

Article

Toward Fully Recycled Asphalt Mixtures: Conditioning 100% RAP with Waste-Engine-Oil-Modified Binders

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Abstract

This study developed a conditioning framework for the sustainable use of waste-engine-oil-modified binders (WEOMBs) in 100% reclaimed asphalt pavement (RAP) mixtures. Binder with a penetration grade of 60–70 was modified by 5%, 8%, and 10% waste engine oil (WEO) by binder weight. The WEOMBs were subjected to physical, chemical, and compositional analyses. For 10% WEOMB, the results showed a reduction of the binder softening point by 18% and an increase in binder penetration of almost 8%, enhancing softening and the workability of the binder. Binder chemical and compositional analyses verified that WEO altered the binder's colloidal structure by augmenting aliphatic fractions and molecular mobility, while diminishing resin content and promoting saturates plus aromatics content. At 160 °C for 45 min, the RAPs were conditioned with 1% WEOMB (containing different WEO percentages) by the total weight of the RAP mixture. Among all the conditioned mixtures, the 100% RAP modified with 1% WEOMB, containing 8% WEO, showed the best performance. Dynamic modulus and phase angle analyses demonstrated that RAP conditioning reduced excessive stiffness and produced a balanced viscoelastic response, enhancing the rutting resistance. The proposed conditioning framework demonstrated the feasibility of producing fully recycled mixtures with balanced mechanical performance and adequate cracking resistance.

Keywords: asphalt; high-RAP conditioning; waste engine oil; FTIR; SARA; sustainable pavements

1. Introduction

Reclaimed asphalt pavement (RAP) recycling is nowadays an indispensable part of sustainable pavement [1,2]. High RAP content lowers energy use and greenhouse gas emissions, hence lowering demand for virgin materials. However, recycled asphalt mixtures with high RAP raise concerns about excessive stiffness and cracking [3]. More than one hundred million tons of RAP is generated each year globally [4]. The inclusion of RAP in asphalt mixes typically improves stiffness and rutting resistance because of the aged binder present [3]. But the aging process raises stiffness and reduces flexibility, therefore negatively influencing thermal cracking resistance and raising susceptibility to fatigue cracking [5]. Rejuvenators are frequently added to restore the maltene components of the stiff binder and enhance its rheological performance to lessen the adverse impacts of aging [2,6].



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Waste engine oil (WEO) is being studied as an efficient rejuvenator for aged asphalt binders [7]. WEO has been validated to replenish the maltene phase in aged binders, thus increasing flexibility, workability, and decreasing stiffness [8]. Furthermore, WEO acts as a lubricant in rubber-modified binders, regulating the interactions between rubber and binder [9]. The addition of WEO resulted in the improvement of the physical and rheological properties of the binders, which enhanced the cracking resistance of the asphalt mixes [10]. Consequently, WEO has the capability of modifying the internal structure of the asphalt binder [11]. By reducing the stiffness of aged binders, WEO improves the long-term performance and aging resistance of the modified binders [11]. As for preparation, WEO has been reported to be added to asphalt binders using a wet technique at a temperature of 130 to 170 °C, followed by mixing for 15 to 60 min to achieve a uniform distribution in the binder matrix [12–14].

Prior studies conditioned RAP with rejuvenators via various methods, regulating interaction time and temperature. WEO was directly sprayed onto a heated RAP at 140 °C and mixed for approximately 5 min to improve oil diffusion and binder coating [15]. Another study [16] added the rejuvenator directly into the RAP immediately before asphalt mixture production, followed by short-term conditioning for 2 h at a compaction temperature of 138 °C. In another study [17], RAP was pretreated using spray-on or foaming techniques, where treated RAP was mixed for 120 s and then conditioned for 1.5–3 h at 135 °C or even marinated for several days at room temperature to enhance diffusion into the aged binder. Another study [18] preheated RAP in an oven at 165 °C for 2 h, then rejuvenators were introduced to RAP materials and kept in the oven at 150 °C for 3 min. These various techniques affected the diffusion of the rejuvenators into the RAP-aged binder, affecting the overall performance of the RAP-containing mixtures.

Controlling RAP conditioning technique, duration, and temperature provides a potential pathway to enhance binder blending and overall mixture performance. Conditioning RAP with a rejuvenator at 135 °C for 3 h has been reported to induce additional aging effects [19], whereas conditioning at 165 °C for 3 h before mixing can enhance rejuvenator diffusion and improve mixture performance [20]. These contrasting findings highlight the lack of a consistent, performance-based approach for RAP conditioning. Current specifications do not provide systematic guidance or control over conditioning practices in RAP-containing mixtures. Accordingly, this study aims to develop a robust and scalable conditioning framework to maximize the effective utilization of RAP in asphalt mixtures.

2. Materials and Methods

2.1. Materials

Limestone coarse aggregates, crushed limestone as fine aggregates, and mineral filler (limestone dust) were utilized in this study in the control mixture, containing 0% RAP. The aggregate and mineral filler samples were collected from the Ataqa Mountain quarries, Suez City, Egypt. The properties of these aggregates and RAP are presented in Table 1. The aggregate gradation was designed to match the RAP gradation and the binder course limits shown in Figure 1. A 60–70 penetration grade asphalt binder was obtained from the Orascom Construction asphalt mixing plant, New Administrative Capital, Egypt, and was used in the 0% RAP mixture and in conditioning the 100% RAP mixtures. The physical properties of this binder are depicted in Table 2. RAP was obtained from 10-year-old Ain Sokhna Road rehabilitation project, Ain Sokhna, Egypt, processed through crushing, and sieved to achieve the combined aggregate gradation of the control mixture.

The RAP binder content was determined to be 4.5% by the mixture weight following ASTM D2172 [21] with trichloroethylene as a solvent, owing to its high efficiency in dissolving asphalt binder [5,22]. The RAP binder was recovered from the extracted solvent

using a rotary evaporator following ASTM D5404 [23]. Further details about the extraction and recovery processes are presented in previous studies [24,25]. The physical properties of the recovered RAP binder are presented in Table 3. WEO was collected from one local automotive service station, Zagazig, Egypt, and its physical and chemical characteristics are depicted in Table 4.

Table 1. Properties of aggregates.

Test	ASTM Standard	Results		Specification Limits
		Coarse Aggregate	RAP	
Los Angeles Abrasion (%), after 500 revolutions	C131 [26]	20.23	21.32	≤ 40
Water Absorption (%)		1.55	1.30	≤ 5
Specific Gravity—Bulk	C127 [27]	2.66	2.64	
Specific Gravity—SSD *		2.73	2.69	
Specific Gravity—Apparent		2.65	2.67	
		Fine Aggregate	Mineral Filler	
Water Absorption (%)		1.20	0.60	≤ 5
Specific Gravity—Bulk	C128 [28]	2.64	2.71	
Specific Gravity—SSD		2.68		
Specific Gravity—Apparent		2.73	2.76	
Finess Modulus	C136 [29]	2.65		2.30–3.10
Materials Finer Than No. 200 Sieve (%)	C117 [30]	3.00	96.00	≤ 100 for Fine Aggregate
Sand Equivalent (%)	D2419 [31]	75		≥ 45

* SSD: Saturated Surface Dry.

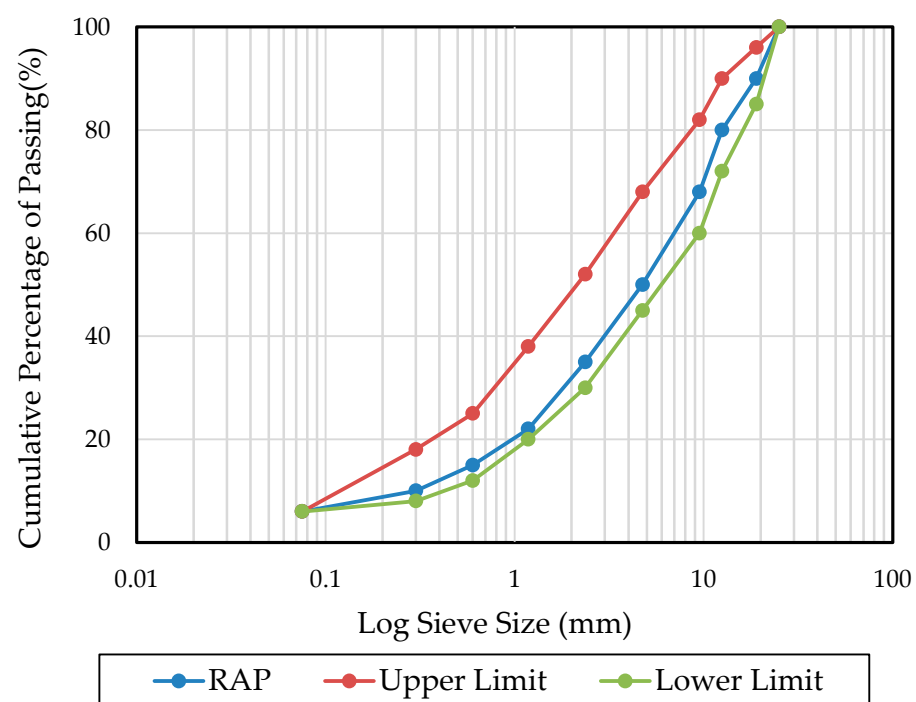


Figure 1. RAP aggregate gradation relative to the binder course gradation limits.

Table 2. Properties of asphalt binder.

Test	ASTM Standard	Results	Specification Limits
Penetration at 25 °C (0.1 mm)	D5 [32]	64	60–70
Softening Point (°C)	D36 [33]	53	≥45
Rotational Viscosity at 135 °C (Pa·s)	D4402 [34]	0.303	≤3
Ductility at 25 °C (cm)	D113 [35]	102	≥100
Flash Point (°C)	D92 [36]	232	≥230
Specific Gravity at 25 °C	D70 [37]	1.02	—

Table 3. Properties of the recovered RAP binder.

Test	ASTM Standard	Results
Penetration at 25 °C (0.1 mm)	D5 [32]	20
Softening Point (°C)	D36 [33]	64
Rotational Viscosity at 135 °C (Pa·s)	D4402 [34]	0.9

Table 4. Properties of WEO.

Test	ASTM Standard	Results	Specification Limits
Kinematic Viscosity at 100 °C (cSt)	D445 [38]	181	150–300
Flash Point (°C)	D92 [36]	193	≥180
Density (g/cm ³)	D1298 [39]	0.91	0.85–1.05
TBN * (mg KOH/g)	D2896 [40]	9.7	5.0–12.0
Oxidation (Abs/cm)	E1252 [41]	1.24	≤2.00
Nitration (Abs/cm)		1.70	
Soot (%)	E2412 [42]	0.10	≤1.00

* TBN: Total Base Number.

2.2. Methods

The experimental program, introduced in Figure 2, was designed to verify the new framework for conditioning RAP in the 100% RAP-containing asphalt mixtures. This experimental program involved three phases. The first phase was for the selection and characterization processes of raw and recycled materials. Raw materials were aggregates and asphalt binder, while recycled materials were RAP and WEO.

The second phase was for the preparation of the WEOMBs and physical and chemical binder testing. Three percentages of the WEO were selected, which were 5, 8, and 10% by weight of the asphalt binder. WEO was added and mixed with the asphalt binder at 130 °C for 20 min. Then, the neat and WEOMBs were characterized physically and chemically. The physical binder testing included penetration, rotational viscosity, and softening point testing. The changes in the binders' chemical indices and functional groups were evaluated using Fourier transform infrared (FTIR) spectroscopy, while the binders' components were assessed via saturates, aromatics, resins, and asphaltenes (SARA) fractions testing.

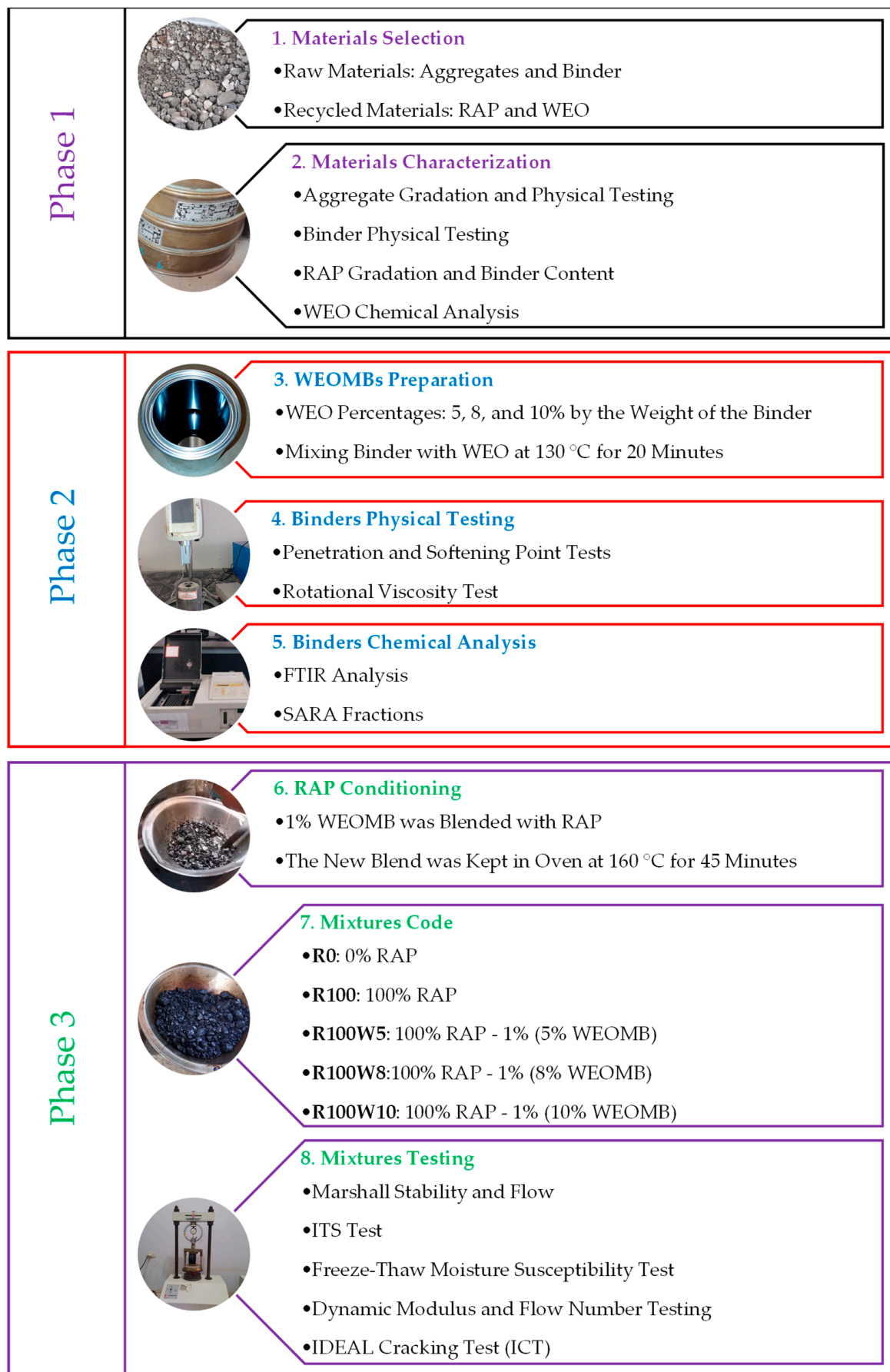


Figure 2. Experimental program.

The third phase focused on the RAP conditioning process, which aimed to enhance the performance and sustainability of 100% RAP mixtures by utilizing 1% of WEOMB. This approach eliminated the need for virgin aggregates and asphalt binder, along with the associated processing of these materials. The WEOMB was heated until the fluid condition at 135 °C, then 1% of the WEOMB by weight of the total mixture was blended with the RAP. Further, the blended RAP was conditioned in the oven at 160 °C for 45 min to enhance the WEOMB diffusion into the aged RAP binder. Subsequently, conditioned-RAP mixtures were compacted at 150 °C. For zero-RAP mixtures, the mixing and compaction temperatures were determined to be 160 and 150 °C, respectively. Moreover, the experimental program involved the mixtures' coding system and testing. R0 represented the control mixture, including 0% RAP, and R100 reflected mixtures with 100% RAP. R100W5, R100W8, and R100W10 simulated the codes for 100% RAP mixtures conditioned with 1% binders modified by 5, 8, and 10% WEO, respectively. For R0 mixtures, the asphalt content was selected to be 5.5% virgin binder, without WEO, by the mixture weight to simulate the conditioned-RAP mixtures. Finally, the mixture testing included Marshall stability and flow, indirect tensile strength (ITS) test, freeze–thaw moisture susceptibility test, dynamic modulus ($|E^*|$) and flow number (FN) testing, and IDEAL cracking test (ICT).

2.2.1. Binders Testing

Neat binder (NB) and WEOMBs were evaluated in this section by physical and chemical analyses as follows:

Penetration Test

The penetration test was performed on binders to assess their consistency at 25 °C, following the ASTM D5 [32] procedure. A standard needle was permitted to descend into each binder sample for 5 s under a 100 g load. Each sample underwent three separate measurements, with the mean value recorded as the penetration depth in tenths of a millimeter.

Softening Point Test

Asphalt binders' softening points expressed in °C were determined using the ring-and-ball technique with a heating rate of 5 °C/min, as described in ASTM D36 [33]. This test assesses the binder's thermal sensitivity by determining the temperature at which it softens enough to allow a steel ball to drop and make contact with the base plate. For each sample, the stated softening point is the average of two measurements.

Rotational Viscosity Test

The test was performed in accordance with ASTM D4402 [34] to evaluate the binder workability at high temperature and to support the selection of suitable mixing and compaction temperatures. The test was carried out using a Brookfield rotating viscometer (AMETEK Brookfield, Middleboro, MA, USA) at temperatures of 135 and 165 °C and a rotational speed of 20 rpm. Each sample has three viscosity measurements, with the average stated in Pa·s.

FTIR Analysis

The functional groups and chemical indices of the NB and WEOMBs were determined using a Bruker ALPHA II FTIR spectrometer (Bruker Optics GmbH, Ettlingen, Germany) with a diamond crystal. With a resolution of 4 cm^{−1} and 24 scans, the spectra were collected over the wavenumber range 4000 to 400 cm^{−1}. The chemical indices included the aromatic (I_{CC}), aliphatic (I_{CH}), carbonyl (I_{CO}), and sulfoxide (I_{SO}). Equation (1) shows that the I_{CO} shows aging due to carbonyl (C=O) at 1700 cm^{−1}. Equation (2) indicates that the

I_{SO} at 1030 cm^{-1} represents sulfoxide (S=O)-induced aging [43,44]. Equations (3) and (4) were used to calculate the C=C stretching in the I_{CC} and the C–H bending in the I_{CH} , respectively [45,46].

The I_{CO} is represented by the following equation:

$$I_{CO} = \frac{\text{Band Area(BA) at } 1700\text{ cm}^{-1}}{\text{BA at } 1460\text{ cm}^{-1} + \text{BA at } 1375\text{ cm}^{-1}} \quad (1)$$

The I_{SO} is defined by the following equation:

$$I_{SO} = \frac{\text{BA at } 1030\text{ cm}^{-1}}{\text{BA at } 1460\text{ cm}^{-1} + \text{BA at } 1375\text{ cm}^{-1}} \quad (2)$$

The I_{CC} is shown in the following equation:

$$I_{CC} = \frac{\text{BA at } 1600\text{ cm}^{-1}}{\Sigma\text{BAs at } 1700, 1600, 1460, 1375, \text{ and } 1030\text{ cm}^{-1}} \quad (3)$$

The I_{CH} is represented by the following equation:

$$I_{CH} = \frac{\Sigma\text{BAs } 1460 \text{ and } 1375\text{ cm}^{-1}}{\Sigma\text{BAs at } 1700, 1600, 1460, 1375, \text{ and } 1030\text{ cm}^{-1}} \quad (4)$$

SARA Fractions

SARA fraction analysis evaluates the chemical composition of the asphalt binder. The binder was separated into SARA in accordance with ASTM D4124 [47]. The test was performed utilizing thin-layer chromatography (TLC) and a hydrogen flame ionization detector (FID) method, with a TLC-FID Iatroscan (Iatron Laboratories, Inc., Tokyo, Japan). Two replicates were analyzed for each sample, and the average results were recorded.

2.2.2. Mixtures Testing

To further investigate the impact of the WEO as a rejuvenator on the conditioning of RAP, mixtures were subjected to testing and assessment according to the following methodology:

Marshall Stability and Flow Test

Following ASTM D6927 [48], the Marshall test was run to assess the stability and flow properties of asphalt mixes. Using 75 blows on each face, cylindrical samples with a diameter of 4.0 inches and a height of roughly 2.5 inches were compacted. The samples were placed in a water bath at $60\text{ }^{\circ}\text{C}$ for 35 min before testing. The greatest load was measured as the Marshall stability (lb), and the corresponding deformation was recorded as the flow value (0.01 in). Two replicates were tested for each mixture, and the average result was analyzed.

ITS Test

To assess the tensile strength of asphalt mixes at $25\text{ }^{\circ}\text{C}$, the test was carried out in conformity with ASTM D6931 [49]. Along the vertical diametral plane of the cylindrical specimens, with a diameter of 4.0 in and a thickness of roughly 2.5 in, a compressive load at a constant rate of 1.97 in/min was applied until failure. Every mixture underwent two replicates and an examination of the average outcome. After capturing the maximum load at failure, the ITS was determined using Equation (5). The ITS values were determined using the equation listed below:

$$\text{ITS} = \frac{2P}{\pi Dt} \quad (5)$$

where

ITS: Indirect tensile strength (psi),

P : Load at failure (lb),

D : Sample diameter (in), and

t : Sample thickness (in).

Freeze–Thaw Moisture Susceptibility Test

The freeze–thaw test was conducted to evaluate the resistance of asphalt mixtures to moisture damage. Following ASTM D4867 [50], the tensile strength ratio (TSR) was evaluated for asphalt mixtures as shown in Equation (6). For every mixture, samples were mixed and compacted to have an air void content of $7 \pm 1\%$. Four samples were made for every mixture and split evenly into two sets: conditioned and unconditioned, with two samples each. The conditioned set was subjected to water saturation followed by a freezing and thawing cycle (16 h at $-18\text{ }^{\circ}\text{C}$ followed by 24 h at $60\text{ }^{\circ}\text{C}$) before testing. The ITS of conditioned and unconditioned samples was determined at $25\text{ }^{\circ}\text{C}$, and the average of the two replicates was computed. The TSR was ascertained via the following equation:

$$\text{TSR} = \frac{\text{ITS}_{\text{conditioned}}}{\text{ITS}_{\text{unconditioned}}} \times 100 \quad (6)$$

where

TSR: Tensile strength ratio (%),

$\text{ITS}_{\text{conditioned}}$: Indirect tensile strength of conditioned samples (psi), and

$\text{ITS}_{\text{unconditioned}}$: Indirect tensile strength of unconditioned samples (psi).

Dynamic Modulus and Flow Number Testing

The objective of this test was to assess the stiffness and viscoelastic behavior of asphalt mixtures under cyclic loading by determining the dynamic modulus ($|E^*|$) via AASHTO T 342 [51] and rutting resistance via flow number under repeated axial loading, of samples in accordance with AASHTO T 378 [52]. The specimens utilized for $|E^*|$ and FN tests were fabricated to achieve a target air void content of $7 \pm 1\%$ to maintain uniformity across all tested mixes. For $|E^*|$ determination, cylindrical test samples, 150 mm in height and 100 mm in diameter, were tested under cyclic sinusoidal compressive loading at temperatures of 4.4, 21.1, 37.8, and $54.4\text{ }^{\circ}\text{C}$ and at frequencies of 0.1, 0.5, 1, 5, 10, and 25 Hz. The $|E^*|$ was determined as the ratio of the applied cyclic stress to the recovered axial strain.

For FN testing, samples with the same dimensions as the $|E^*|$ testing were conditioned and tested at $54.4\text{ }^{\circ}\text{C}$ under a repeated Haversine axial compressive load pulse of 0.1 s every 1.0 s. The accumulated permanent microstrain was recorded as a function of loading cycles. The FN was determined as the number of load cycles corresponding to the beginning of the tertiary flow stage, where the rate of permanent deformation starts to minimize [52]. This dynamic creep test was employed to assess and forecast permanent deformation of asphalt mixtures under cyclic loads [53].

IDEAL Cracking Test (ICT)

The ICT was conducted to evaluate the cracking resistance of asphalt mixtures according to ASTM D8225 [54]. The test measures the resistance of asphalt mixtures to crack initiation and propagation under indirect tensile loading. Cylindrical specimens, with a diameter of 150 mm, a thickness of $62 \pm 2\text{ mm}$, and an air voids content of $7 \pm 0.5\%$, were conditioned and tested at $25\text{ }^{\circ}\text{C}$ under a constant displacement rate of 50 mm/min until failure. The cracking tolerance index (CT_{Index}) was calculated via Equation (7) to assess

the cracking performance of the mixtures. The following equation represents the CT_{Index} as follows:

$$CT_{Index} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D} \right) \times 10^6 \quad (7)$$

where

CT_{Index} : Cracking tolerance index,

t : Specimen thickness (mm),

G_f : Fracture or failure energy (J/m^2) = $\left(\frac{w_f}{t \times D} \right) \times 10^6$,

w_f : Work of failure (J) is the area under the force–displacement curve,

D : Specimen diameter (mm),

$|m_{75}|$: Absolute value of the postpeak slope at 75% of the peak load (N/m), and

l_{75} : Displacement at 75% of the peak load after the peak (mm).

3. Results and Analysis

3.1. Neat and Modified Binders

Figure 3 shows the impact of the WEO percentage on the penetration and softening point values of the asphalt binders. An increase in the WEO dosage resulted in an increase in the penetration values and a decrease in the softening point. The penetration increased from about 6.5 to 7.0 mm, while the softening point decreased from about 56 °C to 46 °C as the WEO content increased from 0% to 10%. The results showed that WEO effectively reduced binder stiffness by increasing lighter fractions, as confirmed by SARA fraction analyses.

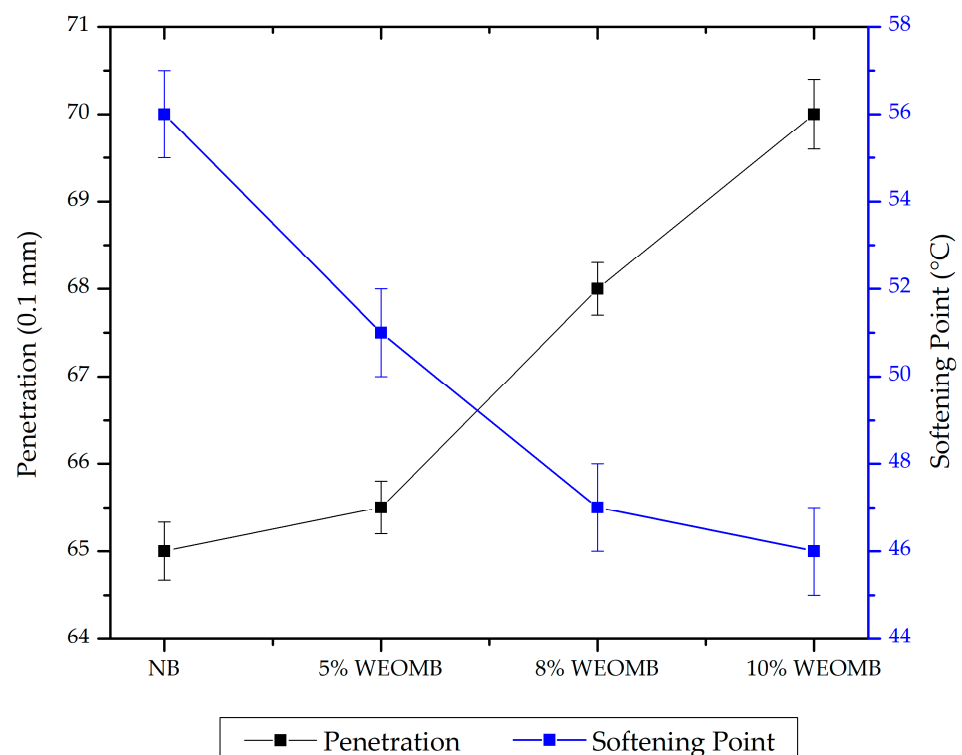


Figure 3. Penetration and softening point values of NB and WEOMBs.

The viscosity values of the NB and WEOMBs at 135 °C and 165 °C are shown in Figure 4. The viscosity of binders decreased with increasing WEO content at both temperatures, from approximately 0.38 Pa·s for the NB to nearly 0.15 Pa·s for the 10% WEOMB at 135 °C and from approximately 0.10 to 0.03 Pa·s at 165 °C. The addition of WEO softened the binder and reduced its viscosity, which can improve workability, mixing efficiency, and coating of aggregates during the production of asphalt mixtures.

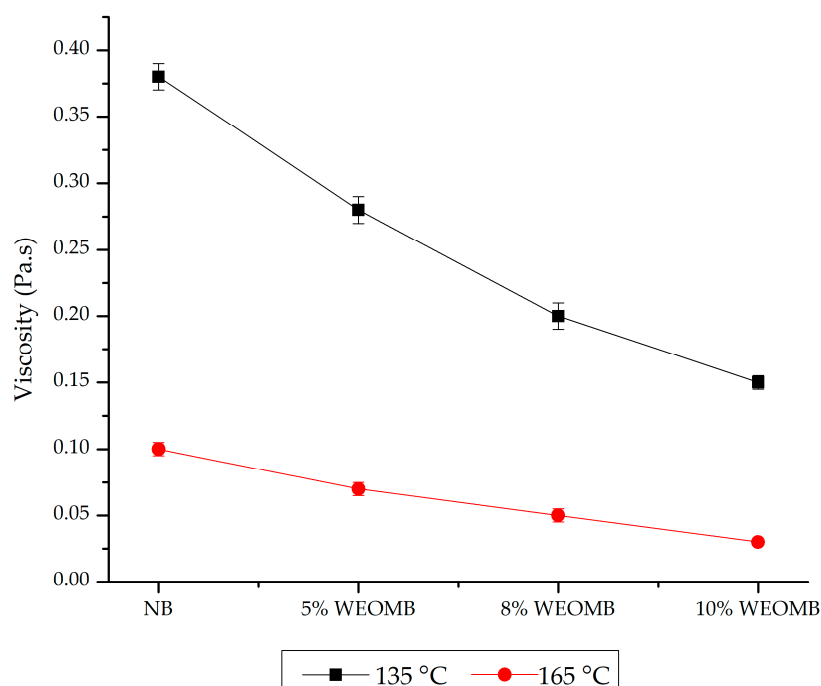


Figure 4. Viscosity values of NB and WEOMBs.

Figure 5 shows the FTIR analyses of WEO. The characteristic bands of WEO were discussed in a previous study [9] and were dominated by aliphatic C–H bands and some aromatic features. WEO is a mixture of long-chain alkanes and aromatics, much like asphalt binder, so its FTIR peaks are very similar to those of bitumen [9,55]. The C–H asymmetric stretching vibrations were noted at 2960 and 2925 cm^{-1} , while the C–H symmetric stretching peak was found at 2855 cm^{-1} . The WEO spectrum shows scissoring of methylene ($-\text{CH}_2-$) and symmetric bending of methyl ($-\text{CH}_3$) at 1465 and 1378 cm^{-1} , respectively. A peak was observed at 725 cm^{-1} , corresponding to aromatic C–H out-of-plane bending (rocking) vibrations [9,56].

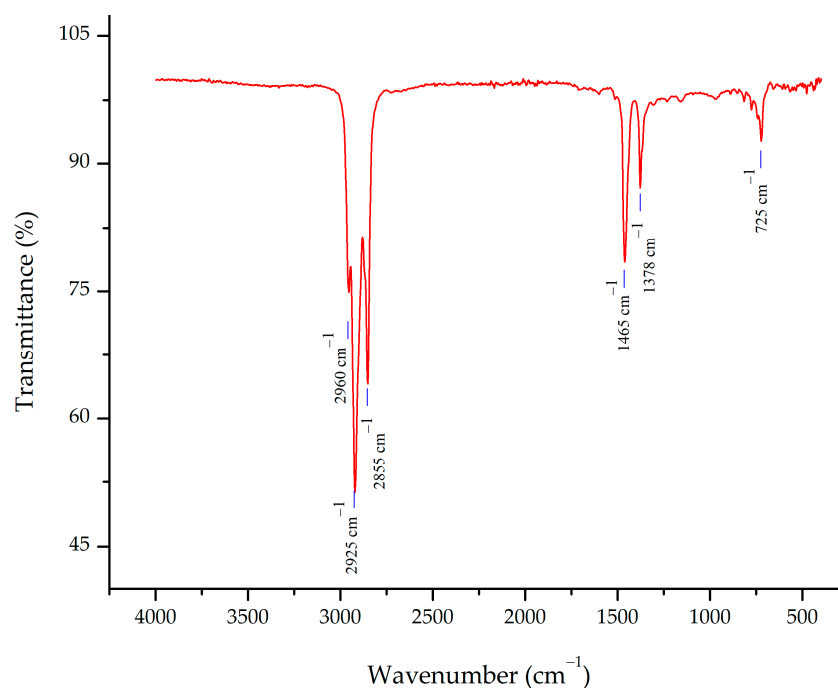


Figure 5. FTIR characteristic bands of WEO.

The FTIR spectra of the NB and WEOMBs are illustrated in Figure 6. A broad O–H stretching band at 3400 cm^{-1} [57] was amplified for 5% WEOMB. However, this band attenuated with 8% WEOMB and further diminished with 10% WEOMB. Increasing the WEO content diluted the polar oxygen-containing functional groups (e.g., O–H) and promoted the predominance of nonpolar aliphatic hydrocarbons, which led to a progressive reduction in O–H absorption intensity. The asymmetric and symmetric aliphatic C–H stretching vibrations of $-\text{CH}_2-$ groups were observed at 2920 and 2850 cm^{-1} , respectively. The carbonyl (C=O) stretching band at 1725 cm^{-1} [46], which was absent in NB, intensified with increasing WEO content. The scissoring vibration of $-\text{CH}_2-$ and the symmetric bending vibration of $-\text{CH}_3$ at 1455 and 1375 cm^{-1} , respectively, were observed in the spectra of both neat and modified binders.

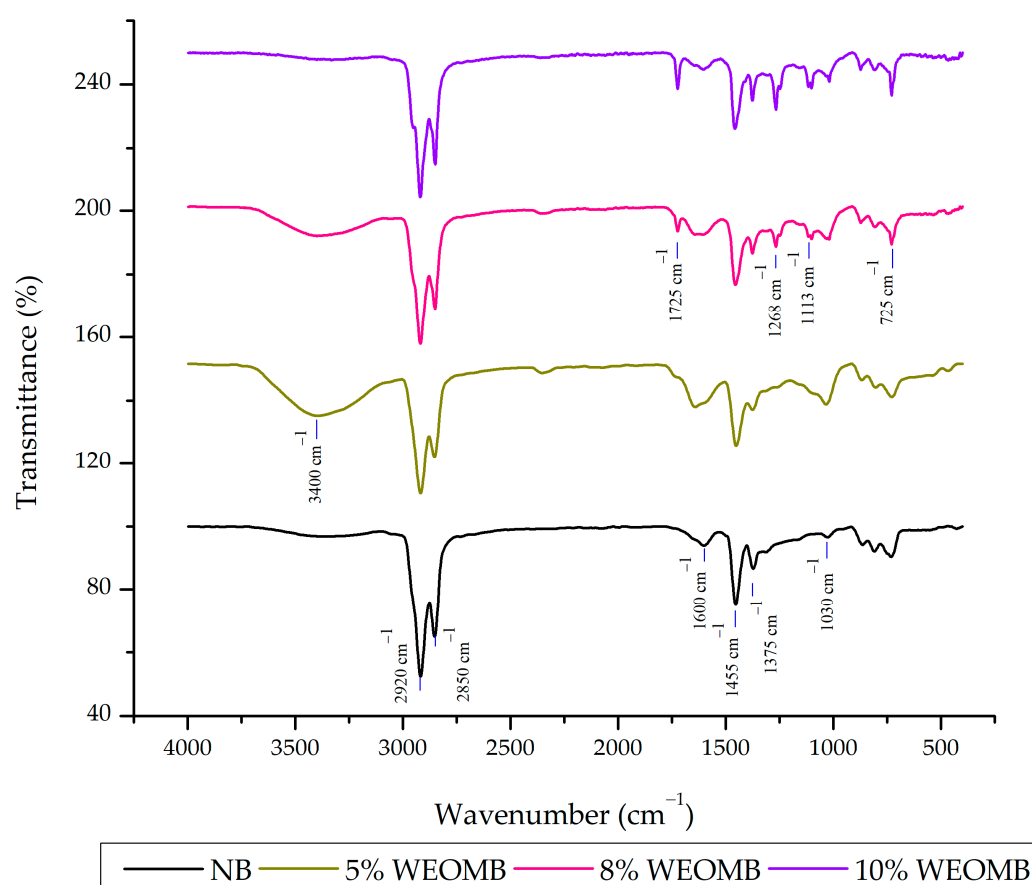


Figure 6. FTIR characteristic bands of NB and WEOMBs.

Two novel absorption peaks were identified for the 8% and 10% WEOMBs at 1268 and 1113 cm^{-1} . Nonetheless, these bands were absent for the NB, 5% WEOMB, and WEO. Thus, high-dosage WEO-modified binders suggest interaction-driven chemical evolution within the asphalt matrix, rather than simple physical mixing. The 1268 cm^{-1} band was linked to aromatic ether (C–O) stretching vibrations associated with oxygenated hydrocarbons. Likewise, the absorption at 1113 cm^{-1} pertained to aliphatic C–O/C–O–C stretching vibrations originating from ether- or alcohol-type oxygenated groups [58,59], which arose from oxidation and interaction with binder during mixing. The aromatic C–H out-of-plane bending peak at 725 cm^{-1} was amplified for 8% and 10% WEOMBs, reflecting enriched aromatic hydrocarbon species.

Figure 7 presents the FTIR quantitative analyses of neat and modified binders. Correlation between I_{CO} and I_{SO} is depicted in Figure 7a, while correlation between I_{CC} and I_{CH} is shown in Figure 7b. Generally, in Figure 7a, I_{CO} and I_{SO} increased after introducing

WEO to NB. However, an inverse exponential relationship was observed between I_{CO} and I_{SO} . Increasing the WEO content enriched the oxygenated hydrocarbons (I_{CO}), while I_{SO} increased for 5% WEOMB and subsequently decreased for the 8% and 10% WEOMBs, indicating dilution or reduced stability of sulfur-containing species. It was found that I_{SO} decreased with the incorporation of WEO or waste cooking oil into aged binders due to the rejuvenation effect of oils [60]. An inverse linear relationship for the WEOMBs was observed in Figure 7b between I_{CC} and I_{CH} : the aromatic content decreased as the aliphatic content increased. It was established that WEO primarily consists of long-chain aliphatic hydrocarbons [61], which means that, with increasing percentages of WEO, the shift in binder composition moved from aromatic to aliphatic components. Therefore, the composition of the binder was changed. With an increase in WEO percentage, there was an increase in saturates and asphaltenes, a slight decrease in aromatics, and a significant decrease in resins, reflecting asphaltene agglomeration due to resin depletion, which will be discussed later in Figure 8.

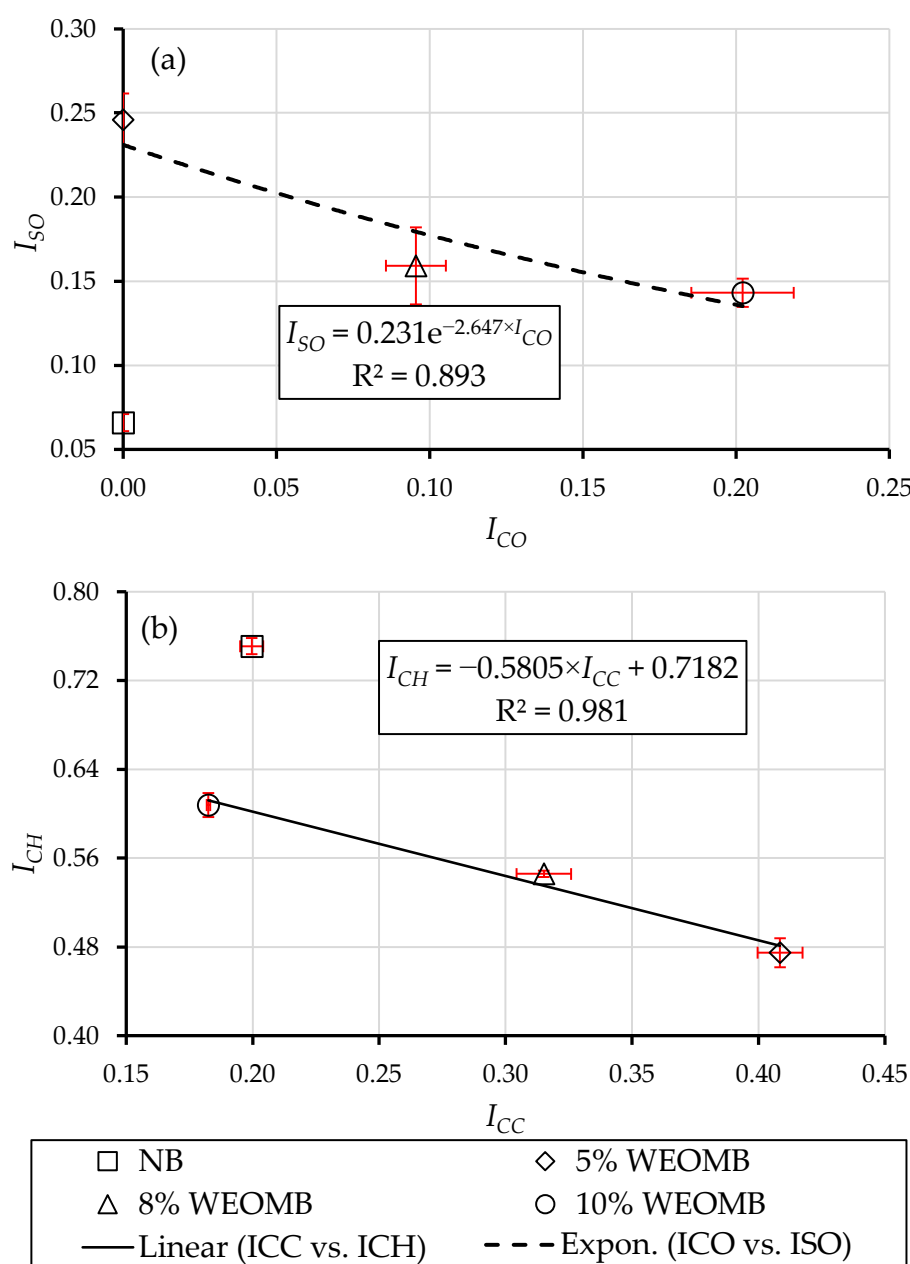


Figure 7. FTIR quantitative analyses: (a) I_{CO} vs. I_{SO} and (b) I_{CC} vs. I_{CH} .

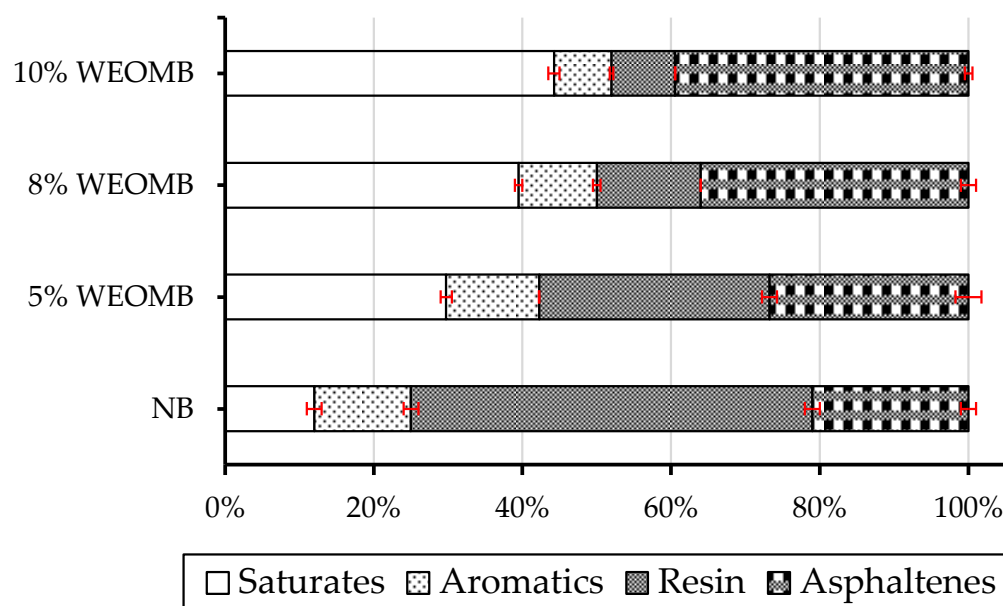


Figure 8. Asphalt SARA fractions for NB and WEOMBs.

A comparison between the SARA fraction distribution of the NB and WEOMBs is illustrated in Figure 8. The increment of WEO content increased the saturates: the fraction increased from 12% for the NB to 44% for the 10% WEOMB. This also indicated that WEO is a significant contributor of long-chain nonpolar aliphatic hydrocarbons (saturates) [62]. In contrast, the resins content decreased significantly from 54% for the NB to 9% for the 10% WEOMB, showing that the peptizing agent was depleted from the asphalt colloidal system. In addition, the aromatics experienced a slight decrease after the WEO was added to the NB, the content changed from 13% for the NB to 8% for the 10% WEOMB due to the dilution impact of WEO. The asphaltenes content increased drastically from 21% for the NB to 40% for the 10% WEOMB. Apart from the decrease in the resins content, this explained the aggregation of the asphaltenes, which was as a result of a reduced peptization [63–65]. Thus, WEO, through resins depletion, saturates enrichment, and asphaltenes aggregation, altered the colloidal structure of the NB. According to the FTIR results, the aliphatic index increased, while the aromatic index decreased, which represents an increase in the WEO binder's aliphatic content following the addition of WEO to the NB and the change in the colloidal structure of the binder. There was an increase in asphaltene content, but when low-molecular-weight saturates increased and there was a decrease in resin content, the resin–asphaltene colloidal stabilizing interactions became disrupted. Overall, saturates plus aromatics, as low-polar fractions with low-to-intermediate molecular weight, increased from 25% for the NB to 52% for the 10% WEOMB. Conversely, resins plus asphaltenes, as high-molecular-weight fractions with high polarity, decreased from 75% to 48%. This change in the internal structure of the binder led to a weakening of intermolecular cohesion and friction characteristics. Therefore, the binder's molecular mobility increased, which confirmed the enhanced softening behavior observed by the physical performance tests.

The FTIR and SARA analyses showed that the addition of WEO changed the chemical composition and colloidal structure of the binder by increasing the aliphatic hydrocarbon fractions and decreasing the polar resin content, weakening intermolecular cohesion and increasing molecular mobility within the binder matrix, which accounts for the increased penetration and reduced softening point and viscosity. Hence, the physical softening behavior of the WEOMBs was closely related to the chemical and compositional changes induced by WEO incorporation.

3.2. Zero% and 100% RAP Mixtures

Marshall stability and flow values of zero%, 100% RAP, and 100% RAP-conditioned asphalt mixtures are depicted in Figure 9. The R100 mixture showed 17% lower stability and 80% higher flow than the R0 control mixture, which indicated weak cohesion within the aged RAP binder. Conditioning RAP with 1% WEOMB enhanced the performance of the mixtures at moderate WEO dosages (5% and 8% by the binder weight), which reflected the enhanced interaction between WEOMB and the RAP-aged binder, promoting mixture integrity. Stability increased by 25% and 60%, respectively, for R100W5 and R100W8 mixtures, while the flow values decreased by 33% and 40%, respectively, compared with the R100 mixture. However, conditioning the RAP with 1% WEOMB with 10% WEO by the weight of the binder reduced the stability of the mixture by 31% and increased the flow by 48% relative to the R100W8 mixture, which was an indication of excessive softening.

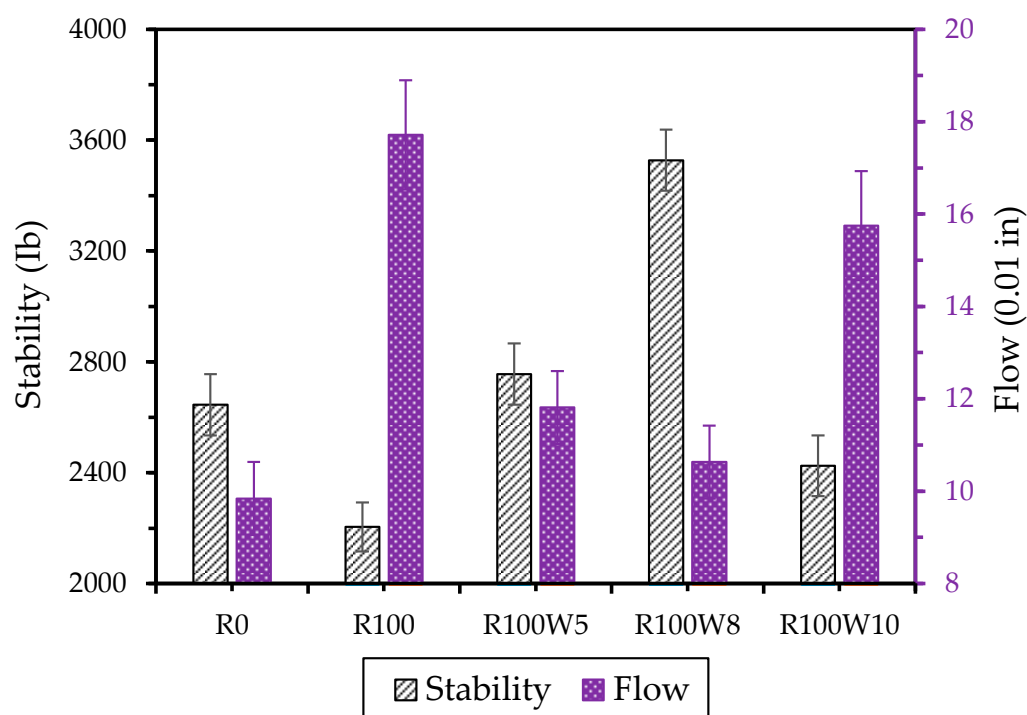


Figure 9. Stability and flow values of asphalt mixtures.

The ITS and TSR values of investigated asphalt mixtures are deemed in Figure 10. The R0 mixture exhibited the highest unconditioned and conditioned ITS values, indicating the superior tensile strength and moisture resistance of the virgin asphalt mixture. In contrast, the R100 mixture showed the lowest ITS and TSR values, reflecting the adverse effect of the stiff and brittle aged RAP binder on tensile performance and moisture damage resistance. The R100 mixture exhibited 35% and 44% reductions in $ITS_{unconditioned}$ and $ITS_{conditioned}$ values, respectively, compared to the R0 mixture. Furthermore, the TSR value of the R0 mixture was 88%, but it dropped to 76% for the R100 mixture, falling below the minimum specification limit of 80%. This reflected the adverse effect of the aged RAP binder on the mixtures' moisture resistance and cohesion.

The $ITS_{unconditioned}$ of the R100W5, R100W8, and R100W10 mixtures increased by 38%, 48%, and 40%, respectively. The $ITS_{conditioned}$ values increased by 40%, 61%, and 44%, and their TSRs increased by 2%, 9%, and 3%, respectively, compared with their unconditioned R100 mixture. The R100W8 mixture exhibited the highest TSR of 3% above the minimum threshold, whereas the R100W10 mixture experienced a decrease in ITS and TSR compared to the R100W8 mixture due to excessive softening of the binder. Therefore, these findings

reflected that the R100W8 offered the best conditioning parameters and had a balanced improvement in internal mixture cohesion, moisture resistance, and tensile strength. These findings are consistent with the binder's physical properties, in which moderate WEO dosages improved binder flexibility and flow characteristics through increased penetration and reduced viscosity. Moreover, the FTIR and SARA analyses demonstrated that WEO modified the binder colloidal structure by increasing aliphatic fractions and molecular mobility, which enhanced binder blending and aggregate coating. Nevertheless, excessive WEO contents weakened intermolecular cohesion and reduced mixture strength due to over-softening of the binder system. Consequently, the comprehensive performance assessment, encompassing the dynamic modulus, phase angle, flow number, and IDEAL cracking tests, was performed on the R0 and R100W8 mixtures.

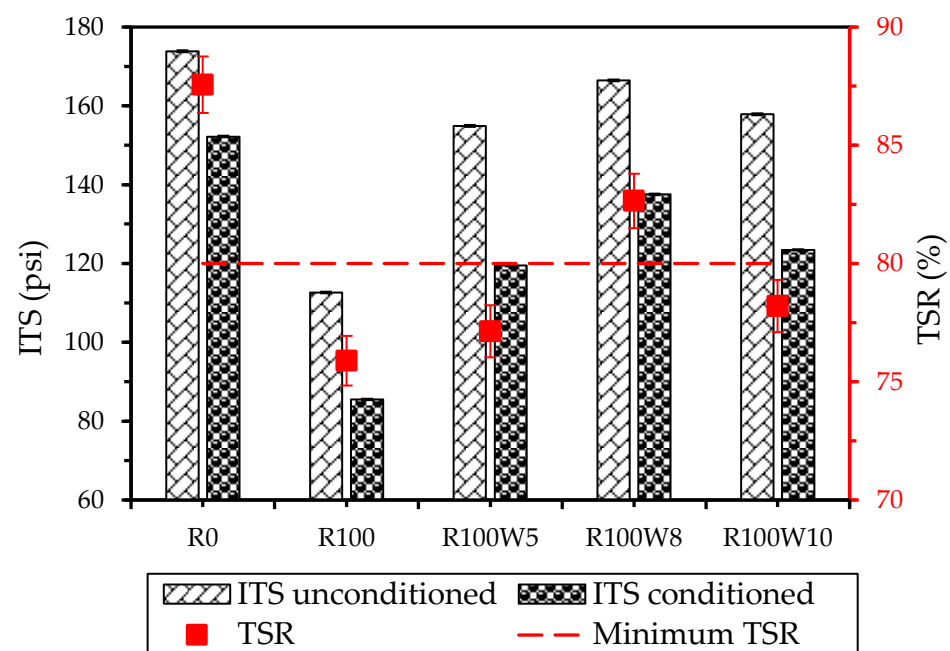


Figure 10. ITS and TSR values of asphalt mixtures.

At various temperatures and loading frequencies, Figure 11 shows $|E^*|$ values for both R0 and R100W8 asphalt mixtures. For both mixtures, $|E^*|$ values increased with increasing loading frequency and decreased with increasing temperature. For the R0 and R100W8 mixtures, at a low loading frequency of 0.1 Hz, the $|E^*|$ values were identical at 4.4 °C, as shown in Figure 11a; however, the R100W8 mixture showed slightly lower $|E^*|$ values at intermediate and high frequencies, indicating that RAP conditioning reduced mixture stiffness while maintaining adequate low-temperature structural response. For the R100W8 mixture, at 4.4 °C and 21.1 °C as seen in Figure 11a,b respectively, the $|E^*|$ values were 10–20% lower and 70–80% lower than $|E^*|$ values of the R0 mixture for all loading frequencies, displaying the R0 mixture's stiffness and R100W8 mixture's flexibility.

At 37.8 °C, Figure 11c, the $|E^*|$ range of the conditioned RAP was inferior to that of the conventional mixture, indicating improved stress relaxation capacity. R0 generally exhibited higher $|E^*|$ values than R100W8, particularly at the intermediate- and high-frequency ranges, indicating that R0 was a stiffer mixture in the context of rapid loading. In the low-frequency range, R100W8 demonstrated $|E^*|$ values that surpassed those of R0, suggesting greater stiffness under slow loading conditions. This led to a slightly better viscoelastic response under slower loading conditions compared to R0. As shown in Figure 11d at 54.4 °C, the R100W8 mixture exhibited somewhat higher $|E^*|$ values than R0 at most frequencies, which points to its superior stiffness and ability to resist deformation

at elevated temperatures. At low frequencies, lower than 0.4 Hz, the R0 mixture was stiffer than the R100W8 one. Nevertheless, conditioning RAP with 1% WEOMB containing 8% WEO reduced the excessive stiffness of RAP and provided a more balanced viscoelastic response at elevated temperatures.

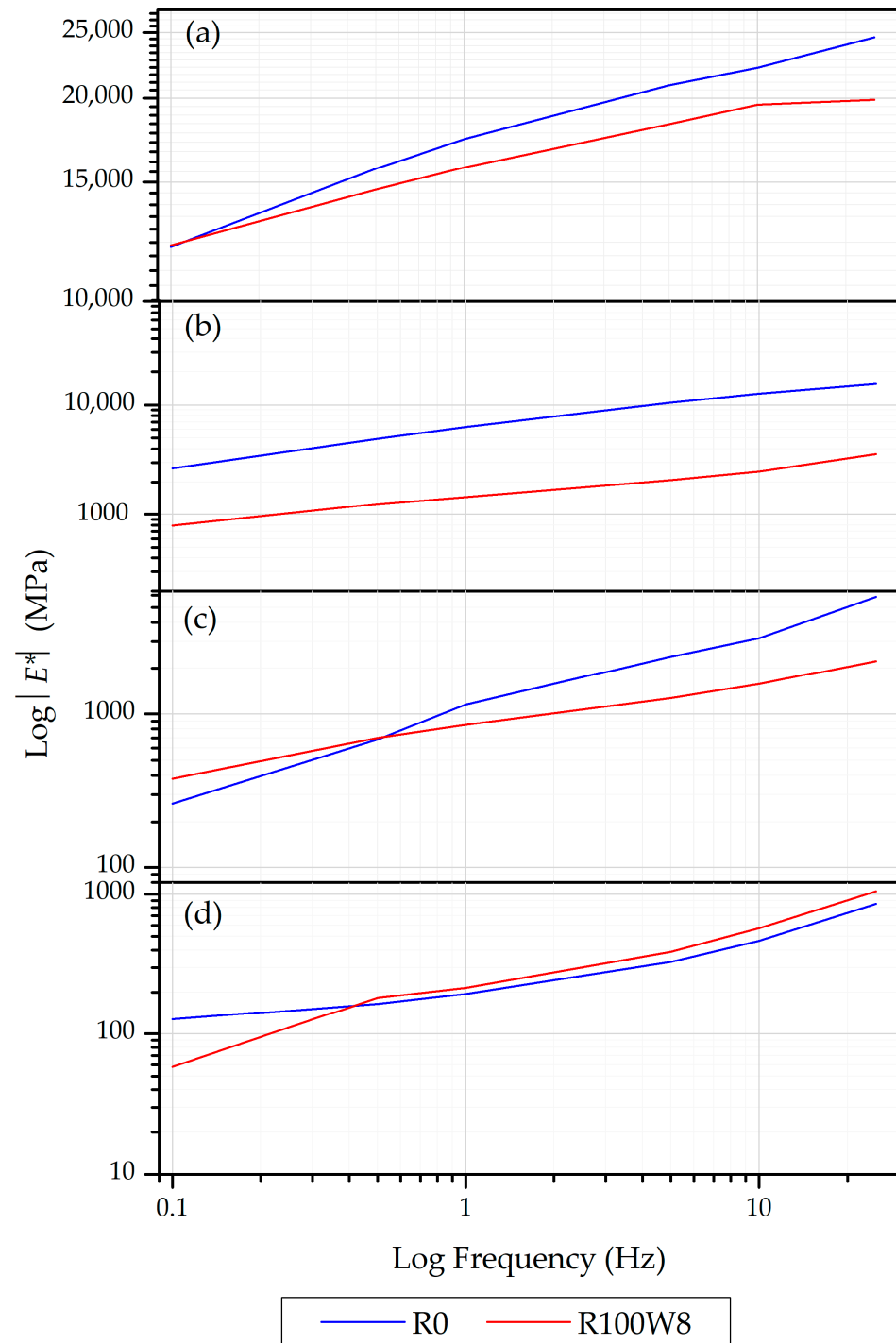


Figure 11. Dynamic moduli of asphalt mixtures at (a) 4.4 °C, (b) 21.1 °C, (c) 37.8 °C, and (d) 54.4 °C.

Figure 12 shows the phase angle (δ) of the asphalt mixtures at different temperatures and loading frequencies. At 4.4 °C and 21.1 °C, as shown in Figure 12a,b, R100W8 was more elastic as compared to R0, having lower δ values. This showed that R100W8 had better resistance to cracking and improved load recovery. At 37.8 °C and as shown in Figure 12c, R100W8 had lower δ values at both intermediate and high frequencies as

compared to R0, indicating better elastic recovery and better stress distribution under repeated traffic loading. In Figure 12d, at 54.4 °C and low frequencies, R100W8 has higher δ values compared to R0, indicating that R100W8 had more viscous behavior and less resistance to permanent deformation. This is a concern as rutting is more critical under slow speeds as compared to higher speeds. However, at intermediate and high frequencies, R100W8 had lower δ values compared to R0, indicating better viscoelastic behavior of R100W8 over R0. Therefore, flow number testing was performed to understand the rutting resistance of the R100W8 and R0 mixtures, as shown in Figure 13.

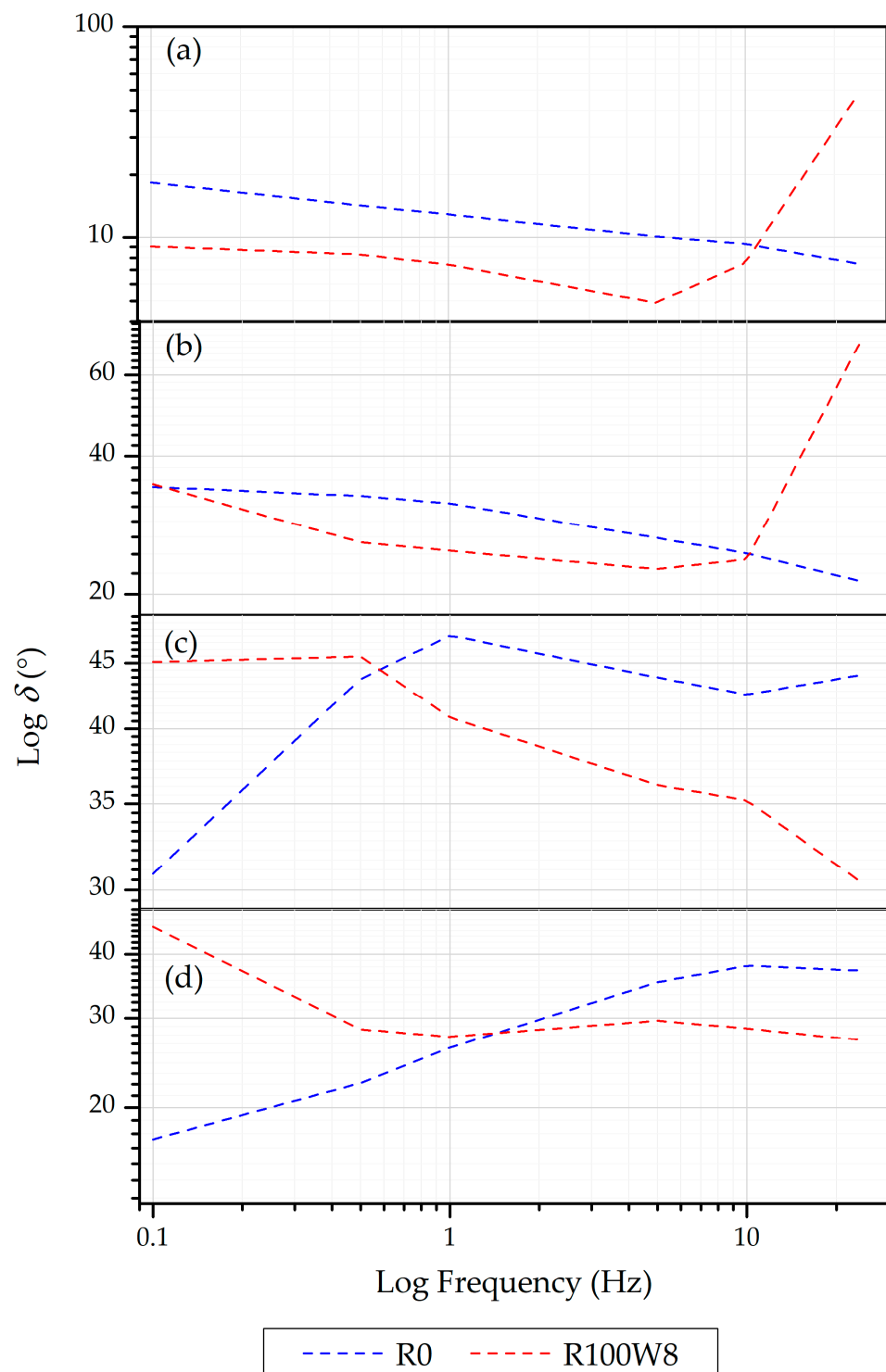


Figure 12. Phase angles of asphalt mixtures at (a) 4.4 °C, (b) 21.1 °C, (c) 37.8 °C, and (d) 54.4 °C.

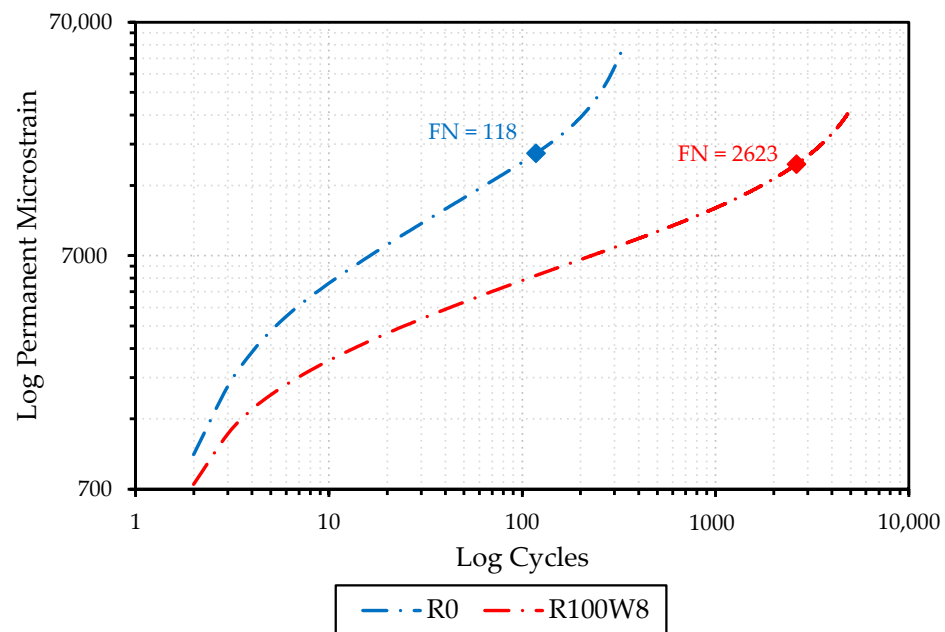


Figure 13. Flow number test analyses of asphalt mixtures.

Figure 13 depicts the relationship between permanent microstrain and number of loading cycles for the investigated mixtures. The curves show the three stages of response to rutting in asphalt mixtures (primary, secondary, and tertiary) [66]. In the first stage, both mixtures experienced the gradual accumulation of microstrain as the loading cycles increased. In the secondary stage, a relatively constant permanent strain was achieved, indicating temporary shear strength in the mixture. The tertiary stage of the microstrain response was characterized by a significant increase in permanent microstrain, indicating a significant reduction in the structural integrity of the mixture and the development of rutting in the mixture.

The R0 had permanent microstrain develop much quicker at lower loading cycles, causing the R0 to enter the tertiary deformation stage much faster than the R100W8. The R100W8 had a much slower accumulation of microstrain and had a much higher flow number (FN = 2623) compared to the control (FN = 118) due to a much longer delay in tertiary flow, meaning the R100W8 had better rutting resistance compared to the control. Even though R100W8 exhibited slightly lower stiffness (lower $|E^*|$) with increased viscous (higher δ) behavior, the FN suggests that the RAP with 1% WEOMB, including 8% WEO, enhanced the mixture's resistance to permanent deformation. This is most likely the result of improved aggregate coating, stress distribution, and a more balanced viscoelastic response within the asphalt mixture.

FN is a more direct indicator of rutting resistance than $|E^*|$ and δ because it characterizes the accumulation of permanent deformation under repeated loading [67]. On the other hand, $|E^*|$ and δ focus on the linear viscoelastic behavior of the mixtures. Additionally, a previous study concluded discrepancies between FN and $|E^*|$ for asphalt mixtures [68]. The R100W8 mixture showed a higher δ and a lower $|E^*|$ at 54.4 °C and at low loading frequencies. However, FN depicted that R100W8 had superior rutting resistance than R0. Consequently, RAP conditioning improved the mixture's internal structure and interlocking, as well as the stress dispersion in the mixture. This resulted in higher rutting resistance and delayed the onset of tertiary flow, despite the more viscous and lower-stiffness response observed at low frequencies.

Figure 14 depicts the CT_{Index} of the R0 and R100W8 mixtures. The CT_{Index} measures cracking resistance—a higher CT_{Index} value indicates greater resistance to cracking [69].

The results revealed that the CT_{Index} of the R100W8 is lower than that of the R0. A previous study [70] found that the CT_{Index} is sensitive to the addition of RAP in asphalt mixtures: 20–RAP asphalt mixtures decreased the CT_{Index} by 76% when compared to the conventional mixtures with zero RAP. Other studies [69,71] determined that mixtures containing 75% and 80% RAP resulted in a decrease in the CT_{Index} by 59% and 79% relative to conventional mixtures, respectively. However, conditioning the 100–RAP mixtures with 1% WEOMB, including 8% WEO, decreased the CT_{Index} by 63% relative to the zero-RAP mixture (R0).

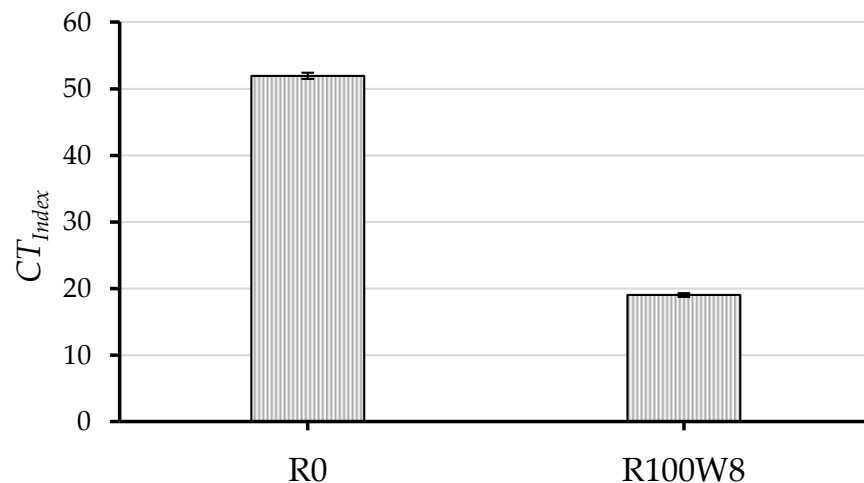


Figure 14. ICT test analyses of asphalt mixtures.

4. Conclusions

A conditioning framework for producing high-RAP mixtures was proposed in this study. The framework involved conditioning 100% RAP mixtures with 1% of WEOMBs, including the optimum WEO dosage, at 160 °C for 45 min. Based on the experimental findings, the following conclusions were drawn:

- The 8% WEO by the binder weight effectively softened the WEOMB and improved its workability. Relative to the neat binder, the penetration of the 8% WEOMB increased by 5%, softening point reduced by 16%, and viscosity decreased by 48%.
- WEO modification led to changes in binder composition, as revealed by FTIR and SARA fraction analysis. The addition of WEO increased aliphatic hydrocarbons, decreased resin fraction, and increased saturates plus aromatics, which improved binder softening by weakening intermolecular cohesion.
- Conditioning RAP with 1% WEOMB, including 8% WEO, significantly improved the mechanical performance of 100% RAP mixtures (R100W8). This mixture performed the best among all mixtures, exhibiting a 60% increase in Marshall stability and a 40% reduction in flow compared with the unconditioned 100% RAP mixture (R100).
- The conditioning framework boosted the tensile properties and moisture resistance of 100% RAP mixtures. In comparison to the R100 mixture, the $ITS_{unconditioned}$ of the R100W8 increased by 48% and the TSR boosted by 9%, satisfying the minimum TSR requirements.
- Dynamic modulus and phase angle analyses revealed that conditioning RAP mixtures enhanced the viscoelastic properties and reduced the excessive stiffness, resulting in improved stress relaxation.
- Conditioned RAP mixture demonstrated much higher rutting resistance compared to the conventional one. The FN increased from 118 for the R100 mixture to 2623 for the R100W8, indicating a significant delay in tertiary deformation and enhanced resistance to rutting.

- The CT_{Index} of the R100W8 mixture was approximately 40% lower than that of the zero-RAP mixture; however, the obtained value remained higher than many reported values for mixtures containing lower RAP percentages.
- Generally, the suggested RAP conditioning framework demonstrated the capability to produce long-term 100% RAP asphalt mixes with balanced mechanical performance, improved rutting resistance, tolerable cracking behavior, and increased durability through optimal WEO-based rejuvenation.

5. Future Work

- Future research should assess multiple sources of WEO to confirm whether the proposed framework is generalizable.
- Future studies should perform binder extraction and recovery on conditioned RAP mixtures to quantify the degree of binder blending and rejuvenation achieved during the conditioning process.

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Abbreviations

The following abbreviations are used in this manuscript:

FID	Flame Ionization Detector
FN	Flow Number
FTIR	Fourier Transform Infrared
ICT	IDEAL Cracking Test
ITS	Indirect Tensile Strength
NB	Neat Binder
RAP	Reclaimed Asphalt Pavement
SARA	Saturates, Aromatics, Resins, and Asphaltenes
TLC	Thin-Layer Chromatography
TSR	Tensile Strength Ratio
WEO	Waste Engine Oil
WEOMB	Waste-Engine-Oil-Modified Binder

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