2365
5	1	1237	712	1240	2.34	2343
5	2	1239	714	1242	2.35	2347
5	3	1241	716	1244	2.35	2350
		Average			2.35	2347

The sample's weight in air and water is represented by "A" and "B," respectively. The saturated surface dry weight is designated as "C." The bulk specific Gravity of the compacted mixture and maximum specific gravity are denoted as "Gmb" and "Gmm," respectively. From Figure 18(a), the bitumen content relative to the maximum unit weight is 4.35%. In Table 3.

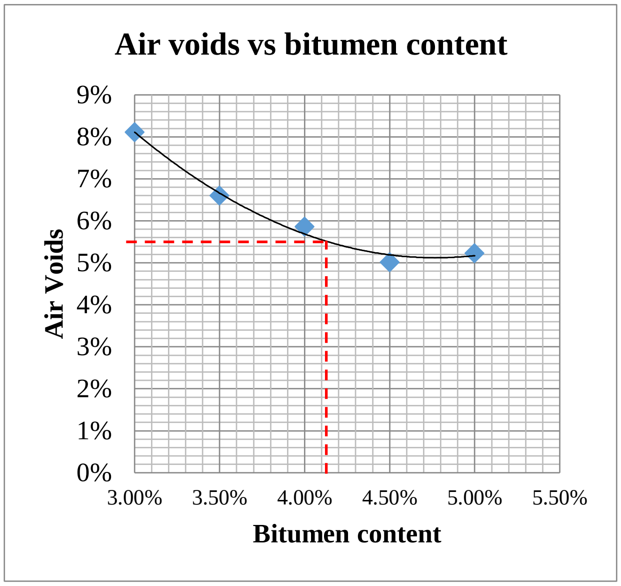
Table 3, the weight of the loose mix is designated as Wmm, the weight of the container and water as W1, the weight of container + sample + water as W2, the maximum specific gravity as Gmm, the bitumen content as Pb (%), the Percentage of total aggregate as Ps (%), and the percentage total mix as Pmm. The bulk specific Gravity of the aggregates, "Gsb", recorded in the laboratory is 2.63.


Unit weight (Gmb) vs bitumen content
Unit weight kg/m3
2.37
2.36
2.35
2.34
2.33
2.32
2.31
3.00%
3.50%
4.00%
4.50%
5.00%
5.50%
Bitumen content

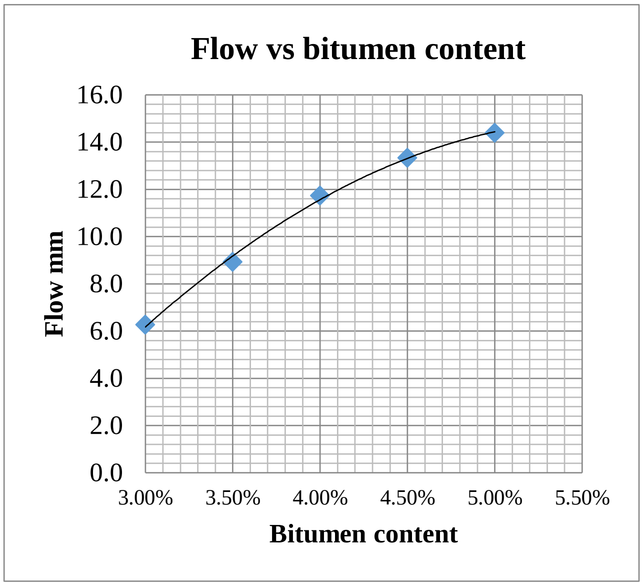
(a)


Stability vs bitumen content
Stability (kg)
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
2.50%
3.00%
3.50%
4.00%
4.50%
5.00%
5.50%
Bitumen content

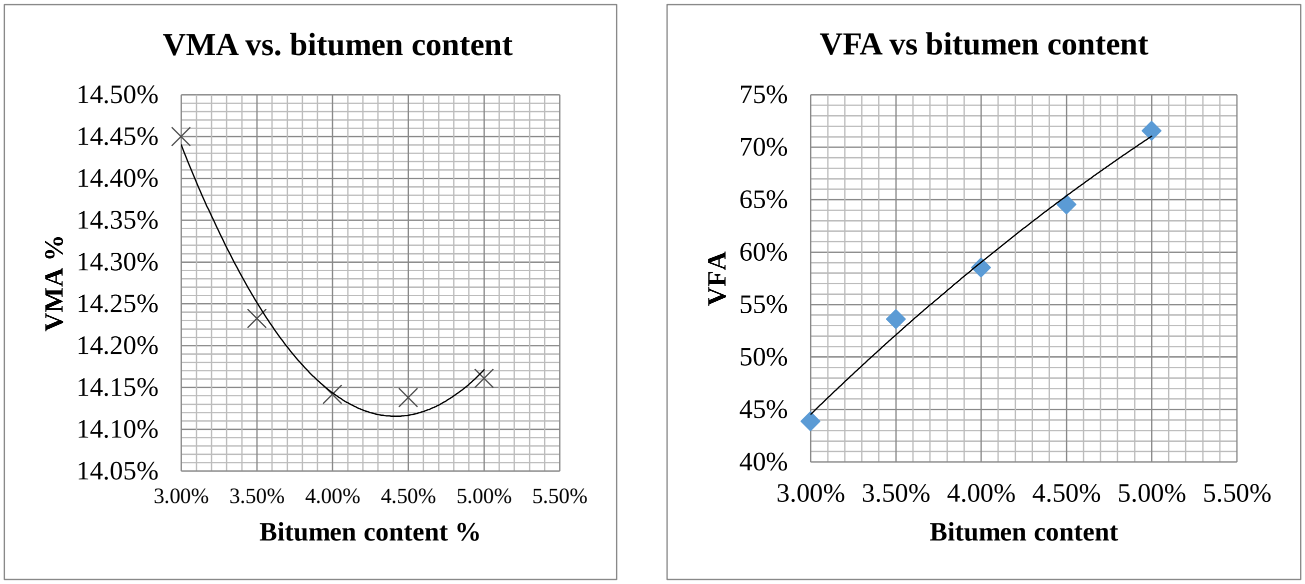
(b)


Air voids vs bitumen content
Air Voids
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
3.00%
3.50%
4.00%
4.50%
5.00%
5.50%
Bitumen content

(c)


Flow vs bitumen content
Flow mm
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
3.00%
3.50%
4.00%
4.50%
5.00%
5.50%
Bitumen content

(d)



(e) (f)

Figure 18. Effect of bitumen content on (a) unit weight; (b) stability; (c) air voids; (d) flow; (e) voids in mineral aggregates; (f) voids filled with asphalt.

The specimens were heated to 60 °C in water for 30 minutes. After the samples dried, a constant deformation rate was applied diametrically until fracture occurred. The force needed to fracture the specimen and the associated diametrical deformation were documented as Marshall stability and flow, respectively (Mistry and Roy, 2020). The stability and flow values recorded from the Marshall test machine are presented in Table 3.

Table 3. Stability and flow readings.

(W_{mm}) g	(W_1) g	(W_2) g	Gmm = (W_{mm}/ ($W_{mm}+W_1-W_2$))	Stability (kN) dial reading	Stability (kg) correction factor 0.96	Flow (mm)	Pb (%)	Ps (%)	Pmm (%)
2452.80	8688	10168.00	2.521	250	1032	3.6	3.00%	97.00%	100.00%
2462.30	8688	10176.00	2.527	245	1011	6.8			
				240	991	8.4			
			2.524		1011	6.3			
2340.00	8688	10094.00	2.505	290	1197	7.6	3.50%	96.50%	100.00%
2210.00	8688	10014.00	2.500	295	1218	10.8			
				310	1280	8.4			
			2.503		1232	8.9			
2410.00	8688	10134.00	2.500	330	1362	12.8	4.00%	96.00%	100.00%
2390.00	8688	10121.00	2.497	335	1383	11.2			
				330	1362	11.2			
			2.499		1369	11.7			
2320.00	8688	10077	2.492	300	1238	14.8	4.50%	95.50%	100.00%
2355.00	8688	10096	2.487	315	1300	13.2			
				318	1313	12			
			2.489		1284	13.3			
2301.00	8688	10061	2.480	290	1197	14	5.00%	95.00%	100.00%
2312.00	8688	10065	2.473	265	1094	15.6			
				270	1115	13.6			
			2.476		1135	14.4			

From Figure 18(b), the bitumen content against maximum stability is 4.1%. The bitumen content against 5.5% air voids is 4.15%, as illustrated in Figure 18(c). At the same time, the effective specific gravity "Gse" of aggregates, effective asphalt content, voids in mineral aggregates (VMA), air voids (Va), and voids filled with asphalt (VFA) calculations are recorded in Table 4. The performance and durability of paving mixes were evaluated by analyzing the volumetric properties of a compacted mixture, including air voids (Va), voids in mineral aggregates (VMA), and voids filled with asphalt (VFA).

Table 4. Volumetric properties of neat ARL 60/70 asphalt mixtures.

The effective specific gravity of aggregates

Bitumen content	Gmm	Pmm	Pb	Gb	Gse
3.00%	2.524	100.00%	3.00%	1.029	2.643
3.50%	2.503	100.00%	3.50%	1.029	2.640
4.00%	2.499	100.00%	4.00%	1.029	2.657
4.50%	2.489	100.00%	4.50%	1.029	2.668
5.00%	2.476	100.00%	5.00%	1.029	2.674

Effective asphalt

Bitumen content	Pb	Ps	Gb	Gsb	Gse	Pba	Pbe
3.00%	3.00%	97.00%	1.029	2.63	2.643	19.4%	2.8%
3.50%	3.50%	96.50%	1.029	2.63	2.640	14.5%	3.4%
4.00%	4.00%	96.00%	1.029	2.63	2.657	39.5%	3.6%
4.50%	4.50%	95.50%	1.029	2.63	2.668	55.4%	4.0%
5.00%	5.00%	95.00%	1.029	2.63	2.674	64.5%	4.4%

Voids in mineral aggregates

Bitumen content	Gmb	Gsb	Ps	VMA
3.00%	2.32	2.63	97.00%	14.45%
3.50%	2.34	2.63	96.50%	14.23%
4.00%	2.35	2.63	96.00%	14.14%
4.50%	2.36	2.63	95.50%	14.14%
5.00%	2.38	2.63	95.00%	14.16%

Air voids

Bitumen content	Gmb	Gmm	Va
3.00%	2.32	2.524	8.11%
3.50%	2.34	2.50	6.60%
4.00%	2.35	2.50	5.86%
4.50%	2.36	2.49	5.01%
5.00%	2.38	2.48	4.03%

Voids filled with asphalt

Bitumen content	Va	VMA	VFA
3.00%	8.11%	14.45%	43.86%
3.50%	6.60%	14.23%	53.63%
4.00%	5.86%	14.14%	58.53%
4.50%	5.01%	14.14%	64.54%
5.00%	4.03%	14.16%	71.56%

The evaluated parameters provided critical insights into the performance and durability of the compacted asphalt mixture. Variations in volumetric properties are known to influence pavement behavior and long-term service life significantly. Mixtures exhibiting air void contents below 3% are particularly vulnerable to rutting and shoving under heavy traffic conditions.

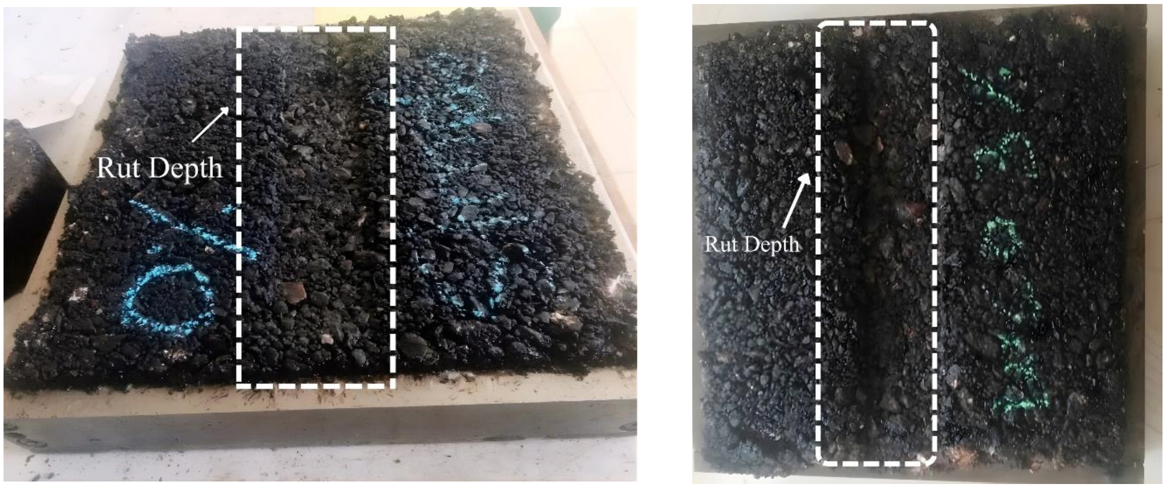
As illustrated in the graph, the maximum unit weight, stability, and 5.5% air voids were recorded at 4.35%, 4.10%, and 4.15%, respectively. The optimum bitumen content (OBC) was determined by averaging these three values, yielding 4.20%. This OBC was subsequently employed in the preparation of asphalt slabs incorporating WCO- and WEO-modified bitumen, which were then subjected to the Cooper wheel tracker test to evaluate the permanent deformation characteristics of the mixtures. The job mix formula (JMF) was applied to identify the optimum aggregate gradation and bitumen content required for the asphalt mixture. The mixtures were designed following the Asphalt Institute Marshall method of mix design (The Asphalt Institute, 1984), and the design properties corresponding to the determined OBC are presented in Table 5.

Table 5. Hot mix asphalt design properties.

Mix types	Optimum AC contents (%)	Loss of stability (%)		Stability (Kg)	Flow (0.25mm)	Stiffness index (stability/ flow)	
ARL 60/70	4.20	11.40		1335	12.37	108	
Mix types	Optimum AC contents (%)	Gsb	Gmm	Gmb	VA (%)	VMA (%)	VFA (%)
ARL 60/70	4.20	2.65	2.495	2.357	5.52	14.14	60.94

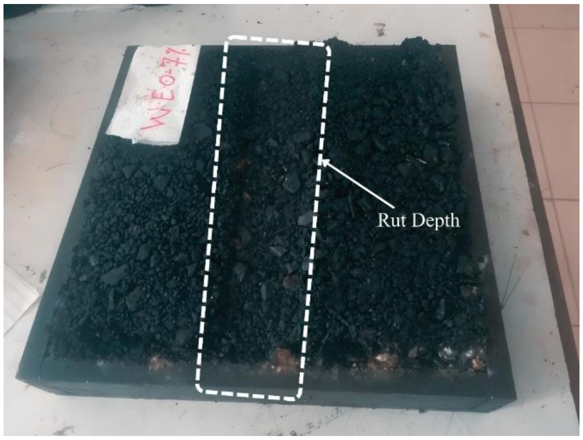
4.9. Wheel tracker test results

A wheel-tracking test was conducted on the WCO- and WEO-modified asphalt mixture to assess its resistance to high-temperature rutting, following the standard test procedure (BS EN 12697-22, 2003). Figure 19 (a, b, and c) illustrates the rut depth calculated from the wheel tracking test conducted for original/modified mixtures. Figure 19(a) shows the permanent deformation recorded of neat bitumen ARL 60/70, and Figure 19 (b) and (c) indicate the rut depth of WCO-3% and WEO-7% at 55 °C. Figure 20(a) displays the wheel tracking results for all original/modified mixtures with WCO at 40 °C. Generally, the specific enhancement is evident in rutting resistance, as the addition of waste oils compromises the stiffness. The original mixture's rut depth (at 10,000 passes) was acquired as 3.28 mm at 40 °C. Similarly, the rut depths (in mm) formulated for WCO-3%, WCO-6%, and WCO-9% were 3.41, 4.23, and 4.32, respectively. Compared to the original asphalt, the percentages enhanced were 4%, 29%, and 32% at WCO concentrations of 3%, 6%, and 9%, respectively. It shows that the WCO concentration in the original mixture slightly compromised rut resistance. The rut depths (in mm) obtained for WEO in the original mix were 3.47, 3.80, and 3.83 at concentrations of 7%, 10%, and 13%, respectively. The total enhancements were 6%, 16%, and 17% at WEO concentrations of 7%, 10%, and 13%, respectively. Additionally, the negative trend observed for WCO-9% and WEO-13% may be due to the increased distance between bitumen particles resulting from excess oil concentration. Therefore, WEO-13% lacked prior adhesion; thus, it may be more prone to rupture even under a small force.



(a)

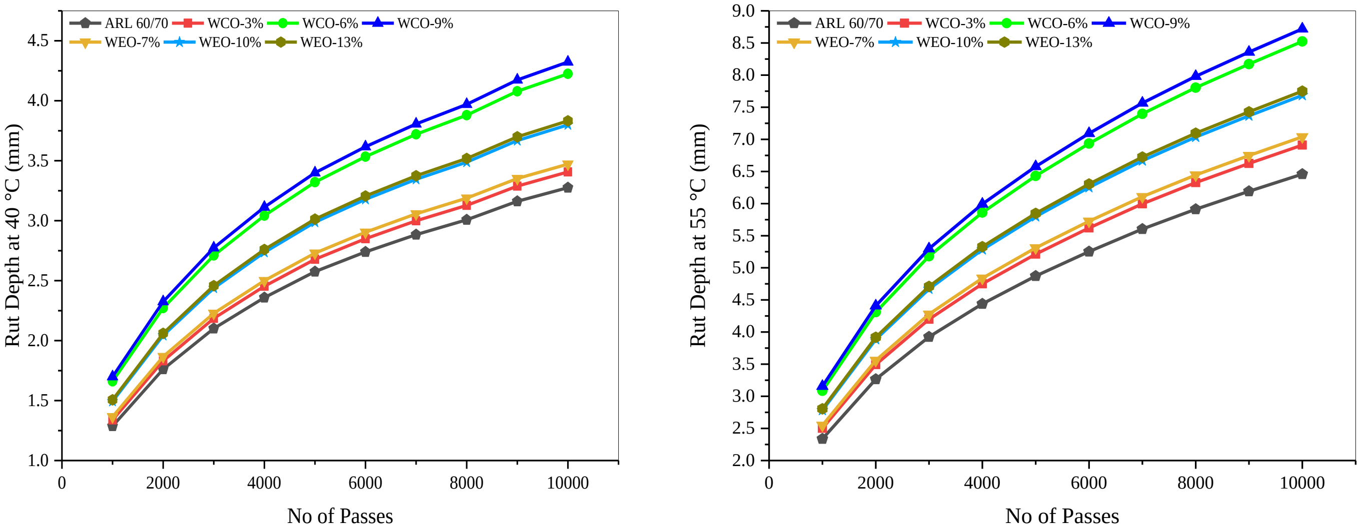
(b)



(c)

Figure 19. Rut Depth (mm) measured at 55 °C; (a) ARL 60/70; (b) WCO-3%; (b) WEO-7%.

Similarly, the wheel tracker test results for ARL 60/70 and modified asphalt with WCO and WEO are recorded at 55 °C. Figure 20(b) illustrates the permanent deformation of WCO- and WEO-modified asphalt at 55 °C. The incorporation of WCO-3%, WCO-6% and WCO-9% enhanced the rutting depth by 7%, 32%, and 35%, respectively, at 55 °C. Furthermore, the recorded rut depths of WEO-7%, WEO-10%, and WEO-13% were 7.04, 7.69, and 7.75 mm, respectively. It indicates that WEO dosages of 7%, 10%, and 13% reduced the permanent deformation of asphalt mixtures by 9%, 19%, and 20%, respectively, at 55 °C.



(a) (b)

Figure 20. Rut depth (mm) of asphalt mixtures measured during wheel tracking test at (a) 40 °C and (b) 55 °C.

The results confirmed that adding WCO-3% to bitumen can improve its resistance to permanent deformation more than any of the waste oil modifications, as evidenced by lower rut depths and residual deformation values in wheel-tracking tests. The recorded rut depth (mm) values of ARL 60/70 bitumen, WCO-3%, and WEO-7% modified bitumen were 6.46, 6.91, and 7.04 mm, respectively, after 10000 passes at 55 °C. Although the rut depth increased across all waste-oil modifications, it remained within permissible limits, i.e., less than 12.5 mm. It is concluded that adding WCO and WEO would promote rutting. Thus, lower dosages of waste oils, i.e., WCO-3% and WCO-7%, may be partially replaced with bitumen in moderate-temperature regions, based on wheel-tracker results. The results are consistent with previous similar studies (Mamun, Al-Abdul Wahhab and Dalhat, 2020; Eltwati *et al.*, 2022).

Overall, it was observed that WCO and WEO exerted distinct influences on bitumen and mixture properties. The incorporation of WCO at moderate dosages improved ductility and elasticity and enhanced rutting resistance when added at 3%. In contrast, higher concentrations of WEO were associated with reductions in ductility and stiffness, leading to diminished rutting performance. These outcomes indicate that the two waste oils interacted differently with bitumen and mixtures, and it is therefore suggested that careful dosage selection is necessary to optimize performance under high-temperature and traffic conditions.

5. Statistical analysis

The statistical analysis of the Dynamic shear rheometer and wheel tracker tests involved analyzing their respective statistical properties. Tukey's primary method was used in the statistical analysis—a one-step comparison method for determining significant differences between means. The complex modulus values at 1 Hz were analyzed statistically, and the results are presented in Table 6.

Table 6. Statistical analysis of complex viscosity and rutting depth.

Statistical analysis of complex modulus					
		Subset at 95% confidence interval			
Additives	N	1	2	3	4
B+WCO-9%	6	48.70			
B+WCO-6%	6	50.50			
B+WEO-13%	6		57.03		
B+WEO-10%	6		59.70		
B+WEO-7%	6			135.03	
B+WCO-3%	6			137.00	
Base bitumen	6				167
Statistical analysis of rutting depth					
		Subset at 95% confidence interval			
Additives	N	1	2	3	4
Base bitumen	6	4.870			
B+WCO-3%	6		5.160		
B+WEO-7%	6		5.250		
B+WEO-10%	6			5.745	
B+WEO-13%	6			5.790	
B+WCO-6%	6				6.375
B+WCO-9%	6				6.520

The analysis indicated that incorporating lower dosages of waste oils, specifically WCO at 3% and WEO at 7%, produced notable improvements in the high-temperature performance of asphalt bitumen compared to higher inclusion levels. This enhancement was primarily due to the softening effect imparted by waste oils, leading to reductions in complex modulus values. These observations are consistent with earlier studies that reported decreases in the complex modulus and softening of bitumen upon the addition of waste oils compared to unmodified bitumen (Chen et al., 2014; Li, Dong, et al., 2019). As shown in Table 6, the statistical analysis of rutting depth values measured at 1000 passes under 40 °C and 55 °C further supports these findings. Mixtures modified with lower dosages of waste oil exhibited significantly improved rutting resistance compared to those with higher dosages. In contrast, the overall permanent deformation performance of all tested mixtures remained superior to that of the control mix. This improvement is attributed to the flow-inducing effect of waste oils, which facilitates bitumen softening and reduces stability values. Such outcomes corroborate previous research that highlighted enhanced resistance to permanent deformation when employing lower proportions of waste oils in asphalt modification (Mamun, Al-Abdul Wahhab and Dalhat, 2020; Eltwati et al., 2022).

6. Conclusions

The conclusions drawn from this study are presented below:

1. The WCO and WEO had ascended the penetrating values of the modified bitumen compared to the base bitumen. The high concentration of the waste oil softens the bitumen. However, it is more pronounced in WEOs than in WCOs, which is feasible in moderate climatic regions. The lower softening values of the WCOs and WEOs modified bitumens follow the same trend as the penetrating values. The optimum dosages of WEO and WCO, at 7% and 3%, respectively, have shown slightly higher softness values than the base bitumen, which is within permissible limits to maintain the bitumen grade. Hence, the higher fluidity indicates its suitability to work at ambient temperatures.
2. The increased dosages of WCO had a positive effect on the ductile nature of the modified bitumen. However, the high WEO concentration reduces the flexibility and cohesiveness of the modified bitumen. The high dosages of WCO and WEO in the base bitumen reduced the penetration index (PI) compared to the base bitumen. It concludes that both the waste oils compromised the thermal susceptibility properties.
3. The blending process of WCO and WEO-modified bitumen was essentially physical, as indicated by the Fourier-transform infrared spectroscopy (FTIR) results, which showed that no new chemicals were formed during the blending process. Further, the reduction in the intensity of C=C bonds confirms the decrease in the asphaltene contents in the modified bitumen, which causes slightly lower stiffness values of the WCO and WEO modified bitumen.
4. Rheological assessments, including the Frequency sweep test, revealed that the addition of WCO and WEO to the bitumen resulted in a minor decrease in high-temperature resistance. The dosages of WCO and WEO, up to 3% and 7%, respectively, had slightly lower failure values at high temperatures; however, the performance grading (PG) is comparable to that of the base bitumen. The incorporation of WCO and WEO has played a notable role in reducing the phase angle of the modified bitumen. This reduction offers advantages for both environmental protection and cost-effectiveness, primarily because lower mixing and compaction temperatures are required.
5. It was concluded that all the high dosages of WCO and WEO asphalt mixtures exhibited the ability to endure load cycles without experiencing settling exceeding rutting depth. However, the low dosages of WCO and WEO asphalt mixtures, i.e., 3% and 7%, respectively, yield permanent deformation values comparable to those of the base asphalt ARL 60/70 at high temperatures. The analysis of test results suggests that, considering the load-carrying capacity requirements of roads, such as Low Volume Roads, Rural Roads, Footpaths, and Cycle Tracks, partial replacement of bitumen with WEO and WCO can be a beneficial option.
6. The statistical analysis results of complex modulus and rut depth align with the current findings and prior literature. The outcomes indicate that using lower doses of WEO and WCO significantly improves moderate-temperature performance.
7. These findings hold significant practical implications for pavement engineering practice. The incorporation of WCO at 3% and WEO at 7% is recommended, as these dosages were shown to maintain performance while improving bitumen flexibility and reducing rutting susceptibility. The adoption of recycled oils in paving projects could lower material costs by partially substituting for virgin bitumen, while simultaneously reducing the environmental impacts associated with waste disposal. Furthermore, the use of these rejuvenators has the potential to enhance pavement durability under high-temperature and traffic conditions, thereby extending service life and reducing maintenance needs. Such outcomes highlight the feasibility of integrating recycled oils into asphalt technology as a sustainable, cost-effective approach to road construction.

WCO and WEO have demonstrated considerable potential in enhancing the physical properties of bituminous binders. The blending of these waste oils with bitumen, however, directly influences variability in material characteristics, which in turn affects the overall quality of the modified bitumen. Experimental results generally indicate that optimal improvements are achieved with incorporation levels of approximately 3% WCO and 7% WEO. To ensure the practicality of such modifications, a comprehensive economic evaluation is essential. In particular, the application of Life Cycle Cost Analysis (LCCA) is recommended for aged asphalt rejuvenated with WCO and WEO, as this approach provides critical insights into both economic feasibility and long-term sustainability. From a performance perspective, key engineering properties—including rheological behavior, rutting resistance, and high-performance grade (PG) classification of reclaimed asphalt pavement (RAP) bitumen—should be rigorously assessed. WCO and WEO, due to their antioxidant potential, may serve as effective agents to restore flexibility and reduce stiffness in RAP bitumen. Moreover, incorporating supplementary additives, such as polyphosphoric acid, into WCO- or WEO-modified asphalt could further enhance stiffness and high-temperature stability, thereby expanding the applicability of these waste-derived rejuvenators in pavement engineering.

Author Contributions: (YR.) conceptualization, methodology, formal analysis, investigation, resources, writing - original draft; (JH.) conceptualization, methodology, investigation, resources, writing - review and editing, supervision; (WH.) supervised, reviewed, and edited; (HA), review and editing; (NM) investigation, resources, reviewed draft.

Funding: No funding is involved in this study.

Institutional Review Board Statement: No institutional review board statement is required in this study.

Informed Consent Statement: No informed consent statement is required in this study.

Data Availability Statement: All recorded data from the experiment are available.

Acknowledgements: The authors would like to thank Mr. Mumtaz Ahmad, lab technician at the Transportation Engineering Laboratory, Department of Civil Engineering, University of Engineering and Technology (UET), Taxila, Pakistan, for his valuable support throughout the experimental process.

Conflicts of Interest: The Authors declare no conflicts of interest.

References

Abukhettala, M. (2016) 'Use of recycled materials in road construction', in Proceedings of the 2nd International Conference on Civil, Structural and Transportation Engineering (ICCSTE'16), pp. 1–8.

Akpolat, M. (2022) 'Investigation of rutting, fatigue and cracking resistance parameters of CR modified warm asphalt binders compare with SBS modified binders', Revista de la Construccion, 21(2), pp. 309–328. Available at: https://doi.org/10.7764/RDLC.21.2.309.

Amigun, B., Sigamoney, R. and von Blottnitz, H. (2008) 'Commercialisation of biofuel industry in Africa: A review', Renewable and Sustainable Energy Reviews, 12(3), pp. 690–711. Available at: https://doi.org/10.1016/j.rser.2006.10.019.

Asli, H. et al. (2012) 'Investigation on physical properties of waste cooking oil - Rejuvenated bitumen binder', Construction and Building Materials, 37, pp. 398–405. Available at: https://doi.org/10.1016/j.conbuildmat.2012.07.042.

Awolusi, T. et al. (2023) 'Utilization of Bitumen Modified with Pet Bottles as an Alternative Binder for the Production of Paving Blocks', Civil Engineering Journal (Iran), 9(1), pp. 104–113. Available at: https://doi.org/10.28991/CEJ-2023-09-01-08.

Azam, M. et al. (2020) 'Status, characterization, and potential utilization of municipal solid waste as renewable energy source: Lahore case study in Pakistan', Environment International, 134, p. 105291. Available at: https://doi.org/10.1016/J.ENVINT.2019.105291.

Bahia, H., Perdomo, D. and Turner, P. (1997) 'Applicability of superpave binder testing protocols to modified binders', Transportation Research Record: Journal of the Transportation Research Board, 1586(971313), pp. 16–23. Available at: https://doi.org/10.3141/1586-03.

Banerji, A.K. et al. (2022) 'Characterization of waste cooking oil and waste engine oil on physical properties of aged bitumen', Materials Today: Proceedings, 59, pp. 1694–1699. Available at: https://doi.org/10.1016/j.matpr.2022.03.401.

Bilema, M. et al. (2021) 'Performance of aged asphalt binder treated with various types of rejuvenators', Civil Engineering Journal (Iran), 7(3), pp. 502–517. Available at: https://doi.org/10.28991/cej-2021-03091669.

Brûlé, B. and Brule, B. (1996) 'Polymer-Modified Asphalt Cements Used in the Road Construction Industry : Basic Principles', Transportation Research Record, 1535(1), pp. 48–53. Available at: https://doi.org/10.3141/1535-07.

BS EN 12697-22 (2003) 'Bituminous Mixtures : Test Methods for Hot Mix Asphalt. Part 22: Wheel Tracking', European Committee for Standardization, 3(1).

Cao, Xinxin et al. (2018) 'Investigation of rheological and chemical properties asphalt binder rejuvenated with waste vegetable oil', Construction and Building Materials, 180, pp. 455–463. Available at: https://doi.org/10.1016/j.conbuildmat.2018.06.001.

Caputo, P. et al. (2019) 'The efficiency of bitumen rejuvenator investigated through Powder X-ray Diffraction (PXRD) analysis and T 2 -NMR spectroscopy', Colloids and Surfaces A: Physicochemical and Engineering Aspects, 571, pp. 50–54. Available at: https://doi.org/10.1016/j.colsurfa.2019.03.059.

Chakravarthi, S., Rajkumar, G. and Shankar, S. (2023) 'Evaluation of cold emulsified bitumen mixes using recycled con-crete aggregates as a base course', Revista de la Construccion, 22(2), pp. 523–552. Available at: https://doi.org/10.7764/RDLC.22.2.523.

Chen, M. et al. (2014) 'High temperature properties of rejuvenating recovered binder with rejuvenator, waste cooking and cotton seed oils', Construction and Building Materials, 59, pp. 10–16. Available at: https://doi.org/10.1016/j.conbuildmat.2014.02.032.

Chirani, M.R. et al. (2021) 'Environmental impact of increased soap consumption during COVID-19 pandemic: Biodegradable soap production and sustainable packaging', Science of the Total Environment, 796. Available at: https://doi.org/10.1016/j.scitotenv.2021.149013.

Counts, T.W. (2023) Tons of solid waste generated. Available at: https://www.theworldcounts.com/challenges/planet-earth/state-of-the-planet/solid-waste.

Dinh, B.H., Park, D.W. and Le, T.H.M. (2018) 'Effect of rejuvenators on the crack healing performance of recycled asphalt pavement by induction heating', Construction and Building Materials, 164, pp. 246–254. Available at: https://doi.org/10.1016/j.conbuildmat.2017.12.193.

El-Shorbagy, A.M., El-Badawy, S.M. and Gabr, A.R. (2019) 'Investigation of waste oils as rejuvenators of aged bitumen for sustainable pavement', Construction and Building Materials, 220, pp. 228–237. Available at: https://doi.org/10.1016/j.conbuildmat.2019.05.180.

Eltwati, A. et al. (2022) 'Effects of waste engine oil and crumb rubber rejuvenator on the performance of 100% RAP binder', Journal of Innovative Transportation, 3(1), pp. 8–15. Available at: https://doi.org/10.53635/jit.1072888.

Eriskin, E. et al. (2017) 'Waste frying oil modified bitumen usage for sustainable hot mix asphalt pavement', Archives of Civil and Mechanical Engineering, 17(4), pp. 863–870. Available at: https://doi.org/10.1016/j.acme.2017.03.006.

Eswan et al. (2021) 'Characteristics of asphalt mixed using mountain stone', Civil Engineering Journal (Iran), 7(2), pp. 268–277. Available at: https://doi.org/10.28991/cej-2021-03091652.

Fareed, A. et al. (2020) 'Use of agricultural waste ashes in asphalt binder and mixture: A sustainable solution to waste management', Construction and Building Materials, 259, p. 120575. Available at: https://doi.org/10.1016/j.conbuildmat.2020.120575.

Felode, O., Jonathan, G. and Ohinola, O. (2012) 'Softening point and Penetration Index of bitumen from parts of Southwestern Nigeria', Nafta, 63(9–10), pp. 319–323.

Fernandes, S. et al. (2017) 'Effect of incorporating different waste materials in bitumen', Ciência and Tecnologia dos Materiais, 29(1), pp. e204–e209. Available at: https://doi.org/10.1016/j.ctmat.2016.07.003.

Fernandes, S.R.M., Silva, H.M.R.D. and Oliveira, J.R.M. (2018) 'Developing enhanced modified bitumens with waste engine oil products combined with polymers', Construction and Building Materials, 160, pp. 714–724. Available at: https://doi.org/10.1016/j.conbuildmat.2017.11.112.

Guesmi, M.L., Nafa, Z. and Bordjiba, A. (2023) 'Evaluation of the uses of treated sawdust as a partial replacement for aggregate in hot mix asphalt', Revista de la Construccion, 22(3), pp. 553–568. Available at: https://doi.org/10.7764/RDLC.22.3.553.

Günay, T. (2022) 'Investigation of physical properties of base and SBS modified bi-tumens by rheological test methods', Revista de la Construccion, 21(2), pp. 281–294. Available at: https://doi.org/10.7764/RDLC.21.2.281.

Haq, M.F. ul et al. (2018) 'Carbon Nanotubes (CNTs) in Asphalt Binder: Homogeneous Dispersion and Performance Enhancement', Applied Sciences, 8(12), p. 2651. Available at: https://doi.org/10.3390/app8122651.

Haroon, W. and Ahmad, N. (2024a) 'Effect of low-content crumb rubber modification on the performance of bitumen and asphalt', Engineering Research Express, 6(3), p. 035116. Available at: https://doi.org/10.1088/2631-8695/ad7558.

Haroon, W. and Ahmad, N. (2024b) 'Effect of nano silica on the performance of modified crumb rubber bitumen and asphalt mixtures', Innovative Infrastructure Solutions, 9(7), p. 280. Available at: https://doi.org/10.1007/s41062-024-01590-7.

Haroon, W., Ahmad, N. and Mashaan, N. (2022) 'Effect of Quartz Nano-Particles on the Performance Characteristics of Asphalt Mixture', Infrastructures, 7(5), p. 60. Available at: https://doi.org/10.3390/infrastructures7050060.

Hesp, S.A.M. and Shurvell, H.F. (2010) 'X-ray fluorescence detection of waste engine oil residue in asphalt and its effect on cracking in service', International Journal of Pavement Engineering, 11(6), pp. 541–553. Available at: https://doi.org/10.1080/10298436.2010.488729.

Irsyad, M. et al. (2023) 'Experimental study of the thermal properties of waste cooking oil applied as thermal energy storage', Results in Engineering, 18(March), p. 101080. Available at: https://doi.org/10.1016/j.rineng.2023.101080.

Javed, H., Zaidi, S.B.A. and Haroon, W. (2024) 'Experimental investigation of the effect of polyphosphoric acid on bitumen containing crumb rubber and waste engine oil', Innovative Infrastructure Solutions, 9(11), p. 415. Available at: https://doi.org/10.1007/s41062-024-01726-9.

Jia, X. et al. (2014) 'Infrared spectra and rheological properties of asphalt cement containing waste engine oil residues', Construction and Building Materials, 50, pp. 683–691. Available at: https://doi.org/10.1016/j.conbuildmat.2013.10.012.

Kabir, I., Yacob, M. and Radam, A. (2014) 'Households' Awareness, Attitudes and Practices Regarding Waste Cooking Oil Recycling in Petaling, Malaysia', IOSR Journal of Environmental Science, Toxicology and Food Technology, 8(10), pp. 45–51. Available at: https://doi.org/10.9790/2402-081034551.

Kamoto, N. et al. (2020) 'Production of modified bitumen from used engine oil, coal tar and waste tyre for construction applications', South African Journal of Chemical Engineering, 33, pp. 67–73. Available at: https://doi.org/10.1016/j.sajce.2020.05.005.

Khan, H.M. et al. (2021) 'Production and utilization aspects of waste cooking oil based biodiesel in Pakistan', Alexandria Engineering Journal, 60(6), pp. 5831–5849. Available at: https://doi.org/10.1016/j.aej.2021.04.043.

Khurshid, I. and Kumar, N. (2021) 'A Study On Replacement of Bitumen Partially with Waste Cooking Oil and Engine Oil in Bituminous Concrete', International Journal of Research in Engineering, Science and Management, 4(5), pp. 204–213.

Kupareva, A., Mäki-Arvela, P. and Murzin, D.Y. (2013) 'Technology for rerefining used lube oils applied in Europe: A review', Journal of Chemical Technology and Biotechnology, 88(10), pp. 1780–1793. Available at: https://doi.org/10.1002/jctb.4137.

Li, H., Dong, B., et al. (2019) 'Effect of Waste Engine Oil and Waste Cooking Oil on Performance Improvement of Aged Asphalt', Applied Sciences, 9(9), p. 1767. Available at: https://doi.org/10.3390/app9091767.

Li, H., Liu, G., et al. (2019) 'Research on the development and regeneration performance of asphalt rejuvenator based on the mixed waste engine oil and waste cooking oil', International Journal of Pavement Research and Technology, 12(3), pp. 336–346. Available at: https://doi.org/10.1007/s42947-019-0040-1.

Li, H. et al. (2021) 'Study on waste engine oil and waste cooking oil on performance improvement of aged asphalt and application in reclaimed asphalt mixture', Construction and Building Materials, 276, p. 122138. Available at: https://doi.org/10.1016/j.conbuildmat.2020.122138.

Liu, S. et al. (2018) 'Evaluation of rheological characteristics of asphalt modified with waste engine oil (WEO)', Petroleum Science and Technology, 36(6), pp. 475–480. Available at: https://doi.org/10.1080/10916466.2018.1430157.

Liu, S. et al. (2019) 'Evaluation of the ageing behaviour of waste engine oil-modified asphalt binders', Construction and Building Materials, 223, pp. 394–408. Available at: https://doi.org/10.1016/j.conbuildmat.2019.07.020.

Loizides, M.I. et al. (2019) 'Circular bioeconomy in action: Collection and recycling of domestic used cooking oil through a social, reverse logistics system', Recycling, 4(2). Available at: https://doi.org/10.3390/recycling4020016.

Ma, J. et al. (2020) 'Rubber asphalt modified with waste cooking oil residue: Optimized preparation, rheological property, storage stability and aging characteristic', Construction and Building Materials, 258, p. 120372. Available at: https://doi.org/10.1016/j.conbuildmat.2020.120372.

Mamun, A. Al, Al-Abdul Wahhab, H.I. and Dalhat, M.A. (2020) 'Comparative Evaluation of Waste Cooking Oil and Waste Engine Oil Rejuvenated Asphalt Concrete Mixtures', Arabian Journal for Science and Engineering, 45(10), pp. 7987–7997. Available at: https://doi.org/10.1007/s13369-020-04523-5.

Mamun, A.A. and Al-Abdul Wahhab, H.I. (2018) 'Evaluation of Waste Engine Oil-Rejuvenated Asphalt Concrete Mixtures with High RAP Content', Advances in Materials Science and Engineering, 2018. Available at: https://doi.org/10.1155/2018/7386256.

Mistry, R. and Roy, T.K. (2020) 'Predicting Marshall stability and flow of bituminous mix containing waste fillers by the adaptive neuro-fuzzy inference system', Revista de la Construccion, 19(2), pp. 209–219. Available at: https://doi.org/10.7764/RDLC.19.2.209.

National Highway Authority (1998) Government of Pakistan, Ministry of Communications, General Specifications. Lahore, Pakistan: Sampak International Pvt Ltd, Engineering Design Supervision and Management Consultants.

Nayak, P. and Sahoo, U.C. (2017) 'Rheological, chemical and thermal investigations on an aged binder rejuvenated with two non-edible oils', Road Materials and Pavement Design, 18(3), pp. 612–629. Available at: https://doi.org/10.1080/14680629.2016.1182058.

Oner, J. and Sengoz, B. (2018) 'Effect of polymers on rheological properties of waxy bitumens', Revista de la Construccion, 17(2), pp. 279–295. Available at: https://doi.org/10.7764/RDLC.17.2.279.

Pakistan, G. of (2017) Population Census Introduction, Pakistan Bureau of Statistics. Available at: https://www.pbs.gov.pk/content/population-census.

Pelitli, V., Dogan, O. and Koroglu, H.. (2017) 'Waste oil management : Analyses of waste oils from vehicle crankcases and gearboxes', Global J. Environ. Sci. Manage., 3(1), pp. 11–20. Available at: https://doi.org/10.22034/gjesm.2017.03.01.002.

Qurashi, I.A. and Swamy, A.K. (2018) 'Viscoelastic properties of recycled asphalt binder containing waste engine oil', Journal of Cleaner Production, 182, pp. 992–1000. Available at: https://doi.org/10.1016/j.jclepro.2018.01.237.

Rasekh, M.A., Haldenbilen, S. and Zengin, D. (2023) 'Investigation of usability of mineral fiber in stone mastic asphalt', Revista de la Construccion, 22(3), pp. 569–580. Available at: https://doi.org/10.7764/RDLC.22.3.569.

Ren, S. et al. (2022) 'Insight into the compatibility behaviors between various rejuvenators and aged bitumen: Molecular dynamics simulation and experimental validation', Materials and Design, 223, p. 111141. Available at: https://doi.org/10.1016/j.matdes.2022.111141.

Rizvi, H.R., Khattak, M.J. and Gallo, A.A. (2014) 'Bone Glue Modified Asphalt: A Step towards Energy Conservation and Environment Friendly Modified Asphalts', International Scholarly Research Notices, 2014, pp. 1–5. Available at: https://doi.org/10.1155/2014/807043.

Rubio, M.C. et al. (2012) 'Warm Mix Asphalt: An overview', Journal of Cleaner Production, 24, pp. 76–84. Available at: https://doi.org/10.1016/j.jclepro.2011.11.053.

Shoukat, T. and Yoo, P.J. (2018) 'Rheology of Asphalt Binder Modified with 5W30 Viscosity Grade Waste Engine Oil', Applied Sciences, 8(7), p. 1194. Available at: https://doi.org/10.3390/app8071194.

The Asphalt Institute (1984) Mix design methods for asphalt concrete and other hot mix types, MS - 2. Sixth. Asphalt Institute.

Zargar, M. et al. (2012) 'Investigation of the possibility of using waste cooking oil as a rejuvenating agent for aged bitumen', Journal of Hazardous Materials, 233–234, pp. 254–258. Available at: https://doi.org/10.1016/j.jhazmat.2012.06.021.

Zhang, D. et al. (2017) 'Analysis of the relationships between waste cooking oil qualities and rejuvenated asphalt properties', Materials, 10(5). Available at: https://doi.org/10.3390/ma10050508.

Zhang, H., Ding, J. and Zhao, Z. (2012) 'Microwave assisted esterification of acidified oil from waste cooking oil by CERP/PES catalytic membrane for biodiesel production', Bioresource Technology, 123, pp. 72–77. Available at: https://doi.org/10.1016/j.biortech.2012.06.082.