

Development of Statistical Models of the Effects of Waste Engine Oil (WEO) on Different Grades of Asphalt

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Article History

Received: 01.06.2025

Revised: 04.08.2025

Accepted: 25.09.2025

Published: 28.09.2025

Communicated by: Prof. Dr. Bayan Salim

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Abstract: This research examines the impact of Waste Engine Oil (WEO) as a modifier on the physical properties of asphalt binders across three different grades (40/50, 50/60, and 60/70). The goal is to explore sustainable alternatives that enhance pavement performance and workability. Asphalt binders were modified with WEO at concentrations of (2%, 4%, 6%, 8%, and 10%) by weight and subjected to selected tests, including penetration, softening point, flash and fire points, and Rolling Thin Film Oven (RTFO) aging. To analyze the effect of WEO content quantitatively, second-degree polynomial regression models were developed for each test across the three grades. The results demonstrated that moderate additions of WEO (2-4%) significantly improved binder flexibility and penetration depth, facilitating better workability, especially in cooler climates. However, higher concentrations of WEO (above 8%) led to excessive softening, reduced thermal stability, and diminished resistance to aging. Despite noticeable reductions in flash and fire points, all modified binders met ASTM safety requirements. The study concludes that optimal WEO content ranges between (2-4%) for scenarios prioritizing long-term durability and thermal stability, while (4-6%) is suitable for applications emphasizing enhanced flexibility and workability. These findings underscore WEO's potential as an environmentally sustainable and performance-enhancing asphalt binder modifier when applied within controlled limits.

Keywords: Waste Engine Oil; Asphalt Binder Properties; Asphalt Modifier; Durability; Flexibility; Sustainability.

1. Introduction

Bitumen is a dense, dark-brown organic material known for its excellent binding and adhesive properties [1]. The major portion of the material consists of hydrocarbons, comprising approximately 80-88% Carbon and 8-11% Hydrogen, with minor percentages of Oxygen, Sulphur, Nitrogen, and trace metals. It has played a crucial role in civil works, mainly in the building and development of roadways, walkways, and pavements, among many such projects as discussed by [1]. Bitumen is obtained from petroleum and is a very valuable product owing to its unique properties of plasticity, resistance to water, and durability over a long period of time. These properties make it very suitable for paving and construction work [2]. Its adaptability is that it can be mixed with other materials such as sand, gravel, and crushed stone to produce asphalt concrete, a composite material that gives smooth, durable, and cost-effective surfaces to both vehicles and pedestrians.

Globally, an estimated 1.5 billion tons of construction waste are generated annually, and this is still increasing, as indicated by [3-4]. Disposal of such wastes is a tremendous challenge due to the complexities of storage, handling, and transportation. The traditional methods of landfilling and

incineration have not only consumed valuable land resources but also generated irreversible environmental pollution, as indicated by [5]. New waste disposal solutions are therefore urgently required. The use of waste material as an alternative to asphalt binders and aggregates in pavement engineering is one of the promising solutions. This has been found capable of reducing the use of asphalt binder while meeting the desired materials property of the asphalt mixture, as indicated by [6]. It also reduces carbon dioxide emissions, offering a sustainable way forward.

In Iraq, because of the adverse environmental conditions, the road network has suffered deterioration, with most of the roads being in poor condition. As a measure for improving the quality and durability of roads, minimizing the costs, and preserving natural resources, additives in asphalt binders are inevitable. Among them, waste engine oil (WEO) has been taken into consideration because of its potential to enhance the properties of the binder and enhance damage resistance, as claimed by [7-8]. This is in line with the worldwide need to consume enormous amounts of oil waste, including waste plastic oil, waste cooking oil (WCO), and WEO, which cumulatively pose enormous pollution, with WEO alone being produced at an enormous rate of 45 million tons per year, as claimed by [3]. By using such a waste product in the production of asphalt, not only can the environmental footprint be reduced, but sustainable and economical solutions can be attained as well, resolving local and worldwide infrastructure issues.

Waste engine oil (WEO) refers to a petroleum-based or synthetic lubricant that has deteriorated and is no longer suitable for its intended purpose due to contamination or the degradation of its properties as highlighted by [9]. The contamination may result from various factors, such as fuel dilution, metal wear particles, coolant infiltration, other fluids, oxidation, and thermal break down. These impurities substantially impair the oil's lubricating capabilities, diminishing its effectiveness in protecting engine components from wear and tear. Figure 1 depicts the difference between ordinary engine oil and waste engine oil.

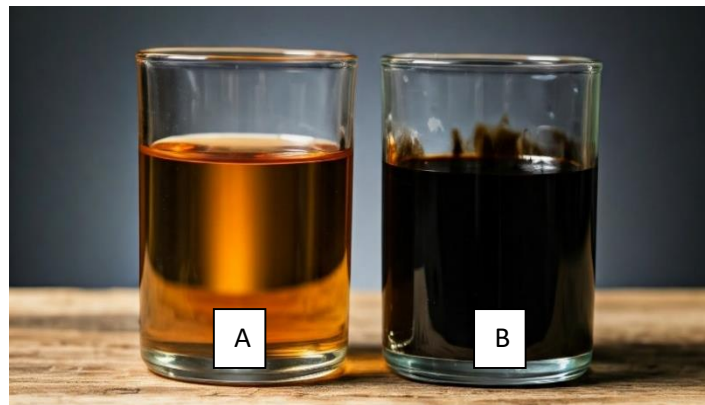


Figure 1: (A) Ordinary engine oil, (B) waste engine oil.

Over the past decade, extensive research has been carried out on asphalt with engine oil, such as [10], in which he examined the use of WEO in asphalt binder. The addition of 4% WEO was established as the optimal percentage, which created a compromise between enhanced flexibility, elasticity, and flow properties without influencing safety and stability. Also, [11] examined an asphalt binder (AH-70, with a penetration grade of 71.9) with different grades of WEO, he stated that the best ratios when from the tests that he did was (2-4%), where the elasticity was moderately reduced without severe compromise and fatigue resistance increased significantly, so (2%-4%) provided the optimal balance of performance for the binder.

2. Methodology

The diagram below summarizes the outline or methodology of the present study:



Materials in the study were readily available from reliable local sources in Erbil, and these materials were good enough in quality to meet the objectives of the research. All three grades in terms of asphalt binder categories, which were specified by their penetration grades (40/50, 50/60, and 60/70), have been procured from the source (Golden Bitumen Refinery) in Erbil City. These grades have been selected in this research because of their frequent usage in the Kurdistan Region, especially in Erbil, where the (40/50) grade is widely used, taking into consideration the climatic conditions of the region. On the other hand, the (45/55) grade is widely used in Duhok and Zaxo, while the (60/70) grade is preferred in colder areas like Haji-Omaran. In addition, (35) liters of composite waste engine oil WEO were collected from a local garage called (Anwar Garage) located on (100 Meter) Street in Erbil. This WEO was selected to be an additive to study its effects on binder performances. The effects of WEO on asphalt binders are investigated in this paper by carrying out some classical asphalt tests according to SORB standards and other related literature. The properties of WEO are shown in Table 1.

Table 1: Properties of WEO.

WEO Properties			
Viscosity @50°C (cP)	Colour	Flash point (°C)	Fire point (°C)
35	Dark brown	172	190

In this study, binders with different WEO concentrations (0% or control, 2%, 4%, 6%, 8%, and 10%) were tested under several tests for the characteristics and behavior of modified binders, as shown in Table 2. these include (Penetration test (ASTM D5), Flash and Fire point test (ASTM D92–01), Rolling Thin Film Oven (ASTM D2872-22), and Softening point test (D36-95)). Penetration Index (PI) was also calculated to evaluate the temperature susceptibility of the binders. These evaluations were carried out to investigate the effect of WEO addition across different penetration grades, expanding the bounds from existing studies and enabling a comprehensive understanding of WEO's impact on asphalt binder characteristics.

2.1 Preparation of WEO-modified asphalt binder

Due to the similar properties and components of WEO and asphalt, they are highly compatible. This makes it straightforward to prepare WEO-modified asphalt using a high shear mixer (Silverson L5T). In this study, the base asphalt was heated to 150°C for asphalt to achieve a flowable state. WEO was then gradually added to the asphalt binders and mixed at a speed of (2300-2500) rpm for 30 minutes to ensure a uniform blend. Asphalt samples were prepared with WEO concentrations of 0%, 2%, 4%, 6%, 8%, and 10% by weight of the base asphalt. In total, eighteen distinct binders were developed and analyzed in this study. The WEO content was chosen based on existing research and practical applications.

Table 2: Test procedure.

No.	Binder grade	WEO ratio	Tests
1	40/50	0%	penetration, RTFO (Penetration), Softening point, Flash and Fire
		2%	
		4%	
		6%	
		8%	
		10%	
2	50/60	0%	penetration, RTFO (Penetration), Softening point, Flash and Fire
		2%	
		4%	
		6%	
		8%	
		10%	
3	60/70	0%	penetration, RTFO (Penetration), Softening point, Flash and Fire
		2%	
		4%	
		6%	
		8%	
		10%	

3. Experimental method

3.1 Penetration test

The consistency test for semisolid and solid bituminous mixtures is covered by (ASTM D 5). The test results are expressed as the depth, in tenths of a millimeter, that a standard needle penetrates the material under specified conditions of load, time, and temperature. This test determines the softness or hardness, which again reflects on the applicability of materials in road construction and other purposes. The higher the values of penetration, the softer the materials. It finds major applications in the quality control of bitumen production for meeting specifications on paving and roofing applications. It helps classify into grades suitable for different climatic conditions and applications. The sample was heated to fluid, poured into a standard container, and cooled under controlled conditions. The test for penetration is done using a calibrated penetrometer in which the needle is lowered onto the surface of the sample. Under a specified load, the needle penetrates for a fixed time, and this depth is recorded. Several readings are taken for the sake of assurance. Results derived from this technique will provide valuable information on material behavior under stress and thus guidelines for the selection of materials for any particular engineering requirement.

3.2 Flash and Fire test

Flash and fire test (ASTM D 92–01) is a test involving the use of the Cleveland open cup apparatus for investigating the flash point and fire point of petroleum products. The flashpoints are the low temperature that gives momentary ignition of vapors, while that at which flames of combustion give sustained burning for at least five seconds on the application is called the fire point. This test involves heating some 70 mL of the sample at a controlled rate and, from time to time, applying a test flame until it defines the flash and fire points at specified conditions. The test is highly important for assessing flammability and safety characteristics in materials.

3.3 Rolling Thin Film Oven (RTFO) test

(ASTM D2872-22), Rolling Thin-Film Oven Test determines the effect of heat and air on semisolid asphaltic materials during the early stages of their service life, simulating the short-term aging that takes place during hot mixing and pavement application. Materials are heated in heat-resistant glass containers at 325°F (163°C) in a convection oven for 85 minutes with rotation to ensure uniform exposure. Heated air jets are forced onto the samples, artificially reproducing in this way the aging action. Testing post-exposure records changes in physical properties, which can include viscosity, ductility, penetration, and mass. The measurements obtained from the penetration test provide information about the hardening of the material through aging, while ductility gives an idea about the flexibility or cracking resistance of asphalt. The procedure standardized here is important in quality control, as it predicts the behavior that the asphalt will show during mixing and laying, assures repetition in the material, and makes an evaluation of the durability of the material for pavement applications.

3.4 Softening point test

(ASTM D36-95), Softening Point Test: The softening point of bitumen is the temperature under stipulated conditions that is measured with the ring-and-ball apparatus. The test is an important one for bitumen classification and control of material uniformity, especially in terms of material flow characteristics at high temperatures. In this procedure, a brass ring containing the bitumen disc is submerged in a liquid bath while it is heated, on which a steel ball is supported in contact with each sample. The temperature at which the bitumen softens to the degree that the ball falls to a depth of 25 mm is considered the softening point. This test has been standardized and found widespread application in quality control to ascertain the thermal performance of bituminous materials in different uses. In addition to determining the softening point, the Penetration Index (PI) was calculated to further assess the temperature susceptibility of the asphalt binder. The PI offers a quantitative evaluation of how binder consistency varies with temperature, providing valuable insight into its expected performance under different climatic conditions. A higher PI value indicates reduced temperature susceptibility, suggesting that the binder retains its properties more consistently over a broad temperature range. PI values suitable for road paving typically fall within the range of (-2 to +2) [12]. The PI was determined based on the results of the penetration test (ASTM D5) and softening point test (ASTM D36) as presented in equation (1).

$$(1) \quad PI = \frac{1952 - 500 \log(\text{Pen}) - 20SP}{50 \log(\text{Pen}) - SP - 120}$$

Where:

Pen= Penetration at 25°C

SP= Softening Point, °C

4. Result and discussion

4.1 Penetration test

The penetration test is an essential technique used to assess the consistency and stiffness of asphalt binders. When Waste Engine Oil (WEO) is added, the penetration depth increases, signaling a decrease in binder stiffness. This change plays a crucial role in influencing pavement workability, resistance to fatigue, and overall rutting performance. The results are shown in Table 3.

The 40/50 and 50/60 grades showed a steady increase up to 6% WEO, but beyond that, penetration values rose sharply. Among them, the 60/70 grade was the most sensitive to WEO modification.

Adding WEO significantly reduced viscosity, making the mixture easier to blend and lowering compaction temperatures, which is particularly beneficial in colder climates. Additionally, the enhanced ductility and elasticity improved fatigue resistance, helping to prevent pavement cracking over time. However, when WEO levels exceed 8%, excessive softening occurs, which negatively affects rutting resistance, making the asphalt more prone to permanent deformation in high-temperature conditions. Quadratic polynomial regression analysis was conducted to quantify the effect of WEO content on penetration depth, resulting in the following regression equations:

- (1) 40/50 grade: Penetration= $0.830(\text{WEO}\%)^2 + 2.682(\text{WEO}\%) + 48.643$, $R^2=1.000$
- (2) 50/60 grade: Penetration= $0.839(\text{WEO}\%)^2 + 3.193(\text{WEO}\%) + 53.429$, $R^2=0.997$
- (3) 60/70 grade: Penetration= $0.580(\text{WEO}\%)^2 + 10.182(\text{WEO}\%) + 64.643$, $R^2=0.987$

These equations statistically confirm the observed trends in penetration behavior due to WEO content, if we replace any (WEO%) from (0-10%) we can precisely find the penetration value for any grade, and the high values of the (R^2) indicate that the chosen quadratic regression models predict the effects on asphalt binders modified by WEO.

The regression models developed for all three asphalt binder grades demonstrated strong statistical validity. For the 40/50 binder, the model showed $R^2=1.000$ and $R=1.000$, indicating a perfect fit and correlation. For the 50/60 and 60/70 binders, R^2 values were 0.997 and 0.994, with corresponding R values 0.999 and 0.997, respectively. All signifying excellent correlation and model fit. In all cases, ANOVA results were highly significant ($p<0.001$), confirming the predictive strength of the models.

Additionally, a two-tailed paired t-test was used to compare predicted and experimental values. The resulting p-values were 0.9555 (40/59), 0.9924 (50/60), and 0.9977 (60/70), all well above the 0.05 threshold, indicating no statistically significant difference between predicted and actual values. These findings confirm that the models are accurate and reliable for representing the effect of WEO on binder penetration and can be confidently used for future performance estimations.

For an optimum balance of flexibility, durability, and rut resistance, the ideal WEO ratios were determined to be 6% for 40/50 and 50/60 grade levels, which resulted in 95 (0.1 mm) and 99 (0.1 mm) penetration values, respectively, while the 60/70 grade performed best with 4-6% WEO, with penetration values between 115-138 (0.1 mm). These findings align with previous reports testifying that moderate WEO content enhances flexibility without compromising structural strength [11] testified that 4-6% WEO improves fatigue resistance without influencing rutting performance, while [10] indicated its role in reducing viscosity and improving workability. [9] also highlighted the necessity of limiting WEO content to prevent excessive softening. The penetration trends indicated a linear increase in all the grades with WEO incorporated, but beyond 8%, the penetration increased exponentially, reflecting excessive softening, and higher concentrations are not practicable for real-world applications. The key takeaway is that maintaining moderate WEO levels (4-6%) is ideal for achieving a balance between flexibility, workability, and durability. Specifically, for 40/50 and 50/60 grade materials, a 6% WEO content enhances flexibility without causing excessive softening. Meanwhile, for the 60/70 grade, a WEO range of 4-6% improves fatigue resistance while preserving structural integrity. These recommendations help optimize pavement performance by leveraging the benefits of WEO while preventing excessive softening. Furthermore, penetration test results confirm that WEO can be an effective binder modifier, as long as its content is carefully regulated. Figure 2 shows the effects of WEO on the different grades.

Table 3: Penetration test results.

Additive Rate (%)	40/50 Grade (0.1 mm)	50/60 Grade (0.1 mm)	60/70 Grade (0.1 mm)
0	49	52	65
2	57	65	88
4	72	82	115
6	95	99	138
8	124	133	195
10	158	170	220

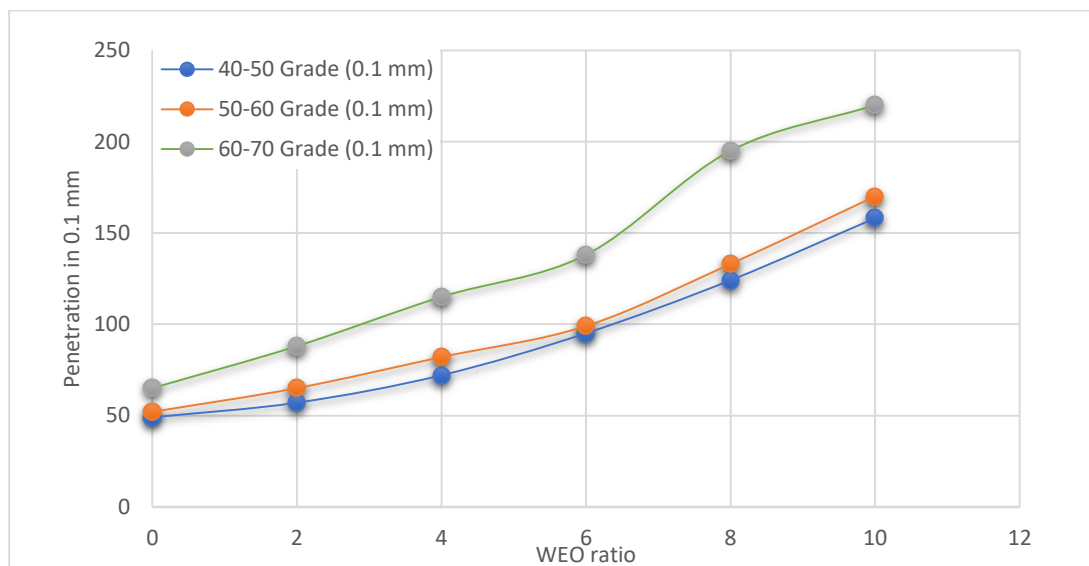


Figure 2: WEO effect on different grades of binder.

4.2 Softening point test

The results of the softening point test for asphalt binders modified with waste engine oil (WEO) reveal a clear trend: as the WEO content increases, the softening point decreases. For the 40/50 grade asphalt, the softening point starts at 52.4°C without WEO, and it declines to 52°C at 2% WEO. Reaching 40°C at 10% WEO. A similar pattern is observed in the 50/60 grade asphalt, where the softening point drops from 51°C at 0% WEO to 40°C at 10% WEO, emphasizing WEO's function as a softening agent. The 60/70 grade asphalt follows the same trend, with its softening point decreasing from 50°C at 0% WEO to 37°C at 10% WEO, as shown in Table 4. Regression analysis yielded quadratic polynomial equations modeling the relationship between WEO content and softening point:

- (4) 40/50 grade: Softening point= $0.013(\text{WEO}\%)^2 - 1.448(\text{WEO}\%) + 53.150$, $R^2=0.960$
(5) 50/60 grade: Softening point= $1.129(\text{WEO}\%) + 51.143$, $R^2= 0.996$
(6) 60/70 grade: Softening point= $0.027(\text{WEO}\%)^2 - 1.525(\text{WEO}\%) + 49.643$, $R^2=0.992$

These equations statistically confirm the observed trends in softening behavior due to WEO content, if we replace any (WEO%) from (0-10%), we can precisely find the softening point for any grade, and the high values of the (R^2) indicate that the chosen quadratic regression models predict the effects on asphalt binders modified by WEO.

The regression models for softening point exhibited strong accuracy across all binder grades. For the 40/50 binder, the model showed $R^2 = 0.960$ and $R = 0.980$, with ANOVA significance ($p = 0.008$). In the 50/60 grade, the 1st part of the equation is very close to zero, it's $(3.254E-16 (WEO\%)^2)$, so we neglected it and started from the 2nd part. This means that if we put any WEO% in this part, the result will be very close to zero. the model achieved $R^2 = 0.996$ and $R = 0.998$, with ANOVA $p < 0.001$. Only the linear term was significant ($p = 0.004$), confirming a nearly linear relationship. For 60/70, results were similarly strong ($R^2 = 0.986$, $R = 0.996$, $p < 0.001$). Two-tailed paired t-tests comparing predicted and experimental values produced p-values of 0.9752 (40/50), 0.9858 (50/60), and 0.9658 (60/70), all well above 0.05, confirming no significant differences and validating the model's reliability. Overall, the regression equations accurately capture the decline in softening point with increasing WEO content.

These findings are consistent with previous research on WEO-modified asphalt, which shows that WEO reduces the high-temperature stiffness of asphalt binders. This is largely due to its high content of light fractions and lubricating nature, as mentioned by [3]. This trend is consistent with the fact that WEO reduces the viscosity of asphalt binders, making them more flexible at low temperatures but more vulnerable to deformation at high-temperature conditions, as mentioned by [9].

The ideal percentage of Waste Engine Oil (WEO) in asphalt varies by grade to balance flexibility and stability. For a 40/50 grade, 2%-4% is ideal, as above 4% rutting increases. In 50/60 and 60/70 grades, 2-6% provides stability, but after 6%, the binder becomes too soft. If the climate is hot, WEO should be less than 4%, but in cold climates, up to 6% increases flexibility. Above 8%-10% causes excessive softening and deformation, so WEO needs to be carefully controlled to maintain pavement durability; the results are shown in Figure 3.

Table 4: Effect of WEO on softening point.

Additive Rate (%)	40/50 Grade (C°)	50/60 Grade (C°)	60/70 Grade (C°)
0	52.4	51	50
2	52	49	46
4	47	47	44
6	44	44	42
8	43	42	39
10	40	40	37

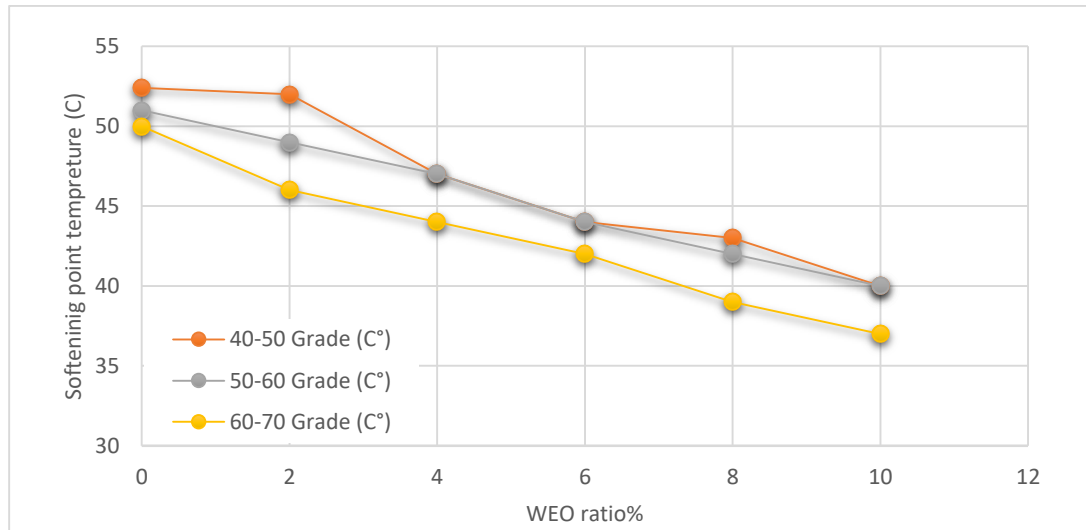


Figure 3: Effect of WEO on softening point.

Based on equation (1), the Penetration Index (PI) generally decreased with increasing WEO content across all asphalt binder grades. At 0% WEO, the PI values were approximately -0.67, -0.87, and -0.75 for the 40/50, 50/60, and 60/70 grades, respectively, as shown in (Table 5). With the addition of 10% WEO, the PI values changed to -1.05, -0.76, and -0.58. this trend indicates increased temperature susceptibility in the 40/50 and 60/70 binders, reflected by lower PI values, interestingly, the 50/60 binder showed a slight increase in PI at 10% WEO, which may suggest a more balanced interaction between the binder and WEO at this grade, potentially enhancing its thermal stability.

Table 5: Penetration Index values.

Penetration Index				
WEO%	asphalt grade	Penetration	Softening point	PI
0	40/50	49	52.4	-0.670176683
2		57	52	-0.404513551
4		72	47	-1.124105729
6		95	44	-1.276813397
8		124	43	-0.776444356
10		158	40	-1.052016364
0	50/60	52	51	-0.868526683
2		65	49	-0.836499015
4		82	47	-0.772593029
6		99	44	-1.155160939
8		133	42	-0.897267449
10		170	40	-0.758609631
0	60/70	65	50	-0.573923571
2		88	46	-0.86889002
4		115	44	-0.683195375
6		138	42	-0.764651527
8		195	39	-0.606376263
10		240	37	-0.576328062

4.3 Rolling Thin Film Oven (RTFO) test

A Rolling Thin Film Oven (RTFO) test was performed as per ASTM D2872 to simulate short-term asphalt binder aging, which occurs normally during mixing and paving. The test is essential for measuring changes to the properties of the binder—specifically, penetration due to oxidative and thermal aging. With this procedure, asphalt samples were transferred to glass bottles and rolled around inside a heated rolling thin film oven at 163 °C for 85 min under a constant supply of hot air. Rolling of the bottles causes a thin binder film to constantly be created and oxidized, mimicking the impact of aging.

During this study, the RTFO process was tested for asphalt binders with three different penetrations, 40/50, 50/60, and 60/70, modified with different contents of Waste Engine Oil (WEO) ranging between 0% and 10%, as shown in Table 6. Results indicated increased penetration upon loss with increased WEO content. Penetration upon RTFO for the 40/50 grade improved between 32 (0.1 mm) at 0% WEO and 80 (0.1 mm) at 10% WEO, In 50/60 grade, penetration improved between 32 (0.1 mm) at 0% to 82 (0.1 mm) at 10%, For 60/70 grade, penetration upon RTFO improved gradually from 38 (0.1 mm) at 0% WEO to 50 (0.1 mm) at 2%, 55 (0.1 mm) at 4%, 65 (0.1 mm) at 6%, 82 (0.1 mm) at 8%, and 98 (0.1 mm) at 10%, precisely reflecting a softening tendency with increased WEO content. The results are shown in Figure 4. Quadratic regression after RTFO aging, demonstrating high predictive accuracy:

$$(7) \quad 40/50 \text{ grade: RTFO-Penetration} = 0.219(\text{WEO}\%)^2 + 2.527(\text{WEO}\%) + 32.679, R^2=0.998$$

$$(8) \quad 50/60 \text{ grade: RTFO-Penetration} = 0.237(\text{WEO}\%)^2 + 2.677(\text{WEO}\%) + 32.107, R^2=0.998$$

$$(9) \quad 60/70 \text{ grade: RTFO-Penetration} = 0.277(\text{WEO}\%)^2 + 2.975(\text{WEO}\%) + 39.643, R^2=0.993$$

These equations statistically confirm the observed trends in aging resistance and softening behavior due to WEO content. If we replaced any (WEO%) from (0-10%) we can precisely find the RTFO-Penetration for any grade, and the high values of the (R^2) indicate that the chosen quadratic regression models predict the effects on asphalt binders modified by WEO.

The regression models for RTFO-aged penetration demonstrated excellent performance. For 40/50 and 50/60 binders, both models showed $R^2 = 0.998$ and $R = 0.999$, with ANOVA $p < 0.001$, indicating strong model fit and statistical significance. All predictors were individually significant (p -values < 0.013), confirming their contribution to the model. For 60/70, the model also showed strong results ($R^2 = 0.993$, $R = 0.996$, $p < 0.001$).

Two-tailed paired t-tests comparing predicted and experimental values yielded p -values of 0.9746 (40/50), 0.8977 (50/60), and 0.9919 (60/70), all above 0.05, confirming no significant difference between predictions and actual data. These results validate the reliability and accuracy of the models for predicting penetration after RTFO aging in WEO-modified binders.

These trends validate that WEO addition leads to a softer and more flexible binder, which offers better initial workability at the expense of compromised aging resistance upon exposure to heat and air, and decreased stiffness. [11] Similarly indicated that WEO enhances fatigue resistance but significantly reduces viscosity and rutting resistance because of its light oil fractions. [7] Also pointed out that elevated levels of re-refined oil bottoms or waste engine oil speed up binder hardening upon aging. [3] concluded that an optimal range for WEO content is 2 to 4%, since it retains advanced performance without inducing unnecessary softening or durability issues. Overall, it is evident through RTFO test results that while the WEO binder presents beneficial properties at low dosing rates, large dosing produces enormous reductions in aging resistance, questioning its long-term application potential.

Table 6: Effect of WEO on RTFO.

Rolling Thin Film Oven			
additive ratio (%)	40/50 Grade (0.1mm)	50/60 Grade (0.1mm)	60/70 Grade (0.1mm)
	penetration after loss	penetration after loss	penetration after loss
0	32	32	38
2	40	39	50
4	46	46	55
6	55	56	67
8	67	70	80
10	80	82	98

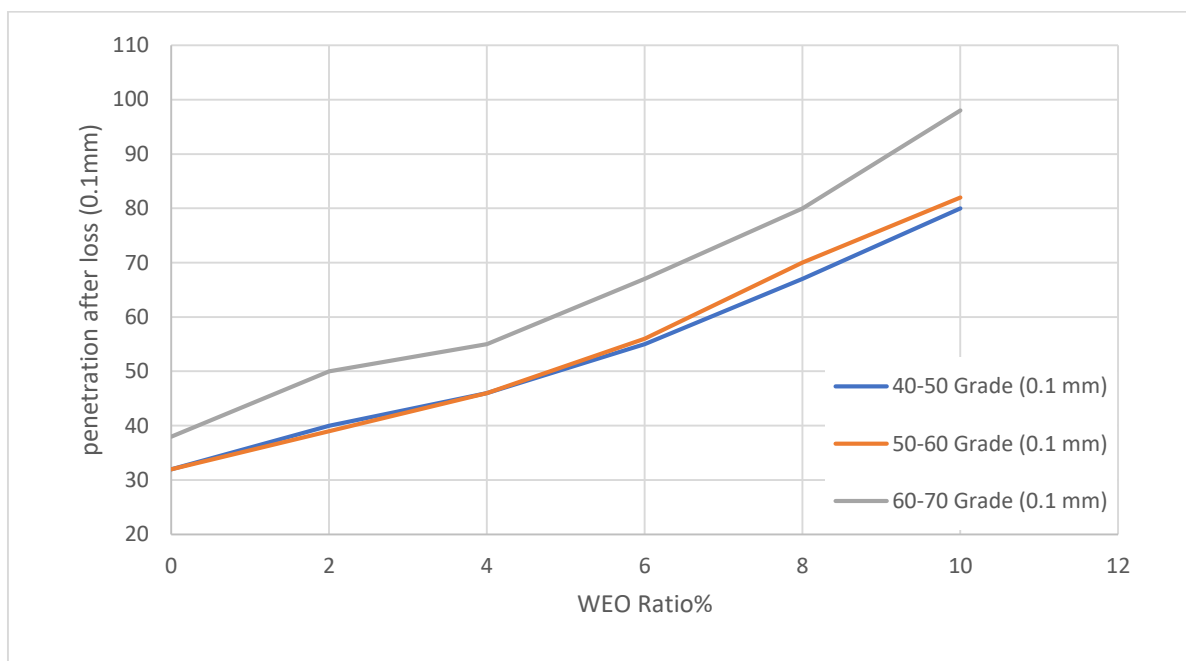


Figure 4: Effect of WEO on penetration after loss in RTFO.

4.4 Flash and Fire test

The test for the flash and fire point is critical in the determination of the thermal and flammability characteristics of the asphalt binders. ASTM D92–01 defines the fire point as the lowest temperature at which the asphalt emits enough vapors that would momentarily ignite when subjected to the introduction of fire, and the flash point as the temperature at which the vapors sustain combustion for five seconds or longer. These tests are not just critical for the safe handling process in the mixing and application process, but also for the determination of the influence additives such as Waste Engine Oil (WEO) have on the high-temperature characteristics of the binder.

In this test, the three grades of asphalt (40/50, 50/60, and 60/70) were subjected to the test for the fire and flash points using WEO addition ranging from 0% up to 10%. From the results shown in Table 7, there exists an overall trend of a decrease in both the fire and the flash points as the WEO content increases. In the case of the 40–50 grade, the flash point decreased from 285°C at 0% WEO down to

250°C at 10%, and the fire point from 316°C down to 275°C. Similarly, the same trend was also shown by the 60/70 grade, where the flash point decreased from 290°C down to 245°C, and the fire point from 315°C down to 270°C. This reduction is caused by the light hydrocarbons in WEO that reduce the ignition temperature of volatile vapors, according to research by [8,11]. These findings are also supported by [10], who observed that WEO increases the flexibility and reduces the viscosity, and also lowers the ignition resistance of the binder at elevated temperatures. Additionally, [3,6] also highlighted that excessive WEO content leads to thermal instability and necessitates controlled dosing. Statistical modeling provided quadratic equations describing the effect of WEO on flash and fire points:

Flash point:

$$(10) \quad 40/50 \text{ grade: flashpoint} = -0.277(\text{WEO}\%)^2 - 1.032(\text{WEO}\%) + 285.643, R^2=0.966$$

$$(11) \quad 50/60 \text{ grade: flashpoint} = -0.112(\text{WEO}\%)^2 - 2.884(\text{WEO}\%) + 290.179, R^2=0.995$$

$$(12) \quad 60/70 \text{ grade: flashpoint} = -0.201(\text{WEO}\%)^2 - 2.648(\text{WEO}\%) + 290.607, R^2=0.996$$

Fire point:

$$(13) \quad 40/50 \text{ grade: fire point} = 0.246(\text{WEO}\%)^2 - 6.384(\text{WEO}\%) + 314.750, R^2=0.987$$

$$(14) \quad 50/60 \text{ grade: fire point} = 0.022(\text{WEO}\%)^2 - 3.652(\text{WEO}\%) + 309.107, R^2=0.988$$

$$(15) \quad 60/70 \text{ grade: fire point} = 0.076(\text{WEO}\%)^2 - 4.788(\text{WEO}\%) + 314.821, R^2=0.997$$

These equations statistically validate the observed trends in aging resistance and softening behavior resulting from WEO modifications. By substituting any WEO% from the (0-10%) range into the models, the flash and fire values for each binder grade can be accurately predicted. The higher the (R^2) values further they confirm the strong predictive capability of the quadratic regression models in capturing the influence of WEO on asphalt binder properties.

The regression models for flash point showed excellent fit and statistical validity across all binder grades. For 40/50, $R^2 = 0.966$ and $R = 0.983$, with ANOVA $p = 0.006$, confirming a statistically significant model. The 50/60 and 60/70 models showed even stronger results, with $R^2 = 0.995$ and 0.996 , and $R = 0.997$ and 0.998 , respectively. Both had highly significant ANOVA p -values < 0.001 .

Two-tailed paired t -tests comparing predicted and experimental values yielded p -values of 0.9952 (40/50), 0.9755 (50/60), and 0.9948 (60/70) — all above 0.05, confirming no significant difference between predicted and actual values. These results validate the models' accuracy in predicting flash point behaviour across all WEO percentages.

The regression models for fire point demonstrated strong reliability across all binder grades. For both 40/50 and 50/60 binders, the models showed $R^2 = 0.987$ and 0.988 , and $R = 0.994$, with statistically significant ANOVA p -values of 0.001. The 60/70 binder model achieved the highest performance with $R^2 = 0.997$, $R = 0.998$, and $p < 0.001$, indicating excellent predictive strength.

Two-tailed paired t -tests comparing experimental and predicted values yielded p -values of 0.9818 (40/50), 0.4422 (50/60), and 0.3545 (60/70) — all above 0.05, confirming no significant differences between predicted and actual results. These findings validate the models' accuracy in predicting fire point behaviour for WEO-modified binders.

The reductions were all within acceptable ASTM D92 safety ranges (flash point $>230^\circ\text{C}$), the binders at 10% WEO were approaching the low limit, and that was most apparent in the softer grades like 60–70. That indicates the potential for risk in hot-mix processing if not managed. According to (7) Having the flash point well above the mixing temperature (typically around $150\text{--}165^\circ\text{C}$) leaves enough margin for safe operation.

The optimum WEO content for safe and effective operation on the basis of fire and flash characteristics is up to 6% for the 40/50 and 50/60 grades and no more than 4% for the 60/70 grade. It combines the benefits of higher flexibility and reduced viscosity without compromising thermal safety. Higher contents, in particular above 8%, significantly reduce the flash/fire point and should only be employed if additional measures (e.g., lowered mixing temperatures or pretreated WEO) are taken.

These results validate the necessity for thermal safety analysis in the reformulation of binders and confirm that the incorporation of up to 6% WEO provides the optimal improvement without exceeding critical safety thresholds. (Figure 5 and Figure 6) graphically depicts the effect of WEO on the flash and fire point for all three grades of the binder, respectively.

Table 7: Effect of WEO on Flash and Fire test.

Flash and Fire test						
additive ratio (%)	40/50 Grade	40/50 Grade	50/60 Grade	50/60 Grade	60/70 Grade	60/70 Grade
	Flash @ C°	Fire @ C°	Flash @ C°	Fire @ C°	Flash @ C°	Fire @ C°
0	285	316	290	310	290	315
2	282	300	285	300	285	305
4	280	295	275	295	278	297
6	270	285	270	290	267	290
8	255	280	260	280	255	280
10	250	275	250	270	245	270

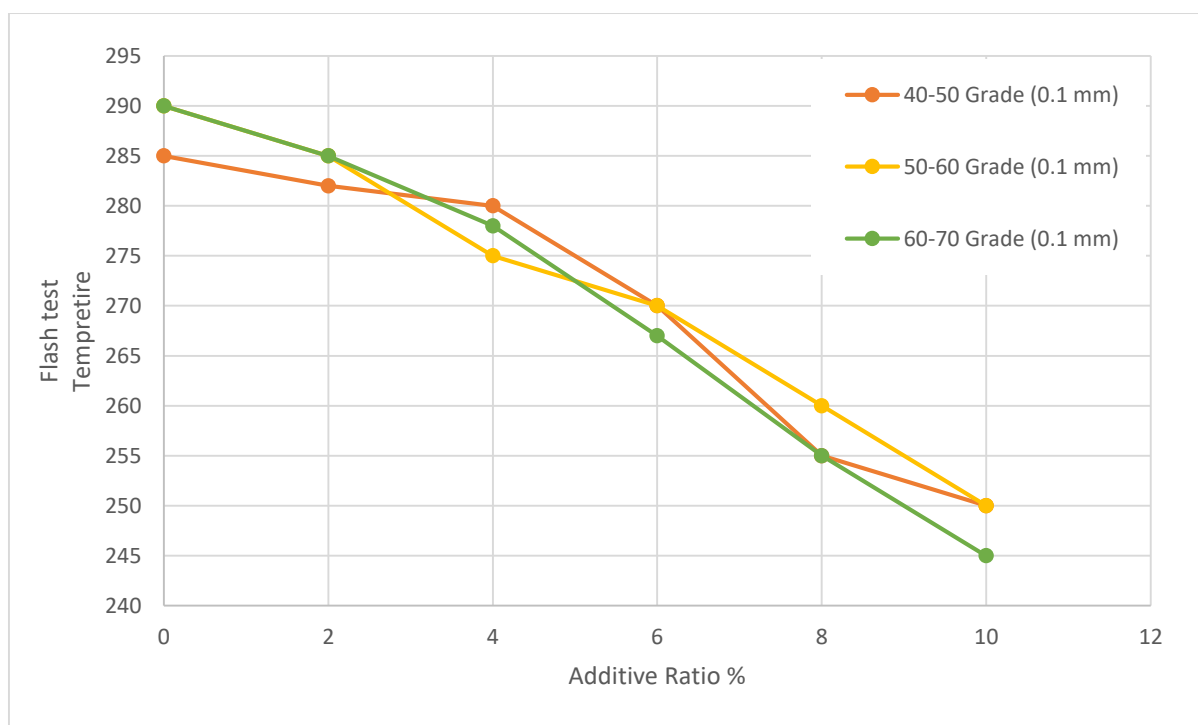


Figure 5: Effect of WEO on Flash point.

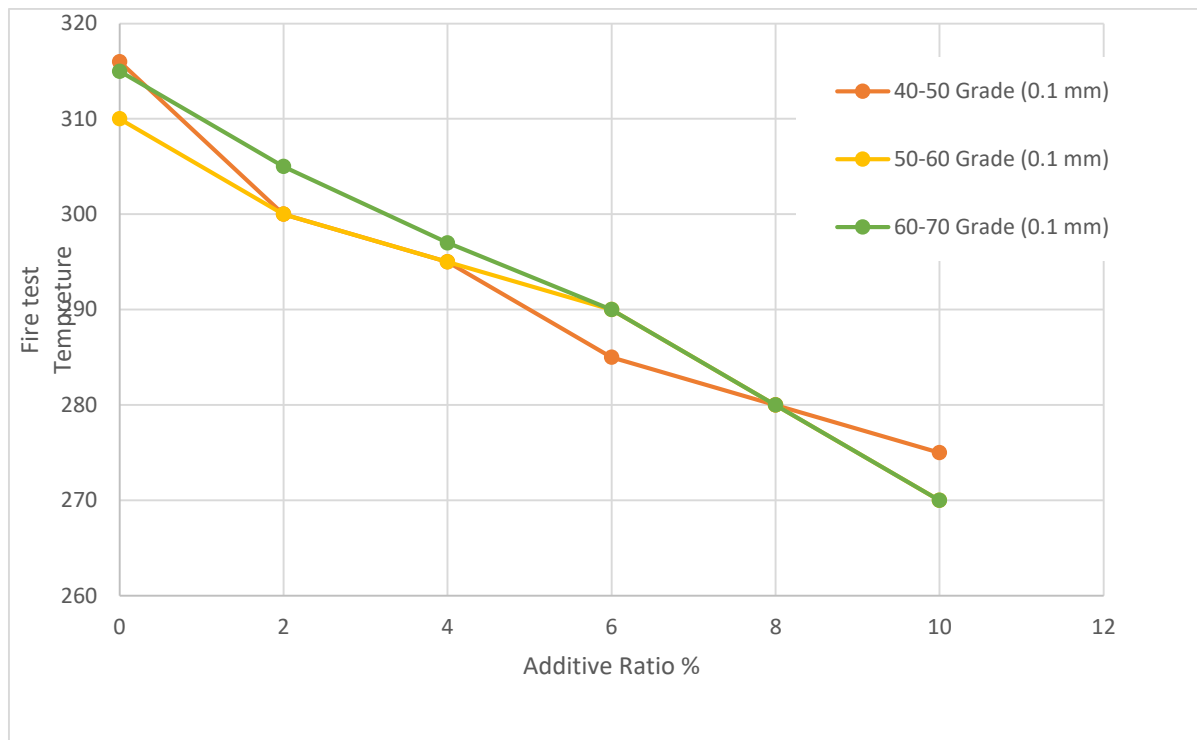


Figure 6: Effect of WEO on Fire point.

5. Conclusions

Although all asphalt binder grades demonstrated a similar general trend with the addition of WEO, the extent of the changes varied across grades, indicating that each binder type responds differently to the modifier. The addition of waste engine oil (WEO) had a profound impact on asphalt binders' physical characteristics for all three penetration grades (40/50, 50/60, and 60/70). Penetration values increased systematically with an increase in WEO content, which is an indication of a softening influence as WEO contains lighter fractions. At 10% WEO, penetration rose by 222.4%, 226.9%, and 269.2% for 40/50, 50/60, and 60/70 binders, respectively, compared to the base unmodified binder. The softening point exhibited a near-linear decreasing trend with increasing WEO content. At 10% WEO, the softening point was reduced by 23.66%, 21.56%, and 26.0% for 40/50, 50/60, and 60/70 binders, respectively. Both flash and fire point tests showed a clear linear decline with WEO addition. At 10% WEO, flash point decreased by 12.28%, 13.79%, and 15.51% for 40/50, 50/60, and 60/70 binders, respectively. Fire points showed a similar trend, dropping by 12.97%, 12.90%, and 16.66% for the same binder grades. This approach offers a sustainable solution for recycling WEO, which is otherwise environmentally hazardous and harmful to human health, by repurposing it as a beneficial additive for enhancing asphalt binder performance, contributing to a cleaner and healthier environment.

Quadratic polynomial regression models were developed to predict binder properties at any WEO concentration within the 0-10% range. These models enabled interpolation of results at intermediate WEO levels not directly tested. The ideal range of WEO is found to be (2–4%), this is due to comparing penetration, softening point, Penetration Index by consideration, enhancing both workability and flexibility at a minimal loss of ductility and thermal resistance, this ensures the pavement remains strong, stable, and resistant to deformation, especially in hotter climates or areas with higher traffics, because this range keeps the asphalt binder relatively firm, preventing it from becoming too soft and ensuring it doesn't deform easily under heavy loads or high temperature.

The application of WEO in asphalt binders shows promising environmental and cost-effectiveness, especially in controlled dosing ranges. Excessive dosing, though, can lead to compromised durability and weathering resistance, requiring proper balancing for practical use.

Acknowledgment

The authors would like to express their sincere gratitude to all individuals and institutions who contributed to the successful completion of this study. Special thanks are extended to Salahaddin University-Erbil and Tishk International University for their Academic support and guidance. The authors also gratefully acknowledge the assistance provided by Erbil Construction Laboratory and Golden Bitumen Refinery, whose facilities and technical support were instrumental in carrying out the experimental work. The contributions of everyone involved, at every level, are deeply appreciated.

Conflict of Interest

The authors declare that there are no financial, institutional, or personal relationships that could be perceived as influencing the research reported in this article. The study was conducted independently, with no external entity involved in the design, execution, analysis, or interpretation of the results.

Author Contributions

Mohammad M. M. Halaq contributed to the conceptualization, methodology design, experimental work, data analysis, manuscript drafting, and revision. At the same time, Abdulhakim O. S. Kozapanky provided supervision, validation of results, guidance in methodology, critical review, and editing of the manuscript.

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