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Mechanical Analysis through Non-Destructive Testing of Recycled Porous Friction Course Asphalt Mixture

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Abstract: This study assessed the mechanical performance of porous asphalt mixtures, specifically the porous friction course (PFC), incorporating 10% Reclaimed Asphalt Pavement (RAP) and rubberized asphalt. Three different methods were investigated to evaluate the stiffness of the mixtures: the resilience modulus (RM) test at a single temperature and loading frequency, the complex modulus $|E^*|$ test from compressive loading conducted at various temperatures and frequencies, and the impact resonance (IR) tests performed at three temperatures with five impacts applied to the mixture. The results demonstrated that the RAP-containing mixture exhibited a higher resilience modulus at all tested temperatures, indicating greater stiffness compared to the mixture without RAP. Additionally, the IR and $|E^*|$ tests revealed similar behavior between the two evaluated mixtures. These findings suggest that both quasi-static and vibrational tests are suitable for characterizing the stiffness of porous asphalt mixtures due to the similarity in the viscoelastic parameters of the two investigated mixtures. This study provides important insights into the practical and scientific application of recycled and modified materials in porous asphalt mixtures.

Keywords: friction porous course; material recycling; non-destructive evaluation; mechanical properties

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1. Introduction

Road infrastructure plays a fundamental role in global connectivity and mobility, being vital for economic and social development [1–3]. However, the construction and maintenance of roadways often generate significant environmental challenges, including the consumption of natural resources, waste generation, and pollutant emissions [4].

As awareness of climate change and environmental sustainability grows, the search for more sustainable solutions and alternatives in the construction or renovation of road pavements becomes urgent. In this context, the recycling of milled asphalt mixtures, internationally known as Reclaimed Asphalt Pavement (RAP), in the production of new asphalt mixtures contributes to reducing the demand for virgin materials, as well as reducing costs and minimizing environmental impacts. Additionally, the use of recycled materials such as RAP and steel slag in permeable asphalt mixtures can result in a reduction of CO_2 emissions of up to 23% [5].

Surveys conducted by the European Asphalt Pavement Association (EAPA) in 2021 indicate that, out of the 91 million tons of RAP generated in the United States, 95% is incorporated into the production of hot and warm mix asphalt. In Europe, Hungary leads in RAP utilization, with 98% of the material being used in hot and warm mix asphalts. Following closely are Germany and Austria, which also stand out, recycling 85% of the available RAP in new asphalt mixtures, along with other countries, such as France, Denmark, Slovakia, and Spain, using RAP for pavement [6]. In Brazil, records of RAP production and destination are still incipient due to asphalt recycling not being considered a routine practice [7]. There are limitations such as the high heterogeneity of RAP and the increased stiffness of the binder caused by aggregate over-heating during the mixing process [8]. These factors impose restrictions on the use of RAP in conventional mixtures, typically limiting it to up to 15% without the use of rejuvenating agents [9,10].

Traditionally, RAP from milled porous layers has been used in the production of new porous asphalt mixtures [11–14]. However, research on the use of RAP from conventional pavements in porous surfacing has recently been advancing, with studies primarily focusing on the functional aspects and durability of these layers [5,15–18]. Few efforts [3,19,20] have been directed toward evaluating the structural contribution of recycled porous asphalt mixtures. When investigating the viscoelastic properties of a porous asphalt mixture containing 15% RAP, Goh and You observed an increase in stiffness in mixtures with RAP, as well as greater tensile strength compared to control mixtures [19]. Xião et al. confirmed the stiffness of porous asphalt mixtures containing 10%, 20%, and 30% RAP. However, the authors also identified a relative mass loss (15%) in mixtures with 30% RAP, indicating a possible limitation when the RAP content in the mixture increases [20].

The Porous Friction Course (PFC) provides better traffic conditions for drivers during rain events due to its porous structure (from 18 to 25% voids), offering users greater comfort and road safety, ranging from eliminating water film on the pavement surface, avoiding hydroplaning and splashes, and reducing heat islands to dropping noise caused by tire/pavement interaction [10,21–24]. Despite the advantages of PFC, challenges persist in improving its structural performance and, consequently, the durability of these pavements.

From the point of view of mechanical characterization, porous asphalt mixtures present drawbacks with respect to conventional mixtures such as susceptibility to permanent deformation, aggregate stripping, and pavement surface disintegration [21]. Another bottleneck identified in the literature is the clogging of voids [25]. These conditions hinder the widespread use of draining mixtures as they compromise their durability and performance over time [26]. In this sense, research has been developed to enhance the mechanical properties of this type of pavement through aggregate and asphalt binder modification [27]. Despite the efforts, there is still a limited amount of knowledge regarding the structural contribution of this type of mixture [28].

Determining the stiffness of the materials and understanding their behavior is a key factor in evaluating the structural performance of PFC considering the viscoelastic nature of the mixtures. In the case of asphalt mixtures, materials considered to present linear viscoelastic behavior, the complex modulus (E^*) is classically obtained through a quasi-static loading test with servo-controlled presses. The complex modulus consists of a complex number that can be described by its absolute value ($|E^*|$) and phase angle (φ) [29]. While $|E^*|$ measures the proportionality between stress amplitudes and strain amplitudes, φ measures the lag between stress and strain signals. The modulus can also be evaluated from other techniques, such as ultrasonic techniques, since it influences the time-of-flight of compressive and shear waves [30,31], and impact resonance techniques, since it influences the frequency response function (FRF) of specimens constituted of the material [32,33].

Given the aforementioned scenario, there is a need to investigate the mechanical performance, particularly stiffness properties, of porous asphalt mixtures incorporating RAP together with rubber-modified asphalt from discarded tires. These mixtures have particularities that require modified binders to optimize their mechanical properties [34]. There is an immediate need for further investigation of PFC in urban pavements in cities such as Fortaleza, Ceará, Brazil, which already has some experience with RAP. This paper sought to characterize the stiffness parameters of two porous asphalt mixtures produced with RAP and rubberized asphalt through destructive and Non-Destructive (ND) techniques such as resilient modulus tests, complex modulus from compressive haversine loading tests, and complex modulus from impact resonance tests. The use of alternative stiffness characterization methods is useful for providing the properties of bituminous mixtures. The main contribution of this research will be the possibility of obtaining stiffness data compatible with the material's behavior using destructive and ND techniques. The objective was to analyze the mixture's performance in terms of stiffness parameters and also to assess the suitability of the chosen tests for the mechanical characterization of the mixtures under analysis.

2. Theoretical Background

Traffic loads impose mechanical stresses on the pavement, causing deformations that can be classified into two types: permanent (plastic) deformations, which result in irreversible changes in the pavement structure, and recoverable (resilient) deformations, which reflect the elastic behavior of the structure, disappearing shortly after the load removal [35]. Non-destructive tests under various conditions of temperature, stress, and frequency are used in the laboratory to detect this behavior, particularly in asphalt mixtures used in the pavement surface layer.

2.1. Resilient Modulus Test (RM)

The Resilient Modulus (RM) test is standardized in Brazil by DNIT 135 (2018)—ME [36], whereas the international procedure follows the guidelines of ASTM D7369-20 [37]. The test consists of applying loading cycles, during which a haversine load pulse is applied during a given time, followed by rest, to approximate the tire loading shape. Each loading cycle lasts 1.0 s (frequency of 1 Hz), with a very particular choice of loading shape: a haversine loading pulse is applied for 0.1 s, followed by 0.9 s of rest, Figure 1. The central parameter in this context is the RM, which represents the relationship between the repeatedly applied maximum stress during the cycle and the resulting recoverable deformation, a relevant measure for pavement analysis and design, even if not a fundamental material property [38]. The RM value is determined by the ratio of the peak tensile stress to the resilient tensile strain, calculated from the test results, including force pulses, and displacement, and considering the specific geometry of the test [39]. However, it should be noted that the RM value is intrinsically related to the shape of the loading, and it is virtually impossible to predict material behavior for a variety of loading conditions in the field [38].

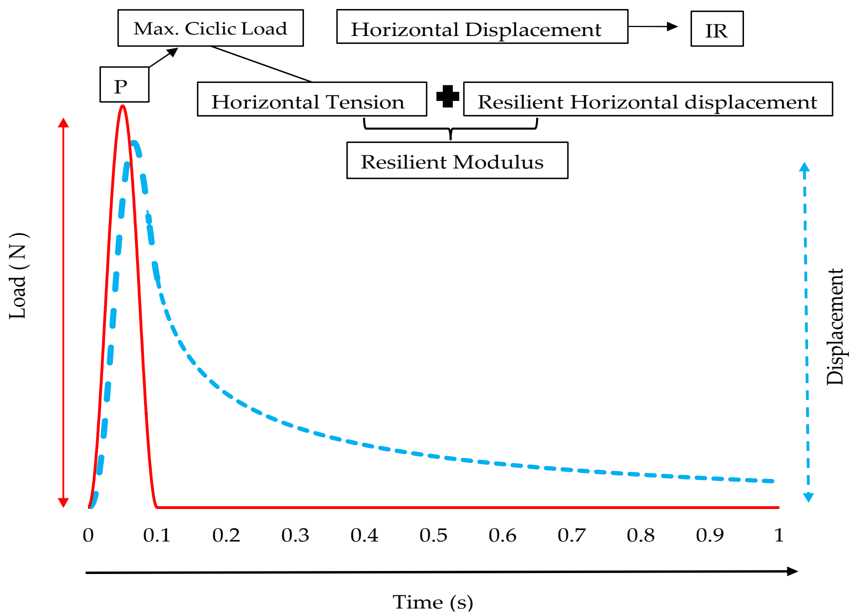

Figure 1. Representation of load signals and the duration of loading and rest time in the RM test.

2.2. Complex Modulus (E) from Compressive Haversine Loading Tests*

Complex modulus is considered the stiffness parameter that characterizes the linear viscoelastic (LVE) behavior of asphalt mixtures, and has been adopted in countries such as France since the 1960s and in the United States since the 1990s [40]. In Brazil, the test is regulated by DNIT 416/2019—ME [29], while some international procedures follow the guidelines of AASHTO T 342/2011 [41], mostly with compressive haversine loading tests with continuous application (without rest between cycles at a given frequency), as shown in Figure 2. In the case of asphalt mixtures, E^* represents a fundamental property for investigating LVE properties, since this test considers the effects of temperature and frequency, and, consequently, the loading time, making it an essential test to characterize the mechanical behavior of asphalt mixtures [39]. By considering the factors (temperature, frequency, and loading), it is possible to predict the behavior of mixtures under variable environmental conditions and traffic loading demands, including the ones to which the material is subjected under the RM test [38]. This is accomplished by applying time–temperature superposition principle and obtaining what is commonly called master curves, for modulus and for phase angle, both as functions of the equivalent frequency at the reference temperature [42–44].

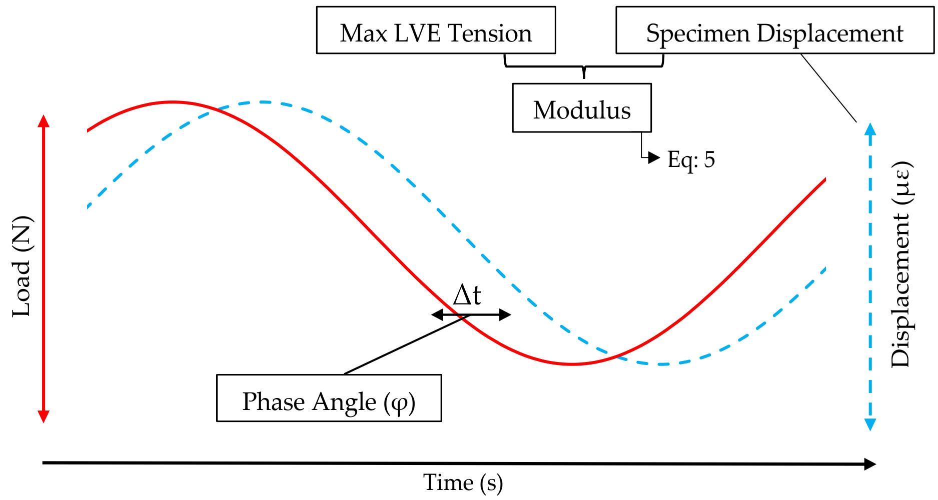

Figure 2. Representation of stress–strain signals from the complex modulus test.

2.3. Complex Modulus from Impact Resonance Tests (IR)

In recent years, ultrasonic and Impact Resonance (IR) tests have been gaining prominence [45], especially the latter. Due to their simplicity of execution and feasibility for construction sites compared to the dynamic axial compression test, IR tests are typically applied for this purpose [46]. Research has been carried out to develop impact resonance testing methodologies using Frequency Response Functions (FRFs) [32,33]. The experimental results allowed theoretical analysis through three-dimensional solid vibration modeling in finite element software accompanied by an iterative optimization process (back calculation of viscoelastic model parameters). The parameters of a linear viscoelastic model determine the vibration amplitudes of that solid over a wide range of frequencies, as shown in Figure 3. The FRFs then provide the possibility to identify not only the resonance frequencies but also the damping properties (linked to peak amplitudes) of a material [47]. Then, the method provides access to complex modulus master curves using a simplified test procedure.

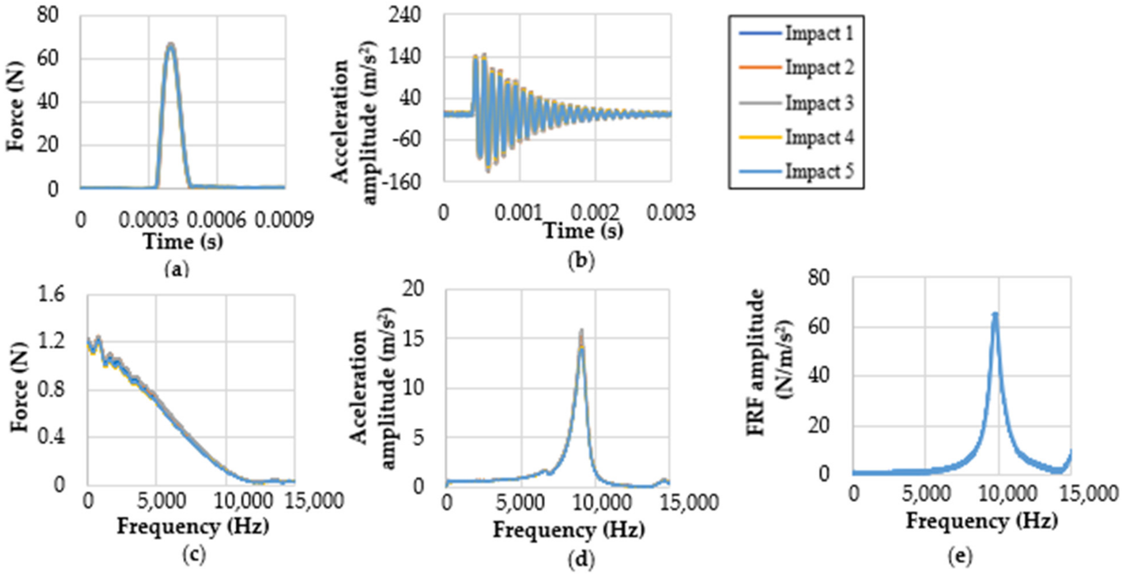

Figure 3. (**a**) Impact hammer load cell results in the time domain; (**b**) accelerometer results in the time domain; (**c**) impact hammer load cell results in the frequency domain; (**d**) accelerometer results in the frequency domain; (**e**) representation of the FRF for the IR test.

3. Materials and Methods

Two porous asphalt mixtures designed following the Superpave methodology, with compaction levels varying between 100, 125, and 130 gyrations. This approach aimed to achieve the volumetric properties required for the Porous Friction Course (PFC), which can range from 18% to 25%. So, the mixtures produced a reference mixture (PFC-REF), without RAP, and a mixture recycled, containing 10% Reclaimed Asphalt Pavement (PFC-RAP). The materials used included 3/8″ crushed stone aggregate and stone dust, both sourced from the OCS quarry, as well as PFC-RAP provided by local asphalt plant that possesses license for milling and managing recycled asphalt pavements, the origin of which was unknown due to the practice of storing it in a single pile. Additionally, 4.5% of Eco-flex-AB8 asphalt binder, a Rubber Modified Asphalt (RMA) supplied by a local asphalt producer, was used, as illustrated in Figure 4.

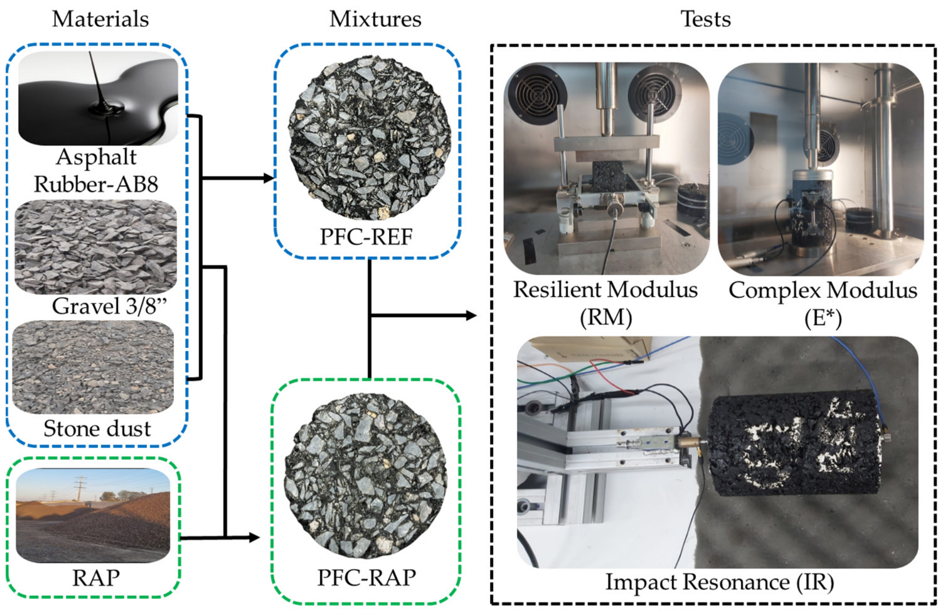

Figure 4. Experimental flowchart.

The aggregate gradation of the mixtures complied with the limits of the II Range DNER-ES 386/1999 [48] of the PFC (approximately equivalent to ASTM 7064/2021 [49], as presented in Figure 5. Next, the particle size distribution curve of the RAP used is presented, both before and after binder extraction, as shown in Figure 6.

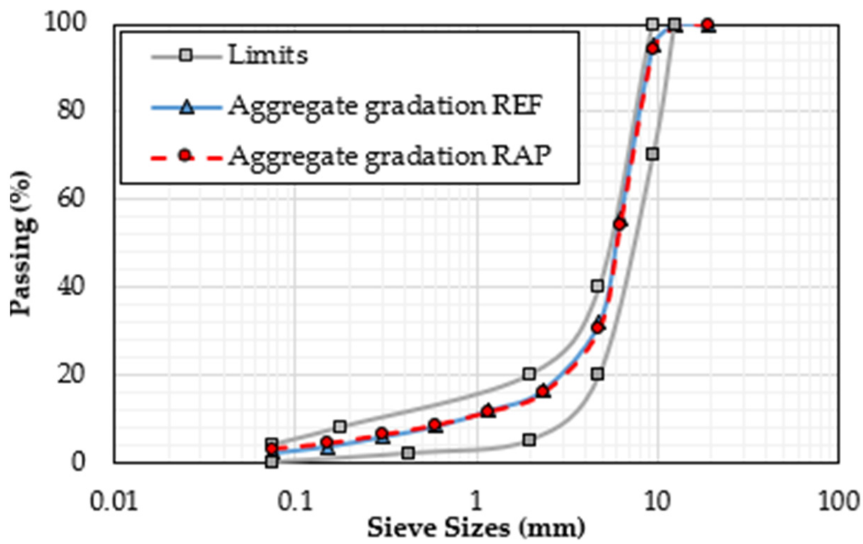

Figure 5. Project particle size curves.

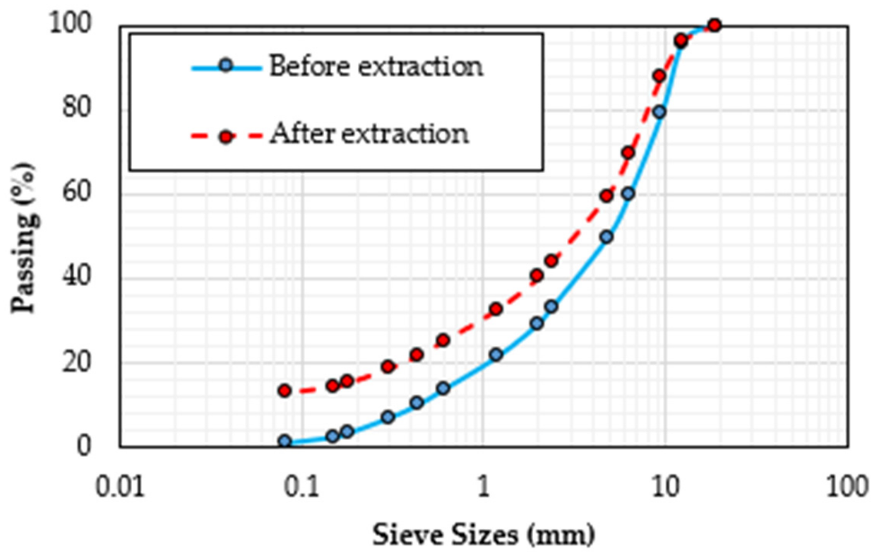

Figure 6. Gradation curves of the RAP (before and after binder extraction).

3.1. Resilient Modulus Tests (RM)

The RM test was conducted following the guidelines of DNIT 135/2018—ME [36], similar to ASTM D7369/2020 [37]. Specimens were conditioned at a temperature of 25 ± 5 °C for 4 h using the Universal Testing Machine (UTM-30) (Figure 7). The maximum load chosen for conducting the RM tests was set to 10% of the load corresponding to the average ultimate load that led to failure and therefore was used to calculate the tensile strength by diametrical compression of the mixtures. The resilient deformation of the mixtures was obtained through the instantaneous horizontal displacement, derived from segmenting the displacement X time curve into three regressions (Equations (1)–(3)) in accordance with DNIT 135/2018 [36].

$$\mathrm{IM} = \frac{P}{|\Delta H_{ist}|t}\,(0.27 + \mu_{ist}) \tag{1}$$

$$\mathrm{IM} = \frac{P}{|\Delta H_{ist}|t}\,(0.23 + 0.78_{ist}) \tag{2}$$

$$\mathrm{IM} = \frac{P}{|\Delta H_{ist}|t}\,(0.14 + 0.45\mu_{ist}) \tag{3}$$

where

IM = is the instantaneous modulus, expressed in MPa;
P = is the cyclic load, expressed in N;
ΔH_{ins} = the instantaneous horizontal displacement, expressed in mm;
t = is the height (thickness) of the specimen, expressed in mm;
μ_{ins} = is the instantaneous Poisson's ratio.

RM is determined by Equation (4) below:

$$\mathrm{RM} = \frac{P}{|\Delta H|h}\,(0.2692 + 0.9976\mu) \tag{4}$$

where

RM = resilient modulus (MPa);
P = the cyclical load (N);
ΔH = horizontal displacement (mm);
h = specimen height (mm);
μ = Poisson ratio (estimated at 0.3 for tests at 25 °C).

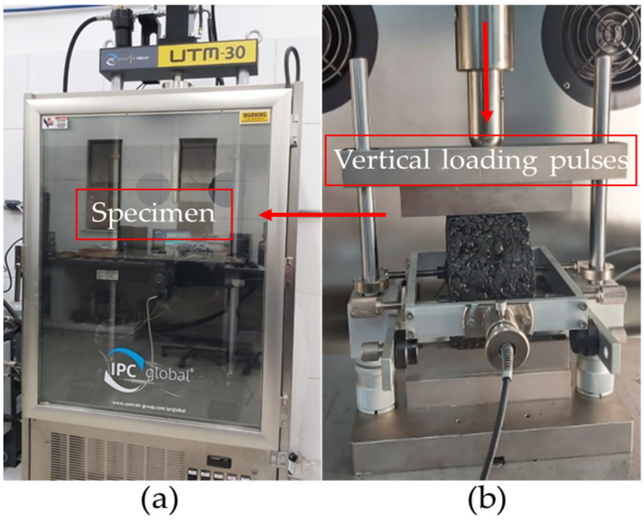

Figure 7. (**a**) Climatic chamber—UTM, (**b**) test in progress.

3.2. Complex Modulus from Compressive Haversine Loading (E*)

The complex modulus of the mixtures was obtained according to the testing procedure of AASHTO T342-11 [41] using the hydraulic equipment UTM-30, with displacements monitored by three LVDTs (Linear Variable Differential Transducers) positioned vertically on the specimens, as shown in Figure 8. Three specimens of each mixture were tested, with an estimated precision of ±12%. The tests were conducted at different temperatures (−10 °C, 4.4 °C, 21.1 °C, and 37.8 °C) and frequencies (25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, and 0.1 Hz). However, due to the high deformability of the porous mixtures, it was not possible to perform the test at 54.4 °C, as established in the standard. The test consisted of applying loads that induced deformation amplitudes (peak-to-peak) within the material's linear viscoelastic domain (about 50–75 μm/m).

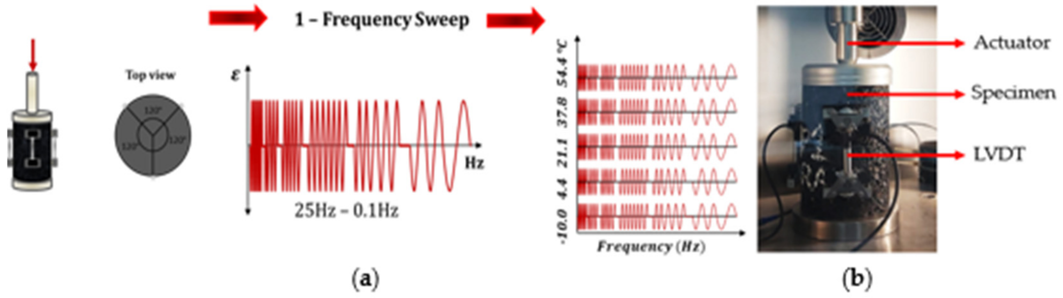

Figure 8. (**a**) Loading frequencies and test temperatures, (**b**) test in progress.

Based on the Time–Temperature Superposition Principle (TTSP), it is possible to establish a relationship between the increase in temperature of asphalt materials and the decrease in the frequency at which the load is applied, and vice versa [42,50]. This allows for the construction of the master curve, which illustrates the behavior of the mixtures from a reference temperature (in this paper, Tref = 21.1 °C), predicting the stiffness of the material at various reduced frequencies (Fred). The modulus value is determined based on the interpretation and mathematical expressions of the 2S2P1D model, with Equation (5) highlighting the key constants used in its calculation.

$$E^{*}\ (i\omega\tau) = E_{\infty} + \frac{E_0 - E_{\infty}}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-h} + (i\omega\beta\tau)^{-1}} \tag{5}$$

where

E_{∞} = Asymptotic modulus as the frequency approaches zero;
E_0 = Asymptotic modulus as the frequency approaches infinity;
δ, β = Dimensionless constants;
k, h = Exponents associated with parabolic dampers;
ω = angular frequency
τ = characteristic time determined using time-temperature shift factors at a given temperature, calibrated using τ_0 as the reference characteristic time.

3.3. Complex Modulus from Impact Resonance (IR)

The impact resonance test was conducted using specific equipment designed for such tests [45] in order to hit specimens placed on foam to simulate free vibration on the surface of the specimens. The circular ends of the specimens were rectified for better positioning of the accelerometer and impact hammer, as shown in Figure 9. The mechanical action of the hammer involves delivering five impacts that excite the specimen in the longitudinal direction towards the accelerometer. The signals for each hammer impact and the accelerometer output signal are measured in both the time and frequency domains. With these results, it was then possible to obtain the FRFs, as discussed in the work by Carret [47]. It is also important to note that, for asphalt mixtures, the impact resonance test was conducted at three temperatures (4.4 °C, 20 °C, and 37.8 °C).

For asphalt mixtures, it is necessary to use an inverse analysis after obtaining the experimental FRFs as established by [45]. To do this, it is necessary to use finite element software to carry out modeling to obtain an optimized FRF by varying the linear viscoelastic parameters of the material [33–45]. In other words, using an iterative process, parameters are determined for the 2S2P1D rheological model, which has 12 variables and characterizes the material’s stiffness behavior for any frequency and temperature. Of the 12 variables in question, only four undergo the interactive process of inverse analysis, as they initially have a greater influence on the behavior of the mixtures. It is also important to note that the interactive process only takes place for the peak of the experimental FRF, where 10 points around the resonance frequency are arbitrated. This interactive process then uses the calculated value of the error between the experimental and optimized response and then determines the values of the viscoelastic model variables that represent the material so that the error is minimized. Through these steps, it is possible to obtain the master curve for porous mixtures with the optimum parameters for each temperature, and the complex modulus values can be calculated for frequencies close to the resonance frequency, constructing parts of the master curve for each test temperature and using the Time–Temperature Superposition Principle (TTPS) [47].

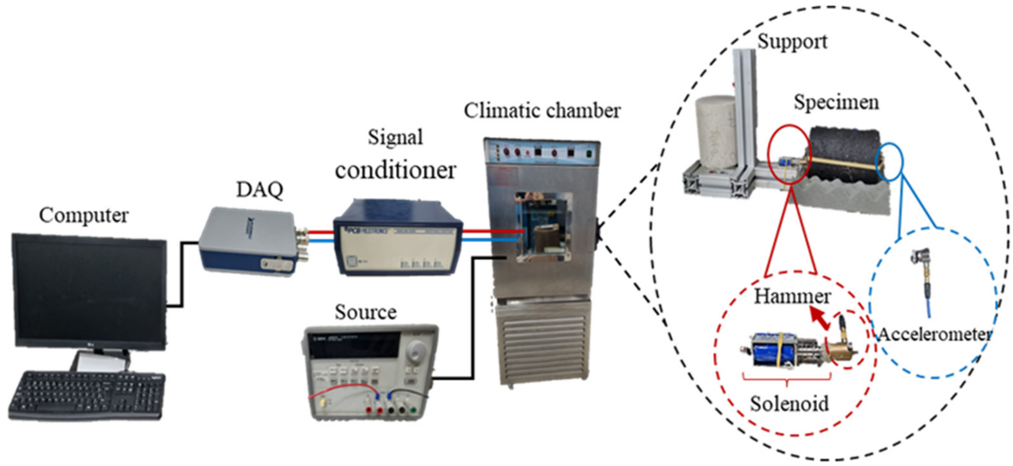

Figure 9. Schematic representation of the IR test.

4. Results and Discussions

4.1. Resilient Modulus (RM)

Figure 10 presents the results of the resilient modulus for the two analyzed mixtures (Reference Mixture—PFC-REF and Recycled Mixture—PFC-RAP). The reference mixture exhibited an average RM of 3209 MPa, whereas the RAP mixture demonstrated an average of 2221 MPa. These values are consistent with those reported by [17], who investigated a porous asphalt mixture containing 15% RAP and found RM values of approximately 2915 and 2722 MPa for the reference and recycled mixture, respectively.

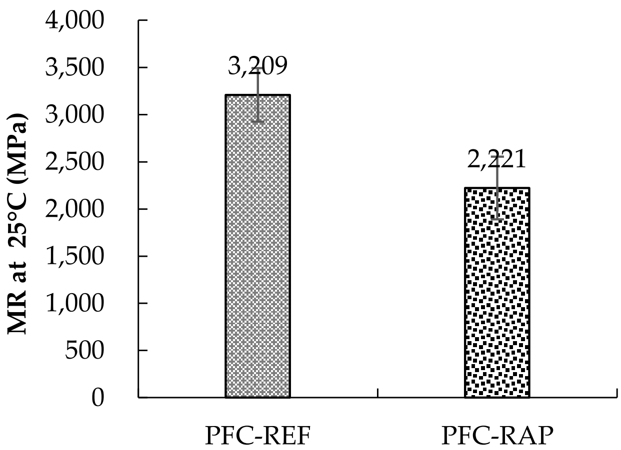

Figure 10. Resilient modulus results at 25 °C.

In contrast, studies conducted by other researchers [1,51] on porous asphalt mixtures containing 4.5% binder content reported higher RM values compared to those observed in this paper, with values in the range of 4760 MPa and (6098–5219 MPa, Range IV and V of the DNER), respectively. This can be attributed to the presence of the rubber-modified asphalt binder, which tends to decrease the stiffness of the mixtures [10].

Additionally, the high void content also contributes to the reduction in the properties of porous asphalt mixtures. These findings are corroborated by laboratory tests conducted in Argentina, where RM values of 2200 MPa were obtained for porous mixtures, equivalent to 60% of the values observed for dense mixtures [52].

Hammes and Thives found RM values of 2764 MPa in a porous asphalt mixture produced with highly modified asphalt binder (HiMA), which is considered high for this type of mixture [53]. They attribute this performance to the binder used. Other researchers, [54,55], also reported RM values for porous mixtures produced with SBS-modified binders, in the range of 1875 and 3281 MPa, respectively.

4.2. Complex Modulus (E)*

The experimental results were analyzed and modeled using the 2S2P1D model to construct the following representations illustrated subsequently: master curves of complex modulus (Figure 11), Cole–Cole space (Figure 12), master curve of the phase angle with the 2S2P1D modeling (Figure 13), and Black Diagram (Figure 14). The values from the 2S2P1D model and the constants of the William, Landel, and Ferry (WLF) model, used for property translation at different temperatures and for the assembly of master curves, are presented in Table 1.

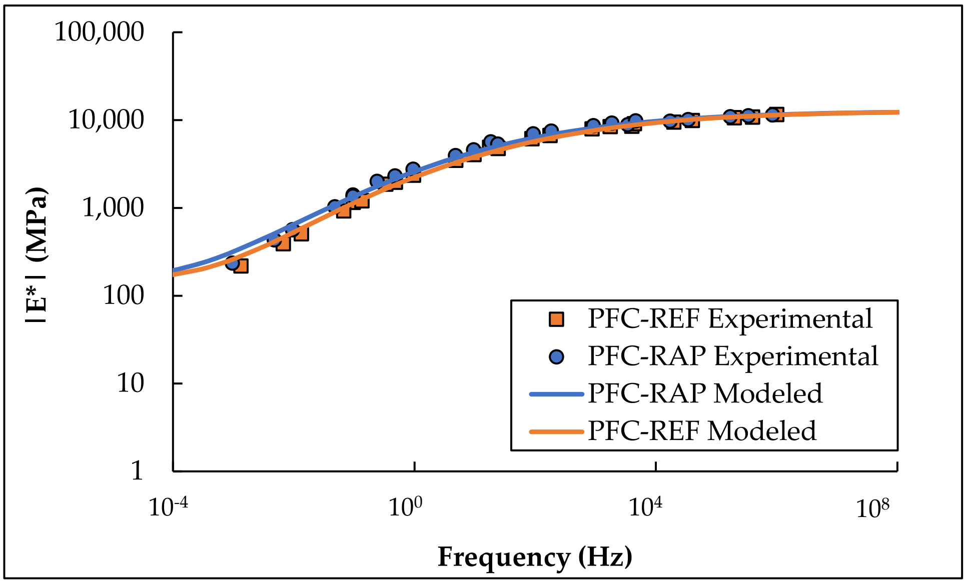

Figure 11. Comparison of the modulus master curves of the mixtures.

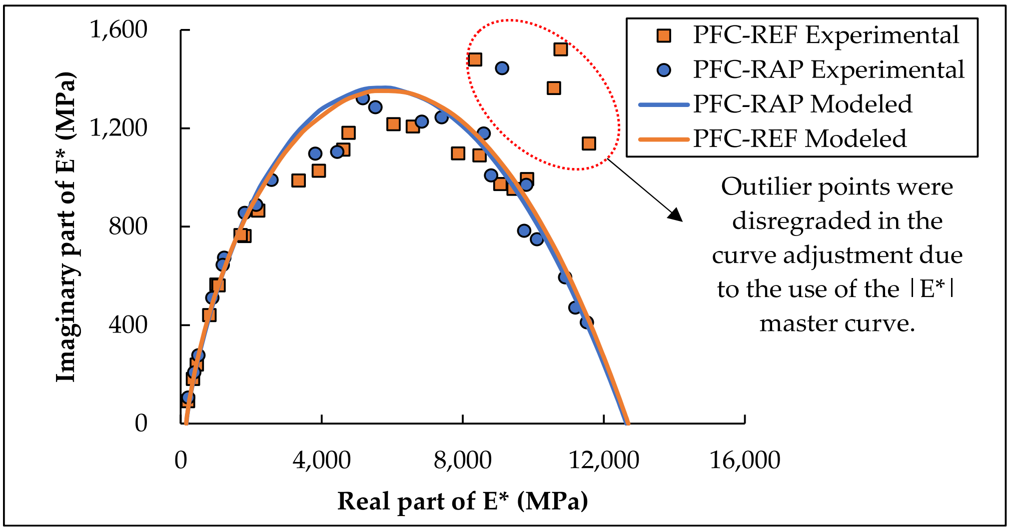

Figure 12. Complex modulus represented in Cole–Cole curves.

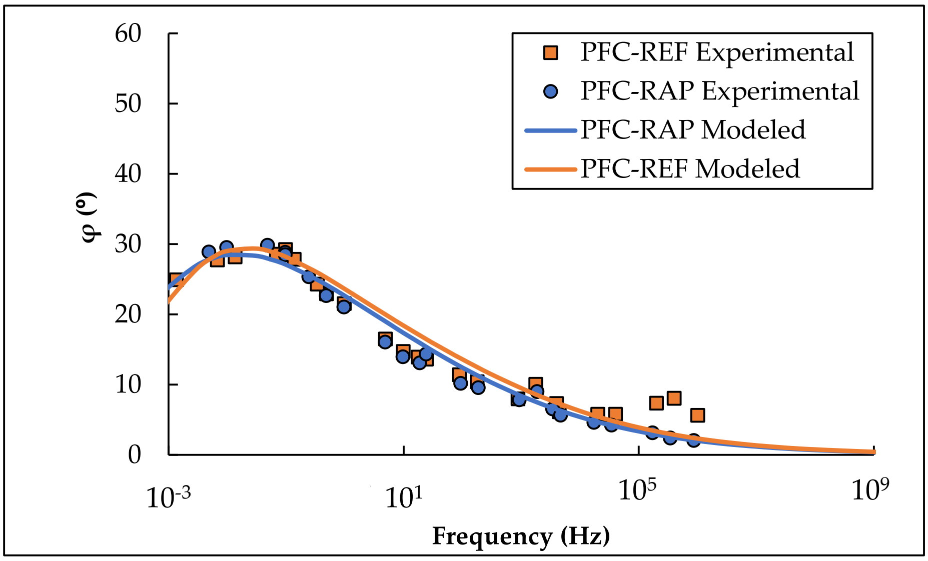

Figure 13. Master curves of the phase angle of the mixtures.

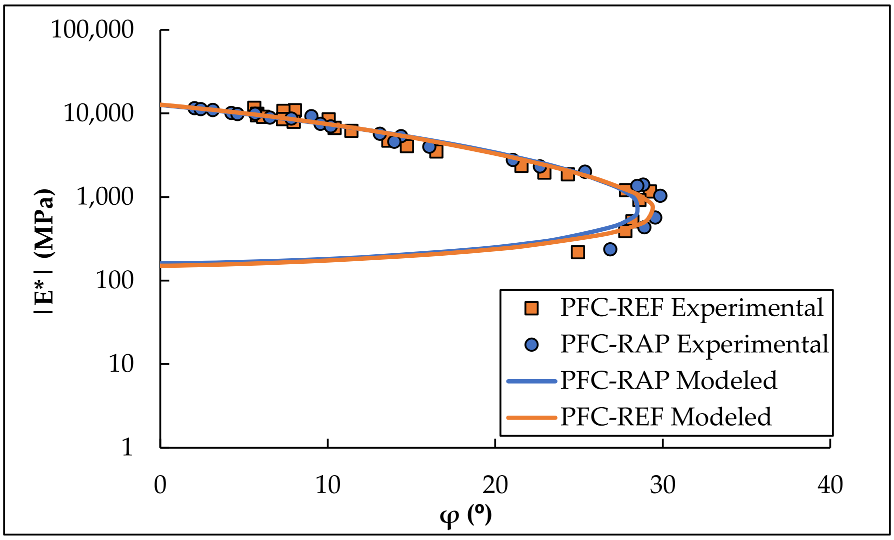

Figure 14. Black diagram with the 2S2P1D modeling.

Table 1. Parameters of the 2S2P1D model and WLF values of C1 and C2.

Mixtures	*E**							WFL	
	E_∞ (MPa)	E_0 (MPa)	*k*	*h*	Δ	tE (s)	*β*	C1	C2
PFC-REF	150	12,700	0.25	0.56	3.24	0.085	250	20.31	167.02
PFC-RAP	160	12,650	0.24	0.51	2.45	0.080	150	29.44	231.76

In Figure 11, the master curves of the mixtures are shown. It can be observed that the complex modulus increases with the frequency for both mixtures evaluated.

These results are attributed to the reduced loading time, during which elastic deformations predominate in the material [51,56]. These findings are consistent with the conclusions of [57], who investigated the viscoelastic behavior of porous asphalt mixtures and observed a decrease in the complex modulus at higher temperatures and lower loading frequencies.

Considering the complex moduli obtained for the mixtures, it is evident that they have structural functionality. The values found are comparable to those reported by Manrique-

Sanchez and Caro [28], which corresponded to from 50% to 66% of the typical moduli for dense mixtures (3000 to 4000 MPa).

When analyzing the Cole–Cole space, it was observed that the recycled mixture (PFC-RAP) exhibited a smaller elastic portion (Real E^*) compared to the reference mixture (PFC-REF), as shown in Figure 12. However, this difference was not significant. This phenomenon can be attributed to the binder (asphalt–rubber), which tends to reduce the stiffness of asphalt mixtures [10]. Although the RAP had little influence on the stiffness of the mixtures, a slight increase in stiffness was still observed for PFC-RAP, which was expected due to the presence of the oxidized binder in the RAP [58,59].

Figure 13 displays the master curves of the phase angles of the investigated mixtures. Both mixtures exhibit similar viscoelastic behavior. However, the reference mixture shows a higher phase angle at nearly all frequencies, except at lower frequencies where the RAP exhibits a higher phase angle. This phase angle behavior supports the complex modulus results, indicating higher stiffness for the RAP mixture.

The phase angles of the mixtures at −10 °C exhibited some variations compared to the experimental points of the 2S2P1D model. However, the mixtures were adjusted to the model based on the master curve of the complex modulus, disregarding the phase angle. Overall, the experimental points demonstrate a good fit between the observed data and the model used.

The Black Diagram is a graphical representation of the complex modulus $|E^*|$, on a logarithmic scale, as a function of the phase angle (φ) for different temperatures. Analyzing the results of this representation, shown in Figure 14, a higher phase angle was obtained for the RAP mixture at high temperatures, while the reference mixture demonstrated a lower phase angle, indicating a more elastic component compared to the recycled mixture. Regarding the complex modulus, it tends to decrease for both mixtures as the temperature increases.

4.3. Impact Resonance Tests (IR)

The analysis of the impact resonance test results enabled the construction of master curves for the mixtures at three different temperatures considered during the test (4.4 °C, 20 °C, and 37.8 °C). Figure 15a presents the master curves reflecting the stiffness of the mixtures. An increase in stiffness with increasing frequency and decreasing temperature is observed, similar to the complex modulus test. These results resemble the values found for E^*, demonstrating the accuracy of both tests in characterizing the viscoelastic properties of porous asphalt mixtures.

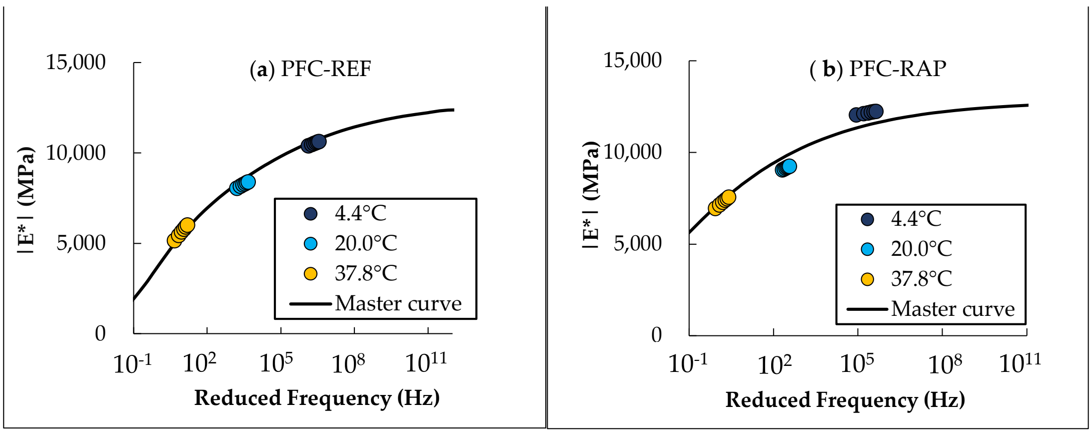

Figure 15. Master curve: (**a**) mixture PFC-REF (**b**) mixture PFC-RAP.

Regarding the mixture PFC-RAP, an increase in stiffness was observed compared to the reference mixture, even at elevated temperatures, as shown in Figure 15b. This phenomenon can be attributed to the presence of aged binder in the RAP. These findings corroborate the studies of [19], which identified higher stiffness in porous mixtures of PFC-RAP. On the other hand, the RM results were lower for the recycled mixture, which may be associated with the test conditions (single temperature and loading frequency). However, it is important to note that the stiffness results for both mixtures in the complex modulus and impact resonance tests were higher for the mixtures containing RAP.

5. Conclusions

This paper evaluated the stiffness of two porous asphalt mixtures: a reference mixture and one containing 10% RAP (Reclaimed Asphalt Pavement), using an ND test and two traditional tests. It also investigated three different methods for stiffness investigation: resilient modulus, complex modulus from compressive haversine loading, and complex modulus from impact resonance tests. Based on the results, the following is concluded:

- The addition of RAP to the mixture impacted the mechanical and viscoelastic properties of the investigated mixture, as it was observed that the mixture with RAP showed reduced elasticity and increased viscosity compared to the reference mixture. This suggests an influence of the oxidized binder of RAP on the increase in mixture stiffness, as indicated in the literature.
- The mixture with RAP exhibited higher stiffness at all analyzed temperatures, confirming the influence of RAP on improving mechanical properties, despite its lower elasticity compared to the reference mixture.
- Analogous behaviors regarding the stiffness of the investigated mixtures were obtained from traditional compressive tests and from impact resonance tests, indicating the possibility of applying an alternative methodology based on vibrational mechanics for the characterization of porous asphalt mixtures. This was not observed for the RM test, which may lack more fundamental aspects of the characterization of asphalt mixtures and also be disturbed by the reduced specimen size.

These findings contribute to the field of asphalt mixtures and pavement structural design by providing a more detailed understanding of the increase in stiffness enhancement induced by the RAP inclusion in porous asphalt mixtures. Additionally, it allows the development of new approaches for characterizing the viscoelasticity of porous asphalt mixtures.

Some suggestions for future developments of this research could include investigating the stiffness of mixtures with different RAP contents beyond 10%. In addition, other ND techniques could be incorporated, such as the use of ultrasonic wave propagation tests. For the impact resonance test, more temperatures could be checked for a master curve with more points. Additionally, it is suggested to increase the specimen size and conduct a statistical analysis for a more in-depth discussion.

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