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Influence of Compaction Energy on the Mechanical Performance of Hot Mix Asphalt with a Reclaimed Asphalt Pavement (RAP) and Rejuvenating Additive

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Abstract: The Mexican asphalt paving industry is increasingly interested in using reclaimed asphalt pavement (RAP) to produce hot mix asphalt (HMA) due to its economic and environmental advantages. However, an ill-defined methodology for integrating RAP into the HMA mix design has hindered its use. This paper investigates how compaction energy affects both rejuvenated and non-rejuvenated recycled HMA mixtures. A Superpave gyratory compactor was used to determine the optimal binder content and find a balance between flexibility and stiffness that meets cracking and rutting resistance requirements. Various recycled HMA mixtures were subjected to different compaction energy levels (75, 100, and 125 gyros), different RAP contents (15%, 30%, and 45%), and various dosages (10%, 15%, and 36%) of the rejuvenating additive Maro-1000®, following the blending chart. Performance was evaluated using the Hamburg wheel tracking test (HWTT) and the fracture energy flexibility index test (I-FIT). The results demonstrate that mixtures with RAP, a rejuvenating admixture, and varying compaction energies exhibit favorable mechanical behavior. However, both rejuvenated and non-rejuvenated mixes with 15% RAP showed performance comparable to conventional mixtures. They improved stiffness by up to 46% while reducing the flexibility index to 25%, striking a balanced equilibrium between rutting resistance and cracking susceptibility.

Keywords: reclaimed asphalt pavement; hot mix asphalt; compaction energy; rejuvenating additive; rutting; cracking

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1. Introduction

In Mexico, the practice of subjecting asphalt pavements to rising traffic volumes and heavy axle loads, combined with exposure to adverse weather conditions, results in issues such as cracking, potholes, and rutting on the pavement surface. These are progressive problems that contribute to the weakening of the pavement, leading to both structural and functional failures. In this context, once deterioration has occurred, either due to poor prediction of the acting loads or because the pavement has reached the end of its useful life, the common practice is to remove and replace the damaged asphalt layer to restore the pavement to an appropriate service level. However, the rehabilitation and reconstruction strategies mentioned above carry a twofold negative impact on the current environmental and political situation. On one hand, there is pollution of the environment and its components due to the exploitation of quarries and oil refining to obtain mineral aggregate and asphalt binder, respectively. On the other hand, the purchase of new materials results in increased production costs for the asphalt mix, which is undesirable considering the limited budgets allocated to road infrastructure. Consequently, the application of sustainability criteria encourages the use of reclaimed asphalt pavement (RAP) as an alternative for improving conditions and/or expanding the highway network.

According to Chen et al. [1], and McDaniel and Anderson [2], reclaimed asphalt pavement (RAP) stands as one of the most recycled materials globally. It is defined as aged asphalt pavement that has been milled or ripped from the road and can be used in the production of new asphalt mixes, since the recovered asphalt and aggregate still possess value. Typically, the term RAP is also applied to materials retrieved from new mixtures that have not been used, either due to a surplus or non-compliance with project specifications [3]. The Asphalt Recovery and Recycling Association recognizes four primary asphalt pavement recycling techniques for manipulating RAP [4]: (1) hot in-plant recycling, (2) cold in-plant recycling, (3) hot in-place recycling, and (4) full-depth cold recycling. However, this research specifically focuses on dense-graded recycled asphalt mixes developed and evaluated in the laboratory, with the intention of being produced in a hot plant. This choice stems from the fact that it is in this scenario where the greatest benefits of using RAP can be realized.

Several studies have shown that the production of HMA with RAP brings significant energy, financial, and environmental benefits. For example, it results in decreased production costs for new HMA, preserves natural resources by reducing the need for asphalt binder and mineral aggregate, reduces CO_2 and greenhouse gas emissions, and decreases the amount of construction debris placed in landfills [5–10]. Finally, reclaimed asphalt pavement reduces energy and fossil fuel consumption, making the pavement industry more sustainable [11]. This reduction is achieved by avoiding the energy-intensive processes of asphalt production and long-distance transportation, thus promoting a more sustainable approach. However, laboratory studies indicate that due to the hard, brittle, and less elastic aged binder present in RAP, recycled mixes tend to exhibit poor flexibility, making them less susceptible to rutting [12–15] but, at the same time, more prone to fatigue [16–20] and thermal cracking [21–24]. As a result, asphalt concrete may be rejected due to durability issues or for failing to achieve the long-term performance standards exhibited by conventional HMA. The high shear modulus of aged binder is beneficial in withstanding tangential critical stresses generated by traffic loads, and this increase in stiffness helps reduce vertical pressures acting on the underlying layers.

Thus, the utilization of RAP in HMA appears to be primarily concerned with addressing the cracking phenomenon. The undesirable response of recycled asphalt concrete to tensile stress can be improved by considering some of the following strategies that have been demonstrated to increase the elasticity and flexibility of HMA in its design:

- Using rejuvenating additives [25,26];
- Utilizing soft asphalt binders [27,28];
- Employing a mix design that strikes a balance between rutting and cracking [29,30];
- Incorporating polymers or additives that enhance low-temperature performance grade [31,32];
- Implementing plant production methods that prevent RAP from overheating or being exposed to direct flames [33,34].

Despite numerous studies focused on improving the long-term performance of HMA with RAP, to this day, the impact of varying the effective binder volume through compaction energy on the engineering properties of recycled HMA, both with and without a rejuvenating additive, has not been directly analyzed. In this context, the volume of effective asphalt binder (V_{be}) has been identified as the primary mix design factor affecting both durability and cracking resistance. For a specific percentage of air voids, it can be increased by reducing the applied densification effort. This results in increased voids in the mineral aggregate (VMA) and, therefore, provides sufficient space to accommodate a thicker asphalt film between the mineral aggregates, promoting cohesive properties and flexible behavior [35–37].

On the other hand, recycling agents have also proven to be effective in promoting the durability of RAP mixtures. These agents are additives formulated with high concentrations of aromatic compounds (maltenes phase) that restore the degraded physical, chemical, and rheological properties of aged binder, favoring their use in a new service cycle [38,39].

For this reason, studying the influence of densification energy is crucial for establishing, during the volumetric mix design, the appropriate number of gyrations in the Superpave gyratory compactor (SGC) that provides sufficient asphalt content to allow for recycled mixes, both with and without a rejuvenating additive, to meet the requirements for withstanding cracking, without sacrificing their resistance to plastic deformation. This achievement strikes a balance between flexibility and stiffness.

In this regard, when addressing the utilization of the RAP content in the construction or rehabilitation of asphalt pavements, it is essential for the mix design to simultaneously resist both cracking and rutting. Research conducted by Ozer et al. [40], Mogawer et al. [41], and [42] indicates that this desired behavior can be identified through the evaluation of recycled HMA in the performance interaction space diagram developed by the University of Illinois [43]. This diagram is based on the results of simple performance tests, such as the Hamburg wheel tracking test (HWTT) and the fracture energy flexibility index test (I-FIT).

Several authors [8,13,44–48] emphasize the importance of designing HMA asphalt mixtures with adequate mechanical performance to withstand repetitive traffic loads. Additionally, due to the environmental and economic impact associated with HMA production, efforts have been made to recycle waste from old pavements by creating sustainable recycled HMA mixes using RAP. However, the inclusion of RAP in a mix stiffens the new recycled HMA and increases its susceptibility to cracking. To address this issue, rejuvenating additives have been employed to soften the RAP asphalt, reducing cracking. However, determining the correct dosage is crucial to mitigate cracking while minimizing asphalt softening to prevent rutting.

Due to the limited methodologies available for addressing this critical aspect in the design of sustainable asphalt mixtures, this research aims to establish an optimal balance between resistance to rutting and reduction in the cracking potential of recycled HMA mixtures. This balance is sought through the utilization of different RAP contents, various compaction energies, and varying percentages of a rejuvenating additive. In this regard, the balanced design approach proposed by the University of Illinois offers a framework for identifying a well-balanced recycled mix. This mix should exhibit behavior and performance comparable to that of a conventional mix, while also being more sustainable and resilient, leading to cost reduction and reduced environmental impact.

The objective of this paper is to evaluate the influence of compaction energy on recycled hot mix asphalt (HMA) mixtures, both with and without the addition of a rejuvenating additive. This assessment will be conducted using a Superpave gyratory compactor with the aim of determining the optimal binder content. The primary goal is to strike a balance between stiffness and flexibility, ensuring that these blends meet the minimum requirements for resistance to cracking and rutting, as specified for conventional HMA mixes.

To accomplish this, we designed a control mix of HMA and compared it with recycled HMA mixtures containing varying percentages of reclaimed asphalt pavement (RAP), specifically, 15%, 30%, and 45%. These mixtures were also subjected to different compaction energies (75, 100, and 125 gyrations) and various dosages (10%, 15%, and 36%) of the Maro-1000® rejuvenating additive, as determined from the blending chart.

The performance evaluation was carried out employing the Hamburg wheel tracking test (HWTT) and the fracture energy flexibility index test (I-FIT). Furthermore, we verified the mechanical performance of HMA, considering different RAP percentages and the presence of a rejuvenating additive, using the interaction space diagram proposed by the University of Illinois (I-BMD).

2. Materials and Methods

2.1. Experimental Plan

To achieve the objective of this article, the experimental design was conducted in three phases, outlined in Figure 1. In the initial phase, nine recycled asphalt mixes (HMA with RAP) were formulated, alongside a control mix (HMA without RAP), all featuring identical gradation and virgin aggregate. The air void content was maintained at 4% ± 0.1%. These mixes utilized a virgin PG 64-22 binder, which was modified with an SBS polymer to achieve a PG 76-22 grade.

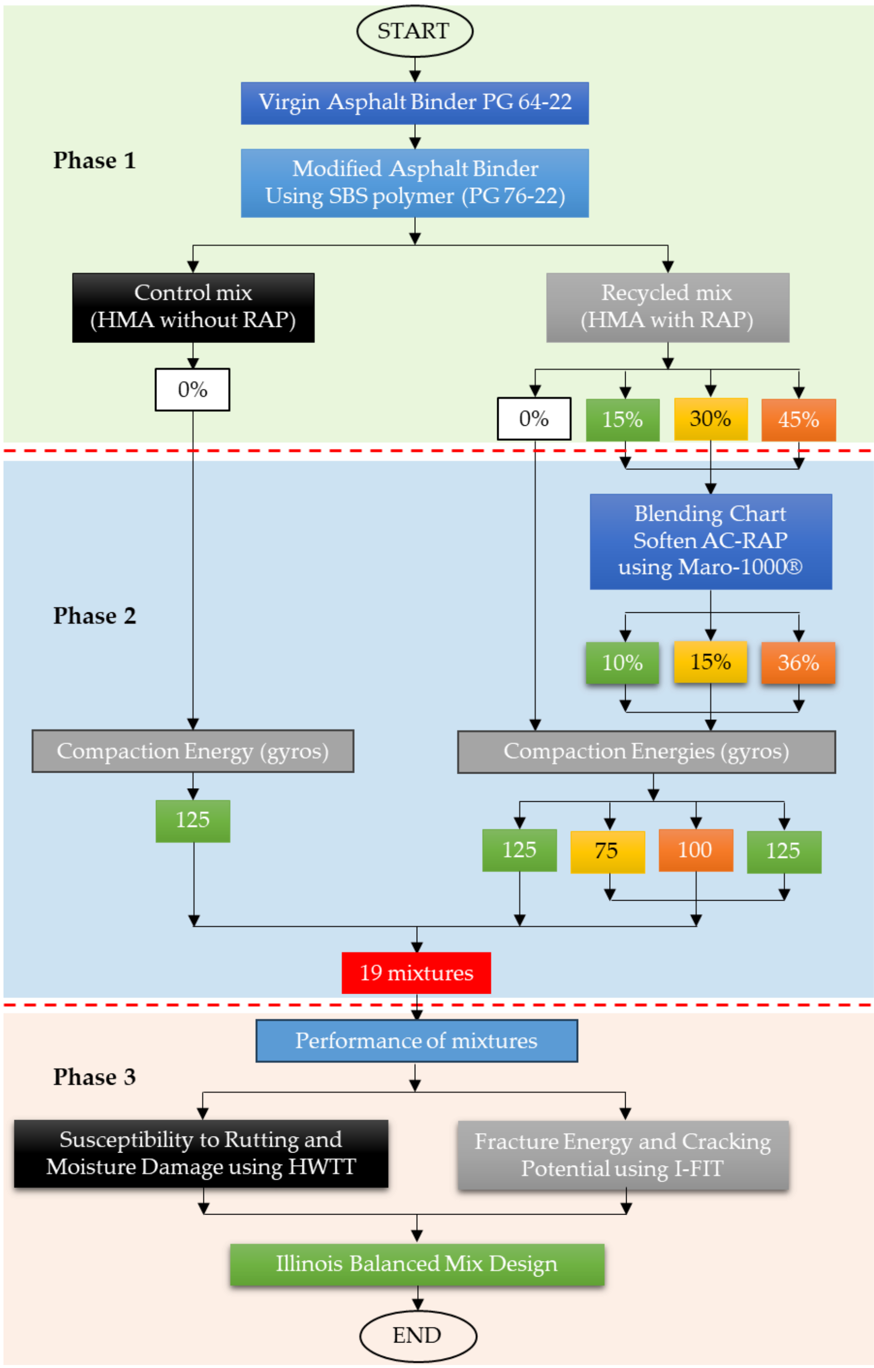

Figure 1. Flow chart of the experimental design.

The recycled HMA mixtures incorporated three different percentages of RAP (15%, 30%, and 45%), all sourced from the same origin. Simultaneously, the control mixture

(0% RAP) was designed with a nominal size of 12.5 mm, following the application of 125 gyrations in accordance with AASHTO 323 [49] and AASHTO R35 [50] standards. These specifications were specifically chosen to simulate a traffic intensity of 30 million equivalent load axles.

The second phase focused on compensating for the high stiffness of the age-hardened binder present in RAP. This was achieved using soft binders, obtained by incorporating a rejuvenating additive (Maro-1000®) into the modified asphalt binder (PG 76-22). To determine the amount of additive needed, it was first necessary to extract and recover the oxidized asphalt present in the RAP using centrifugal force in a Rotarex device with trichloroethylene as a solvent [51]. Once the binder was separated from the solvent through the Abson distillation method [52], the corresponding upper PG classification was determined. Then, the high critical temperatures of both the aged binder and the project binder, as stipulated in McDaniel and Anderson [2], were used to calculate the required performance grade for each of the rejuvenated binders based on the percentage of RAP added to the HMA. Subsequently, specimens were prepared for each hot mix asphalt (HMA) mixture containing recycled asphalt pavement (RAP) using three different compaction energies (75, 100, and 125 gyrations). The control HMA mixture without RAP was compacted with 125 gyrations in the Superpave gyratory compactor (SGC).

In the third phase, the performance of the recycled and reference asphalt mixtures was evaluated by measuring rutting susceptibility using the Hamburg wheel tracking test (HWTT) and assessing their cracking potential through the evaluation of the fracture energy flexibility index test (I-FIT). Finally, using the information obtained from these tests, the mechanical behavior of nineteen HMA mixes was qualitatively categorized. For this purpose, the performance interaction space diagram, as embodied in the recent balanced mix design methodology proposed by the University of Illinois, was employed.

2.2. Materials

Every material employed in this study was sourced from within the state of Jalisco, with the exception of the neat binder, which was procured from a refinery in the state of Guanajuato.

2.2.1. Mineral Aggregates

The mineral aggregates employed in this research encompassed three distinct fractions acquired through the process of crushing basaltic stone. These aggregates corresponded to 19.00 gravel, 9.50 mm chip seal, and crushed sand. The physical, chemical, and resistance characteristics of these materials are presented in Table 1.

Table 1. Mineral aggregate properties.

Property	Standard Test Method	Aggregate		
		19.0 mm	**9.50 mm**	**Crushed Sand**
Los Angeles abrasion %	ASTM C131	10.9	13.4	-
Micro-deval degradation, %	ASTM D6928	9.5	6.9	-
Sodium sulfate soundness, %	ASTM C88	7.2	2.3	-
Fracture particles (two faces), %	ASTM D5821	95.8	96.3	-
Flat and elongated particles (5:1), %	ASTM D4791	6.2	5.5	-
Sand equivalent, %	ASTM D2419	-	-	73.0
Fine angularity, %	AASHTO T304	-	-	41.8
Methylene blue adsorption value, mL/g	AMAAC recommendation RA/05	-	-	14.0

2.2.2. Reclaimed Asphalt Pavement (RAP)

The RAP utilized in this study originated from various reconstruction and rehabilitation projects conducted along the MEX-80D Zapotlanejo-Lagos de Moreno highway. The key properties are outlined in Table 2.

Table 2. Characteristics of reclaimed asphalt pavement.

Property				**Standard Test Method**				**Result**		
Binder content, %				ASTM D2172				5.30		
Theoretical Maximum Specific Gravity, Gmm				ASTM D2041				2.451		
Size distribution—AASHTO T27										
Sieve	3/4″	1/2″	3/8″	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
% Passing	100.0	98.0	94.6	65.1	45.8	29.1	19.6	13.6	9.7	4.4
Dynamic Shear Rheometer (RTFO binder)—AASHTO T315										
Test temperature [°C]	δ [°]		G* [kPa]		G*/Senδ		Critical failure temperature [°C]			
112	67.3		3.38		3.67		117.2			

It is important to note that all rheological analyses were conducted after subjecting the recovered binder to a short-term aging process in the rolling thin film oven test (RTFOT). This step was taken to simulate the aging of the asphalt binder present in the RAP during the HMA manufacturing process and, additionally, eliminate any solvent residue that could potentially impact the results of the rheological tests. The DSR results for high-temperature failure were employed in the development of blending charts to select the rejuvenated PG binders, as illustrated in Figure 2.

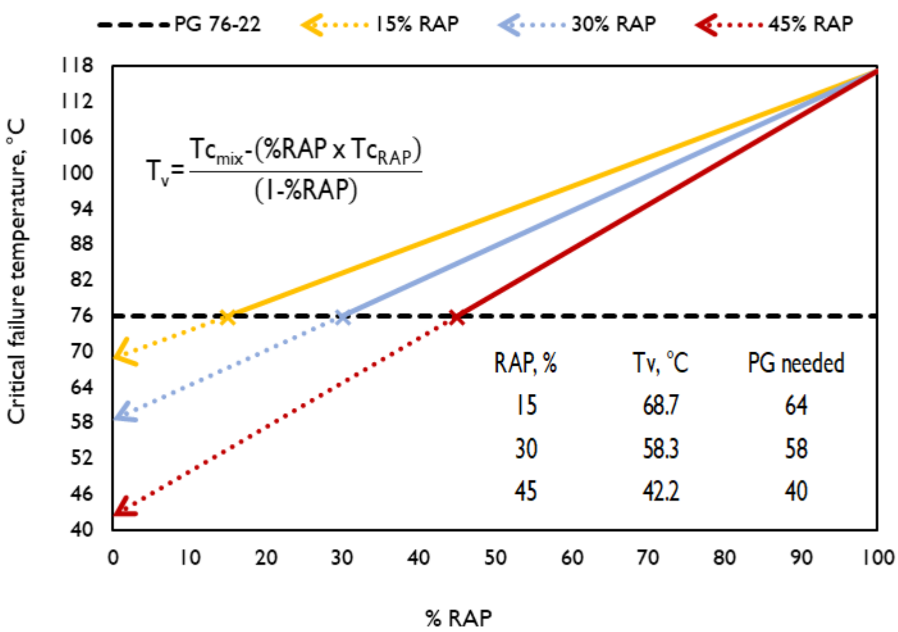

Figure 2. High-temperature blending charts.

The use of a high critical failure temperature in the blending charts was aimed at maximizing the impact of the rejuvenating additive on the mechanical performance of recycled HMA. This is a crucial aspect that aligns with one of the objectives of this research.

2.2.3. Asphalt Binders

The primary asphalt binder utilized in this research is classified as an EKBE® with a performance grade of 64-22. However, this base asphalt underwent modification with a styrene–butadiene–styrene co-polymer to produce the project binder PG 76-22, which possessed improved adhesive characteristics. The visco-elastic properties of this modified binder are summarized in Table 3.

Table 3. Rheological properties of the project binder.

Dynamic Shear Rheometer (DSR) [53]			
Property	Control parameter	Temperature, °C	Result
High temperature (Original)	$G^*/Sen\delta \geq 1.0$ kPa	76	1.07
High temperature (RTFO)	$G^*/Sen\delta \geq 2.2$ kPa	76	5.07
Intermediate temperature (PAV)	$G^* \times Sen\delta \leq 5000$ kPa	31	1365.93
Multi-stress creep recovery (MSCR-AASHTO TP70)	$Jnr_{3.2\ kPa}$	76	1.36
	$\%RE_{3.2\ kPa}$		19.31
Bending Beam Rheometer (BBR) [54]			
Property	Control parameter	Temperature, °C	Result
Creep stiffness	$St \leq 300$ MPa	−12	100.93
Creep slope	m-value ≥ 0.300		0.303

The PG 76-22 binder remained constant in all HMA mixtures without additives. In the case of HMA with recycled additives, small samples of the PG 76-22 binder with varying doses of rejuvenator were initially prepared. This allowed for the creation of a representation showing the amount of additive incorporated in relation to the high critical failure temperature, using a dynamic shear rheometer (DSR). Through this approach, the reduction in the stiffness of the project binder was tracked in terms of the complex shear modulus (G*) and phase angle (δ). Figure 3 shows the percentage of additive incorporated against the critical failure temperature as obtained under the original condition ($G^*/Sin\delta \geq$ 1.0 kPa).

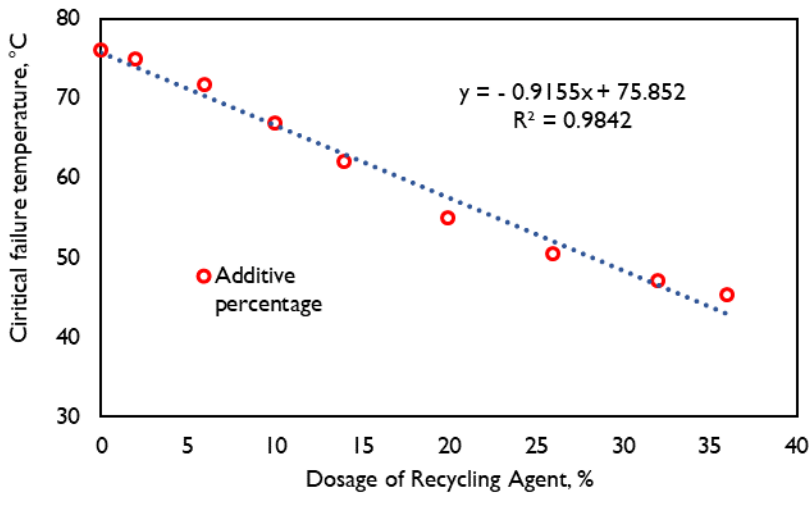

Figure 3. Determination of the additive content.

Based on these results, it was determined that to meet the blending charts for compositions containing 15%, 30%, and 45% RAP in the HMA, it was necessary to incorporate 10%, 15%, and 36% of the rejuvenating additive into the project binder, respectively.

2.2.4. Rejuvenating Additive

To enhance the rheological properties of a modified binder (PG 76-22) and mitigate the stiffness resulting from oxidation and the aging of recycled asphalt (AC-RAP) at varying proportions (15%, 30%, and 36% by weight), we introduced the rejuvenating additive Maro-1000®. This rejuvenating agent is a viscous liquid with a yellow-greenish hue at a temperature of 25 °C. It possesses a moisture content of only 0.314%, a specific density of 0.9546 g/cm^3, and a Saybolt FUROL viscosity of 292. Its high flash point does not adversely affect its performance. These properties render Maro-1000® an effective addition for enhancing the binder and preserving the desired qualities in the recycled asphalt mix.

2.2.5. HMA Design

The mineral skeleton was defined through analytical calculations and graphical methods to achieve an aggregate structure that fell within the control points for a 12.5 mm Superpave mix. Figure 4 and Table 4 show the size distribution of recycled and non-RAP HMA.

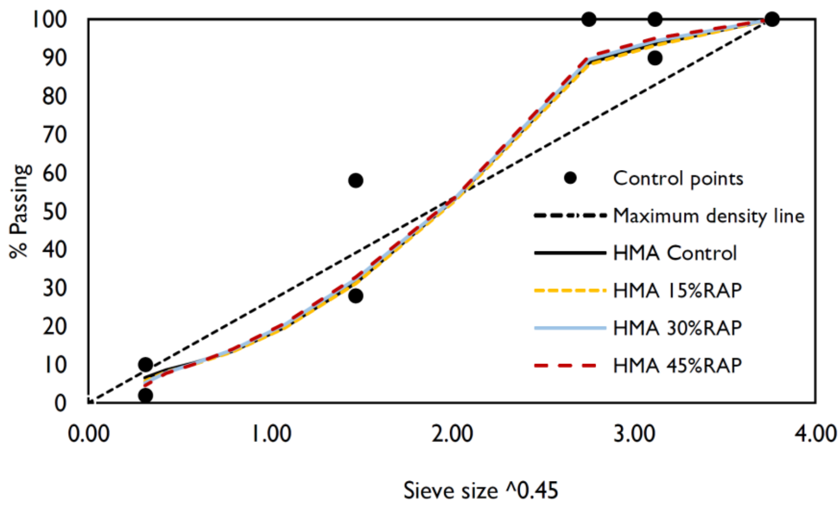

Figure 4. Designed aggregate gradation aligned with the control points for a $\frac{1}{2}$″ nominal size diameter HMA.

Table 4. Components and volumetric properties of non-additive recycled HMA.

Evaluated Property	Control Mix	HMA 15% RAP			HMA 30% RAP			HMA 45% RAP		
Gyratory number	125	125	100	75	125	100	75	125	100	75
New binder	6.5	5.0	5.4	5.7	3.8	4.0	4.6	2.9	3.4	3.7
Total binder	6.5	5.7	6.1	6.4	5.3	5.5	6.0	5.1	5.6	5.8
Va, %	3.9	4.0	3.9	4.0	3.9	3.9	3.9	3.9	3.9	4.0
Gmm	2.517	2.533	2.517	2.500	2.517	2.509	2.496	2.507	2.481	2.471
Gmb	2.417	2.431	2.419	2.398	2.419	2.410	2.398	2.410	2.384	2.371
VMA, %	16.3	14.4	15.2	16.2	13.7	14.3	15.1	13.8	15.1	15.8
VFA, %	75.6	72.1	74.4	74.8	71.7	72.4	74.1	71.9	74	74.5
V_{be}, %	12.3	10.4	11.3	12.2	9.9	10.3	11.2	9.9	11.3	11.8
AFT, µm	6.9	5.9	6.5	7.1	5.5	5.8	6.3	5.5	6.4	6.7
Dp	1.29	1.35	1.23	1.15	1.34	1.27	1.13	1.17	1.03	0.99

Note: Va = air voids, Gmm = theoretical maximum specific gravity from the loose sample (ASTM D2041), Gmb = bulk specific gravity of compacted specimens (ASTM D2726), VMA = voids in mineral aggregate, VFA = voids filled with asphalt, V_{be} = effective binder volume, AFT = apparent film thickness, and Dp = dust ratio.

The binder content that met the volumetric requirements established for each combination of RAP and number of gyrations was determined through four-to-five trial percentages in each HMA. Table 4 displays the new asphalt content added as a percentage of the total mixture weight and their corresponding volumetric characteristics.

2.2.6. Fabrication of the Test Specimens

All test specimens were manufactured using a mechanical device with 180 s mixing cycles, incorporating the reclaimed asphalt pavement without heating. This approach aimed to replicate the conditions of HMA production using a continuous double-barrel plant production and/or a discontinuous gravimetric plant production, commonly referred to as the "batch plant". Based on viscosity analyses conducted on the project binder, the mixing and compaction temperatures were set at 175 ± 3 °C and 163 ± 3 °C, respectively, for both non-additive HMA and rejuvenating HMA. The asphalt concrete subjected to mechanical performance tests was compacted with an air void target content of 7 ± 1%. The variables considered in each HMA are outlined in Table 5.

Table 5. Experimental matrix.

HMA Number	HMA-ID	% RAP	Gyratory Number	% Additive	% C.A	PG Binder	HWTT Specimens	I-FIT Specimens
1	0%R-125G	0	125	0	6.5	76-22	4	2
2	15%R-125G	15	125	0	5.0	76-22	36	18
3	15%R-100G		100		5.4			
4	15%R-75G		75		5.7			
5	30%R-125G	30	125		3.8			
6	30%R-100G		100		4.0			
7	30%R-75G		75		4.6			
8	45%R-125G	45	125		2.9			
9	45%R-100G		100		3.4			
10	45%RAP-75G		75		3.7			
11	15%R-125G-10A	15	125	10	5.0	64-28	12	6
12	15%R-100G-10A		100		5.4			
13	15%R-75G-10A		75		5.7			
14	30%R-125G-15A	30	125	15	3.8	58-34	12	6
15	30%R-100G-15A		100		4.0			
16	30%R-75G-15A		75		4.6			
17	45%R-125G-36A	45	125	36	2.9	40-46	12	6
18	45%R-100G-36A		100		3.4			
19	45%R-75G-36A		75		3.7			

In total, 114 specimens were tested to characterize the rigidity and flexibility of the following: the control mix (0% RAP), nine recycled HMA mixtures without additives, and nine recycled HMA mixtures with rejuvenating additives.

2.3. Performance Tests

The mechanical behavior of HMA was assessed through the lens of two performance tests. Firstly, the Hamburg wheel tracking test (HWTT) was employed to estimate susceptibility to permanent deformation and moisture damage, and secondly, the flexibility index (I-FIT), determined from fracture energy tests, provided valuable insights into the cracking potential.

2.3.1. Assessing Rutting Susceptibility and Moisture Damage Using HWTT

The implementation of this empirical, yet highly field-correlated test aimed to analyze the resistance of HMA under the combined influence of thousands of load repetitions, humidity, and high temperature. The susceptibility test for rutting and moisture damage was conducted in accordance with AASHTO T324 [55]. This test method measured the depth of accumulated plastic deformation in the wheel path and the number of load repetitions required for the specimen to fail. To perform this test, the Hamburg wheel tracking device was utilized. It involves the circulation of two steel wheels, each 47 mm wide and 203.2 mm in diameter, with a concentrated load of 71 kg on water-submerged test specimens at 50 °C. The test was set up to run until either 20,000 passes were completed or until a rutting depth of 20 mm was reached.

In this setup, the load repetitions of heavy vehicles were simulated to mimic the conditions HMA experiences when they are part of a pavement in service.

2.3.2. Fracture Energy and Cracking Potential

The recently introduced AASHTO TP124 [56] test method was utilized to assess the toughness and resistance to cracking of HMA at intermediate temperatures (25 °C). The purpose of conducting this test was to analyze the fatigue-related mechanical behavior by measuring the dissipated energy during the fracture process. We also calculated a quality indicator that is well-correlated with field cracking and other performance tests, known as the flexibility index (FI), as developed by Ozer et al. [57].

This test was performed on semi-circular specimens with a vertical notch at the bottom midpoint, subjected to three-point bending to induce a fracture in mode I (tensile opening mode during crack propagation). During the test, a load was monotonically applied along the vertical diameter of the test specimen at a displacement rate of 50 mm per minute until the rupture occurred. Throughout each test, the applied loads and generated displacements were continuously recorded. Data analysis allows us to create a load–displacement curve, enabling the determination of parameters such as maximum load, critical displacement, slope at the post-peak inflection point, dissipated work, fracture energy, and secant modulus. A typical representation of the results obtained from the semi-circular bending beam test is shown in Figure 5.

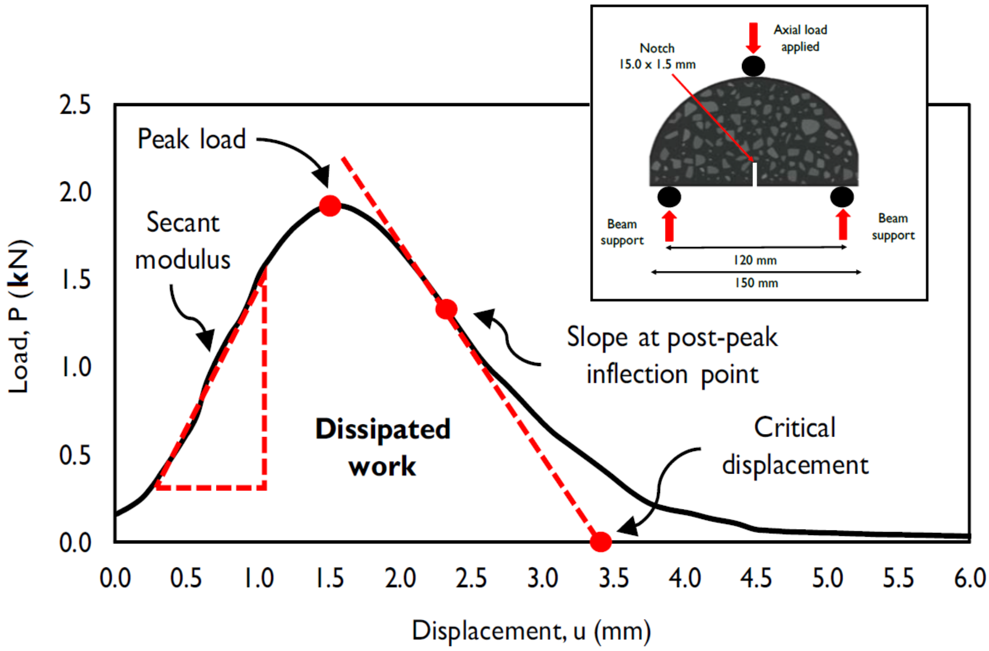

Figure 5. Typical representation of the flexibility index in the semi-circular load–displacement curve.

Based on the load–displacement curve, fracture work and fracture energy can be calculated using Equations (1) and (2), respectively, where Gf is defined as

$$G_f = \frac{W_f}{BL} \tag{1}$$

Here, G_f represents the fracture energy in J/m^2, B stands for the thickness of the specimen in millimeters, L denotes the height of the fracture area in millimeters, and W_f is the work performed during the cracking process in kN/mm, which is given by

$$W_f = \int_0^{\Delta R} P \cdot du \tag{2}$$

On the other hand, the flexibility index (FI), which is expressed mathematically in Equation (3), combines the fracture energy of HMA and its post-peak failure behavior to determine crack resistance. It is defined as follows:

$$FI = \frac{G_f}{abs(m)} A, \tag{3}$$

where FI represents the flexibility index, m is the slope of the tangent formed at the inflection point of the post-peak curve in kN/mm, G_f stands for the fracture energy in J/m^2, and A is a conversion and scaling factor set to 0.01.

3. Results and Discussion

3.1. Results of Rutting Susceptibility and Moisture Damage Assessment Using HWTT

From the tests conducted to determine susceptibility to rutting and moisture damage using the Hamburg wheel tracking test (HWTT), the primary results are summarized in Table 6. These values represent the results obtained from duplicate tests.

Table 6. Results of susceptibility to permanent deformation and moisture damage in HWTT.

HMA ID	Rutting Depth, mm	Standard Deviation Rutting Depth, mm	Plastic Flow Slope, mm/1000 Passes	Stripping Point
0%R-125G	4.72	2.37	0.192	N.P.
15%R-125G	2.53	0.04	0.080	N.P.
15%R-100G	3.20	0.77	0.106	N.P.
15%R-75G	4.51	1.88	0.168	N.P.
30%R-125G	2.31	0.15	0.068	N.P.
30%R-100G	2.81	0.57	0.096	N.P.
30%R-75G	3.10	0.42	0.106	N.P.
45%R-125G	1.68	0.12	0.057	N.P.
45%R-100G	1.80	0.20	0.058	N.P.
45%R-75G	2.49	0.66	0.094	N.P.
15%R-125G-10A	3.91	0.27	0.146	N.P.
15%R-100G-10A	5.43	2.59	0.204	N.P.
15%R-75G-10A	5.86	0.81	0.222	N.P.
30%R-125G-15A	3.15	0.27	0.111	N.P.
30%R-100G-15A	5.49	2.50	0.208	N.P.
30%R-75G-15A	4.81	0.25	0.172	N.P.
45%R-125G-36A	3.24	0.21	0.110	N.P.
45%R-100G-36A	6.41	2.99	0.274	N.P.
45%R-75G-36A	3.93	0.41	0.148	N.P.

Table 6 and Figure 6 present the results of susceptibility to permanent deformation (rutting) and moisture damage as determined by the HWTT. The 0%R-125G control mix exhibited a rutting depth of 4.72 mm, which is a conservative yet satisfactory value, falling within the range of 0 to 12.5 mm. When rutting was analyzed in mixes with 15% RAP without a rejuvenating additive (15%R-75G, 15%R-100G, and 15%R-125G), it was observed that the rutting depth values decreased by 4.45%, 32.20%, and 46.40%, respectively. This trend was similarly observed in mixtures containing 30% and 45% RAP without the additive. This reduction could be primarily attributed to the stiffness provided by the age-hardened RAP binder and the increase in internal friction resulting from denser structures.

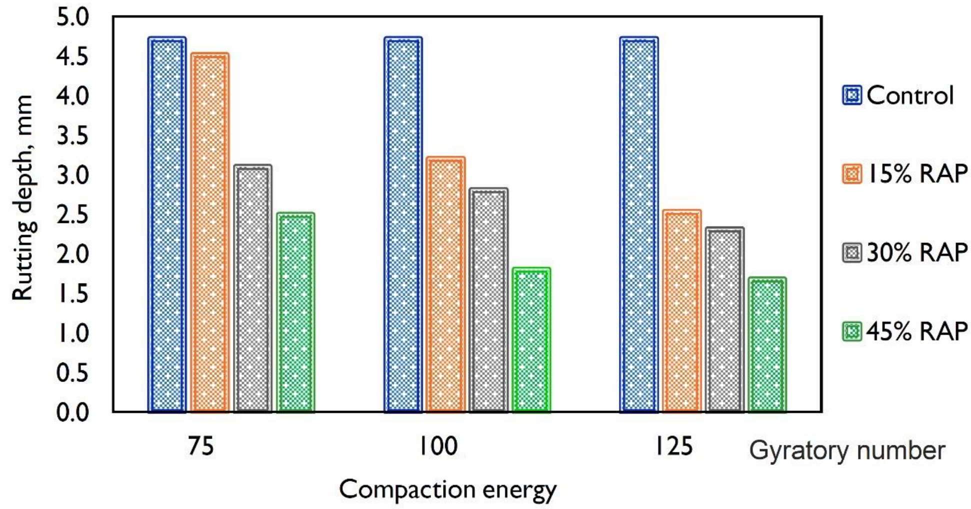

Figure 6. Results of the permanent deformation tests (HMA without additives).

Secondly, when examining the impact of compaction energy on rutting, it is noteworthy that the recycled mix "15%R-75G" experienced 4.51 mm of rutting, similar to the control mix (4.72 mm). However, the "15%R-100G" mix exhibited lower resistance to rutting, with a depth of 3.20 mm, making it 32.20% more susceptible to rutting. Consequently, the "15%R-125G" mix demonstrated a rutting depth of 2.53 mm, resulting in a reduction of 46.40% compared to the control mix. This trend was consistent for recycled mixes with 30% and 45% RAP. This suggests that as the number of gyrations increases, the mix experiences shallower rutting depths due to greater compaction. In mixes compacted with 75 gyrations (15%R-75G), the asphalt layer between the aggregates was thicker, allowing for more rearrangement of the aggregates and greater strain and flexibility in the binder thickness. Conversely, in the mix compacted at 125 gyrations (15%R-125G), the binder thickness was smaller, resulting in reduced rutting.

Overall, all recycled HMA mixtures without additives demonstrated between 4% and 65% less susceptibility to permanent deformation (rutting). Additionally, the plastic flow slopes were up to three times lower compared to control HMA, even though some mixtures were designed with a higher binder volume due to a reduction in compaction energy by 25 or 50 gyrations during the volumetric mix design.

On the other hand, Figure 7 depicts the permanent strain behavior of the recycled mixes when combined with the rejuvenating additive. Upon analyzing Figure 7, it becomes evident that the recycled mixes "15%R-125G-10A", "30%R-125-G-15A", and "45%R-125-G-36A" exhibited rutting depths of 3.91 mm, 3.15 mm, and 3.24 mm, respectively. Notably, this represents a reduction of 17.16%, 33.26%, and 31.36%, respectively, compared to the control mix. Consequently, the stiffness of the recycled mix increased once again due to the stiffening effect of the aged RAP asphalt. However, the stiffness remained lower when the rejuvenating additive was incorporated compared to the recycled mixes without the additive.

Likewise, upon analyzing Figure 7, it becomes evident that the inclusion of a rejuvenating agent in the recycled asphalt mixes significantly reduced the stiffness of the RAP asphalt binder. Essentially, all recycled mixes containing 15%, 30%, and 45% RAP, rejuvenated with 10%, 15%, and 36% of the additive, demonstrated lower stiffness when compared to the non-rejuvenated recycled mixes. Consequently, this resulted in greater rutting depths. However, they still complied very well with the high-performance standards (<12.5 mm). This is noteworthy considering the use of low-viscosity binders with critical failure temperatures very close to or even below the test temperature set in this study (50 °C).

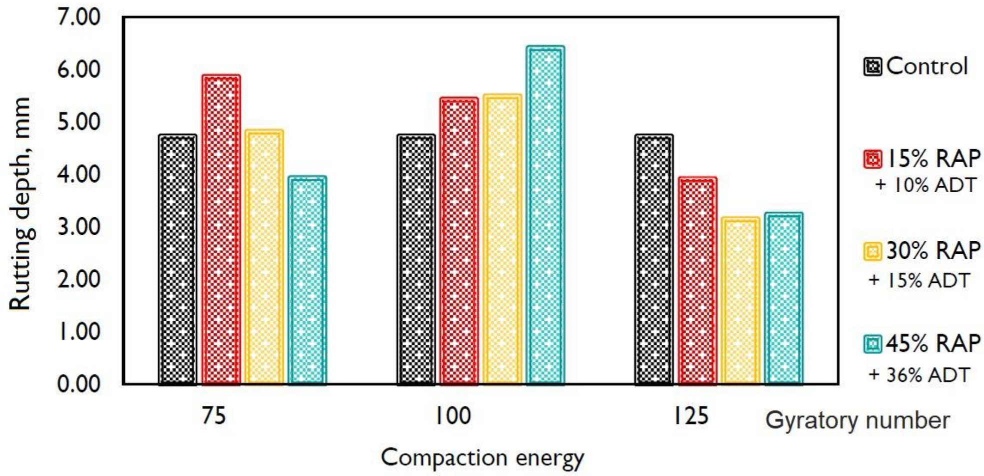

Figure 7. Results of the permanent deformation test (HMA with additive).

Considering the impact of compaction energy (gyrations), Figure 7 provides evidence that the rutting depth decreased from 4.72 mm in the control mix to 3.91 mm, 3.15 mm, and 3.24 mm for the samples subjected to 125 gyrations in the Superpave gyratory compactor (15%R-125G-10A, 30%R-125G-15A, and 45%R-125G-36A). This suggests that these mixes offer robust resistance to rutting, but are less rigid due to the rejuvenation of the aged asphalt. In contrast, the recycled mixes subjected to compaction energies of 75 and 100 gyrations experienced an increase in rutting depth ranging from 2% to 36% when compared to the control mix. Therefore, reducing compaction energy and achieving a thicker asphalt film was not sufficient to trigger rutting potential or compromise the stability of HMA fabricated with significant quantities of rejuvenating additive.

Contrary to expectations, recycled HMA mixtures rejuvenated with 30% and 45% RAP showed greater rutting depths when compacted under 100 gyros as compared to their counterparts tested under 75 gyros. This contradicts the trend observed in recycled HMA mixtures without additives. In both cases, this discrepancy is attributed to the nature of the test, which is not always able to distinguish small changes in asphalt binder content, or it could be due to variations in the RAP composition (particle size and asphalt content) used in the fabrication of these specimens.

In summary, the non-rejuvenated recycled mixes containing 15% RAP compacted at different energy levels (75, 100, and 125 gyrations) demonstrated well-balanced behavior. This indicates that, due to the presence of aged RAP, the recycled mix exhibited increased stiffness, resulting in a significant improvement in rutting resistance, without inducing excessive hardening that could lead to cracking.

Lastly, it is important to note that no stripping phenomenon occurred in any recycled HMA. This could be explained by the fact that the RAP aggregates in HMA are covered by a double asphalt film, which hinders water penetration into the internal structure of the mineral aggregate, thus reducing the possibility of breaking the bond between the binder and the aggregate surface.

3.2. Fracture Energy and Cracking Potential Using the I-FIT

Additionally, tests were conducted on the specimens to assess their cracking potential using the fracture energy flexibility index test (I-FIT) for recycled asphalt mixtures with varying RAP contents, compaction energy levels, and proportions of rejuvenating additive. Table 7 presents a comparison of the most noteworthy results obtained in the cracking potential study.

Table 7. Results of the I-FIT cracking potential test.

HMA ID	Maximum Load (kN)	Secant Modulus (kN/mm)	Dissipated Work (kN-mm)	Fracture Energy (J/m^2)	Slope (kN/mm)	Flexibility Index (FI)	FI Coefficient of Variation (%)
0%R-125G	2.09	1.30	4.40	1520	1.40	10.9	12.4
15%R-125G	2.22	1.57	4.71	1635	1.65	10.0	13.2
15%R-100G	2.83	1.40	4.64	1593	2.79	8.5	3.7
15%R-75G	2.32	1.49	5.39	1837	2.24	8.2	1.8
30%R-125G	3.33	2.13	4.04	1397	5.53	2.6	12.3
30%R-100G	3.3	2.16	4.15	1436	3.55	4.0	2.4
30%R-75G	3.3	2.00	5.03	1726	3.80	4.5	9.4
45%R-125G	2.72	1.94	2.9	998	6.21	1.6	13.4
45%R-100G	3.33	2.23	3.36	1138	6.18	1.8	9.8
45%RAP-75G	3.10	2.42	3.75	1268	5.48	2.3	6.6
15%R-125G-10A	1.97	1.4	4.25	1477	1.27	11.6	2.9
15%R-100G-10A	1.62	1.00	3.14	1098	1.30	11.3	16.2
15%R-75G-10A	1.68	1.12	3.59	1231	1.18	10.4	12.6
30%R-125G-15A	1.99	1.12	3.25	1110	2.05	5.5	12.2
30%R-100G-15A	1.77	1.49	3.22	1142	1.42	8.0	4.5
30%R-75G-15A	1.78	1.10	3.32	1126	1.35	8.4	7.7
45%R-125G-36A	1.65	1.41	2.44	840	1.77	4.9	17.6
45%R-100G-36A	1.66	1.37	2.36	806	1.47	5.5	13.5
45%R-75G-36A	1.44	1.08	3.00	1008	0.93	11.0	13.0

The results presented in Table 7 reveal a significant increase in stiffness for HMA mixtures recycled with RAP (15%, 30%, and 45%) in the absence of a rejuvenating admixture. This is evident in the flexibility index (FI), which decreased across all mixtures, ranging from 8.26% to 85.32% (see Figure 8).

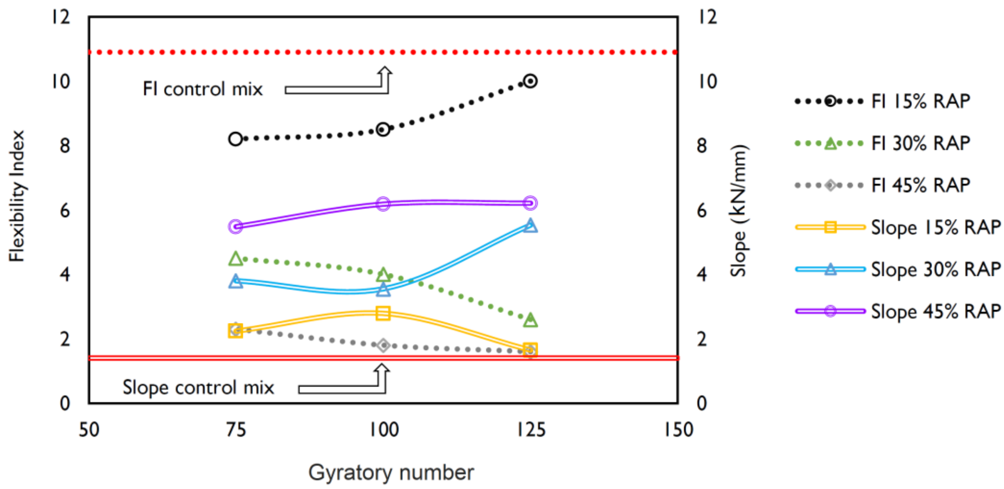

Figure 8. Results of the flexibility index test (I-FIT) for recycled HMA without additive.

Consequently, there was a notable rise in the peak load, increasing from 6.22% to 59.33% compared to the control mixture. This behavior was also reflected in significant increases in both the secant modulus and the slope in the post-peak failure region. These findings underscore the inclination of these recycled HMA mixtures toward cracking rather than rutting, resulting in brittle behavior characterized by reduced fatigue strength and accelerated crack propagation.

Table 7 and Figure 8 demonstrate that the non-rejuvenated recycled mixes containing 15% RAP (15%R-125G, 15%R-100G, and 15%R-75G) had flexibility indexes of 10.00, 8.50, and 8.20, respectively. While these values were lower compared to the control mix (10.90), they still surpassed the minimum acceptable threshold (8.00), indicating that these 15% RAP mixes behave similarly to a conventional mix. However, they were stiffer due to the aged asphalt in the RAP, making them more brittle but better equipped to resist rutting. In addition, the flexibility index results obtained in non-rejuvenated HMA with 15% RAP, compacted by applying 100 and 75 gyrations, were lower than expected. These mixtures exhibited reduced ability to resist cracking, even when provided with a thicker asphalt film. The heterogeneity of milled material components may explain this phenomenon. However, both mixes demonstrated reasonable toughness compared to the reference mix and slightly less than the mix with 15% RAP compacted at 125 gyros.

In contrast, the performances of recycled HMAs without additive containing 30% and 45% RAP were notably poor. Their flexibility indexes fell far below the minimum value. This finding is not surprising given the very high stiffness and embrittlement exhibited by the RAP binder, which cannot be compensated for solely by minor variations in the mix design asphalt content.

Table 7 shows that the rejuvenated recycled HMA with 15% RAP exhibited a flexibility index similar to that of the control mix (FI = 10.90). However, the 15%RAP-100G-10A and 15%RAP-125G-10A mixes demonstrated an increase of 3.67% and 6.42% in the flexibility index, respectively. This indicates that these mixes were slightly more flexible than the control mix, making them more resistant to cracking but also more deformable. Similarly, the rejuvenated recycled HMA mixtures with 30% and 45% RAP experienced a reduction in the flexibility index ranging from 22.94% to 55.05% compared to the control mix. This suggests that the rejuvenated recycled HMA mixtures with 30% and 45% RAP were stiffer and more brittle, making them more prone to cracking. However, for the 30% and 45% RAP percentages, a higher asphalt film thickness is recommended to attain a flexibility index similar to that of the control mix, which can be achieved by using a lower compaction energy: 100 gyros for 30% RAP and 75 gyros for 45% RAP.

Thus, when analyzing the maximum load, it is noticeable that all the rejuvenated recycled HMA mixtures exhibit a significant reduction in these values. This implies that a decreased load was required to fracture the mix, indicating that the mix is more deformable and less prone to cracking.

Figure 9 illustrates the behavior of rejuvenated recycled HMA. It is evident that the rejuvenating compound had a positive effect on reducing the cracking potential. The utilization of softer binders allowed these asphalt concretes to maintain their structural integrity even after reaching maximum strength. This is reflected in the notable decrease in the post-peak slope value. The improved toughness, as expressed through the flexibility index in this study, was significantly increased for all combinations of RAPs and numbers of gyrations. In some cases, it even surpassed the performance of the no-RAP control mix. For instance, HMA mixtures identified as "15%R-125G-10A", "15%R-100G-10A", and "45%R-75G-36A" achieved flexibility index values of 11.6, 11.3, and 11.0, respectively.

When observing the effect of compaction energy on the rejuvenated recycled HMA mixtures, it became apparent that as the number of gyrations increased, the flexibility index decreased. For instance, the 15%R-125G-10A, 30%R-125G-15A, and 45%R-125G-36A mixes exhibited higher flexibility indexes (10.40, 8.40, and 11.0, respectively) when compared to the mixes compacted with 100 and 125 gyrations. In essence, a lower number of gyrations resulted in a less dense mixture, leading to a greater binder thickness. This increased thickness made the binder more susceptible to permanent deformations and reduced the potential for cracking. Conversely, a higher number of gyrations led to a denser mix, resulting in a thinner binder thickness. Consequently, the mixture was less deformable, less prone to cracking, and demonstrated lower flexibility indexes.

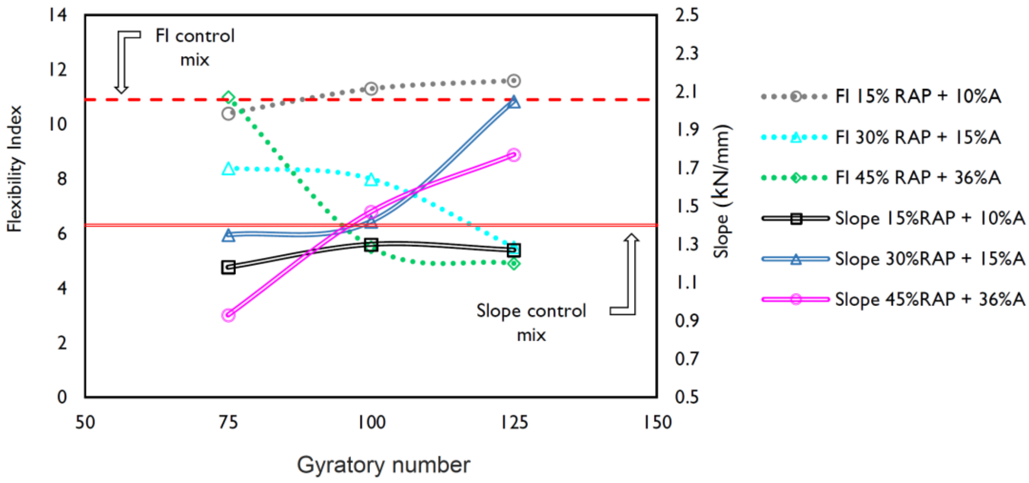

Figure 9. Results of the flexibility index test (I-FIT) for the recycled HMA with a rejuvenating additive.

Analyzing the data presented in Figures 8 and 9, it becomes evident that the influence of densification energy on the cracking susceptibility test became more significant in HMA with additives and higher RAP proportions. This is because, with the same increase in asphalt content (achieved by reducing the number of gyrations during volumetric design), rejuvenated recycled HMA mixtures exhibited more significant improvements in the flexibility index compared to non-additive mixes, rendering them more flexible and less brittle.

Again, to summarize, non-rejuvenated and rejuvenated recycled HMA mixtures containing 15% RAP, compacted at different energy levels (75, 100, and 125 gyros) showed more balanced behavior compared to mixtures with 30% and 45% RAP. This implies that, due to the lower quantity of aged RAP present in the mix, a flexibility index similar to the control mix was presented, leading to a remarkable improvement in cracking resistance, without causing excessive softening that would induce permanent strain (rutting).

Therefore, the use of 15% RAP content alone or a combination of 15% RAP with a rejuvenating additive can effectively reduce the excessive stiffness and brittleness typically associated with high-RAP HMAs. This transformation resulted in mixtures with more effective binders and rejuvenating additives, making them more ductile materials capable of dissipating energy slowly and withstanding larger critical rupture displacements. This enhanced ductility translates to greater resistance to various tensile cracking distresses.

3.3. *Performance Interaction Diagram Analysis (Illinois Balanced Mix Design)*

The application of the balanced mix design approach (BMD) provided the necessary information for a relative performance comparison of all HMAs under study. The adopted method involves analyzing the interaction diagram space between two experimental parameters measured in the laboratory: the flexibility index (FI) and the rutting depth (RD). The acceptance thresholds for the maximum deformation and minimum flexibility were set at 12.5 mm and 8.0 (dimensionless), respectively. These values correspond to the limits defined in the original methodology and are based on previous research conducted by the Illinois Center for Transportation [58,59].

Figure 10 displays a dispersion plot of points, illustrating the relationship between RD and FI for non-rejuvenated recycled HMA mixtures. As highlighted in Figure 10, only three recycled mixtures managed to position themselves in the desired quadrant: QI—Rigid and Flexible. In other words, this analysis mode suggests that the non-rejuvenated recycled HMA mixtures labeled as “15%R-125G”, “15%R-100G”, and “15%R-75G” exhibit behavior comparable to the control mix. These mixtures demonstrate high-quality performance and may be suitable for use on roads with high traffic volumes, showing excellent resistance to both cracking and rutting.

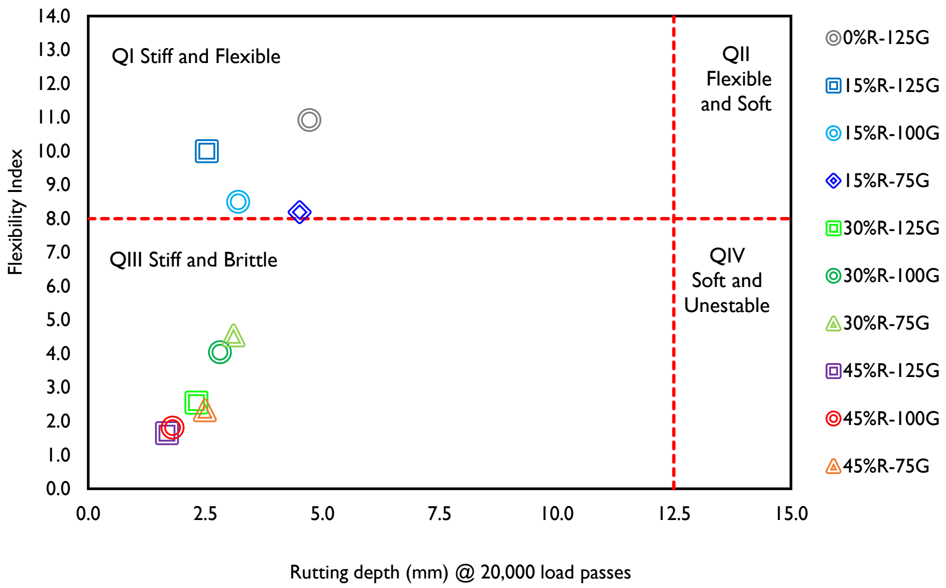

Figure 10. Performance interaction diagram for HMA without the rejuvenating additive—relationship between RD and FI.

In contrast, non-rejuvenated recycled HMA mixtures produced with 30% and 45% RAP, regardless of the compaction energy applied, fell into the third quadrant (Stiff and Brittle). This indicates that their behavior is not conducive to withstanding fatigue cracking and various other modes of cracking distress, especially if they experience high deflections in the field. While these mixes exhibit better rutting resistance, they are less tolerant to the tensile stresses produced by repeated traffic loading that ultimately lead to cracking in the mix.

In other words, in mixtures with a high RAP content, stiffness is correlated with greater resistance to rutting (permanent strains), thus better supporting traffic loads without rutting. However, higher stiffness in the mix results in a loss of flexibility, which is reflected in a lower tolerance to tensile stress. In other words, although resistant to permanent strain (rutting), they may be less able to withstand the tension that can generate cracks in the mix surface.

On the other hand, Figure 11 illustrates the mechanical behavior of the rejuvenated recycled HMA mixtures with the additive. It is once again evident that the rejuvenated recycled HMA mixes containing 15% RAP exhibited behavior similar to the control mix, falling within the QI—Stiff and Flexible quadrant. Furthermore, it can be observed that the combination of 15% and 36% rejuvenation dosages with compaction energies between 75 and 100 gyrations effectively imparted greater flexibility to recycled mixes with intermediate (30%) and high (45%) RAP contents. As a result, the rejuvenated recycled HMA mixes denoted as "30%R-100G-15A", "30%R-75G-15A", "45%R-100G-36A", and "45%R-75G-36A" successfully transitioned from quadrant QIII—Stiff and Brittle to the first quadrant, QI—Stiff and Flexible. In other words, their new classification positions them at a performance level comparable to the control mix (0%R-125G) in terms of quality and performance. They now possess sufficient flexibility to withstand the required level of cracking without experiencing a drastic loss in their ability to resist permanent strain (rutting).

The results in the performance interaction diagram space demonstrate that solely increasing the effective asphalt volume or incorporating a rejuvenating additive does not lead to a significant increase in resistance to cracking propagation. However, when both factors are combined, very promising results are achieved. Therefore, it is reasonable to conclude that the selection and combination of durability improvement strategies adopted in this study have successfully achieved the objective.

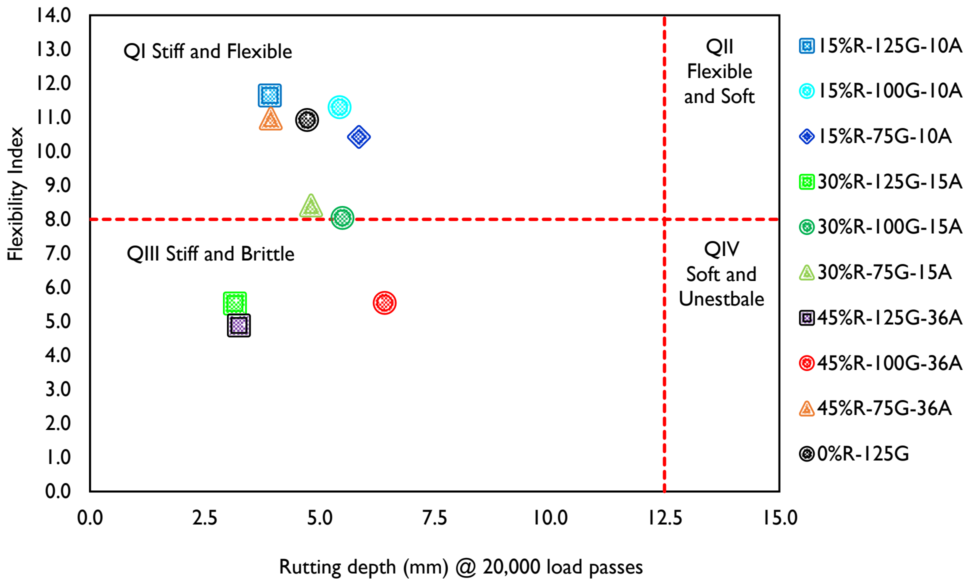

Figure 11. Performance interaction diagram of RD and FI for HMA with a rejuvenating additive.

4. Conclusions

The objective of this paper was to assess the impact of compaction energy on recycled HMA blends, both with and without a rejuvenating additive, using a Superpave gyratory compactor to determine the optimal binder content and achieve a balance between stiffness and flexibility, meeting the minimum requirements for cracking and rutting resistance typical of conventional HMA mixes. A control HMA mix was designed for comparison with recycled HMA blends containing varying RAP contents (15%, 30%, and 45%), compaction energies (75, 100, and 125 gyrations), and dosages (10%, 15%, and 36%) of the Maro-1000® rejuvenating additive. Performance was assessed through the Hamburg wheel tracking test (HWTT) and the fracture energy flexibility index test (I-FIT). Mechanical performance was further evaluated using the interaction space diagram proposed by the University of Illinois (I-BMD). Based on this research, the following conclusions are presented below.

The HMA mixes that contained RAP underwent a significant reduction in rutting depths in comparison to the conventional mix. Interestingly, as the RAP content in the mix rose, the stiffness of the mix increased, reducing the rutting depth. Thus, the non-rejuvenated HMA mixes containing 15% RAP compacted at 75, 100, and 125 gyros reached 4.45%, 32.20%, and 46.40% reduction, respectively. On the other hand, in the 15% RAP and rejuvenated mixes, rutting was reduced to a lesser degree. The reason for this is attributed to the stiffness of RAP because of its aging, increasing the rutting resistance. In contrast, when a rejuvenating additive is added, the stiffness decreases, resulting in greater rutting strain.

Compaction energy directly influenced rutting; as the number of gyros increased, compaction (densification) increased, causing lower rutting depths. In other words, the mixes containing 15% RAP and compacted at 125 gyros showed less rutting (non-rejuvenated 46.40%, rejuvenated 31.36%) compared to the conventional mix. At 75- and 100-gyro compaction, permanent strain in non-rejuvenated mixes decreased by 4.45% and 32.20%, respectively, while in rejuvenated mixes it increased by 24.15% and 15.04%, respectively. The reason for this increase is due to the thicker asphalt layer between the aggregates, which allows a greater reorganization of the aggregates, greater tension, flexibilization, and greater rutting depth. Conversely, a thinner binder layer between the aggregates helps reduce rutting.

The addition of a rejuvenating additive to the HMA mixes resulted in a reduction in the stiffness of the RAP asphalt binder. It is notable that as the additive content increased, the flexibility of the mix increased as the stiffness decreased, which translated into a reduction in rutting resistance. In recycled and rejuvenated mixes with 10%, 15%, and 36% admixture and compacted under 75 and 100 gyros, the rutting resistance was reduced. However, at a higher compaction energy (125 gyros), the rejuvenating admixture made the mixes more flexible, allowing for a reduction in susceptibility to cracking and rutting compared to the conventional mix.

Regarding the flexibility index, the higher the RAP content in the mix, the lower the index, resulting in a mix with higher tenacity but greater fragility, making it brittle. However, when a rejuvenating additive was added, the FI was lower than in the control mix but increased compared to the non-rejuvenated mixes. In the mixes with 30% and 45%, it was observed that as the additive content increased, the FI increased; but in mixes containing 15% RAP, the FI decreased as the additive content increased. Likewise, regarding the compaction energy, as the number of gyros increased, the FI decreased in the mixes with 30% and 45% RAP, but with 15%, the FI increased as the compaction energy rose. Therefore, to find a balance between stiffness and flexibility in recycled mixes, it is necessary to obtain the proportion of RAP and rejuvenating admixture that allows the FI value to be close to conventional mixes.

Mixtures containing 15% RAP, whether rejuvenated or not, achieved an adequate balance between stiffness and flexibility. These mixes showed a flexibility index that was comparable to that of the control mix, indicating a resistance to cracking and a capacity for stress absorption without compromising the resistance to permanent strain.

The implementation of a balanced mix design (BMD) provides a solid framework for achieving sustainable, durable, and high-quality recycled asphalt mixes. Asphalt mixes containing 15% RAP are positioned in the QI—Stiff and Flexible quadrant of the performance interaction diagram, reinforcing their excellence in terms of quality and performance.

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