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Effect of Warm Mix Asphalt (WMA) Antistripping Agent on Performance of Waste Engine Oil-Rejuvenated Asphalt Binders and Mixtures

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Abstract: Evaluating the performance of rejuvenated asphalt mixes is crucial for pavement design and construction, as using a rejuvenator not only boosts recycling and contributes to positive effects on the environment but also increases the sensitivity to rutting and moisture. This study was executed to evaluate the effect of a warm mix asphalt (WMA) antistripping agent, namely nano-ZycoTherm, on the moisture-induced damage and rutting potential of asphalt mixtures containing 30% and 60% aged (RAP) binder and rejuvenated with 12% waste engine oil (WEO). For this purpose, the rutting resistance of asphalt mixes in wet and dry conditions was examined utilizing a loaded wheel tracker. In addition, the impacts of moisture on the performance of the mixtures were evaluated using different experiments, such as modified Lottman (AASHTO T283), resilient modulus, dynamic creep, aggregate coating and wheel tracking tests. Fourier transform infrared (FTIR) spectroscopy and thermogravimetric (TG) analysis were performed to identify the functional groups, which would be significant in terms of moisture damage, and to assess the thermal stability of binder samples, respectively. The results revealed that the rejuvenation of aged binder with WEO increases the moisture susceptibility of the mixtures; however, the addition of ZycoTherm was found to enhance the moisture resistance of WEO-rejuvenated mixtures. Furthermore, the results indicated that the WEO-rejuvenated mixtures modified with ZycoTherm exhibited a better rutting resistance in a wet condition compared to that of WEO-rejuvenated and conventional HMA mixtures. However, the rejuvenated mixtures modified with ZycoTherm showed poorer rutting performance in a dry condition. In summary, the adoption of the WMA antistripping agent, RAP binder and WEO rejuvenation techniques demonstrated satisfactory outcomes in terms of rutting resistance and moisture susceptibility, and also, these techniques are much less expensive to implement.

Keywords: aged asphalt; antistripping additive; moisture susceptibility; RAP; warm mix asphalt; ZycoTherm

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1. Introduction

Currently, the construction and maintenance of pavements adhere to the philosophy of sustainable development, which helps reduce resource reliance and energy usage [1]. From the sustainable perspective, the environmental impacts, economic benefits and performance of the pavement must be critically considered. The combination of waste materials in asphalt mixtures tackles three environmental issues, which are solid waste management, air pollution and global warming. Recycled asphalt pavement (RAP) has substantial socio-economic advantages and may address the issues of environmental deterioration, coarse aggregates, asphalt depletion, operating cost and maintenance effectiveness [2]. Currently, most US states only permit RAP to account for between 15 and 40 % of the total mix design [3]. This is because using a huge amount of aged binder causes the mix to age prematurely and crack at low temperatures. During the lifespan of the pavement, oxidation alters the chemical configuration of the binder by loosening the maltenes and raising the ratio of asphaltenes to maltenes, which results in a stiffening of the binder [4]. However, several studies have evaluated the inclusion of greater dosages of RAP with recycling agents and found promising outcomes, i.e., improving resistance to cracking at a lower temperature [5,6]. The efficiency of the recycling agent in reducing the viscosity of an aged binder and restoring its rheological characteristics can be an indication of its effectiveness [7]. Rejuvenators could be petroleum-based, bio-based, waste-cooking- or industrial-oil-based, or based on specially created additives from various sources of oil [8,9]. These rejuvenators can restore the asphaltenes/maltenes ratio in the asphalt binder, reducing the hardening impact of the old binder [10].

Nonetheless, rejuvenators from distinct sources may have a variable degree of efficiency in increasing the performance of the mixes. For instance, waste engine oil (WEO), which shares many molecular properties with asphalt, could be utilized as a rejuvenator for aged asphalt. Engine oil's characteristics degrade with continued usage over time, and if it is not disposed of properly, it poses a threat to both the environment and human health. Due to the demand from the economy and environment to properly manage waste, the interest in reusing WEO has increased [11]. Several researchers have looked into the idea of employing WEO to rejuvenate the characteristics of aged asphalt binders [12]. The studies found that adding waste oil to RAP asphalt improved the workability and lowered the mixing temperature. Moreover, the insertion of WEO enhanced the low-temperature cracking resistance. According to Shoukat and Yoo [13], WEO improves asphalt's resistance to thermal cracking. However, Al-Saffar, et al. [14] revealed that WEO decreased the rutting performance; this is due to the decreased cohesive and adhesive bond of the aggregate–binder, especially at high temperatures. A study was conducted to estimate the potential of WEO as a rejuvenator and suggested that WEO can be used to restore the characteristics of aged asphalt binders; however, it was also observed that WEO had a negative impact on the aggregate–binder bond, necessitating the application of antistripping agents [15]. Another study [16] found that WEO harms asphalt characteristics, such as decreased adhesiveness to aggregates, which contributed to stripping and raveling. Jia, et al. [17] also recommended against using WEO in asphalt due to the detrimental impact on the fatigue properties of the binder. Jahanbakhsh, et al. [18] found that the moisture susceptibility of RAP mixtures increased after adding WEO into blended binders containing 60% RAP. Further, Eltwati, et al. [19] developed asphalt mixtures containing 60%, 70% and 80% RAP binders with different dosages of WEO (6%, 9%, 12%) and glass fibers. The results revealed that the application of WEO decreased the resistance of the rejuvenated mixtures to moisture damage compared to virgin mixtures, and it was also shown that increasing the WEO content in the RAP binder made the mixture more susceptible to stripping. Despite the numerous benefits provided by WEO rejuvenation processes, they may have a detrimental effect on the resistance to moisture damage and rutting of asphalt mixtures due to wet aggregates and the lack of electrical and chemical tendency between the aged binder and aggregate exterior due to low production temperatures.

Even though the precise cause of moisture degradation is not entirely established, the characteristics of the aggregate and binder, the degree of compaction and the dynamic impacts of passing vehicles all have a substantial impact on moisture-induced damage [20]. One of the most frequent methods for preventing or delaying the development of moisture damage is to improve the characteristics of the aggregates [21]. On the other hand, the asphalt binder has a substantial impact on the mix's moisture characteristics [22,23]. It is known that the adhesion between aggregates and binders can be improved by using either solid or liquid antistripping additives, whereby liquid substances are more frequent. Liquid antistripping additives have been used since the 1930s, but they have poor durability when subjected to high temperatures. Mirzababaei [24] examined the influence of warm mix asphalt (WMA) antistripping additive, i.e., ZycoTherm, on the moisture sensitivity of hot mix asphalt (HMA) and WMA mixes. It was noted that the influence of ZycoTherm on antistripping attributes is better in WMA mixes than in HMA mixes. In addition, WMA is a well-known green pavement. Thus, if combined with RAP, it gives added value to the overall production cost and environmental impact, as it reduces fuel consumption during the production phase [25]. Ayazi, et al. [26] used ZycoTherm as a warm mix additive for an asphalt mixture containing RAP material. The findings revealed that ZycoTherm can raise the mixes′ resilient modulus ratio (MRR) and tensile strength ratio (TSR), indicating an improvement in moisture resistance. Sukhija, et al. [27] found that the use of antistripping additives can enhance the stripping resistance of rejuvenated binders. Further, Yousefi, et al. [28] assessed the moisture resistance of asphalt mixtures containing the RAP binder, ZycoTherm, and different types of rejuvenators (aromatic extract and tall oil). The study found that the rejuvenators could decrease the moisture susceptibility and rutting resistance of asphalt mixtures containing RAP; however, the addition of ZycoTherm enhanced their resistance to rutting and moisture damage.

Although WMA mixes incorporating RAP have a desirable economic and environmental impact, designing such mixes presents some difficulties. Furthermore, there have been few research works on the influence of using WEO, RAP and WMA antistripping additives at the same time on the mechanical performance of asphalt mixes. Therefore, the current study was conducted to examine the effects of an antistripping agent, i.e., nano-ZycoTherm, on the properties of asphalt mixtures incorporating WEO-rejuvenated binders. Water damage assessment test procedures, such as indirect tensile strength (modified Lottman), resilient modulus, dynamic creep, Marshall stability and aggregate coating tests, have been used. The post-compaction (PC), stripping inflection point (SIP) and rutting depth in wet and dry conditions as a consequence of loading cycles and final cycles for 20 mm rutting depth parameters obtained from the wheel track test were used to assess the performance of rutting resistance and moisture susceptibility of the WEO-rejuvenated samples containing WMA additive, i.e., ZycoTherm, and WEO-rejuvenated HMA samples. FTIR was performed on binders to further examine and assess the factors affecting the stripping of the mixtures. It was also postulated that failure of the samples due to water damage was simply a result of the cohesive and adhesive bonds formed between the binders (RAP and virgin binder) and the aggregate.

2. Materials, Sample Preparation and Methods

2.1. Materials

2.1.1. Virgin Asphalt Binder and Aggregate

The binder utilized in this experiment had a penetration grade of 60/70, a widely used binder for pavement construction in several countries. The asphalt binder was obtained from a local supplier, and its attributes are revealed in Table 1. The virgin aggregate employed in this investigation was limestone aggregate, with a nominal maximum size of 19 mm.

Table 1. Properties of RAP and virgin binders.

Property	Units	Base Binder	Aged Binder	Standard
Penetration (25 °C, 10 g, 5 s)	0.1 mm	67	20.1	ASTM-D5
Softening point (R&B)	°C	50.5	66.80	ASTM-D36
Ductility (25 °C, 5 cm/mm)	cm	117	9.30	ASTM-D113
Kinematic viscosity (135 °C)	Pa.s	0.51	3.52	ASTM-D4402
Specific gravity	-	1.02	1.10	ASTM-D70

2.1.2. Waste Engine Oil (WEO) and Antistripping Additive

The WEO used is a 4000 km use 10W40 synthetic oil. The WEO has a flash point of 265 °C (ASTM-D92) and kinematic viscosity of 41.0 cSt (ASTM-D4402) at 135 °C.

ZycoTherm has been approved worldwide as a warming blend, antistripping additive technology, and it reduces moisture damage by creating permanent chemical bonds. ZycoTherm, a nano-organosilane produced by Zydex Commerce, was chosen as a wetting agent. It has been established that ZycoTherm is safe at standard pressures and temperatures [29]. The ZycoTherm additive has a viscosity of 400 centipoises and a flash point of 90 °C. Figure 1 shows the ZycoTherm used in this study.

Figure 1. ZycoTherm additive.

2.1.3. Recycled Asphalt Pavement (RAP)

The RAP material was collected from a milled 12-year-old roadway. To recover the aged binder from RAP materials, a centrifugal extraction technique with methylene chloride as a flush was performed as stated in ASTM D2172. Subsequently, the aged binder was recovered using a rotary evaporator in accordance with ASTM D5404 to eliminate the methylene chloride. The original asphalt mixture used to produce this asphalt includes siliceous aggregates and 60/70 penetration grade binder. The binder percentage of the RAP material was estimated to be 4.85% based on the ignition experiment (ASTM D6307). Table 1 displays the physical properties of the RAP binder.

2.2. Sample Preparation

The RAP (aged binder) with varying proportions, specifically 30% and 60%, was heated up to 145 °C before being combined with the virgin binder (70% and 40%). Then, the WEO was immediately admixed with the blended binders for 60 ± 5 s. Afterward, ZycoTherm with a content of 0.1% (by weight of total binder) was added to the rejuvenated binders [30]. The penetration (ASTM-D5-20) [31] and softening point (ASTM-D36-14) [32] tests were carried out to ascertain the appropriate WEO percentage, which recovers the characteristics of the aged asphalt binder.

The reference asphalt mixture and mixtures containing 30% and 60% RAP binders were produced using coarse aggregates of crushed dolomite, fine aggregates of siliceous sand and a mineral filler of limestone dust. Table 2 lists the various asphalt mixtures tested in this study and their designations. The aggregate of a nominal maximum size of 19 mm was used in this study, and Figure 2 shows the gradation and the specified limitations of the aggregates. The reference and RAP mixtures (30R and 60R) were prepared according to Table 3. The mixture was thereafter given time to cool to the compaction temperature, which was fixed at 280 ± 30 cSt. The mixture was then placed into a steel mold and compacted using 75 blows per side to form Marshall samples, which met the standard's requirements for height and radius of 63.50 mm and 50.80 mm, respectively. Based on the Marshall method, a design asphalt content of 5.0% was selected with an air void content of 4%. Figure 3 shows the experimental flowchart followed in this study.

Table 2. Asphalt mixtures tested in the study.

Mixture ID	Type of Binder
HMA	Hot mix asphalt mixture containing virgin binder (VA) and aggregate
30R	HMA containing 30% RAP
30R+WEO	12%WEO Rejuvenated HMA containing 30% RAP
WMA-30R-WEO	12%WEO Rejuvenated HMA containing 30% RAP and 0.1% ZycoTherm
60R	HMA containing 30% RAP
60R+WEO	12%WEO Rejuvenated HMA containing 60% RAP
WMA-60R-WEO	12%WEO Rejuvenated HMA containing 60% RAP and 0.1% ZycoTherm

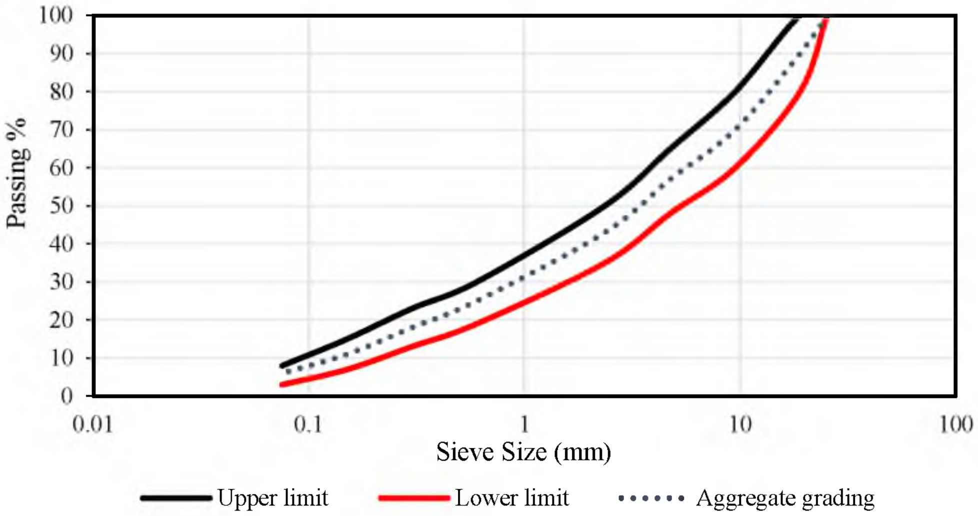

Figure 2. Gradation of the aggregate and specification.

Table 3. Mixture content for Marshall sample.

Mixture ID	Weight of Different Mixes' Content (grams)				
	RAP	Fresh Agg.	Fresh Bit.	WEO	ZycoTherm
HMA	–	1140	60	–	–
30R	360	798	42	–	–
30R+WEO	360	798	42	2.16	–
WMA-30R-WEO	360	798	42	2.16	0.06
60R	720	456	24	–	–
60R+WEO	720	456	24	4.32	–
WMA-60R-WEO	720	456	24	4.32	0.06

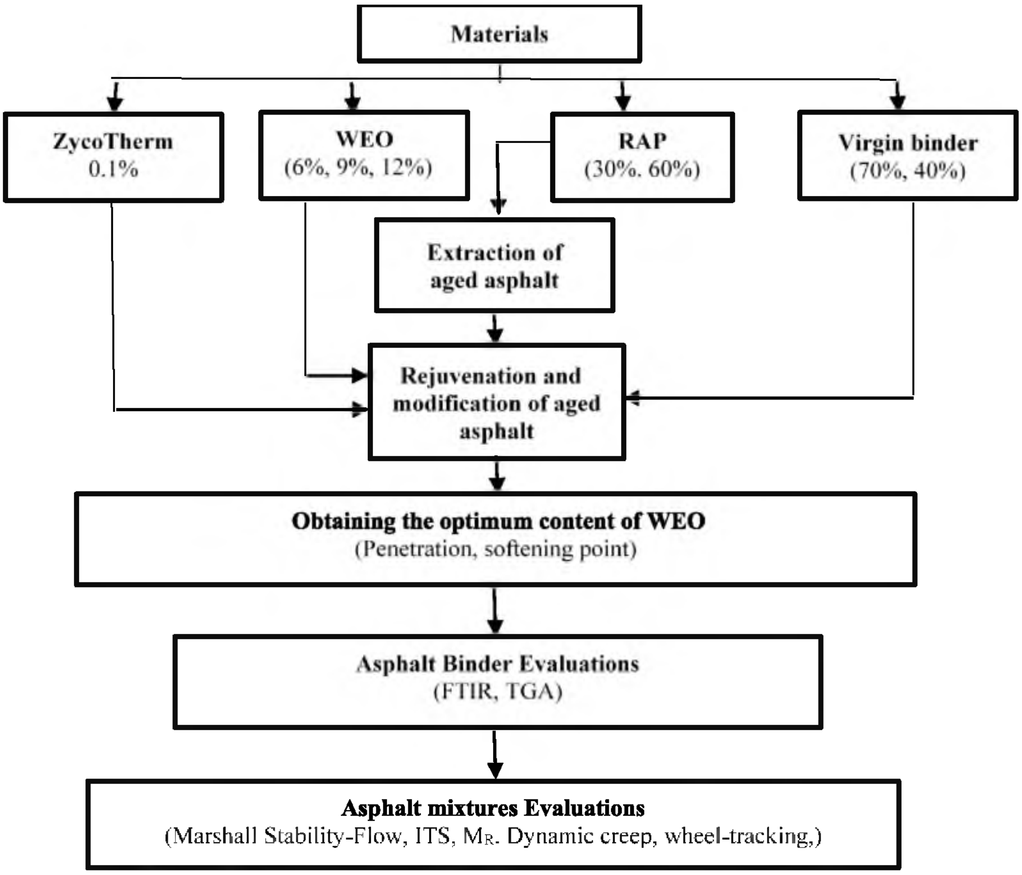

Figure 3. Flowchart of the study.

2.3. Testing Methods

2.3.1. Fourier Transform Infrared (FTIR) Spectroscopy

FTIR spectroscopy was employed to examine and provide a comprehensive grasp of the functional categorizations of binders. A total of 32 scans were performed on virgin and rejuvenated binders, with 5% iris and a resolution of 4 cm^{-1} at wave numbers varying from 4000 to 400 cm^{-1}. The carboxylic acids in the binder have a significant influence on stripping, particularly when combined with siliceous particles, resulting in absorbance peaks of interest spanning from 1710 to 1690 cm^{-1}. This area is commonly utilized to characterize asphalt binders, and the findings of functional groups, i.e., carboxylic acids, 2-quinolones, anhydrides and ketones, may be important in terms of moisture damage [26].

2.3.2. Thermogravimetric (TG) Analysis

TG analysis is a technique, which ascertains the mass loss of material as a function of temperature. The test was performed according to ASTM E1131 [33] in a nitrogen environment with a sample mass of about 5 mg at a flow frequency of 10 mL/min; the temperature was constantly increased from 40 to 800 °C at a heating rate of 10 °C/min. Each test sample was enclosed in an aluminum pan.

2.3.3. Marshall Stability and Flow Test

The maximum load that asphalt mixes can sustain before failure is determined by the stability and flow test. The experiment was conducted according to ASTM D6927. The Marshall samples underwent a 30 min conditioning period in a water bath set at 60 °C. The Marshall samples were then subjected to loading at a constant pace of 50 mm/min, while the deformation patterns were measured until the entire failure occurred.

2.3.4. Indirect Tensile Strength (ITS) Test

The tensile strength of mixtures is an essential property, which illustrates the adhesion and cohesion characteristics of the aggregate–binder interaction, resulting in improved resistance to tensile strength in the pavement. The resistance of the mixes to moisture damage was investigated using the AASHTO T283 standard [34]. A tensile force with a continuous deformation pace of 5.1 cm/min at 25 °C was applied according to AASHTO T322 [35] to attain the ITS.

The tensile strength ratio (TSR) denotes a decrease in mixture integrity caused by moisture degradation and is computed by dividing the tensile strength of the conditioned sample by the unconditioned sample. A minimum ratio of 80% has often been employed as a failure criterion for the TSR.

2.3.5. Resilient Modulus (M_R) Test

The resilient modulus test was carried out as specified in ASTM D7369 [36]. Five conditioned and five unconditioned specimens with repetition for each kind of specimen were tested at 25 °C. This test evaluates the mixture's resistance to irreversible deformation as well as its capacity to recover to its original state after being subjected to a 1000 kN load. An estimation of the mix's reaction to the impact of moisture is given by the proportion of the resilient modulus of the conditioned samples to the unconditioned samples. Since the resilient modulus test is non-destructive, it is appropriate for assessing the damage caused by moisture in the mix.

The resilient modulus ratio (RMR) is a parameter used to determine the moisture resistance of the mixture using the resilient modulus test. A mixture with a higher RMR is more resistant to moisture damage. An RMR of 70% is commonly used as the lowest value required for HMA mixes [37]. The mixes' RMR values are calculated as follows:

$$RMR = \frac{M_R\ (wet)}{M_R\ (dry)} \tag{1}$$

2.3.6. Dynamic Creep Test

Rutting has become a major challenge in the development of WMA technology as a result of the WMA's reduced stiffness. When the pavement is exposed to moisture, the problem worsens. The rutting resistance of the WMA mixes comprising RAP was examined using a dynamic creep test for unconditioned and conditioned samples at 50 °C. The testing was carried out using the universal testing machine (UTM) in line with NCHRP 9-19 [38]. The cumulative permanent vertical stresses were measured under haversine compressive loading with a deviator stress level of 450 kPa. After a certain number of cycles, the slope tangent of the permanent strain versus loading cycle curve, which is known as the flow number (FN), intensified substantially. The FN was determined for both conditioned and unconditioned samples, and the creep ratio (CR) value (see Equation (2)) was utilized as an indicator to assess the influence of moisture on the rutting. Mixtures with higher values of CR are less susceptible to moisture.

$$CR = \frac{Flow\ number(wet)}{Flow\ number(dry)} \tag{2}$$

2.3.7. Aggregate Coating Test

The aggregate coating test was carried out according to AASHTO T195 [39]. The coating was only determined for particles that remained on the 9.5 mm sieve. As a result, the aggregates were filtrated on a 3/8″ sieve, and roughly 500 gm of the sieved specimen was obtained and analyzed. According to the design requirement, at least 95% of the coarse aggregate particles must be completely coated.

2.3.8. Rutting Resistance Test

The rutting resistance of the asphalt mixtures was determined using a double-wheel tracker (EN 12697-22). The mixtures were submersed in hot water for 30 min at 50 °C. Subsequently, the samples were exposed to numerous loadings passes of 705.0 N at 53.0 passes/min. The test is run until the loaded wheel has completed 20,000 passes, or until a 20 mm rut depth has developed, whichever comes first.

3. Results and Discussion

3.1. Physical and Chemical Evaluations of Asphalt Binder Samples

3.1.1. Penetration and Softening Point

Figures 4 and 5 depict the influence of different contents of WEO on the penetration and softening point of RAP binders incorporating ZycoTherm. The addition of a RAP binder, as predicted, greatly lowered the penetration and raised the softening point of the virgin binder. The findings also showed that the increase in WEO content led to an increase in penetration and a decrease in the softening point of the RAP binders. It was noted that blending 12% of WEO (by weight of aged binder) with 30% and 60% RAP binders restored the penetration and softening point of blended binders to the value of the virgin asphalt (VA). The recovery tendency was relatively similar under various dosages of WEO, implying that asphalt efficiency was restored accordingly. This indicates that adding WEO boosted the aromatic percentage of aged asphalt [40]. Previous studies recommended that 9 to 12% WEO content could recover the physical properties of asphalt binders containing a high content of RAP [19,41]. Wang, et al. [15] indicated that the mixing of WEO has both positive and negative impacts. The optimal dosage of WEO depends on the stiffness properties of aged binders. It is known that WEO is used to restore the RAP binder to its original state by reducing its viscosity and increasing its ductility. However, a higher dosage of WEO may not be more suitable for high-temperature performance asphalt pavement than that for low temperature due to the reduction in adhesion between the binder and the aggregate. Thus, a moderate amount of antistripping additive is required to control the required properties and to improve the adhesion between the binder and the aggregate.

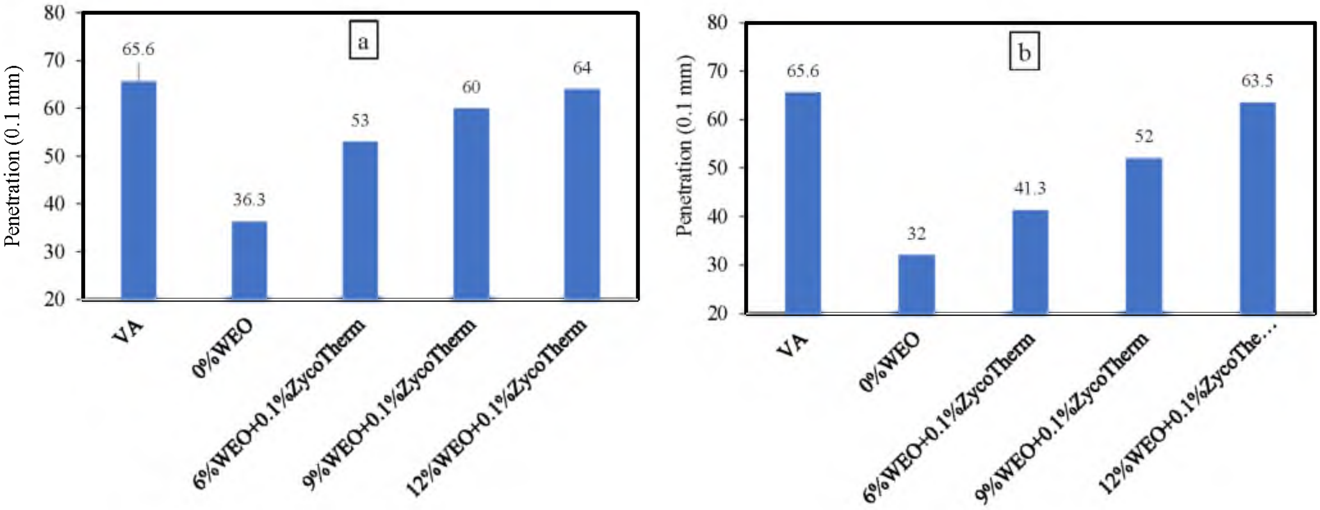

Figure 4. Penetration values of asphalt mixtures containing (**a**) 30% RAP binder and (**b**) 60% RAP binder.

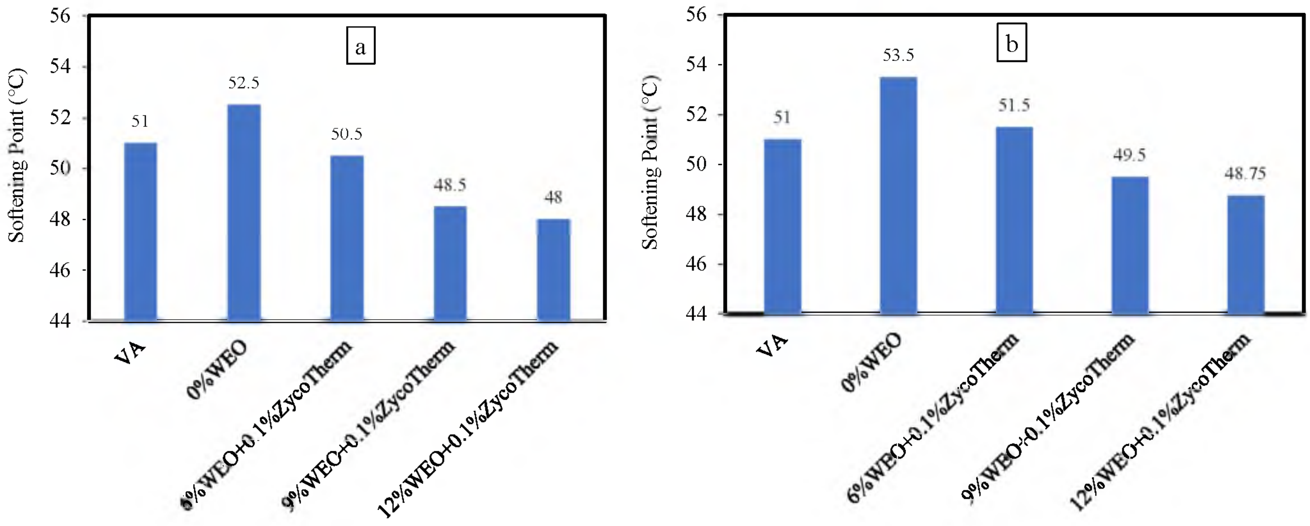

Figure 5. Softening point values of asphalt mixtures containing (**a**) 30% RAP binder and (**b**) 60% RAP binder.

3.1.2. FTIR Results

Figures 6 and 7 show the master curves of infrared spectroscopy examination of ZycoTherm-modified and WEO-rejuvenated binders containing 30% and 60% RAP binders, respectively. The RAP binder underwent physical and chemical transformations over time when it was exposed to a thermal-oxidative procedure, as evidenced by the different increases in oxidative functional groups. This could be caused by the elimination of volatile components or low-molecular-mass materials, or it could be due to the formation of hydrogen atoms [42]. The production of sulfoxide groups was also observed, as shown by the band at 1030 cm^{-1} frequency (S=O stretching). The absorption at 1160 cm^{-1} can be due to the anhydride groups generated following oxidation. Carbonyl groups were also detected in the RAP at a frequency of 1700 cm^{-1}. However, the addition of WEO to the RAP binder decreased these oxidative peaks; it is hypothesized that the WEO might decrease the aging of asphalt [43]. The results also indicated that adding ZycoTherm into the WEO-rejuvenated binders had no obvious effect on the oxidative peaks (carbonyl groups), showing identical performance to the WEO-rejuvenated binders.

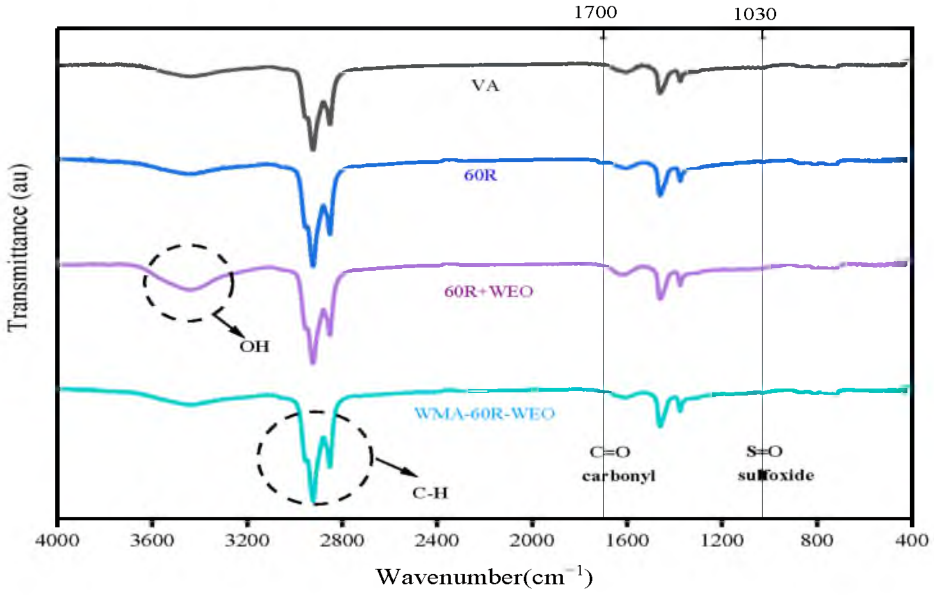

Figure 6. Infrared spectra of asphalt binder samples containing 60% RAP binder.

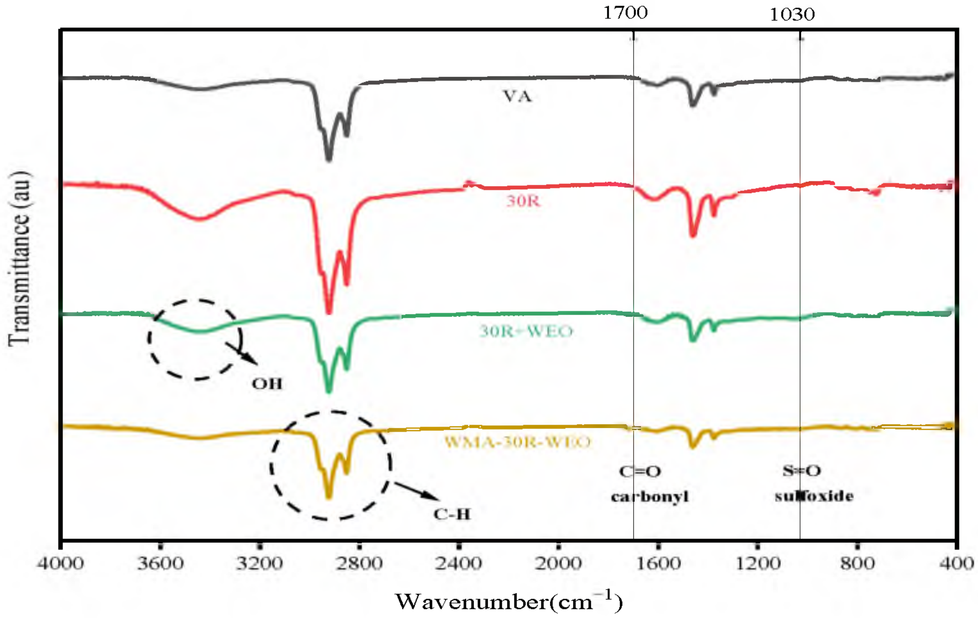

Figure 7. Infrared spectra of asphalt binder samples containing 30% RAP binder.

FTIR spectroscopy is also applied to estimate the chemical variations in the binder caused by moisture conditioning. The acidic components are important in determining the moisture damage of an asphalt mixture. Carboxylic acids, ketones, anhydrides and 2-quinolone groups are largely prevalent in the adsorbed portion of the asphalt binder on the aggregate exterior. The wide peak of about 3000 to 3500 cm^{-1} indicates carboxylic acid, with extremely strong and extensive O-H stretching absorption. Carboxylic acid is easily absorbed by aggregates in the binder–aggregate mixing. At the binder–aggregate contact, the connections of carboxylic acids and Si-OH molecules on the aggregate exterior are weak. According to Mannan, et al. [44], if the asphalt binder is immersed in water for numerous days, the absorbed water in the binder can be seen in the FTIR spectrum at the 3100–3700 cm^{-1} wavenumber section.

It can be seen in Figures 6 and 7 that the moisture-conditioned samples of WEO-rejuvenated binders had a peak at 3400 cm^{-1}, demonstrating that the WEO-rejuvenated binders were exposed to moisture damage. However, this functional group vanished when the WEO-rejuvenated binders were modified with ZycoTherm, indicating that the ZycoTherm additive works adequately as an antistripping agent to remove this water-sensitive group.

3.1.3. TG Analysis

TG analysis of binder samples is presented in Figure 8. The curves were divided into four major regions. All binder specimens in the first region had lost only a minimal quantity of weight. The initial decomposition temperature, defined as the temperature at which mass loss exceeds 2%, denotes the ending of this region. The following region (200–400 °C) exhibits an increased rate of weight loss, demonstrating that the binder fractions were thermally decomposing. The TG analysis reveals that there was no significant mass loss up to 285 °C, demonstrating that the specimen was thermally stable up to that temperature and that breakdown occurred above this temperature, causing weight loss. Mass loss decreased even further in the third region of the TG analysis (400–600 °C). The greatest weight loss was observed at temperatures between 385 and 480 °C. In the last region (600–800 °C), the specimens showed a virtually flat peak, indicating no additional weight loss. The residues remaining after decomposition were determined to be 18% of the original weight.

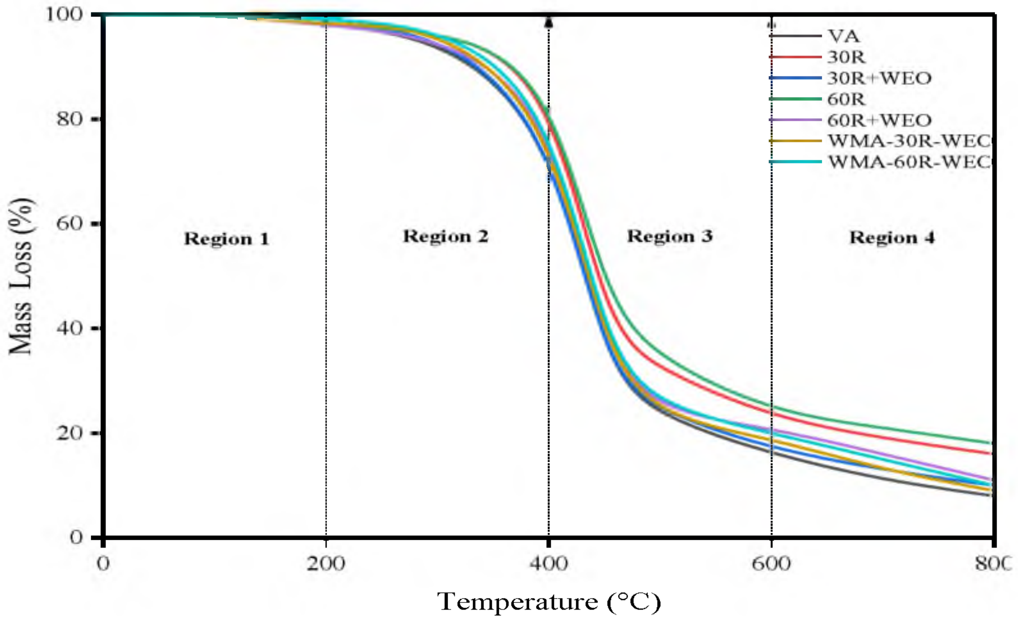

Figure 8. TG analysis of asphalt binder samples.

The TG analysis also revealed that the samples containing RAP binders had the highest thermostability of the binders tested. These data lend credence to the hypothesis that the RAP binder contains a considerable amount of asphaltene, which maintains its thermal stability at elevated temperatures [45]. However, the ZycoTherm and WEO addition appear not to affect the thermal stability of the blended binders, since the decomposition temperature (flash point) is not significantly altered. The TG curves of the WEO-rejuvenated binders (with and without ZycoTherm) and virgin binder were nearly similar. It is also noted that no thermal breakdown of the rejuvenator was seen at the typical temperatures for mixing and compacting asphalt, which are 140 °C and 163 °C, respectively. The findings of this test are similar to earlier research [46,47], demonstrating that regenerated binders are unsusceptible to regenerating agent loss through mixing.

3.2. Asphalt Mixtures' Evaluations

3.2.1. Marshall Stability and Flow Test

Table 4 depicts the findings of the Marshall test on asphalt mixture samples with virgin materials and rejuvenated samples with varying concentrations of RAP and containing the ZycoTherm additive. Marshall stability quantifies the ultimate load that the mixture can resist and corresponds well with in-service pavement rutting data. Marshall stability increases, whereas the flow decreases with the incorporation of RAP. This demonstrates that the addition of RAP raises the rutting resistance. The highest stability was achieved at 26.37 kN for an asphalt mix made with 60% RAP, while the stability of HMA was 15.49 kN. This is due to the stiff aged binder increasing the strength of the mix. The findings are consistent with those of earlier researchers, Taherkhani and Noorian [48], as well as Katla, et al. [49].

Table 4. Volumetric characteristics of mixtures.

Mixture ID	Optimal Binder Content%	Mixes' Properties			
		Air Voids in Total Volume%	Stability (kN) Min 8.83 kN	Flow (mm) (2–4 mm)	Marshall Quotient (kN/mm) (2.95–4.91)
Reference Mix	5.0	4.00	15.49	3.50	4.43
30R	5.0	4.10	24.05	3.25	7.40
30R+WEO	5.0	4.14	16.15	3.95	4.09
WMA-30R-WEO	5.0	4.18	17.56	3.85	4.56
60R	5.0	3.95	26.37	2.95	8.94
60R+WEO	5.0	4.16	17.82	3.84	4.64
WMA-60R-WEO	5.0	4.20	18.23	3.79	4.81

Table 4 also demonstrates that stability was reduced when WEO (12%) was added. The oil's softening action can be associated with the decrease in stability of the rejuvenated HMA mixtures. The colloidal structure of the RAP binder is restored by the chemical reaction between the polar group of the WEO and asphaltene molecules [50]. The rejuvenated HMA mixtures containing 30% and 60% RAP binders had stability values of 16.15 kN and 17.82 kN, respectively. The results indicated that the stability values of the WEO-regenerated HMA mixtures exceeded those of the reference HMA (15.49 kN). The results indicate that all samples exceeded the minimal stability criterion (8.83 kN). The results also showed that the rejuvenated mixture had higher flow values than those of the HMA and RAP mixtures. This may increase the rutting of WEO-rejuvenated asphalt. The flow values recorded for rejuvenated mixtures containing 30% and 60% RAP are 3.95 mm and 3.84 mm, respectively, and fall within the specification limit (2–4 mm). The findings are consistent with earlier research [51].

Meanwhile, the addition of the antistripping additive to rejuvenated mixtures was found to increase the stability and decrease the flow of mixtures. The results of this test clearly show that rejuvenated mixtures containing antistripping additive function better than the unmodified rejuvenated mixtures with respect to stability and flow. This may be explained by the surplus of adhesion bonds created by siloxane groups between the aggregate and the asphalt binder [52]. The ZycoTherm modification of rejuvenated mixtures containing 30% and 60% RAP yielded stability values of 17.56 kN and 18.23 kN, respectively. According to Wang, et al. [53], adding liquid antistripping additives to the mix causes the aggregate to react with the binder instead of water. Furthermore, incorporating antistripping additives into the mixture enhances the bond between the binder and the aggregate particles [52].

3.2.2. Indirect Tensile Strength (ITS) Test

The result of the indirect tensile strength (ITS) of mixtures for two different conditions is presented in Figure 9. Based on the results, the moisture significantly affects the ITS values for all mixtures. This may be due to the mechanism of adhesion loss between the asphalt binder and the aggregate surface or the cohesive failure of the asphalt mixtures due to the interaction with moisture. Nonetheless, it needs to be underlined that the bonding between the binder and the aggregate under wet circumstances is highly reliant on binder modification type and conditioning duration [54].

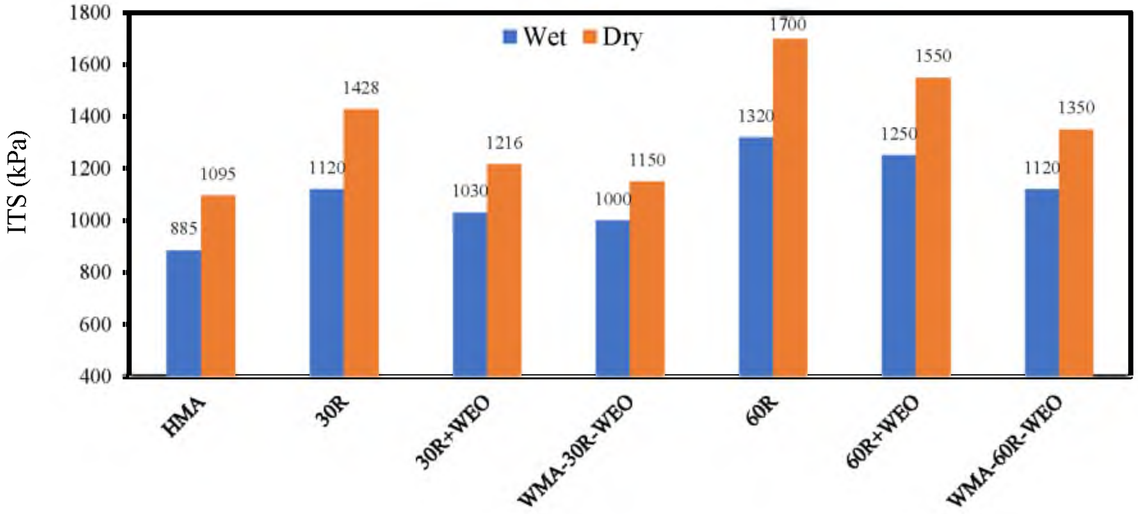

Figure 9. Indirect tensile strength (ITS) values of different specimens for wet and dry conditions.

The inclusion of RAP binders in HMA improves the tensile strength from 21 to 36% as compared to control HMA for both wet and dry conditions, respectively. This indicates that the mixture containing 60R has the highest resistance to fatigue as a result of rising stiffness. The tensile strength of the mixture was seen to be slightly diminished due to further modification with WEO addition and using the WMA antistripping method. Both modified mixtures can sustain relatively high tensile strength as compared to HMA. This clarifies that mixtures containing ZycoTherm developed a better adhesion and thus enhanced the binder–aggregate mechanical interlocking. The adherence of the mixture containing ZycoTherm against fatigue and cracking damage was verified, as the tensile strength increased up to 21% compared to HMA. Furthermore, decreasing the mixing temperatures of WMA mixes results in reduced cracking resistance under tensile loading.

Figure 10 presents the tensile strength ratio (TSR) of the asphalt mixtures. The results reveal that asphalt mixes containing RAP have lower TSR values than the reference mixture, indicating a poorer resistance to moisture degradation. This can be attributed to the decreased alkalinity and hydrophilic characteristics of the aggregates included in RAP-containing mixes. However, the WEO rejuvenation of RAP mixtures increased the TSR of mixtures, demonstrating a better resistance to moisture damage. In terms of the influence of antistripping agent additions on TSR values, mixtures containing ZycoTherm have the uppermost values of TSR. This proves that the use of an antistripping agent enhanced the resistance of the mixture against stripping. This is due to the additives forming a strong link between the negative electrical ions on aggregate surfaces and the binder [55]. Goli and Latifi [56] acquired similar results, whereby the lower production and mixing temperature of WMA affected the ITS values of the WMA–RAP specimen.

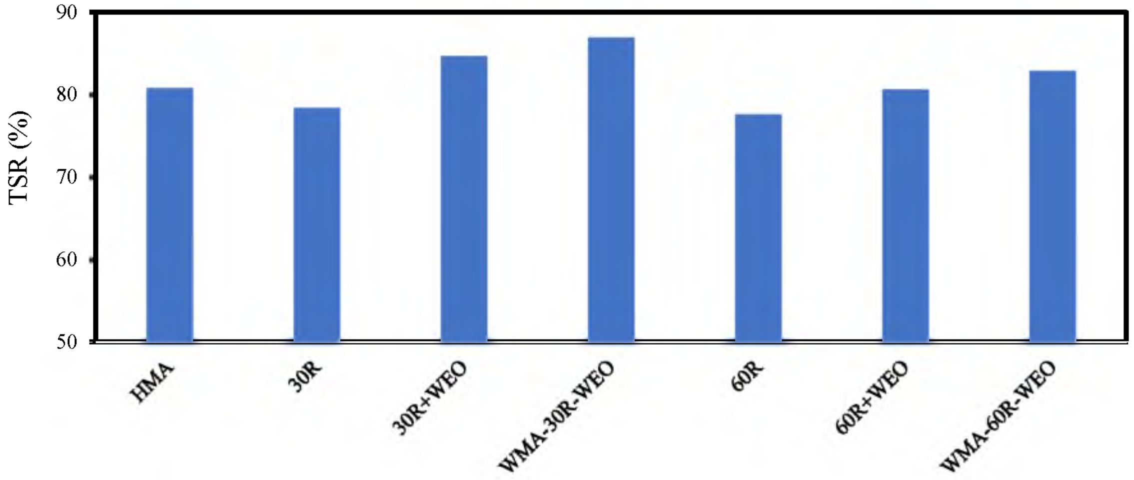

Figure 10. Tensile strength ratio (TSR) of different asphalt mixtures.

The lowest TSR of 80% is often provided to determine the mixes with adequate moisture resistance [57]. It can be perceived from Figure 10 that the TSR values of all mixes are greater than 80%, indicating the mixtures have a good resistance to moisture damage. However, mixtures containing RAP binders had TSR values of less than 80%, which might indicate moisture-sensitive mixtures. According to Abed, et al. [58], antistripping additives are utilized when the mixture fails the TSR test's required standards, exhibiting moisture degradation. The antistripping additives function in the mix, causing the aggregate exterior to interact with bitumen instead of water.

3.2.3. Resilient Modulus (M_R) Test

The resilient modulus (M_R) values for wet and dry conditions of asphalt mixtures are revealed in Figure 11. Based on the presented results, the mixtures incorporating RAP binders had a greater resilient modulus than that of HMA. This is due to the high RAP content, which ultimately increases the stiffness of the mixture, thus resulting in a greater resilient modulus. The stiffness increases owing to the increase in viscosity functional groups, such as ketones and aromatics [59]. Furthermore, the addition of WEO affects the M_R values of mixtures. The WEO, as specified by Fernandes, et al. [60], is primarily used as a softening additive for the asphalt binder, lowering the viscosity and increasing rutting tendency. The combinations of WMA, RAP binders and WEO show interesting behavior, where the RAP stiffens the mix, while WEO acts as a softening agent, consequently resulting in a balanced mix with optimum properties. Lower mixing and production temperature of the WMA method leads to a higher viscosity, thus reducing the strain and ability of the mixture to flow. As a result, the mixtures incorporating RAP, WEO and ZycoTherm agents have a greater resilient modulus than that of HMA. As in the ITS values presented in Figure 9, a similar pattern was recorded in Figure 11, as the moisture effect was significant relative to the M_R values for all types of mixtures. The M_R values were reduced by approximately 6.4% and 11.2% for WMA-60R-WEO and WMA-30R-WEO, respectively, as the samples were exposed to moisture.

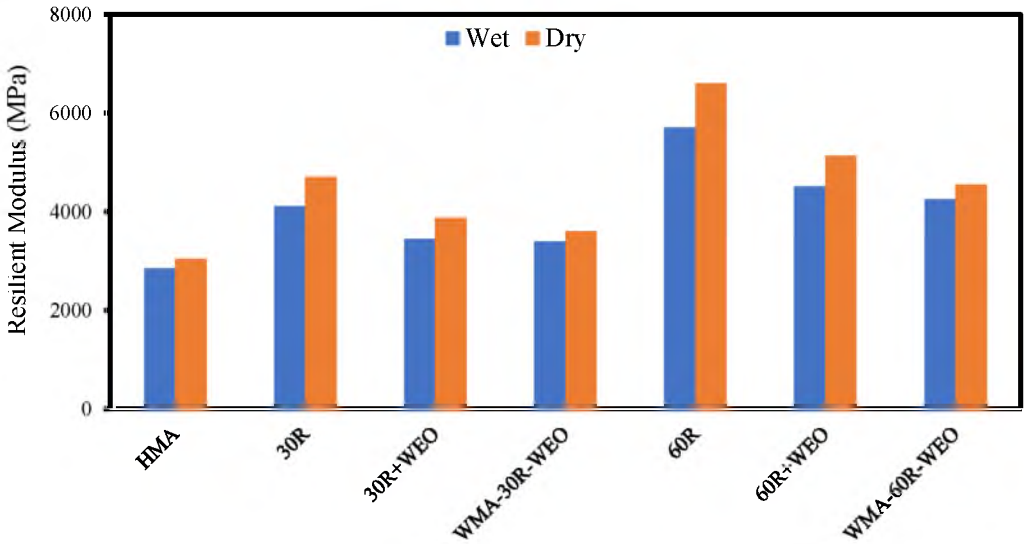

Figure 11. Resilient modulus (M_R) of different asphalt mixtures under dry and wet conditions.

The resilient modulus (M_R) values for wet and dry conditions of asphalt mixtures are revealed in Figure 11. Based on the presented results, the mixtures incorporating RAP binders had a greater resilient modulus than that of HMA. This is due to the high RAP content, which ultimately increases the stiffness of the mixture, thus resulting in a greater resilient modulus. The stiffness increases owing to the increase in viscosity functional groups, such as ketones and aromatics [59]. Furthermore, the addition of WEO affects the M_R values of mixtures. The WEO, as specified by Fernandes, et al. [60], is primarily used as a softening additive for the asphalt binder, lowering the viscosity and increasing rutting tendency. The combinations of WMA, RAP binders and WEO show interesting behavior, where the RAP stiffens the mix, while WEO acts as a softening agent, consequently resulting in a balanced mix with optimum properties. Lower mixing and production temperature of the WMA method leads to a higher viscosity, thus reducing the strain and ability of the mixture to flow. As a result, the mixtures incorporating RAP, WEO and ZycoTherm agents have a greater resilient modulus than that of HMA. As in the ITS values presented in Figure 9, a similar pattern was recorded in Figure 11, as the moisture effect was significant relative to the M_R values for all types of mixtures. The M_R values were reduced by approximately 6.4% and 11.2% for WMA-60R-WEO and WMA-30R-WEO, respectively, as the samples were exposed to moisture.

The resilient modulus ratio (RMR) for the mixtures is presented in Figure 12, and the findings reveal that WMA mixtures had greater RMR values than the reference and other mixes, indicating a better resistance to moisture and cracks. The decreased viscosity of the rejuvenated binders modified with ZycoTherm allows the binder to penetrate the porous structure in the aggregate exterior morphology. Furthermore, lower mixing temperatures in WMA mixtures can lead to less aging and therefore lower possibility of cracking and moisture intrusion to the binder–aggregate interface during the conditioning phase [61]. According to Goli and Latifi [56], lower mixing temperatures in the WMA mixture lead to delayed aging, which in turn slows down moisture intrusion to the binder–aggregate interface during the conditioning phase.

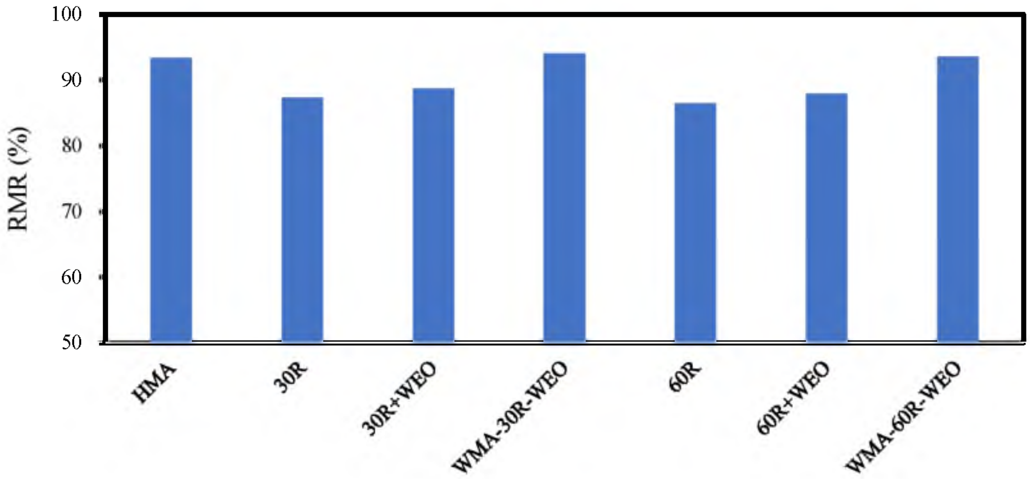

Figure 12. Resilient modulus ratio (RMR) for different asphalt mixtures.

3.2.4. Dynamic Creep Test

Figures 13 and 14 illustrate the dynamic creep test findings for different types of mixtures. Dynamic creep is known as the response relationship between the load and deformation. By examining the plot in Figure 13, the incorporation of the RAP binder into asphalt mixes raises the FN value of all mixes. The 30R and 60R increase the FN value of the reference HMA mixture by 144% and 357%, respectively. The binder adhering to the aggregate during the recycling process is tougher than the newly added binder. This is mostly caused by the pavement being exposed to oxidation while being used and weathered. Overall, lower temperatures result in less oxidative activity, thus reducing the rutting resistance. Meanwhile, the addition of WEO contributed to decreasing the FN of mixtures; this was due to the oil's softening impact on the RAP binder. Nevertheless, the rejuvenated mixture had a relatively higher FN value than the reference HMA. Several studies made a similar observation [1]. Li, et al. [62] also disclosed that aged binders' physical features may be improved by applying a suitable amount of WEO, which would also raise their light constituents (saturates and aromatics). Furthermore, the results show that mixes incorporating RAP and WEO have a relatively higher resistance to moisture degradation in respect of a decline in FN value.

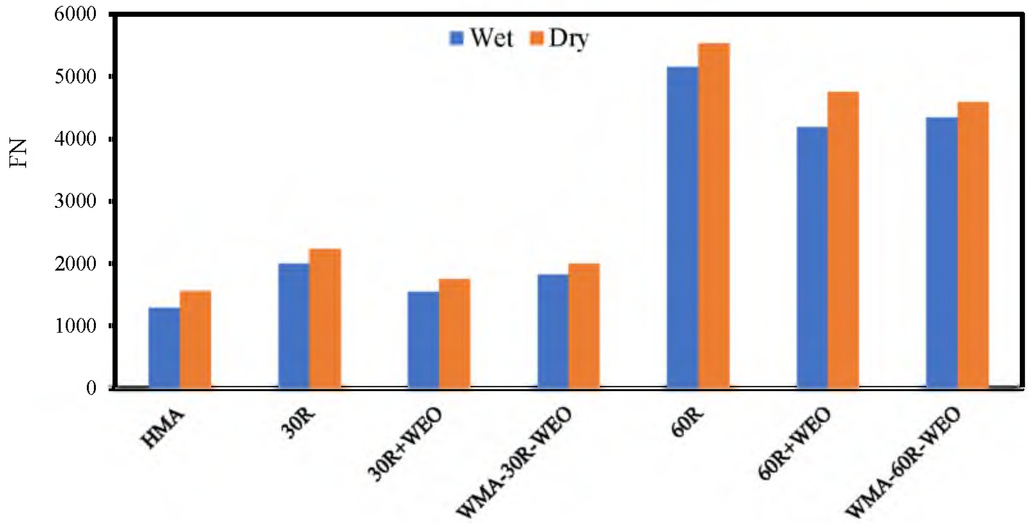

Figure 13. Flow number (FN) for asphalt mixtures.

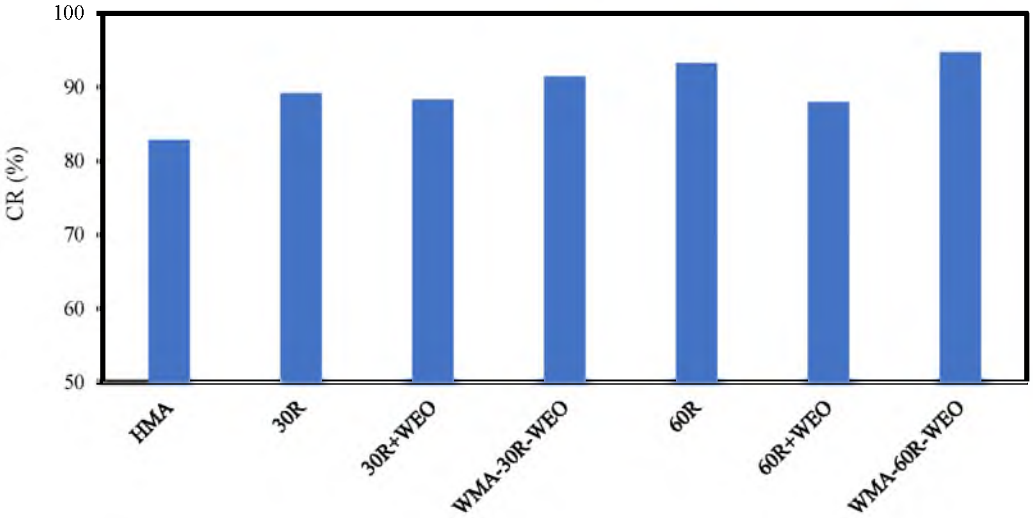

Figure 14. Dynamic creep ratio (CR) results for different mixtures.

The results from Figures 13 and 14 also showed that modifying the rejuvenated mixtures with ZycoTherm increased the FN of mixtures, thus improving the rutting resistance of mixtures in wet and dry conditions. Furthermore, the findings from Figure 14 indicate that the rejuvenated mixtures modified with the antistripping agent acquired the highest rutting resistance toward moisture under repeated load. The WMA-60R-WEO mixture records a greater number of flow cycles compared to HMA, and the mixture contains 30% RAP binder. This is due to ZycoTherm, which increased the adherence of bitumen to the aggregates, and the FN was also affected by the content of stiff RAP used in the mixture [29]. Khani Sanij, et al. [63] demonstrated that the FN of WMA samples increased with the use of ZycoTherm as an antistripping additive; this demonstrates that ZycoTherm lessens the asphalt sample's tendency to rut.

ZycoTherm is an organosilane additive, meaning it contains silanol groups. Silanol groups are functional siloxane chains (Si-O-Si film structure) formed by mineral material surface silanol groups. These groups are resistant to moisture (hydrophobic film) and limit water infiltration and the development of H-bonds at the aggregate–binder bond, hence enhancing the resistance of the aggregate and binder adhesion to moisture degradation. However, this chemical theory appears to be closely aligned with experimental observations from this study. Yet, the additive is disseminated in the binder, and no definite remark on this chemical diffusion and response at the binder–aggregate interface has been made [52].

Although various conditioning procedures and moisture resistance criteria were utilized in this laboratory investigation, the findings show a similar pattern. The differences might be ascribed to diverse conditioning methods and load operations utilized in water sensitivity assessment methodologies, as well as the experimental methodologies' limitations in assessing moisture damage.

3.2.5. Aggregate Coating Test

The percentage of coating for the aggregates of different mixtures is presented in Figure 15. In general, asphalt binder is an adhesive material employed to uniformly coat the aggregate interface. The coating percentage in Figure 15 demonstrated a significant drop once the RAP binder started to be incorporated into the HMA. This is because the RAP binder is an oxidatively aged binder, resulting in higher viscosity compared to the virgin asphalt binder [42].

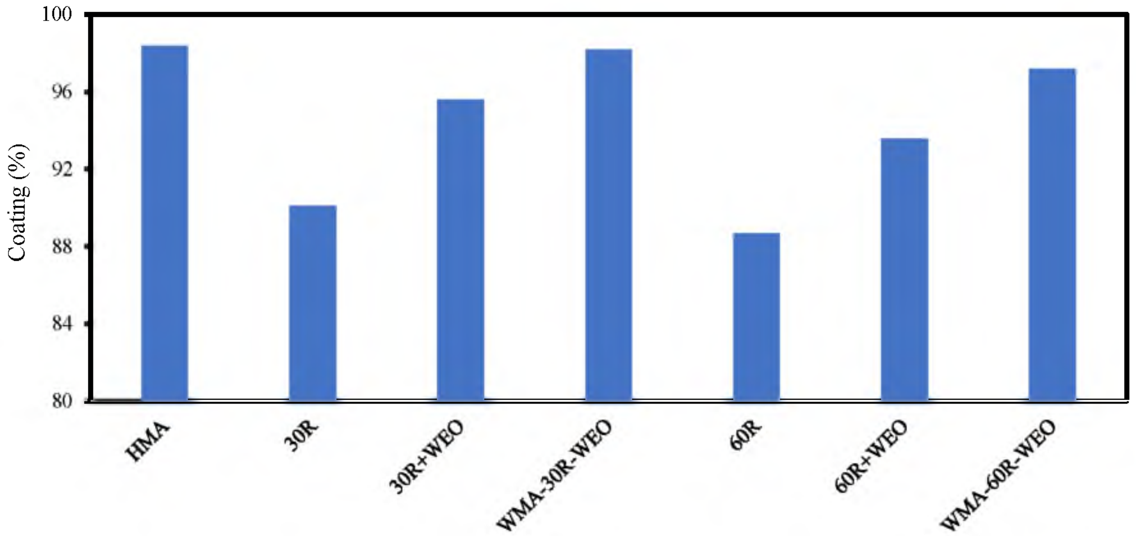

Figure 15. Aggregate coating of different mixtures.

However, the coating percentage increased consistently as the WEO and WMA methods were adopted. The coating percentage increased by 8.2% and 8.7% for WMA-30R-WEO and WMA-60R-WEO, respectively. The nature of WEO, which acts as a softening agent in the mixture, is reducing the viscosity, thus improving the binder distribution. A study conducted by Eltwati, et al. [64] explained that the aromatic compounds in WEO softened the RAP binder, causing an increase in the coating of aggregates.

In general, moisture damage in asphalt mixtures can be attributed to adhesive and/or cohesive failure. This is understandable, since the chemical interaction between the binder and the aggregate is extremely complex. Adhesive failure occurs when the binder and the aggregate are detached from each other. Thus, the coating ability of the binder to coat the aggregate is of the utmost importance for good adhesion [65]. Suitable coating properties ensure that the binder can penetrate the surface structure and lead to better mechanical interlocking at the interface [66]. Han, et al. [67] describe cohesive failure as the loss of cohesion force in the binder due to moisture. The failure is typically attributed to two causes: the degradation of the binder caused by permeation into the binder and the passage of water through the binder–aggregate contact.

According to AASHTO T195 (2011) [39], 95% coating is the lowest degree allowed in the HMA design. Inadequate coating may raise the susceptibility to moisture damage. When water permeates the asphalt films and directly interacts with the surface of the aggregate, it is noted that insufficient coating may accelerate the break of the connection between the binder and the aggregate. The WEO-rejuvenated mixtures modified with ZycoTherm recorded 98.2% and 97.2% coating values, which is only a 0.2% and 1.2% difference from the coating value of the HMA (98.4%). This may be characterized by WEO's efficiency in encircling the aggregates' interface by reducing the aged binder's viscosity and increasing its fluidity, hence increasing the interaction between the aged and virgin asphalts [64]. Furthermore, it is also known that ZycoTherm, a type of chemical additive, helps reduce the frictional force of the microscopic interface between the binder and the aggregate, typically between 85 and 140 °C [25]. ZycoTherm improves the ability of WEO-rejuvenated mixtures to coat by overcoming or reducing friction forces. The frictional forces between the binder and the aggregate are mainly van der Waals forces, which include hydrogen bonding, dispersion forces and dipole–dipole interactions. Caputo, et al. [25] highlighted that the reduction in frictional force improves the mixing and compaction stage; thus, higher adhesion is obtained. Based on the results, the combination of ZycoTherm with WEO-rejuvenated binder proved to have a positive impact on binder coating abilities.

3.2.6. Wheel Tracking Test

Post-Compaction (PC)

PC consolidation is the deformation described in millimeters at 500 cycles or 1000 wheel passes in the sample. Post-compaction takes place rapidly due to the mixture densification during the first few minutes of the test [68]. The rut depth of different mixtures in wet and dry conditions due to the PC effect is shown in Figure 16. The results reveal that the inclusion of the RAP binder into HMA reduced the PC resistance in dry and wet conditions, as predicted, owing to asphalt stiffening. This indicates that the samples incorporating RAP have a greater resistance to rutting in the PC area. The results also exhibited that raising the dosage of the RAP binder in HMA samples in both wet and dry conditions reduced the PC values; this is because the virgin binder was replaced with a stiffer binder. Meanwhile, the rejuvenation of the RAP binder with WEO led to an increase in the PC rut depth for both conditions; however, the PC rut depth for rejuvenated mixtures containing ZycoTherm was much lower. This shows that rejuvenated mixtures modified with ZycoTherm were more consistent and readily well compacted even before the wheel tracking loadings started to be applied. The PC rut depth of WMA-60R-WEO is relatively lower (for both conditions) compared to WMA-30R-WEO due to a higher percentage of RAP, which is believed to yield a stiffer binder within the mix. A similar observation was obtained by Fakhri and Hosseini [69]. In addition, the lower production and mixing temperature of the WMA method also influenced the stiffness of the mix. According to the results, the moisture effect on all mixtures was relatively significant. A drastic increase was observed in PC rut depth as a result of the presence of moisture, which affects the binder–aggregate adhesion and/or binder cohesion.

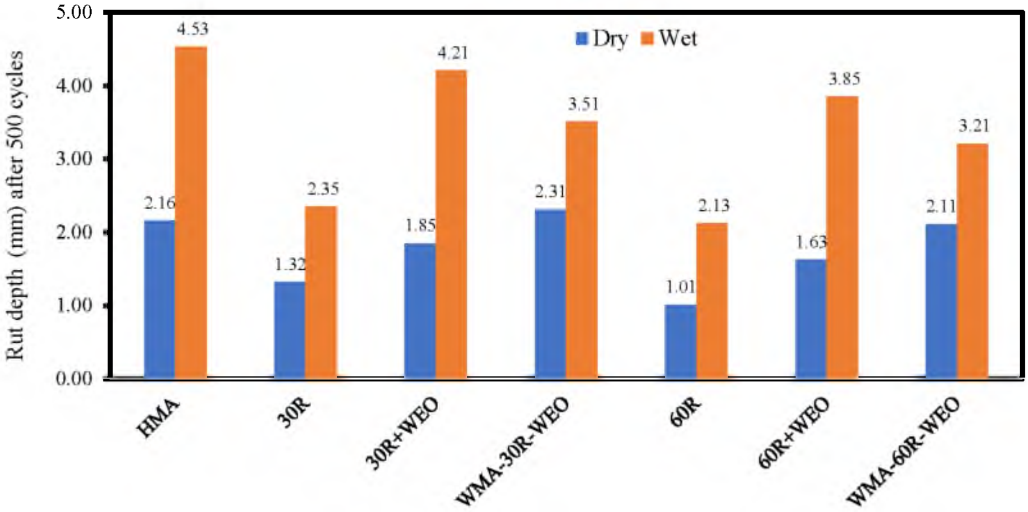

Figure 16. Post-compaction of different mixtures for wet and dry conditions.

Rutting Depth Versus Load Cycle

Figures 17 and 18 illustrate the rutting depth of samples per loading cycle under dry and wet conditions. These results were projected to assess the influence of water on rutting resistance. It is noted that the presence of moisture influences the rut depths. In comparison to both conditions, the loading cycles of a wet rut for all mixtures are superior to those of a dry rut. This is due to the moisture affecting the aggregate coating and accelerating the loss of contact between bitumen and the aggregates [70].

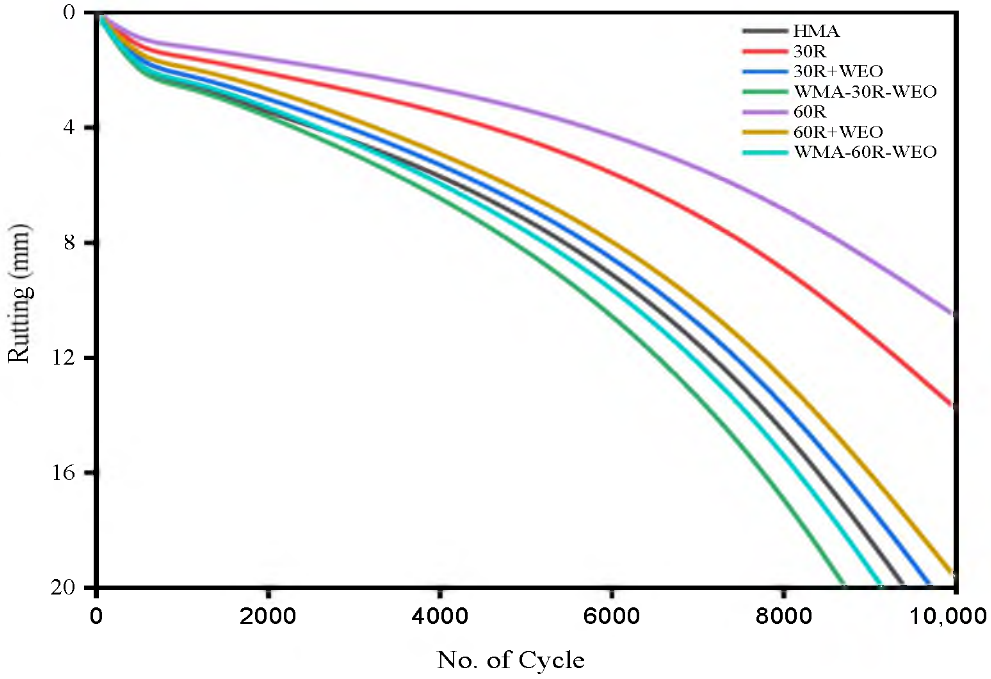

Figure 17. Rutting depth versus load cycle in a dry condition.

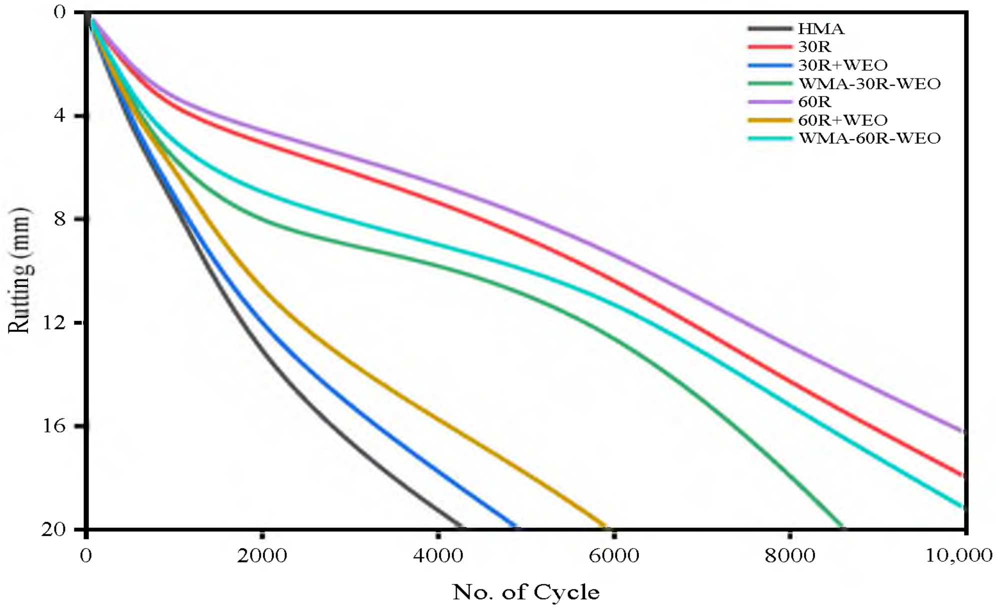

Figure 18. Rutting depth versus load cycle in a wet condition.

By examining the plot in Figure 17, the mixtures containing RAP reduced the rutting depth at the same loading cycles. The 60R exhibits the highest rutting resistance, followed by 30R. Increasing the RAP content in the mixture contributed to raising the final loading cycles compared to HMA, as shown in Figure 19. This corresponds to the presence of RAP, which stiffens the composite binder, thus creating a more rigid structure. Meanwhile, the addition of WEO into RAP mixtures slightly accelerated the rutting, regardless of the amount of RAP, yet performed better than HMA. Higher rutting for mixtures containing WEO is due to the softening effect of the WEO aromatic molecules [71]. Fernandes, et al. [72] and Ren, et al. [73] shared a similar observation, whereby adding WEO to an asphalt mixture weakens the resistance of asphalt toward rutting.

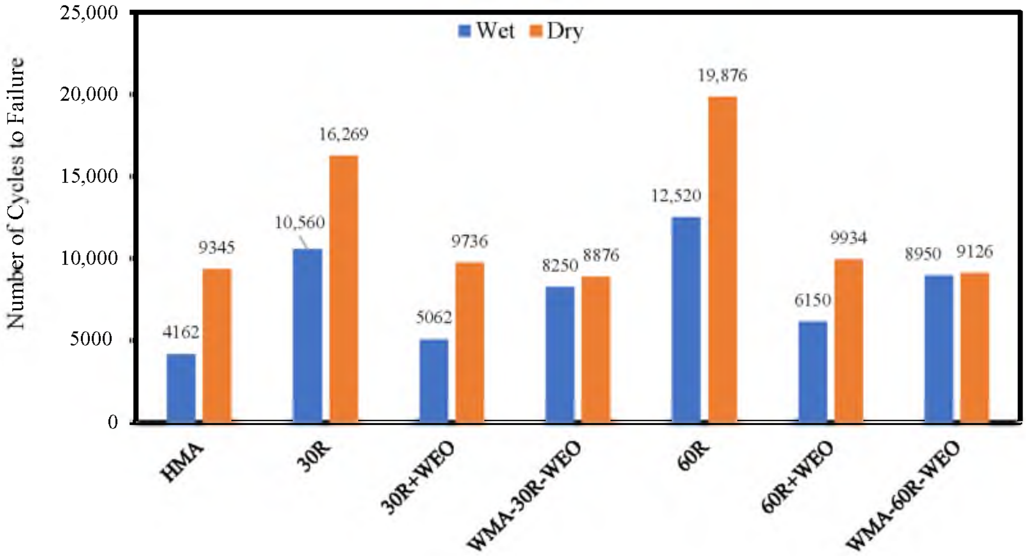

Figure 19. No. of cycles to achieve the maximum rut depth of 20 mm.

The results illustrated in Figure 18 display the different rutting behaviors, especially for WEO-rejuvenated mixtures modified with ZycoTherm. The performance of rejuvenated mixtures was improved once the WMA antistripping agent (ZycoTherm) was adopted. The results reveal that an antistripping agent has a positive impact on rutting resistance in the presence of moisture. This may be attributed to the fact that rejuvenated samples modified with ZycoTherm exhibited a high coating percentage, as shown in Figure 15, which impedes water infiltration to disrupt the binder–aggregate interface. This also denotes that, although the HMA mixture has a significantly high PC value, it nevertheless loses its cohesive and adhesive connections more quickly when subjected to recurrent loading in the presence of moisture.

Moreover, the results shown in Figure 19 indicate that rejuvenated samples modified with ZycoTherm accelerated the maximum rutting of 20 mm compared to other mixtures, including the reference HMA. WMA-30R-WEO exhibited the lowest rutting resistance, whereby it reached the maximum rutting value at 8250 and 8876 cycles for wet and dry conditions, respectively. On the other hand, WMA-60R-WEO attained maximum rutting at 8950 and 9126 cycles for wet and dry conditions, respectively. Increases in cycles of approximately 7.8% and 2.7% over WMA-30R-WEO can be observed. Further observation in Figure 19 indicates that the cycle differences between dry and wet conditions for rejuvenated samples modified with ZycoTherm are incredibly low. Based on the result, reductions as low as 2% and 7% in load cycle numbers to failure for WMA-60R-WEO and WMA-30R-WEO, respectively, were observed when the condition changed from dry to wet. This shows that rejuvenated samples modified with ZycoTherm have the optimum performance because it is comparable to HMA with 9345 load cycles to failure as a benchmark.

Stripping Inflection Point (SIP)

SIP is the number of wheel passes completed, where the creep slope and the stripping slope intersect on the graph [74]. SIP indicates when the mixture begins to suffer moisture degradation [75]. Figure 20 illustrates the example of rut depth against loading cycles to identify the SIP for the WMA-30R-WEO sample. In general, three regions were observed in the plot, which are the creep slope, SIP and the stripping slope. According to Zhang, et al. [76], the first or the creep region denotes permanent deformation corresponding to a mechanism, such as plastic flow, whereas the tertiary or stripping region indicates rapid failure, which is mainly attributed to moisture damage. Walubita, et al. [77] also highlighted that the tendency to lose the fine aggregate (adhesion failure) would start from the SIP onwards. Moreover, higher creep slopes, stripping points and stripping slopes indicate less damage. A study carried out to evaluate the performance of the Hamburg Wheel Track Device (HWTD) on mixtures with known field performance found that the SIP for pavements with excellent field performance was typically larger than 5000 cycles (10,000 passes), whereas pavements with reduced field function had a SIP lower than 1500 cycles (3000 passes) [78]. The smaller quantity of SIP indicates a weaker contact between the asphalt and the aggregate when there is water present [69].

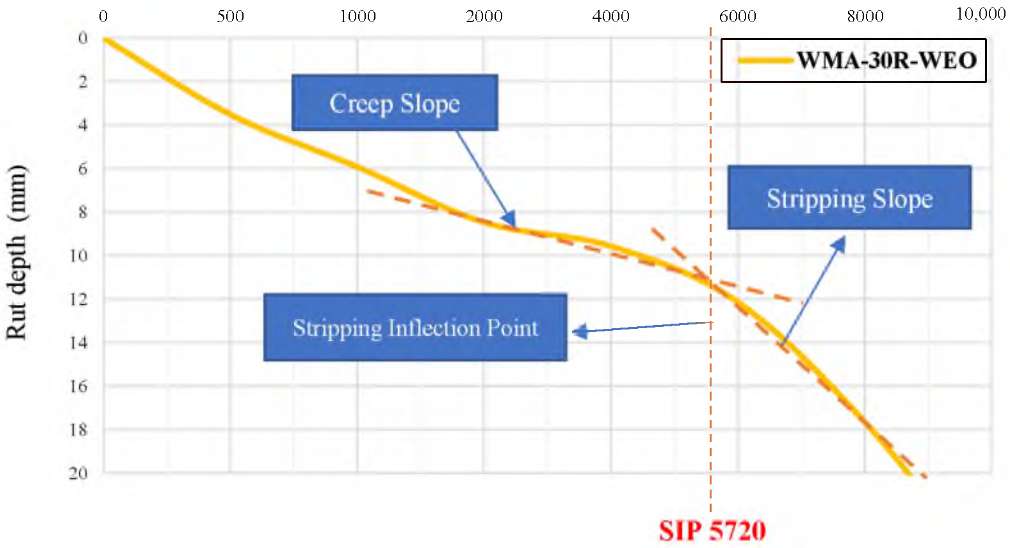

Figure 20. Stripping inflection point (SIP) for WMA-30R-WEO.

The SIP values for each mixture are shown in Figure 21. Overall, the SIP values of RAP mixtures and rejuvenated mixtures with and without ZycoTherm are greater than that of HMA. Steady improvement can be observed as the RAP binder was added; however, the incorporation of WEO slightly lowered the SIP values. The implementation of the WMA antistripping agent subsequently improved the SIP values of mixtures. The SIP values are incredibly higher, with an 80 to 82% increase compared to HMA. The SIP recorded for WMA-30R-WEO and WMA-60R-WEO was 5720 and 6150, respectively, whereas the SIP for the others ranged from 1245 to 2505 only. The results reveal that rejuvenated mixtures modified with ZycoTherm had SIP values greater than 5000 cycles, indicating that ZycoTherm-modified mixtures have a good resistance to stripping in the field. This means that the antistripping agent improves the stripping resistance of the WEO-rejuvenated mixture. According to Padhan, et al. [79], antistripping additives considerably enhance the stripping resistance of the mixes in the water stripping, stability and wheel tracking tests, implying that this binder strengthened the contact area at the aggregate–binder contact.

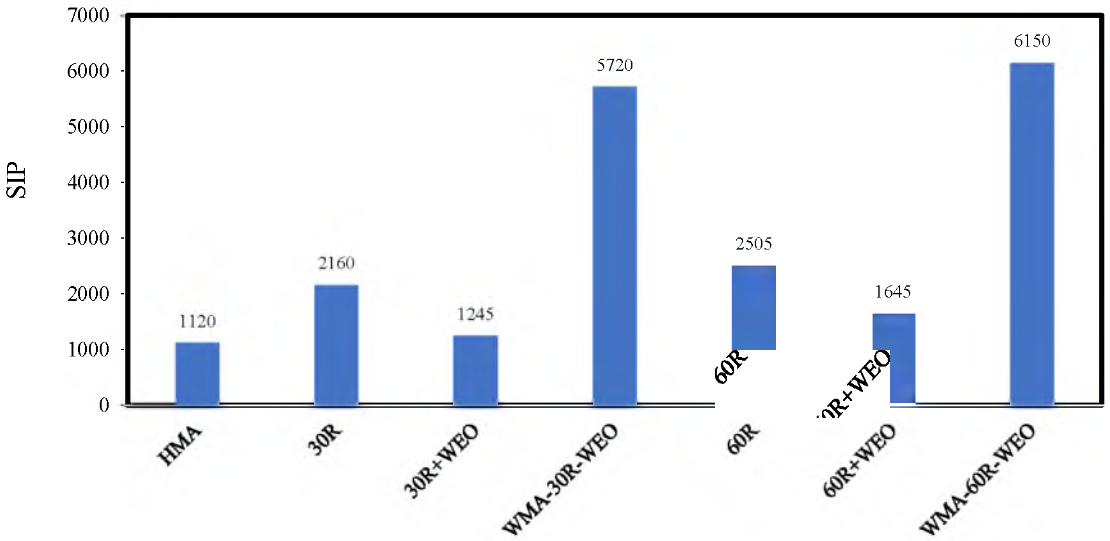

Figure 21. Stripping inflection point (SIP) for different mixtures.

4. Conclusions

This study was carried out to investigate the effect of ZycoTherm as a WMA anti-stripping agent on the performance of WEO-rejuvenated asphalt mixtures. Seven asphalt binders, including virgin asphalt, were tested. It is known that blending 12% of WEO and 0.1% ZycoTherm with the RAP binder (30% and 60%) restores the penetration and softening point to the value of the virgin binder due to the boosted aromatic percentage of aged asphalt. The following conclusions are drawn:

- FTIR showed that the water-sensitive functional group (carboxylic acids and Si-OH compounds) vanished when the WEO-rejuvenated binders were modified with ZycoTherm, indicating that ZycoTherm works adequately as an antistripping agent. TG analysis also revealed that the additions of ZycoTherm and WEO did not affect the thermal stability of the blended binders.
- The addition of ZycoTherm to rejuvenated mixtures was found to increase the stability and decrease the flow of mixtures, which indicates a better adhesion and thus enhances the binder–aggregate mechanical interlocking.
- Mixtures containing ZycoTherm have relatively higher ITS, TSR, M_R and RMR values. The decrease in viscosity of the rejuvenated binders modified with ZycoTherm allows the binder to penetrate the pore on the aggregate external morphology. Furthermore, lower mixing temperatures in the WMA mixtures lead to less aging and therefore lower possibility of cracking and moisture intrusion to the binder–aggregate bond during the conditioning phase.
- The results revealed that ZycoTherm has a positive impact on the rutting resistance in the presence of moisture. This may be attributed to the fact that the modified samples exhibited a high coating percentage, which impedes water infiltration to disrupt the binder–aggregate interface.

In conclusion, the study reveals that ZycoTherm improves the physical and mechanical characteristics of both binders and mixtures. However, the suggested procedure has a few limitations, which will be addressed in future research. Compared to the benefits of WMA mixtures incorporating RAP and the great impact of moisture on their performance, it could be beneficial to examine the field efficiency of these mixtures against moisture damage and relate it to laboratory findings. The study showed that ZycoTherm improved rutting and moisture resistances; however, it would be useful to conduct additional research to assess its low-temperature cracking resistance. Moreover, this study evaluated only one type and source of asphalt binder; therefore, further research is needed to determine the influence of RAP source and binder type on moisture susceptibility. In addition, future investigation is also necessary to assess the impact of short-term aging and long-term aging on the performances of the WMA antistripping additive examined in this study.

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