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The Influence of Reclaimed Asphalt Pavement on the Mechanical Performance of Bituminous Mixtures. An Analysis at the Mortar Scale

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Abstract: The main characteristics of bituminous mixtures manufactured with a considerable amount of reclaimed asphalt pavement (RAP), compared to conventional mixtures, are a reduction in workability, an increase in stiffness, and a loss of ductility, due to the presence of the aged bitumen contained in the RAP particles. To minimize these impacts, softer binders or rejuvenators are commonly used in the design of these mixtures in order to restore part of the ductility lost and to reduce the stiffness. In spite of previous investigations demonstrating that the mortar plays an essential role in the workability, long-term performance, and durability of bituminous mixtures (where cracking, cohesion, and adhesion problems all start at this scale), not many studies have assessed the impacts caused by the presence of RAP. In response to this, the present paper analyzes the workability, fatigue performance, and water sensitivity of bituminous mortars containing different amounts of RAP (from 0% to 100%) and rejuvenators. Mortar specimens were compacted using a gyratory compactor and studied via dynamic mechanical analysis under three point bending configuration. The results demonstrated that the presence of RAP reduces the workability and ductility of asphalt mortars. However, it also causes an increase in their stiffness, which induces a more elastic response and causes an increase in their resistance to fatigue, which could compensate for the loss of ductility. This aspect, together with the low water sensitivity shown, when using Portland cement as an active filler, would make it possible to produce asphalt materials with high RAP contents with a similar long-term mechanical performance as traditional ones. In addition, the use of rejuvenators was demonstrated to effectively correct the negative workability and ductility impacts caused by using RAP, without affecting the fatigue resistance and material adhesion/cohesion.

Keywords: bituminous mixtures; RAP; rejuvenators; sustainability; fatigue; water sensitivity

1. Introduction

Sustainability is currently a large global concern and a concept which involves balance between the environment, society, and the economy. One of its principal aims in developed countries is to achieve a resource-efficient and low carbon economy, with a focus on improving waste management across all life cycle stages and reducing energy consumption. In recent years, a key challenge has been to incorporate this concept into different human activities, where the construction and transportation sectors play a significant role. Therefore, having a sustainable road system is a necessity for solving the mobility needs for a safe and healthy society, while not incurring a negative impact on the environment and ensuring the technical and economic feasibility of projects [1]. This can be addressed through the eco-design of solutions used for the construction of these infrastructures [2,3].

In response to these needs, the use of reclaimed asphalt pavement (RAP) has the potential to become a viable and attractive alternative material for road construction [3,4]. The use of RAP presents environmental and economic benefits, such as the reduction of contaminant emissions, natural resource exploitation, raw material transportation, mixture production costs, energy consumption, fuel usage, and pressure on landfill disposal sites [5].

When properly crushed and screened, RAP consists of high-quality aggregates for new asphalt pavement layers, which can be used to replace an amount of virgin aggregate and asphalt binder in the mixture [6]. However, the presence of high amounts of RAP in bituminous materials could provide some drawbacks, such as loss of ductility or a lower cohesion inside the mixture (due to the higher stiffness and lower adhesion provided by the aged bitumen contained in the RAP). To compensate for these drawbacks, soft new bitumen can be used (which would be blended with the aged one to recompense for its deteriorated rheological properties), or rejuvenating agents [7] can be added to restore part of the chemical composition of the aged binder (which has been lost due to the oxidation and volatilization of the lighter compounds, [8]). Traditionally, asphalt rejuvenators are composed of the molecular fractions with the lowest weight found in asphalt binders (saturates and aromatics) [9]. Nonetheless, in recent years, new types of rejuvenators from other sources (most notably from plants) have started to emerge. Depending on their nature, these additives can interact differently with the aged binder contained in the RAP, leading to variations in the performance of the mixture [10]. Therefore, while these additives could potentially reduce the penetration or viscosity of an aged binder (since they are oil-based), not all rejuvenators would exert the same effect on the rheological properties of the aged binder, which will govern the final mechanical performance of the asphalt mixture [11].

Research concerning RAP has been especially prominent over the last few decades due to the increase in road transportation distances (due to the globalization of trade) and the reduction of investment in road conservation (due to the economic situation), which have resulted in the acceleration of road network deterioration around the world [12]. Rehabilitation works, consisting of the removal of the deteriorated upper layers of the pavement and their replacement using new asphalt materials, have become one of the most common and important activities for road administrations. However, these works have caused the development of an environmental problem: RAP waste is increasing considerably, while its potential for use is still low, as its understanding as an employable recycled material is still limited, so it cannot yet be incorporated in high quantities for new asphalt surface layers where high mechanical and environmental resistance is needed.

While scientific advances have been made in recent decades for rejuvenating agents, the use of high amounts of RAP in the construction of asphalt surface layers is still a challenge. Due to their lower workability, ductility, and inner cohesion, asphalt materials manufactured with high amounts of RAP tend to fail prematurely due to pathologies such as cracks or stripping when they are directly exposed to the impacts of traffic, rain, temperature, etc. [13]. Both pathologies are strongly related to asphalt mortar characteristics (the part of the mixture composed of binder, filler, and sand [14]), as this part plays a very important role in the mechanical performance of asphalt surface layer mixtures such as BBTM (Betón Bitumineux Très Mince, EN-13108-2 [15]), SMA (Stone Mastic Asphalt, EN-13108-5 [16]) or PA (Porous Asphalt, EN-13108-7 [17]). Thus, the understanding of the effect of RAP and rejuvenating agents at this scale would be of crucial importance for the successful implementation of RAP at high recycling rates in the manufacture of asphalt surface layers.

Within this framework, the main objective of this study is to evaluate the effects of RAP and rejuvenators on the workability, fatigue performance, and water sensitivity of hot recycled bituminous mortars by using the dynamic mechanical analyzer (DMA).

2. Materials and Methods

2.1. Materials

During this study, four asphalt mortars were evaluated (Table 1): a reference mortar without RAP that was designed according to the characteristics of the mortars used for BBTM mixtures (composed of 64.4% of sand, 27.6% of filler, and 8.0% of asphalt binder, over the total weight of the mortar); two mortars with RAP, replacing part of the natural aggregates used in the reference mortar (one with a medium RAP content and other with a high RAP content); a mortar with a high RAP content, and a rejuvenating agent. The materials used for the manufacture of the mortars were a conventional asphalt binder (B35/50), limestone sand (with a maximum aggregate size of 2 mm and washed to remove filler particles contained in it), cement filler, RAP milled from a road after 20 years of service life (using only the fraction lower than 2 mm), and a liquid organosilane-based asphalt rejuvenator additive at a nanometric scale (which restores the aged bitumen closer to the maltenes phase, by capturing asphaltenes and/or polar oxidized molecules and surrounds them with nonpolar tails). It was decided to use the reference mortar of an asphalt mixture where this fraction plays an essential role and to manufacture it with a base asphalt binder in order to avoid other variables (such as the presence of polymers), which could interfere with properly studying the interaction between a virgin bitumen and an aged one at this scale. The main characteristics of these materials are summarized in Tables 2–4 and Figure 1.

Table 1. Components of the mortars evaluated during this study.

Components	Mortar without RAP (MRef)	Mortar with Medium RAP Rate (MM)	Mortar with High RAP Rate (MH)	Mortar with High RAP Rate + Rejuvenator (MH+R)
Asphalt binder B35/50 (% over the total weight of the mortar)	8.0	5.5	3.0	3.0
Limestone Sand (% over the total weight of the mortar)	64.4	35	0.0	0.0
Cement Filler (% over the total weight of the mortar)	27.6	22.5	15.0	15.0
RAP (% over the total weight of the mortar)	0.0	37.0	82.0	82.0
Rejuvenating agent (% over the total weight of the binder contained in the RAP)	0.0	0.0	0.0	0.15

Table 2. Properties of the sand used in the study.

Parameter	Sieve (mm)	Percentage of Material Passing (%)
Granulometry (EN 933-1)	*2*	100
	0.5	18
	0.063	0
Sand equivalent (EN 933-8)		77.0
Density (Mg/m^3) (EN 1097-6)		2.77
Water absorption (%) (EN 1097-6)		0.88

Table 3. Properties of the reclaimed asphalt pavement (RAP) used in the mortars.

Parameter	Sieve (mm)	Percentage of Material Passing (%)
Granulometry (EN 933-1)	*2*	100
	0.5	54
	0.063	14.7
Percentage of asphalt bitumen extracted from RAP (%)		5.8
Penetration at 25 °C of the asphalt bitumen extracted from RAP (dmm, EN 1426 [18])		16
Softening point of the asphalt bitumen extracted from RAP (°C, EN 1427 [19])		71

Table 4. Characteristics of the cement filler used in the mortars.

Parameter	Sieve (mm)	Percentage of Material Passing (%)
Granulometry (EN 933-1)	2	100
	0.5	100
	0.125	100
	0.063	96.0
Density (Mg/m^3) (EN 1097-3, annex A)		3.12

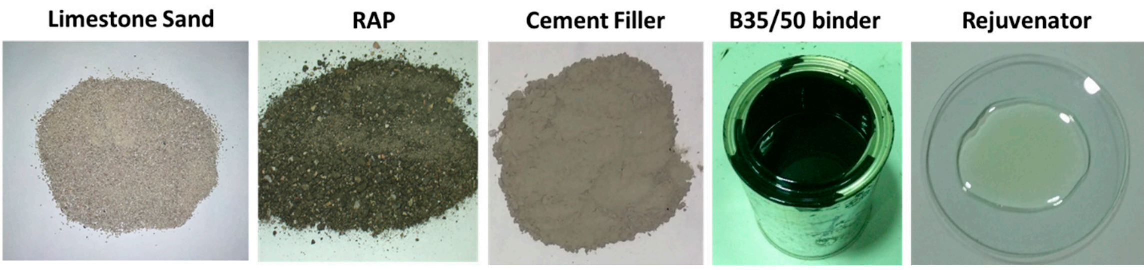

Figure 1. Materials used for the manufacture of the mortars studied.

The specimens used during this study were manufactured by heating the aggregates (sand, filler, and/or RAP) and binder to a temperature of 165 °C. The control of the temperature of the samples was reviewed throughout the manufacturing and compaction process using a thermal imaging camera.

According to previous studies [20], the asphalt mortars were manufactured at a temperature of 165 °C and cylindrical specimens of 150 mm diameter and 40 mm high were compacted to an air void content close to 0% using a gyratory compactor (EN-12697-31 [21]) at a temperature of 155 °C. By minimizing the air voids content, the adhesiveness between aggregates and bitumen, as well as the interaction between aged and virgin binder, can be studied without the influence of this variable. Following on, cylindrical specimens were sawed into pieces 8.5 mm × 8.5 mm × 50.0 mm large to produce prismatic specimens for testing in the dynamic mechanical analyzer (DMA). Figure 2 displays the specimens manufactured, and Table 5 shows the density of the different mortars tested.

Table 5. Densities of the mortars tested.

Mortar	Mortar without RAP (MRef)	Mortar with Medium RAP Rate (MM)	Mortar with High RAP Rate (MH)	Mortar with High RAP Rate + Rejuvenator (MH+R)
Apparent Density (kg/m^3) EN-12697-6 [22]	2399	2406	2261	2247

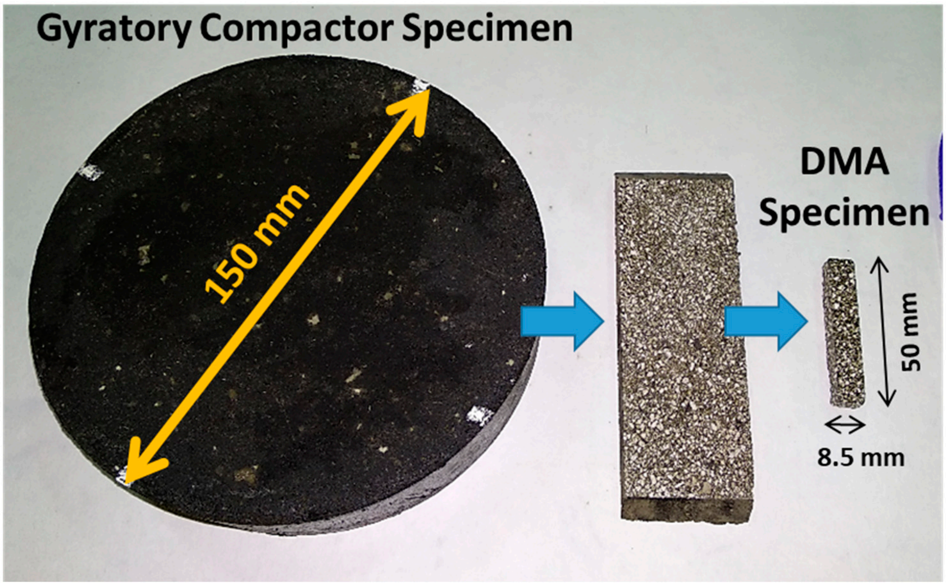

Figure 2. Specimens used in the dynamic mechanical analyzer (DMA) tests.

2.2. Methods

The present research study has the objective of studying the workability, fatigue resistance, and water sensitivity of asphalt mortars manufactured with different dosages of RAP and rejuvenators. The workability of the specimens was assessed based on the compaction curve (density vs. number of gyros) obtained from the gyratory compactor. In this curve, three different regions can be observed (Figure 3): The first region is associated with the contact between particles (where density increases fast and the compaction efficiency is related to the initial organization of the aggregates); the second region is associated to the real compaction of the material (once the aggregates are in contact, the compaction energy reorganizes them and causes the reduction of the air voids in the material); the third region is associated to the residual compaction of the material (where density grows very slowly, probably due to punctual aggregate movements or aggregate fractures). Based on the results obtained during the compaction of each mortar, the workability parameter (W-P) is calculated in the middle part of the second region of the curve (where compaction energy is effective), which is measured as the energy (number of gyros) needed to increase the density of the mortar in 50 kg/m^3. As this parameter increases, the workability of the mortar decreases, therefore making its compaction more difficult and the probability of stripping or fatigue-related problems higher. As a reference, it can be said that the end of the first region is determined when more than 10 gyros are needed to increase the density of the mortar to 1000 kg/m^3 and the beginning of the third region when more than 80 gyros are needed to increase the density of the mortar to 50 kg/m^3.

Fatigue performance and water sensitivity of asphalt materials with RAP at a mortar scale were studied using the 3-point bending test in the DMA device. Based on these considerations, 18 prismatic specimens of each asphalt mortar were divided into two groups of 9 specimens: a dry and a wet group. The dry group was stored at room temperature in the laboratory (20 ± 5 °C). For the wet group, a vacuum was applied for 30 ± 5 min until reaching a pressure of 6.7 ± 0.3 kPa and then immersed in water at a temperature of 40 °C for 72 h. After that, the 9 specimens of each group were subdivided into 3 subgroups of 3 specimens (each with different strain amplitudes in strain-controlled mode), and each subgroup was tested until reaching fatigue cracking failure (Figure 4) by applying a sinusoidal load at a frequency of 5 Hz at a temperature of 35 °C.

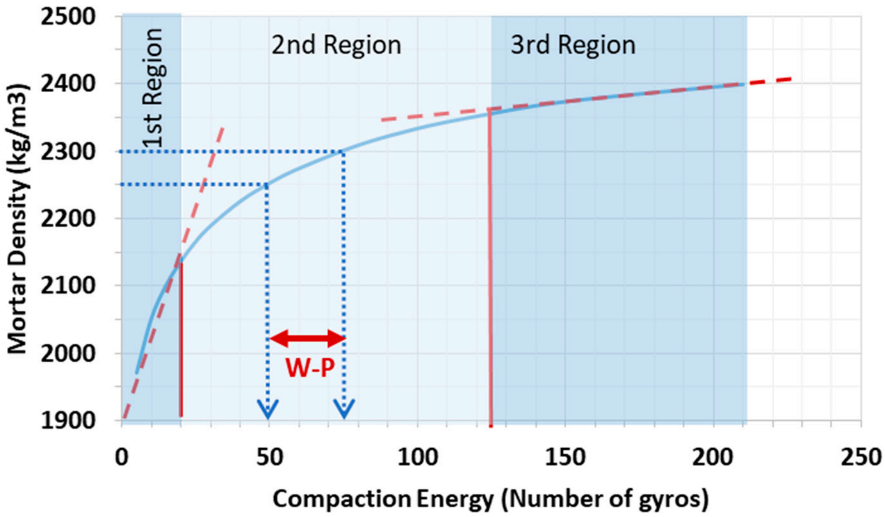

Figure 3. Sketch of the calculation of the workability parameters (W-P) in asphalt mortars.

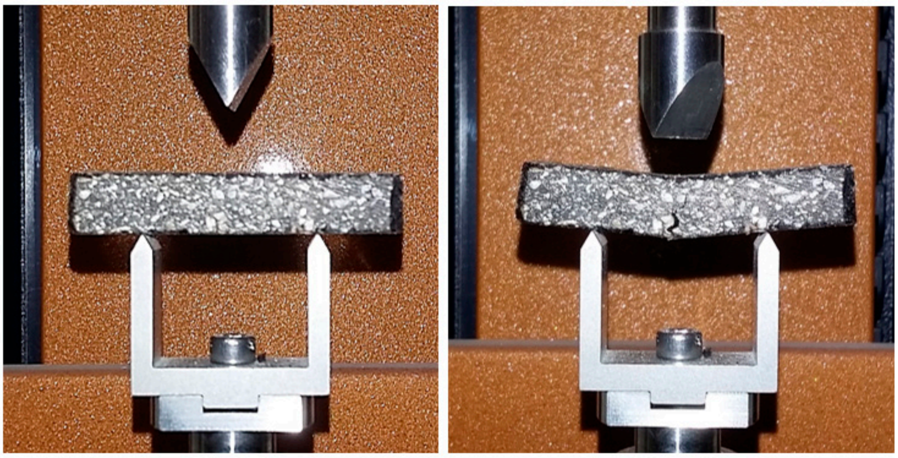

Figure 4. Aspect of the mortar specimen before and after fatigue with the 3-point bending test in the DMA.

Based on the results obtained in the different tests, the fatigue performance was evaluated in both the dry and wet groups, while the water sensitivity was analyzed by comparing the results obtained between the two groups. The fatigue failure criterion used was the creation of a macro-crack in the specimens, which was identified using a camera installed in the DMA device (Figure 5) and by comparing the images recorded with the maximum force measured by the machine in each load cycle (when this force starts to drop down sharply, the macro-crack has appeared, Figure 6). A maximum of 250,000 load cycles was also established as a failure criterion in the event of a macro-crack not occurring.

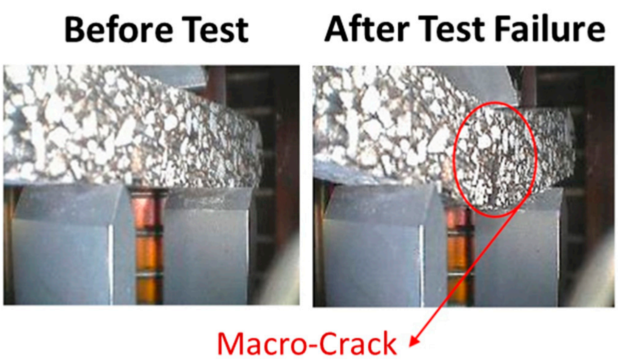

Figure 5. Detail of the crack evolution control performed during the tests.

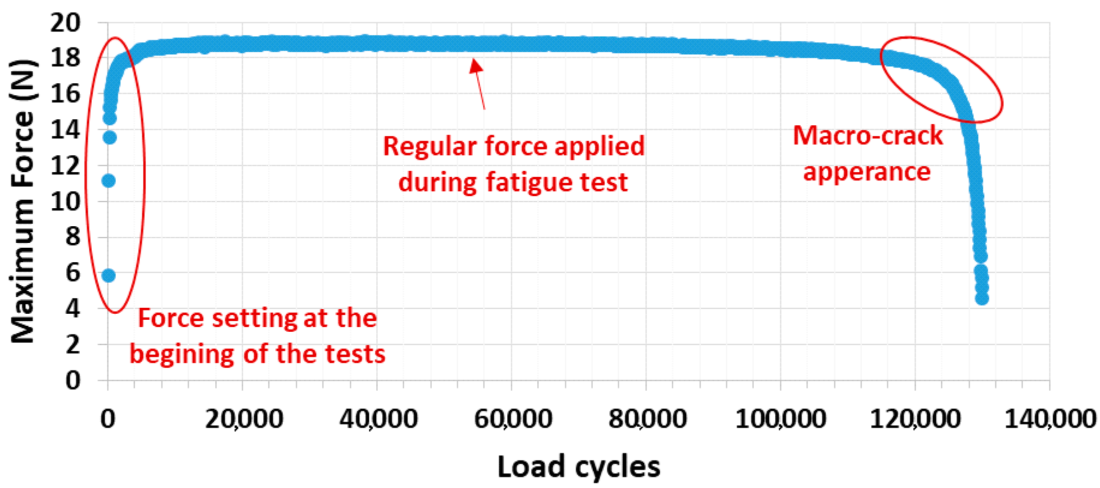

Figure 6. Example of the maximum force vs. load cycles graph obtained from the fatigue 3-point bending test in the DMA.

The mechanical performance of the mortars was evaluated according to the following parameters during the tests:

- Cycles to failure (N_f). Number of load cycles applied to the specimen until the appearance of a macro-crack. This parameter is set to 250,000. If a macro-crack did not appear in the specimens after 250,000 load cycles, a direct measurement of the mechanical resistance of the mortars was taken (the higher the parameter, the more resistant the mortars);
- Stiffness (S). Relationship between the force applied and the deflection produced in the mortar specimen after 1000 load cycles (Figure 7). This stiffness is calculated based on Young's modulus (Equation (1) [23]), which measures the viscoelastic response of the mortar (as it increases, the mortar behaves more elastically), as all the tests has been conducted under the same loading conditions (amplitude and frequency) and temperature;

$$S = \frac{F \times l^3}{4 \times d \times b \times h^3} \quad (1)$$

where F is the maximum force applied at the 1000th load cycle (where the specimen is considered undamaged); l is the length between the supports; d is the deflection displacement measured at the 1000th cycle; b is the width of the specimen; and h is the height of the specimen;

- Maximum deflection (d_{max}). Measured as the accumulated deflection in the specimen before the crack appears (Figure 7), this parameter measures the ductility (ability to deform before cracking) of the mortar studied. As the maximum deflection increases, the ductility of the mortar increases.

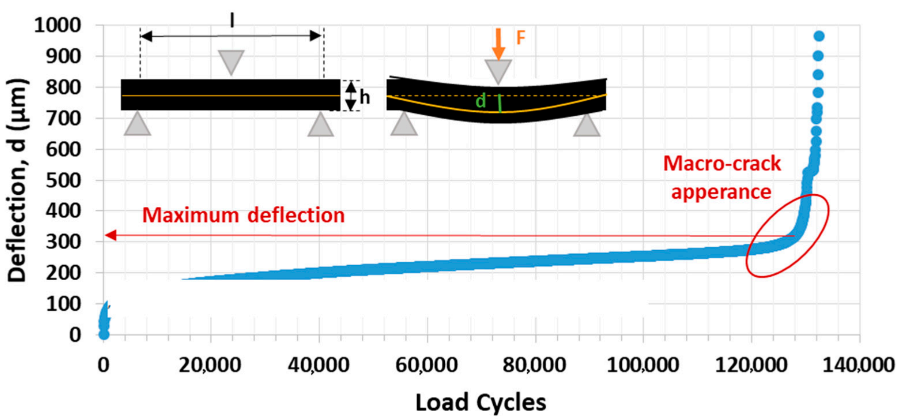

Figure 7. Deflection d (µm) registered during the 3-point bending fatigue tests.

3. Results

Figure 8 shows the compaction curves and the W-P of the different mortars studied. It can be observed that as the amount of RAP increases, the workability of the mortar decreases (having a W-P reduction of 37% when passing from high rates of RAP to medium rates, and of 55% when passing from medium rates to no RAP in the mortar manufacturing), which agrees with the findings of previous research studies at mixture scale [24,25]. This could be due to the lower presence of the original binder, as the RAP content is increased in the mortar (the aged binder contained in the RAP is more viscous than the virgin one, and therefore, its capacity to lubricate the aggregates is smaller). In this respect, it is interesting to highlight that the use of rejuvenators helps to improve the workability of the mortars (having a reduction of 22% in the W-P when using this additive with high rates of RAP), which should be due to its capacity to restore the aged bitumen.

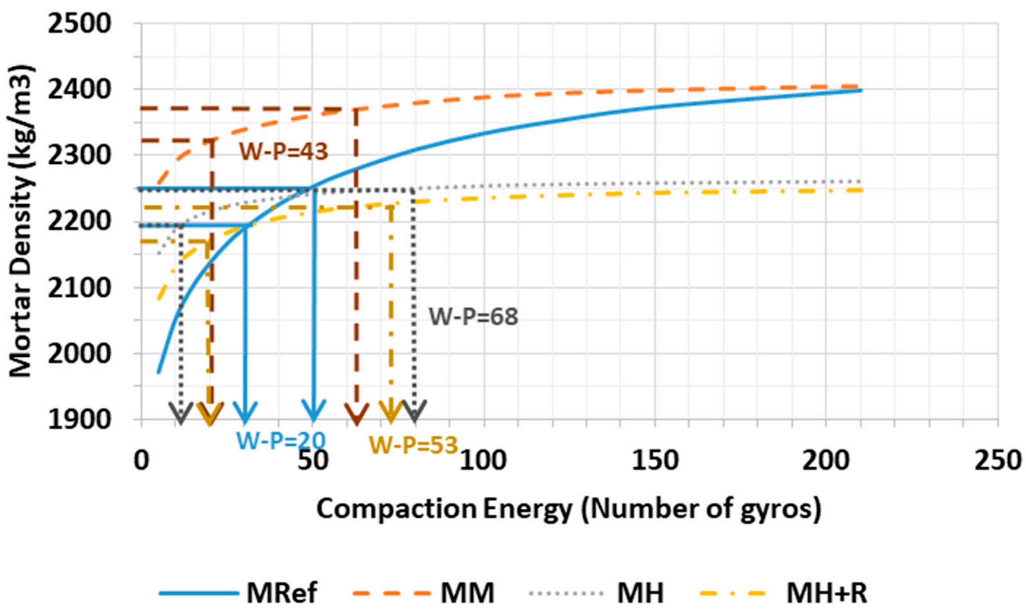

Figure 8. Compaction curves of the mortars studied.

Figure 9 shows the fatigue life of the mortars, studied under dry and wet conditions, as a function of the regular force applied during the test. As can be oberved, the differences found for the fatigue resistances are clearer between mortars as a function of the RAP content, rather than between the dry and wet conditions. This infers that the presence of water does not seem to affect the mechanical performance of asphalt mortars (probably due to the high presence of asphalt binder in the material). Particulary, when portland cement was used as an active filler, the fatigue resistance was found to improve even after the conditioning of the specimens in water. Meanwhile, it can be observed that, for the same load amplitude, as the RAP content is increased in the mortars, the fatigue life is also increased when analyzing the mechanical performance as a function of the RAP content. This aspect could be due to the higher elastic performance of the mortars as the RAP content increases (Figure 10). The results obtained demonstrate that as the RAP content increases, the specimen stiffness also increases (having a reduction in stiffness of around 25% when passing from high RAP quantities to medium ones, and of around 50% when passing from medium RAP amounts to mortars without RAP). By contrast, the ductility (measured in terms of maximum deflection) is reduced (having around a 40% less ductility when using medium RAP rates in the mortar, and around a 70% less when using high RAP rates). Thus, the presence of RAP was found to increase the elastic response of the mortars (which makes them more resistant against mechanical loads) but reduce its ductility (which makes them more brittle and more prone to fracture if large deformations are suffered). The use of rejuvenators could reduce the stiffness of high RAP rate mortars by around 15% and increase their ductility by around 10%, which could indicate that the aged binder contained in the RAP would have been partially reactivated.

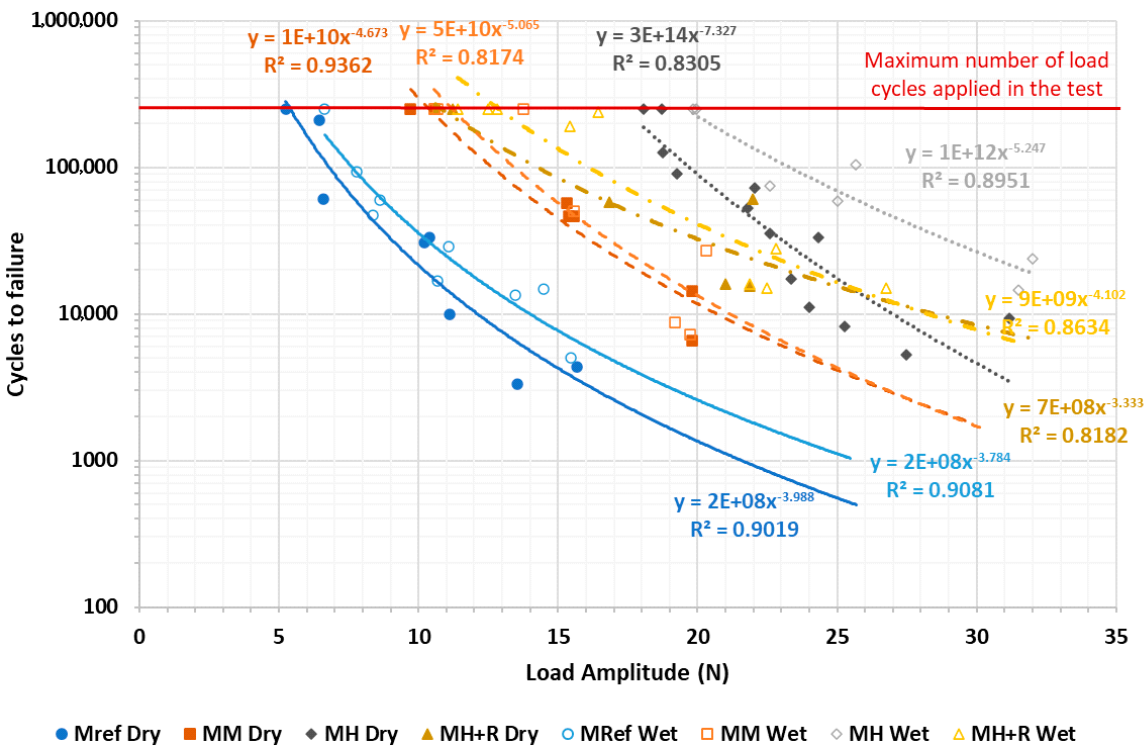

Figure 9. Fatigue laws of the mortars studied in the 3-point bending fatigue test using the DMA.

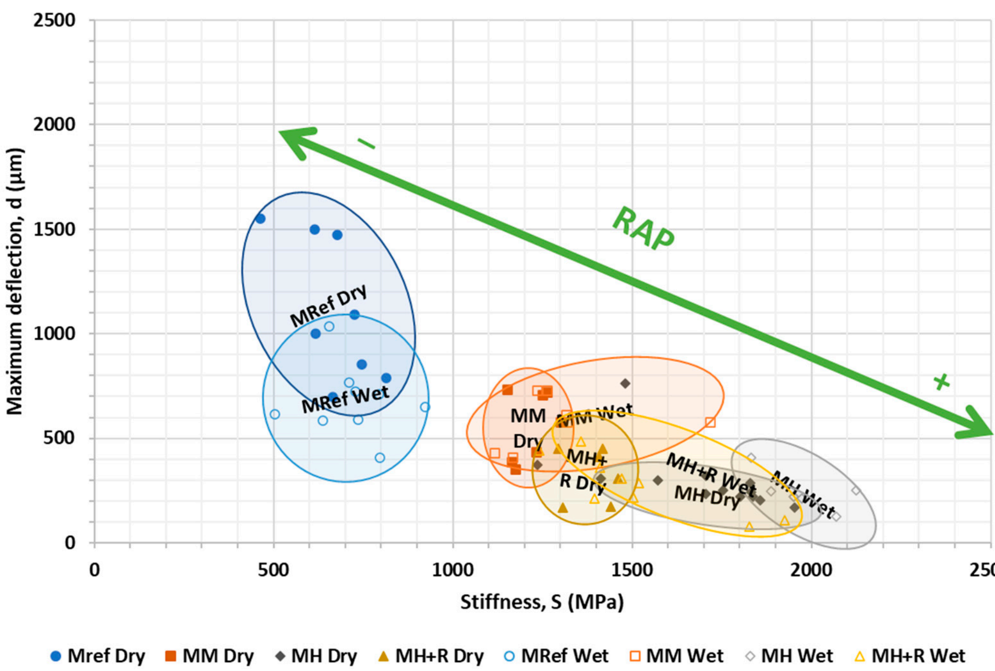

Figure 10. Results of the stiffnesses and maximum deflections measured for the different mortars studied.

Based on the results analyzed, it can be said that the presence of RAP only negatively affects the ductility of asphalt mortars, but that it can also offer mechanical advantages (as its inclusion allows for a more elastic response). Therefore, it is also interesting to analyze the mechanical performance of the mortars for a given level of deflection (Figure 11). In this respect, it is observed that in spite of the larger load amplitude needed to produce the same level of deflection as a larger quantity of RAP is added to the mortar, the number of load cycles that can be resisted is very similar (being even slightly higher in the case of the MH and MH+R). Thus, it can be said that, despite a loss in ductility, the performance of asphalt mortars with RAP would be similar to those manufactured with virgin materials.

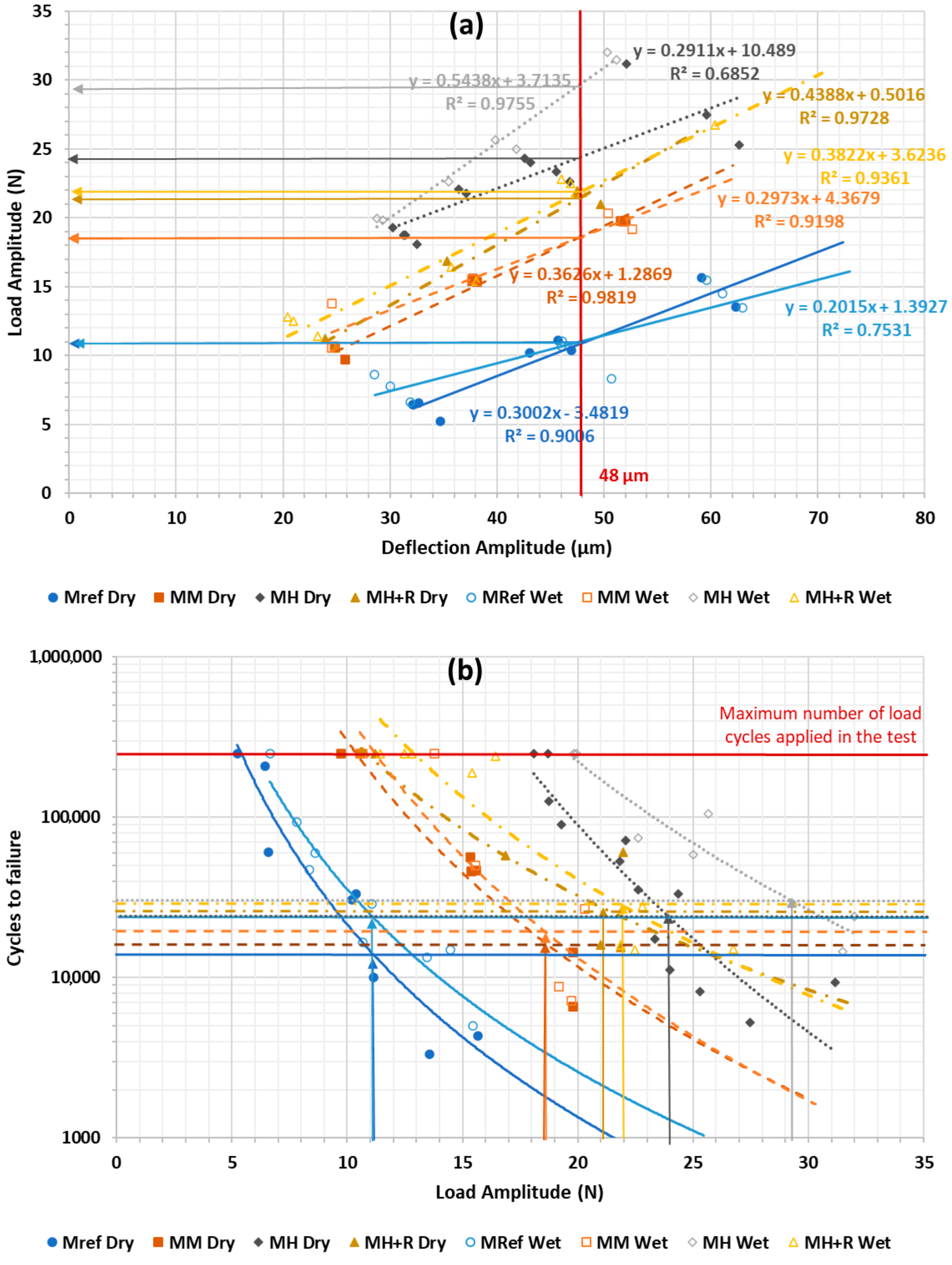

Figure 11. Analysis of the mechanical performance of the mortars studied: (**a**) load amplitude for a given displacement; (**b**) fatigue resistance for a given load amplitude.

4. Conclusions

This paper presents the results obtained in a research project focused on analyzing the workability, fatigue resistance, and water sensitivity of asphalt mortars manufactured with different amounts of RAP and a rejuvenator. For this purpose, the gyratory compactor and the 3-point bending fatigue test using the DMA under dry and wet conditions were implemented. On the basis of the results obtained, the following observations can be made:

- As the amount of RAP increases, the workability of the asphalt mortars was reduced. However, the use of rejuvenators would facilitate the paving and compaction of materials with high RAP quantities;
- When using an active filler (e.g., Portland cement), the use of high RAP quantities does not affect the water sensitivity of asphalt mortars;
- As RAP content is increased, asphalt mortars offer a more elastic response, and therefore, they are more resistant to fatigue loads;
- In spite of the presence of RAP reducing the ductility of the asphalt mortars, for a given deformation level, the long-term mechanical resistance (fatigue) seems to be unaffected due to its contribution in their elastic response.

Considering the findings of this study as a whole, it can be said that it would be possible to produce asphalt materials with high RAP quantities and with a similar long-term mechanical performance to that of traditional ones (manufactured with virgin aggregates and bitumen). In addition, the use of rejuvenators has demonstrated to be effective to correct the lower workability and brittleness of asphalt mixtures manufactured with high amounts of RAP.

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