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CHARACTERIZATION OF BITUMEN PROPERTIES INCORPORATING USED COOKING OIL AS A MODIFIER

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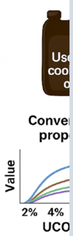
Graphical abstract



Abstract

The investigation of waste-derived resources as modifiers for asphalt binders has been prompted by the growing need for high-performance and sustainable paving materials. Among these, used cooking oil (UCO) has attracted considerable interest because it can improve binder properties while also addressing environmental issues related to waste disposal. The long-term performance and longevity of bituminous pavements are nevertheless impacted by pavement distress such as fatigue cracking, rutting, bleeding, and irreversible deformation, despite advancements in asphalt technology. Therefore, to improve the properties of bitumen, this study explores characterization and bitumen modification using UCO. In this study, various contents of UCO, ranging from 2% to 10% by binder weight, were added to typical penetration grade bitumen (50/60). To assess the impact of UCO on the bitumen properties, laboratory tests such as penetration, softening point, flash point, and fire point were carried out. The findings show that adding UCO greatly increases the workability and flexibility of the bitumen while preserving acceptable properties. Additionally, the modification lessens the bitumen's vulnerability to hardening brought on by aging, which may enhance pavement performance over time. An optimum UCO dosage of 4% was found among the mixes tested, offering the most balanced increase in penetration and thermal stability. The results show that UCO is a promising, environmentally friendly modifier that can improve bitumen performance and encourage reusing waste-derived resources.

Keywords: Used cooking oil, bitumen modification, sustainable asphalt, pavement performance, binder characterization, waste valorization.

1.0 INTRODUCTION

One of the main ingredients used to produce asphalt mixtures is bitumen. Aggregates, binder, and filler make up asphalt, a composite material that is frequently utilized in transportation infrastructure. The binder is one of these elements that is crucial to the mechanical performance, longevity, and resistance to pavement degradation, such as fatigue cracking and rutting. As a result, altering the binder, especially with sustainable additions such as UCO, has emerged as a crucial strategy for improving the longevity and performance of asphalt [1][2][3]. Asphalt mixtures can be designed to provide robust and long-lasting pavements that can withstand harsh service conditions and lessen the occurrence of pavement surface distress by using the proper modification and mixture design processes [4][5]. UCO is an abundant resource obtained from waste that needs effective management techniques, especially in the road construction industry, where its value can improve pavement engineering's sustainability and resource efficiency [6]. Reusing UCO in asphalt mixtures is therefore crucial for the development of sustainable pavements. The potential of UCO as an efficient bio-based modifier for bitumen binders in bituminous pavements has been brought to light by developments in contemporary pavement technology. Instead of discarding bio-oil waste as an environmental burden, this method encourages its valorization by turning it into a practical engineering material [7]. UCO has been widely used as a modifier in the manufacturing of asphalt concrete because of its advantageous engineering qualities.

The purpose of this study is to produce and assess bitumen mixes with different dosages of UCO for use in asphalt mixtures. By lowering reliance on traditional petroleum-based binders and minimizing environmental pollution, the use of UCO, a waste by-product, as a binder modifier encourages sustainability in road construction. Additionally, UCO-modified mixtures show increased structural behaviour in bituminous pavements, boosting fatigue and rutting resistance, which extends service life and improves pavement durability. By presenting a thorough, context-specific, and safety-focused assessment, this study goes beyond validating current knowledge and provides useful insights into the best usage of UCO for long-lasting and sustainable pavement applications.

Asli et al. (2012) discovered that the use of UCO as a performance-improving bitumen binder modifier and sustainable green additive in recent studies. The findings show that aged asphalt concrete's rheological and physical characteristics can be considerably restored to contents similar to their original state with the right UCO dosages. Chhetri et al [8] discovered the highest value of oleic acid (52.9 mm), in contrast to Foroutan et al [9] (41.04 mm) and Sharma et al [10] (24.69 mm). Similarly, Sharma et al [10] found that their value for linoleic acid was highest at 40.88 mm compared to Foroutan et al [9] (17.98 mm) and Sharma et al [10] (13.50 mm).

Asli et al [11] and Zargar et al [12] revealed that the physical characteristics of modified aged asphalt can be improved by adding low UCO concentrations. Sun et al [13] revealed that the performance of asphalt concrete pavements can be harmed by an excessive UCO component. However, in aged asphalt, low UCO concentrations react and volatilize harmlessly, but in polymer-modified binder, polymerization may take place and may alter its structural characteristics [13][14]. Compared to asphalt treated with UCO, fuel-based asphalt deteriorates more quickly when exposed to high temperatures [15][16][17]. As the temperature rises, UCO's kinematic viscosity drops, measuring 47.444 mm²/s at 40°C and 10.645 mm²/s at 100°C [17][18]. Pavement distresses, such as rutting, fatigue cracking, and permanent deformation, are the main engineering problems impacting asphalt pavements and seriously impair pavement behaviour and design life [19][20]. Bitumen treated with UCO can lessen typical pavement distress, and laboratory characterisation makes it easy to evaluate its conventional features [21][22].

UCO is a sustainable and efficient bitumen modifier, as numerous studies have shown. It is frequently utilized in applications involving binder and asphalt mixtures, especially to enhance workability, flexibility, and fatigue resistance. By altering the binder's internal structure, UCO improves its viscoelastic qualities and lessens its vulnerability to aging and cracking, acting as a softening and revitalizing agent. However, because too much UCO might decrease stiffness and rutting resistance, the performance enhancement is strongly dependent on dosage. Overall, there is substantial evidence in the literature that UCO-modified asphalt binder can lessen typical pavement distress and that established laboratory characterisation techniques can accurately assess its effectiveness. These findings show that UCO's viscosity rises with decreasing temperature and falls with increasing temperature. Previous research on UCO has mostly concentrated on its mechanical characteristics, with little assessment of its thermal safety and uneven ideal dosages. This study offers a balanced, long-term solution for better bitumen performance by thoroughly evaluating both mechanical and thermal characteristics and determining that 4% UCO is the ideal content.

2.0 METHODOLOGY

2.1 Materials

UCO and penetration grade 50/60 bitumen were among the materials chosen due to their accessibility, affordability, and appropriateness for pavement applications. All material preparation and selection were done in accordance with standard specifications for the construction of asphalt pavement. Conventional characteristics and mixing procedures were taken from earlier research and confirmed by lab testing to guarantee a consistent and homogenous blend. Figure 1 shows the flowchart for bitumen 50/60 and UCO.

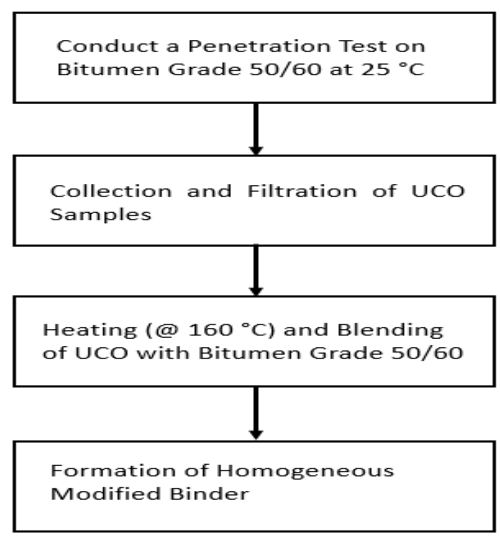


Figure 1 Flowchart for bitumen grade 50/60 and UCO

2.2 Preparation of the Materials and Samples

Penetration grade 50/60 bitumen and UCO were manufactured in accordance with specified procedures to guarantee uniformity and compatibility for pavement stabilization. While UCO was preheated to about 110°C (ASTM International and AASHTO) to lower viscosity and encourage uniform mixing following filtering to remove impurities, bitumen was heated to 160°C (ASTM D6925/D6926 and AASHTO) to produce a fluid state suited for blending. Because bitumen grade 50/60 provides a balanced blend of stiffness and flexibility appropriate for tropical and subtropical areas like Nigeria, it was chosen for this investigation. 50/60 asphalt binder offers greater rutting resistance than 60/70 bitumen, which is softer and more susceptible to displacement under heavy traffic loads and high temperatures, making it more suitable for intensively travelled asphalt pavements. Furthermore, 50/60 bitumen is frequently utilized in conventional pavement designs and satisfies regional and global requirements for pavement construction, offering a trustworthy baseline for evaluating the impacts of UCO rejuvenation [23][24]. Its modest hardness prevents the binder from being unduly softened by UCO changes, which could impair high-temperature performance [25]. Additionally, previous studies have shown that bitumen 50/60 reacts consistently to polymeric and waste-derived modifiers, enabling reliable laboratory characterisation and comparison with traditional performance criteria like penetration, softening point, flash point, and fire point [26][27][28][29]. Thus, utilizing 50/60 allows for the assessment of viable bitumen modification techniques while guaranteeing both experimental reliability and practical relevance [28]. To produce a homogenous modified binder, UCO was progressively added to the heated bitumen while being continuously stirred for 20 to 30 minutes (ASTM D6925 and AASHTO). To achieve a homogeneous and stable blend, a mixing time of 20 to 30 minutes was chosen to guarantee even spreading of UCO inside the bitumen. While a longer blending duration may result in the binder's heat deterioration, shorter mixing times may result in incomplete blending. As a result, this range offers the best possible compromise between efficient mixing and binder property maintenance. These materials' suitability for use in sustainable pavement applications was verified using accepted standard criteria. Figure 2 shows the stages involved in sample production and preparation.

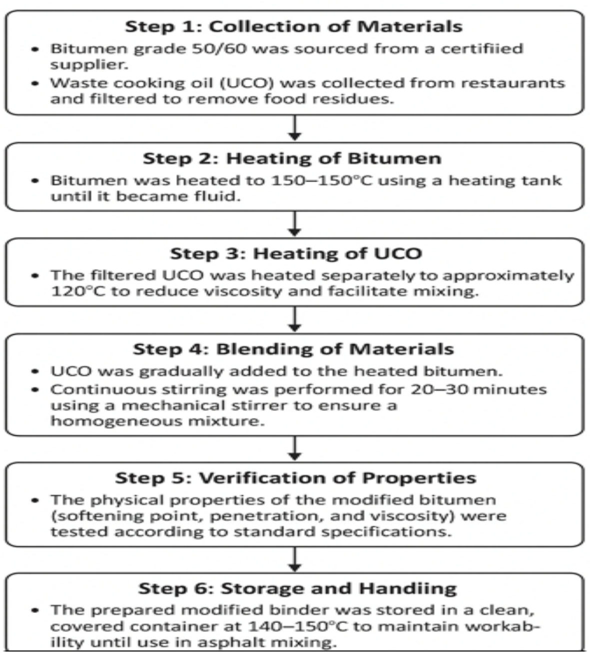


Figure 2 Steps for the preparation of materials and samples

2.3 Chemical Properties of UCO

Gas chromatography-mass spectrometry is one of the standard techniques frequently used to identify the chemical composition of UCO. The gasification technique, solvent separation technique, hydro-treatment technique, transesterification reaction technique, and membrane technique are some of the other techniques that have recently been used to evaluate waste oil treatment and recovery [30][31][32]. According to Frota et al. [33]; Banga & Pathak [22]; and Oldham et al. [34], transesterification does not take place when the dose of FFA is greater than three percent. Furthermore, it was stated by Shiung et al. [30]; Xu et al. [36]; Xiong et al. [32]; and Buyang et al. [37] that although pyrolysis methods have been acknowledged as an alternative method for repurposing reprocessed waste oils, their use has not yet gained extensive acceptance. According to Jacobson et al. [38] and Kim et al. [15], oxidation, polymerization, and valorization reactions yield a higher UCO saponification number and viscosity than unused oil. Additionally, Allen & Watts [39] revealed that there is more water in the UCO than water due to the heat and matter transfer in the frying process.

According to the discoveries of Azahar et al. [40]; Ma et al. [41]; and Cavalli et al. [42], oleic and heneicosanoic acids have the highest and lowest composition of UCO, respectively Zhang et al. [43] discovered that for UCO to react as a rejuvenated bitumen, UCO acid contents between 0.40 and 3.20 mg KOH/g are necessary. The researchers further discovered that the range acid value typically satisfies all necessary specification criteria for binder modification if it falls between 0.40 and 0.70 mg KOH/g. Based on its acid, iodine, and saponification number, UCO is a superior material [44][45]. Different chemical and physical properties can result from the difference in the chemical arrangement of fuel asphalt and bio-oil asphalt [46][47][48].

Zhang et al. [43] found that a minor acid value in milligrams required to neutralize 1 g of UCO is estimated for an improved property of UCO to modify the binder. The acid value increases with the content of FFAs in the UCO. At lower temperatures, the integration of UCO content exhibits a positive effect on the chemical and rheological properties of bio-bitumen binder [33][39][49]. Characteristically, UCO is applied as a protective layer or modifier for the binder, and the degree of mixing depends on the material's chemical properties [33][50][51]. According to Rodrigues et al. [52], UCO advances the better-controlled asphaltic blend's relaxation pressure property. According to Al-Sabaeei et al. [53], UCO can operate as a binding modifier to improve the rheological properties and reduce the possibility of cracking at lower temperatures of bio-asphalt pavement aging. Table 1 shows the chemical properties of UCO.

Table 1 Chemical properties of UCO

Type of FFA	Carbon chain	Sharma et al. [10]	Foroutan et al. [9]	Chhetri et al. [8]
Myristic acid	C14:0	0.99	0.77	0.90
Palmitic Acid	C16:0	28.65	31.88	20.40
Palmitoleic acid	C16:1	0.97	-	4.60
Stearic acid	C18:0	2.55	6.45	4.80
Oleic Acid	C18:1	24.69	41.04	52.90
Linoleic acid	C18:2	40.88	17.98	13.50
Linolenic acid	C18:3	1.27	0.43	0.80
Others	-	-	1.45	1.10

2.4 Physical Properties of UCO

Viscosity, penetration, softening point, and Dynamic Shear Rheometer (DSR) tests can all be used to assess the physical properties of asphalt modifiers [54]. Temperature and cooking time are two factors that affect the physical properties of UCO [55]. According to Mamun & Wahhab [56], when a certain content of UCO is added, the viscosity of the asphalt blend reduces. However, this study opposes this discovery. The researchers further discovered that when the binder mix is too soft, pavement rutting increases. Sun et al. [58] also discovered that pavement creep reduces with increasing UCO contents. This suggested that the quantity of pavement deformation increased with the quantity of rutting. The utilization of UCO, according to Azahar et al. [40] and Hosseinzadeh-bandbafha et al. [59], weakens the aging asphalt pavement. However, this study also opposes this discovery.

Yel-Shorbag et al. [21] discovered that the repeated inclusion of UCO increases the asphalt mixture's fatigue resistance. This discovery has been verified by the contemporary study. For the workability and compaction of asphalt pavements, the WMA contemporary skills primarily decrease the viscosity of the asphalt binders [60][61][62]. The rheological characteristics of bitumen and the physical and durability characteristics of WMA mixtures can also be affected differently by these contemporary skills [63][64]. Table 2 depicts the physical properties of UCO.

Table 2 Physical properties of UCO [65]

Property	Unit	Wt. of UCO	Standard method
Density at 15 ^{0}C	g/cm^3	0.9252	-
Viscosity at 40 ^{0}C	mm^2/sec	47.444	ASTM D445
Viscosity at 100 ^{0}C	mm^2/sec	10.645	ASTM D445
Viscosity index	-	223.000	-
Flash point	^{0}C	-	ASTM D92
Pour point	^{0}C	-3.000	ASTM D97
Colour	-	-	-
TAN	-	9.130	-
Carbon residue	%	0.390	-
Refractive index at 20 ^{0}C	-	-	-

2.5 Characterization of the Materials

Because of its balanced performance under varied streams of traffic loads and climatic conditions, penetration grade 50/60 bitumen is frequently utilized in pavement construction. It is relatively hard and appropriate for tropical and subtropical areas because it provides the best possible balance between low-temperature elasticity and high-temperature rutting resistance. Table 3 provides an overview of the usual characteristics of the materials employed in this investigation.

Table 3 Typical description of the materials' characterization [13][66][67]

Property	Test Standard	Result Standard
Penetration at 25 °C (dmm)	ASTM D5 / BS EN 1426	50 – 60
Softening Point (°C)	ASTM D36 / BS EN 1427	45 – 55
Flash Point (°C)	ASTM D92 / BS EN ISO 2592	≥ 220
Ductility at 25 °C (cm)	ASTM D113 / BS EN 13589	≥ 75
Specific Gravity	ASTM D70 / BS EN 1427	1.01 1.05
Penetration Index (PI)	Calculated	-1 – +1
Viscosity at 60 °C (Pa·s)	ASTM D2171 / BS EN 12591	220 – 300

2.6 Softening Point Test

The softening point test was performed to determine the temperature at which the binder changes from solid to liquid (ASTM D36). A brass ring mould, glass beaker, 9.5 mm steel ball, ball and ring support, ball guides, stirrer, forceps, stopwatch, and digital thermometer were all part of the experimental apparatus. To ensure homogeneity for UCO-modified samples, UCO was combined with penetration grade 50/60 bitumen while being continuously stirred for 35 minutes, and the sample was heated at 100°C [68].

After placement, the specimens were placed in the brass rings and allowed to cool for half an hour at room temperature. Warm water was introduced to the ring-and-ball contraption 50 mm above the ring surfaces after it had been levelled and any surplus material removed with a hot pallet knife. Steel balls were inserted into the cantering guides, the specimens were shaken, and the bath was gradually heated until the asphalt binder completely flowed into the rings after a 15-minute equilibration interval (Figure 3). The average of three duplicate measurements for each mixture was used to calculate the softening point.

Figure 3 Testing of softening point

2.7 Penetration Test

The penetration test measured penetration depth by applying a 100 g vertical force for 5 seconds at 25°C to assess the bitumen's homogeneity and consistency [69]. The penetration test was carried out utilizing standard tools, such as a needle, penetrometer, and cylindrical container (ASTM D5)[69]. The modified samples were prepared by blending bitumen with UCO for 35 minutes (ASTM D5)[69]. The samples were then heated and put into a cylindrical container with the thermometer set to zero. After positioning the needle so that it made contact with the sample surface (Figure 4), it was given five seconds to pierce. The process was carried out three times for each mixture, recording the penetration depth in millimetres and reporting the average value.

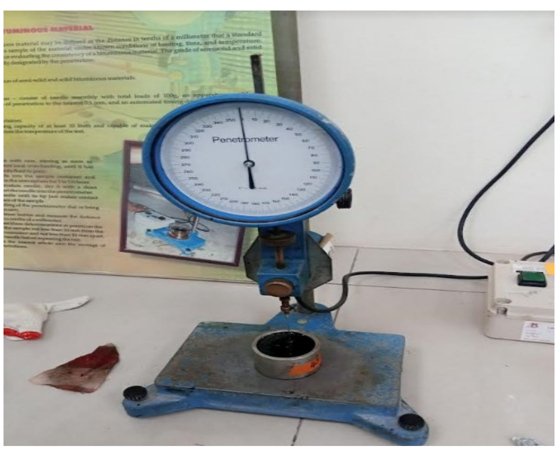


Figure 4 Testing of penetration grade

2.8 Flash Point Test

A Cleveland Open Cup tester was used to find bitumen's flash point, or the highest temperature at which flashing is observable. Modified samples were produced by blending bitumen and UCO for 35 minutes. The samples were then heated and added to the cup until the fill line was reached. The temperature was raised at a regulated pace of 14–17°C (ASTM D92 – Cleveland Open Cup Technique and AASHTO T48) per minute until the flash point was reached while the thermometer probe was submerged in the sample. The heating rate was lowered to 5–6°C (ASTM D92 – Cleveland Open Cup Technique and AASHTO T48) per minute when the specimen temperature dropped to about 56°C below the anticipated flash threshold. Until the temperature was roughly 28°C below the expected flash point, an experimental flame was applied at intervals of 2°C (ASTM D92 – Cleveland Open Cup Technique and AASHTO T48). The flame was then delivered at regular intervals until vapor ignition continued for at least five seconds after the thermometer reading at this point was noted. The thermometer reading during the time of continuous flashing was used to calculate the flash point (Figure 5).

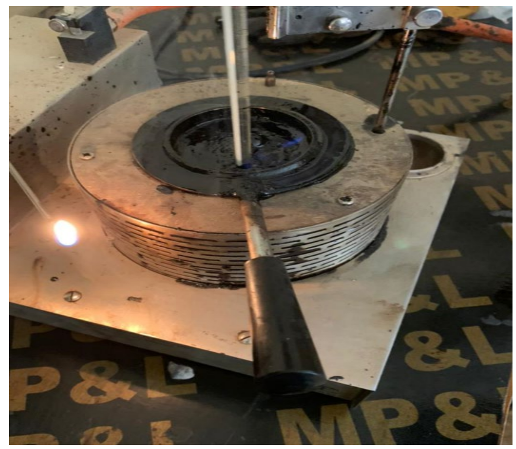


Figure 5 Testing of flash point

2.9 Fire Point Test

A suitable solvent was used to clean the experimental cup for the fire point determination until a reflecting metallic surface was achieved. After carefully pouring the heated sample to the fill line, any surface air bubbles were eliminated. The thermometer was placed vertically, with the bulb positioned 0.5 inches (0.635 cm) above the midpoint and between the front and back of the cup. After that, the sample was heated at a regulated rate of 25–300°F (−3.89 to 148.89°C) per minute (ASTM D92 – Cleveland Open Cup Technique and AASHTO T48). At the moment of vapor ignition, the thermometer reading was taken. A test flame was delivered at intervals of 50°F (10°C) while the specimen was heated at a rate of 10 ± 1°F (5.5 ± 0.6°C) per minute until sustained ignition occurred for at least 5 secs (ASTM D92 – Cleveland Open Cup Technique and AASHTO T48). At this point, the thermometer data was used to calculate the fire point temperature. The experimental setup for the fire point test is presented in Figure 6.

Figure 6 Testing of the fire point

3.0 RESULTS AND DISCUSSIONS

3.1 Softening Point

To ascertain the temperature at which bitumen changes from a semi-solid to a viscous liquid state, a crucial indicator of binder performance at high temperatures and its resistance to rutting, the softening point test was carried out. The findings demonstrated that the relevant ASTM requirements for pavement applications were met by both the regular bitumen and the UCO-modified mixtures. However, depending on the proportion added, UCO has an impact on the binder's softening point.

The results of the experiment showed that, in comparison to the unmodified bitumen (0% UCO), mixes containing 6%, 8%, and 10% UCO had slightly lower softening point values. This drop implies that the binder's resilience to softening at high temperatures may be weakened by greater UCO concentrations. The comparatively low viscosity and lubricating properties of UCO, which tend to decrease intermolecular cohesion within the binder matrix, are responsible for the observed behaviour. Similar patterns have been documented in earlier research, where the addition of UCO or bio-oils decreased bitumen's softening point because of their plasticizing influence on the binder structure.

For example, Zargar et al [70] found that adding UCO to aged asphalt improved binder workability and flexibility while lowering the softening point. Similarly, Asli et al [11] found that by softening the asphalt matrix and enhancing its rejuvenation qualities, modest dosages of UCO could alter binder properties. These results are in line with the current study's findings, which show that UCO functions as a softening agent in the binder system.

Despite this decrease, the highest difference in softening point between normal bitumen and UCO-modified mixes was only around 2°C (ASTM D92 – Cleveland Open Cup Technique and AASHTO T48), suggesting that UCO's impact on high-temperature stability is still negligible within the studied dosage range. This implies that binder flexibility and workability can be enhanced by mild UCO inclusion without appreciably reducing the binder's resistance to high-temperature deformation.

The softening point values' standard deviation (SD) varied from 0.00°C to 1.05°C, demonstrating low experimental variability and proving the test results' strong repeatability and dependability across all mixes (Figure 7). This minimal variation attests to the consistency and suitability of the testing protocol and sample preparation techniques for assessing the impact of UCO on binder behaviour. The findings also showed that, in comparison to the control mixture, smaller UCO contents (up to 4%) marginally raised the softening point, indicating that little UCO addition may improve bitumen's thermal stability without negatively impacting its high-temperature performance. This enhancement could be explained by the interaction between the substantial ingredients of the bitumen binder and the light oil fractions of UCO, which can alter the bitumen matrix's internal structure and improve binder cohesiveness.

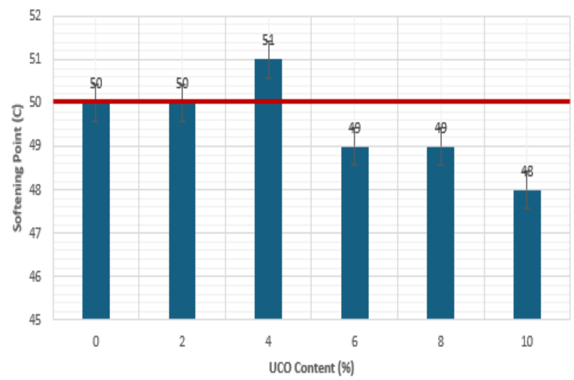


Figure 7 Effect of softening point

These results align with earlier research that has been documented in the literature. For instance, Asli et al [71] found that while retaining adequate thermal stability, low contents of UCO could enhance specific rheological characteristics of asphalt binders. In a similar vein, Zargar et al [70] found that adding UCO to aged asphalt in moderation improved asphalt binder workability and reinstated desired physical properties without appreciably lowering the softening point. Small contents of these additives can enhance binder elasticity and workability while preserving sufficient resistance to high-temperature deformation, according to other researchers looking into bio-oil and waste-derived modifiers.

According to the study's experimental findings, 4% UCO was determined to be the ideal dosage because it improved workability, asphalt binder elasticity, and heat stability in a balanced manner. The modified binder benefited from better handling and mixing properties at this concentration while maintaining a softening point similar to the control sample. Therefore, adding small volumes of UCO offers a viable and sustainable way to improve the performance of asphalt binder while also encouraging the advantageous reuse of waste material.

According to Cao & Wang [61], adding about 3% UCO greatly increased the fatigue resistance of asphalt binders, proving that low UCO dosages can improve binder performance. In a similar vein, Keymanesh et al [72], found that asphalt binders' softening point decreased with greater UCO dosages, especially around 7%. This observation is in line with the current study's findings, which suggest that the binder's resistance to high-temperature deformation may be slightly diminished by excessive UCO inclusion.

Overall, the findings show that UCO can be employed as a sustainable bitumen modifier as long as the dose is carefully regulated to retain the asphalt binder's proper high-temperature performance. The softening point analysis indicates that bitumen performance can be enhanced while keeping sufficient thermal stability for roadway applications with a minor UCO alteration of about 4% by weight of the binder. However, because of the softening action of the oil, excessive UCO addition may negatively impact high-temperature performance. Thus, figuring out the ideal UCO dose is crucial to striking a balance between increased workability, binder flexibility, and thermal stability, which will eventually improve pavement longevity and promote environmentally friendly pavement-construction techniques.

3.2 Penetration Grade

The standard bitumen (0% UCO), as seen in Figure 8, demonstrated a penetration value of 62 mm, which is within the usual range for penetration grade 50/60 binders and validates the base material's viability for pavement applications. It's interesting to note that the combination with 2% UCO achieved the same penetration value (62 mm), suggesting that adding a modest amount of UCO does not substantially change the consistency of the binder. This implies that UCO may only marginally weaken the asphalt binder structure while preserving its general stiffness at low dosages. The slight alteration could also be explained by better oil molecule dispersion in the binder matrix, which can increase the binder's homogeneity without significantly changing its hardness.

As the UCO content increases, the penetration results show a nonlinear relationship. At low dosages (0–4%), there is an initial rise in penetration; at 4% UCO, the greatest value is reported, suggesting a softening effect. This activity is in line with research by Zargar et al [70]. and Asli et al. [11], who showed that low concentrations of UCO function as a plasticizing and rejuvenating agent, improving molecular flexibility within the asphalt binder matrix and decreasing binder viscosity. Fatty acids in UCO enhance the maltene phase, resulting in higher penetration and ductility values.

Nevertheless, the penetration levels drop with more UCO addition (6–10%) after the optimal level (4%). This pattern is consistent with findings by Keymanesh et al [72]. and Sun et al. [58], who noted that a high UCO content can upset the asphaltene–maltene equilibrium, leading to decreased compatibility and uneven dispersion in the binder. Higher dosages of UCO may cause microstructural variability, which can enhance resistance to penetration, rather than acting only as a softening agent. Thermal exposure during blending may occasionally cause lighter fractions to partially volatilize or interact chemically, which would further affect the consistency of the binder.

These results demonstrate that the impact of UCO on penetration is dose-dependent, with greater contents perhaps leading to structural imbalance and low to moderate concentrations enhancing binder softness. Therefore, the finding that 4% UCO is the ideal dosage is in line with other research, which typically reports ideal varies between 3% and 5%, guaranteeing increased flexibility without compromising binder integrity.

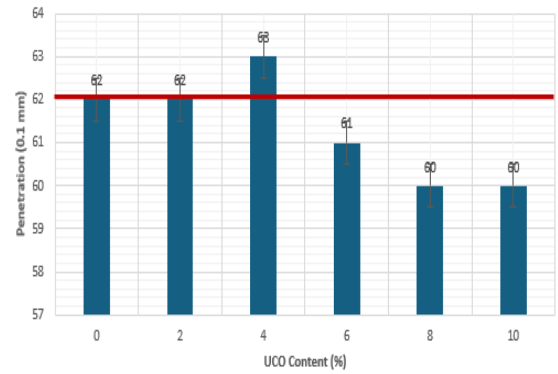


Figure 8 Effect of penetration grade

The optimal modification dosage was found to be 4% UCO, where a notable improvement in binder performance was noted. Stronger correlations and better cohesiveness between the base bitumen and UCO molecules increased binder flexibility at this dosage while preserving sufficient stiffness [58][72]. This behaviour could be explained by the fatty acid chains from UCO penetrating the bitumen matrix and enhancing the viscoelastic and flow characteristics of the binder. However, the binder tends to become softer and less stiff when the UCO content surpasses this ideal level, which may lessen its resistance to deformation at high temperatures. Similar patterns of decreased binder stiffness due to high bio-oil additives have been documented in earlier research [58][72]. In general, binder performance can be enhanced by moderate UCO integration (about 4%), while higher dosages may have a detrimental effect on high-temperature stability [58][72].

The satisfactory standard for penetration-grade binders (50 – 60 (0.1 mm)) was met by all recorded penetration values (ASTM D5 and AASHTO M20), which were all greater than 30 mm. According to Ye et al, [73] and Ye [74], bitumen with penetration values larger than 30 mm can retain significant resistance to fatigue cracking as long as the right mixing and compaction techniques are used. Both traditional bitumen and UCO-modified binders are appropriate for pavement applications, according to this observation. Additionally, the SD values varied from 0.00 mm to 1.21 mm, demonstrating little change across repeated measurements and verifying the consistency and dependability of the experimental protocols.

The study's conclusions align with those of earlier investigations. According to Banerji et al [75], adding 3% UCO greatly enhanced bitumen binder characteristics, which is consistent with the favourable results seen at 4% UCO in the present study. Together, these results show that low to moderate UCO concentrations can improve binder performance without significantly compromising stiffness, especially by boosting flexibility and fatigue resistance. Overall, the penetration test findings show that 4% UCO is the ideal content, offering a useful compromise between binder flexibility and hardness. This ideal degree of modification highlights UCO's potential as a sustainable and performance-boosting binder modifier that can enhance the characteristics of asphalt binder while encouraging ecologically friendly pavement construction techniques.

3.3 Flash Point

A crucial indicator of asphalt binder thermal stability and safety during manufacturing, handling, and field activities is the flash point test. It determines the temperature at which, in the presence of an external flame, the binder releases enough vapours to briefly ignite. Enhanced resistance to premature ignition is correlated with higher flash points, suggesting safer working conditions during high-temperature mixing and compaction. The flash point of the UCO-modified bitumen in this investigation was 298°C, which is higher than the 285°C found for normal bitumen (Figure 9). This improvement shows that adding UCO increases the thermal stability of the binder and lessens its vulnerability to igniting at high temperatures. The improvement is ascribed to UCO's chemical compositions, specifically its fatty acids and triglycerides, which function as stabilizing agents in the bitumen matrix. By lowering the instability of light hydrocarbons in the binder, these substances postpone the release of flammable fumes.

Additionally, for both standard and modified mixtures, the data showed nonlinear trends across flash point levels. While greater dosages slightly reduced overall bitumen consistency and changed vaporization behaviour, moderate UCO contents, roughly 4%, effectively improved molecular connections within the binder and limited volatilization. This finding is consistent with earlier research by Khan et al [24] and Banerji et al [75], which found that while low to moderate UCO or bio-oil additions enhance thermal stability, excessive modifier content may decrease high-temperature resistance because of softening and decreased cohesiveness in the binder matrix. SD values between 0.00°C and 4.43°C, which show low experimental variability and strong reproducibility, further bolster the data's dependability. Confidence in the presented trends is strengthened by the fact that the highest variation observed fits within the typical ranges reported for flash point testing of rejuvenated binders.

In summary, the flash point data show that UCO modification significantly improves bitumen's handling and high-temperature safety properties; 298°C is a significant improvement over the standard mixture. These results are in line with previous studies and show that UCO-modified bitumen can be safely incorporated into conventional asphalt manufacturing procedures, lowering heating risks and encouraging ecologically friendly and sustainable pavement construction methods.

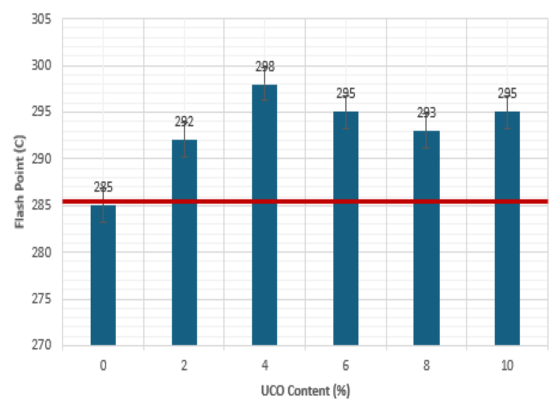


Figure 9 Effect of flash point

3.4 Fire Point

The fire point of the UCO-modified binder in this study was 336°C, higher than the 332°C found for normal bitumen (Figure 10). This increase shows that UCO insertion improves the binder's general thermal safety during high-temperature fabrication and paving developments by strengthening its resistance to protracted ignition. The improvement is explained by the chemical interactions in the new asphalt binder, where the fatty acid ingredients of UCO slow the initiation of sustained burning by lowering the volatility of light hydrocarbons. This result is in line with patterns found in the flash point evaluation, where thermal resistance was similarly enhanced by mild UCO additions.

The results of the fire point showed nonlinear tendencies throughout the spectrum of UCO concentrations, suggesting that the effect of UCO on thermal stability is content-dependent. While larger contents may soften the bitumen and slightly change its combustion and vaporization characteristics, moderate UCO contents, especially around 4%, improve molecular interactions and reduce volatilization. The safe application of UCO-modified mixes was confirmed by the fact that all measured fire points stayed within allowable temperature limits for bituminous binders. These results are in line with earlier studies. For instance, Khan et al [24] and Banerji et al [75] found that while excessive dosages may marginally lower high-temperature resistance due to decreased cohesion in the binder matrix, low to moderate UCO additions enhance bitumen's flash and fire points by improving thermal stability. These results are consistent with the ideal 4% UCO level found in this study, which offers a balanced improvement in handling qualities, binder stability, and thermal safety.

Overall, the fire point study shows that bitumen's high-temperature safety is much enhanced by UCO modification, making it appropriate for hot-mix asphalt manufacturing. These findings highlight UCO's potential as an eco-friendly and sustainable binder modifier that supports safe and effective pavement construction methods while providing improved thermal performance. Further confirming the efficacy of this dosage for improving bitumen performance, the current results closely match the ideal UCO modification range of 3.5% to 4.0% reported by Yel-Shorbagy et al [21]. This agreement supports the authenticity and dependability of the current findings by confirming that a 4% UCO content is ideal for creating both conventional and modified asphalt mixtures. In conclusion, the fire point results show that 4% UCO is the best modifier concentration for improving asphalt binder qualities because it offers the most balanced combination of thermal steadiness, high-temperature behaviour, and safety. The observed increase in fire point and trends in line with earlier research highlight UCO's efficacy as a sustainable and behaviour-improving binder modifier, showing its potential to increase binder durability while encouraging ecologically friendly pavement construction methods.

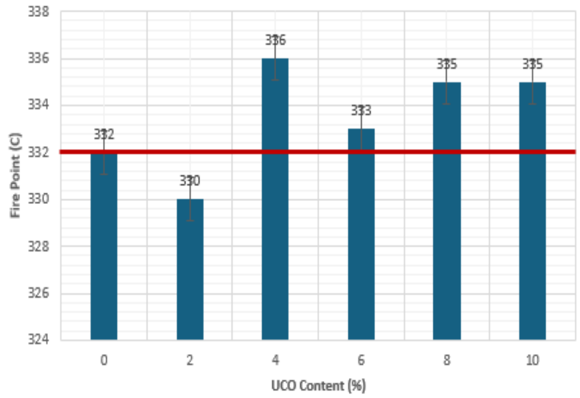


Figure 10 Effect of fire point

4.0 CONCLUSIONS

To improve the binder's thermal, mechanical, and rheological behaviour for bituminous pavement applications, this study thoroughly assessed the efficacy of UCO as a sustainable modifier for penetration-grade bitumen (50/60). The study evaluated both conventional and UCO-modified binders at various dosages using a variety of laboratory experiments, such as penetration, softening point, flash point, and fire point studies. The results show that bitumen's workability, elasticity, and high-temperature steadiness are greatly improved by mild UCO additions, improving bitumen's performance under service circumstances.

Triglycerides, FFAs, and negligible oxidation compounds produce the majority of UCO, and these components greatly affect how it behaves as a bitumen modifier. Chemically, the presence of long-chain fatty acids improves dispersion within the binder matrix and increases compatibility with bituminous binders. Additionally, these ingredients serve as plasticizing agents, enhancing viscoelastic qualities and decreasing binder stiffness.

UCO's physical characteristics, such as its high fluidity and comparatively low viscosity, improve workability and enable consistent mixing with bitumen at high temperatures. When combined with bitumen, its reduced volatility relative to lighter hydrocarbons enhances thermal stability, as seen by higher flash and fire point values. Furthermore, UCO improves flexibility and resistance to fatigue cracking by making the binder less brittle. UCO is an efficient, sustainable modifier that can enhance binder performance while promoting waste valorization and ecologically friendly pavement construction techniques due to its unique chemical and physical properties.

The ideal dosage of 4% UCO by binder weight offers the best compromise between stiffness and elasticity while also enhancing thermal safety. The binder showed better molecular cohesion, greater resistance to premature ignition and prolonged combustion, and improved resistance to rutting and fatigue at this concentration. Because of UCO's low viscosity and lubricating qualities, higher dosages (>6%) were shown to slightly reduce high-temperature stiffness and binder cohesiveness, whereas lower dosages (<4%) offered marginal improvements. These results emphasize how crucial it is to optimize UCO content in order to maximize performance benefits without compromising traditional bitumen properties.

The robustness and dependability of the contemporary findings are supported by a significant agreement with published optimal UCO values (3.5–4.0%) when compared to previous investigations. The study demonstrates that UCO can function as a sustainable, economical, and environmentally friendly bitumen modifier, providing the twin advantages of improved pavement performance and agricultural waste valorisation. By adding UCO to asphalt binders, it is possible to lessen reliance on petroleum-based goods, reduce pollution in the environment, and encourage environmentally friendly pavement-construction techniques. All things considered, UCO-modified bitumen is a potential solution for contemporary transportation infrastructure since it offers a practical means to produce long-lasting, high-performance bituminous pavements while tackling issues of economic and environmental sustainability.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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