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Performance of High Rap Half-Warm Mix Asphalt

Ana R. Pasandín [1,*], Ignacio Pérez [1] and Breixo Gómez-Meijide [2]

[1] Campus de Elviña s/n, Coruña University, E. T. S. I. Caminos, Canales y Puertos, 15071 Coruña, Spain; ignacio.perez1@udc.es
[2] European Asphalt Pavement Association (EAPA), Rue du Commerce 77, 1040 Brussels, Belgium; breixo@eapa.org
* Correspondence: arodriguezpa@udc.es; Tel.: +34-881011438

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Abstract: The current global situation regarding climate change makes it necessary to promote the circular economy and the use of more environmentally friendly technologies in the construction sector. To that end, it is of interest to deepen our understanding of the performance of half-warm mix asphalt (HWMA) manufactured with high proportions of reclaimed asphalt pavement (RAP). Thus, in the present study, a laboratory analysis was carried out in which the behavior of HWMA manufactured with 100% RAP and without rejuvenators was compared with that of a control mix, i.e., an HWMA manufactured with 0% RAP. In particular, we analyzed the compaction energy with a gyratory compactor, mixing time and temperature, volumetric properties, moisture damage resistance through indirect tensile tests after immersion (ITS), stiffness based on the resilient modulus, resistance to permanent deformation using wheel tracking tests, and fatigue resistance through indirect tensile fatigue tests (ITFT). Both mixtures displayed adequate volumetric and mechanical properties, but the performance of the high-RAP HWMA was better than that of the control mixture in terms of resistance to permanent deformation in hot areas. In addition, the high-RAP HWMA without rejuvenators could provide energy and material savings, thus promoting sustainable development.

Keywords: half-warm mix asphalt; RAP; circular economy; mechanical properties

1. Introduction

The German Bitumen Forum was created in 1997 in Europe, with the aim of clarifying the possible hazards of bitumen and solving specific health and safety problems faced by asphalt workers [1]. The same year, the Kyoto Protocol was adopted, with the aim of reducing greenhouse gas emissions to 1990 levels [2]. Reducing asphalt mixing and laying temperatures would lead to the fulfilment of both objectives [2]. Thus, it is of interest to promote the use of asphalt mixtures with reduced mixing and laying temperatures.

In this regard, two new technologies are currently being used for the construction of flexible road pavements at lower temperatures: warm mix asphalt (WMA) and half-warm mix asphalt (HWMA). These are mixtures that are manufactured and positioned at lower temperatures than conventional hot mix asphalt (HMA) and that display an appropriate performance, similar to that of the HMA. Table 1 shows the mixing and laying temperatures for both mixtures compared with those of conventional HMA. In the case of HWMA, a minimum reduction of approximately 50 °C is achieved.

Table 1. Mixing and laying temperatures for HWMA, WMA, and HMA (from Rubio et al. [3]).

Mixture	Temperature (°C)
HMA	150 to 190
WMA	100 to 140
HMWA	60 to 100

Both WMA and HWMA reduce the exposure of employees and the release of greenhouse gases such as CO_2. Some authors have reported 58% reductions in CO_2 emissions with HWMA [3]. Other chemical pollutants are also reduced by using HWMA or WMA, contributing to improved air quality [3]. For example, a 99.9% reduction in SO_2 particles has been reported for HWMA [3]. Moreover, a reduction in fossil fuel consumption can also be achieved. Particularly, energy savings of up to 35% or more have been reported with WMA [4]. With HWMA, there have been reports of reductions in energy consumption of up to 50% [3]. Another advantage of these mixtures is that unlike cold mix asphalt, their mechanical performance is similar to that of HMA [3].

Bituminous mixtures can be manufactured using recycled aggregates such as construction and demolition waste (C&DW) [5] or reclaimed asphalt pavement (RAP). If RAP is used in the manufacture of WMA or HWMA, additional environmental benefits could be achieved, such as reduced waste, conservation of natural resources [6], and reduced consumption of aggregates and bitumen. In addition, cost savings can be achieved using RAP in place of natural aggregates [7]. In Europe, approximately 50 million tons of RAP are produced each year [8]. Thus, the incorporation of RAP into WMA and HWMA is highly interesting both environmentally and economically, and can contribute to promoting the circular economy.

The incorporation of RAP into HWMA or WMA can not only provide the sum of the positive effects of both techniques (improved working conditions, energy and cost savings, reduction of emissions, and lower consumption of fuel, bitumen, and aggregates and their associated production impacts), it can also lead to positive synergistic effects. In this sense, some authors have emphasized that the incorporation of RAP into this type of mixture can help decrease water sensitivity, resistance to permanent deformation, and asphalt aging [7].

In the last decade, some investigations on the use of RAP in WMA [7,9–11] and HWMA have been conducted. In the case of HWMA with a high RAP content, only a few studies have been reported. Some of these are manufactured with foamed bitumen as a binder [12], but even fewer have considered the use of bitumen emulsion. Yuliestian et al. [13] manufactured a 100% RAP HWMA of type AC 16. For its manufacture, they employed a bituminous emulsion using Kraft lignin as the emulsifying agent. They compared the results of their mixture with that of a control mix (100% natural aggregate). They concluded that the recycled mixture displayed higher mechanical resistance as a result of the partial blending of the fresh bitumen with the RAP containing aged bitumen. Lizárraga et al. [14,15] analyzed the performance of HWMAs containing 70% and 100% RAP in the laboratory and in situ. They used a prototype plant for the manufacture. They noted that the performance of the recycled mixtures could be compared to that of the HMA mixtures in terms of the fatigue resistance and resistance to permanent deformation. Marcobal et al. [16] selected 70 gyros in a gyratory compactor as the most suitable compaction method for 100% RAP HWMA. They also found that these mixtures displayed adequate volumetric and mechanical performance in terms of the moisture damage, indirect tensile strength, stiffness modulus, rutting, and fatigue cracking.

It is of interest to deepen the understanding of the performance of HWMA manufactured with high proportions of RAP and analyze whether they are competitive when compared with HWMA manufactured with 0% RAP. For this purpose, and with the aims of promoting sustainable development and the circular economy, fighting against anthropogenic climate change, and reducing safety problems of asphalt workers, the present research was conducted. In this study, a laboratory analysis was carried out in which the behavior of HWMA manufactured with 100% RAP and without rejuvenators was compared with a control mix, i.e., HWMA manufactured with 0% RAP.

2. Materials and Methods

2.1. Basic Materials

2.1.1. Natural Aggregates

Two aggregates were used in this investigation: natural aggregates and RAP. Natural aggregates were used for the control HWMA. Four fractions of a siliceous aggregate provided by a local supplier were used as virgin aggregates. The particle size distribution of the four selected fractions is listed in Table 2.

Table 2. Particle size distribution of virgin aggregates (cumulative percentage passing).

Sieve Size (mm)	0/4 mm	0/4 mm (Clean)	6/12 mm	10/16 mm
22.4	100.00	100.00	100.00	100.00
16	100.00	100.00	100.00	96.85
8	100.00	100.00	30.30	1.08
4	73.01	100.00	1.22	0.90
2	45.54	87.22	1.14	0.88
0.5	22.47	30.71	1.09	0.87
0.25	16.82	16.21	1.06	0.85
0.063	9.38	3.27	0.88	0.70

Following the EN 1097-6 [17] standard, the bulk density (ρ_a), density of dried particles (ρ_{rd}), dry saturated surface density (ρ_{ssd}), and water absorption (WA_{24}) of the four natural aggregate fractions were determined. The results are presented in Table 3.

Table 3. Main properties of the natural aggregates.

Property	0/4 m	0/4 mm (Clean)	6/12 mm	10/16 mm
ρ_a (Mg/m^3)	2.9525	2.8236	2.8740	2.8771
ρ_{rd} (Mg/m^3)	2.9121	2.8008	2.8308	2.8430
ρ_{ssd} (Mg/m^3)	2.9259	2.8089	2.8458	2.8549
WA_{24} (%)	0.4723	0.4	0.5303	0.4162

2.1.2. RAP

For the RAP characterization, Article 22 of the Spanish Specifications for Highway Maintenance (known as PG-4) [18] was followed along with the recommendations included in the publication "Half-warm mix asphalt with bituminous emulsion" by the ATEB (Technical Association of Bituminous Emulsions) [19].

The bulk saturated surface-dry specific gravity (ρ_{SSD}) and water absorption (WA_{24}) of RAP were determined according to EN 1097-6 [17] and are presented in Table 4.

Table 4. Bulk specific gravity and water absorption of RAP.

Property	Fraction	Value
ρ_{ssd} (Mg/m^3)	0.063/4 mm	2.390
	4/5.6 mm	2.478
	5.6/32 mm	2.510
WA_{24} (%)	0.063/4 mm	0.68
	4/5.6 mm	2.24
	5.6/32 mm	1.52

The bulk specific gravity of the filler (0/0.063 mm) was also determined according to EN 1097-7 [20]. This RAP fraction displayed a bulk specific gravity of 2.417 Mg/m^3.

To ensure the uniformity of the characteristics of the bituminous mixture, particularly with regard to its binder content, two granulometric fractions were considered [19]: the 0/5.6 mm (fine) and 5.6/32 mm (coarse) fractions.

Following EN 933-1 [21], the grain size distribution of these two fractions was determined as shown in Figure 1.

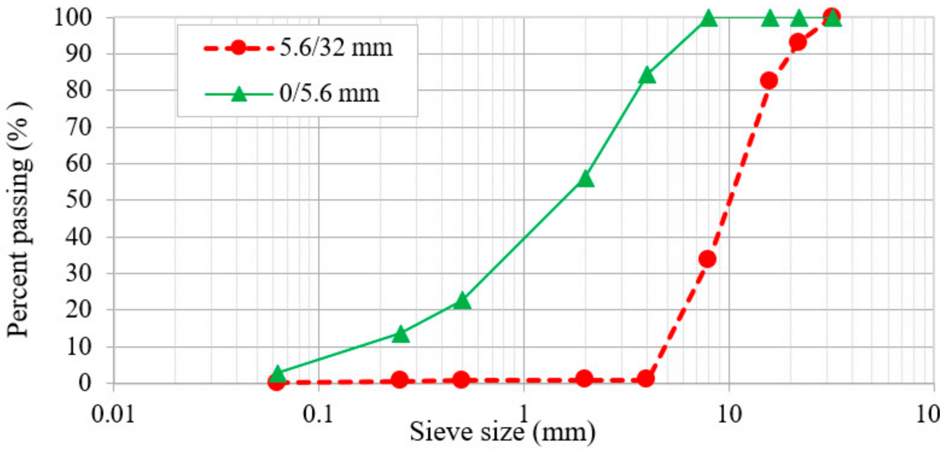


Figure 1. Grain size distributions of RAP.

An extraction test was conducted according to EN-12697-1 [22] to determine the bitumen content of the RAP and to separate the asphalt from the aggregate. Rotary extraction of the RAP indicated an average bitumen content of 7.3% by weight of the mix in the fine fraction (0/5.6 mm) and 3.7% in the coarse fraction (5.6/32 mm). The recovered asphalt had a ring and ball temperature of 64.4 °C according to EN-1427 [23] and a penetration of 20.32 × 0.1 mm according to EN-1426 [24]. These results indicate that the asphalt contained in the RAP was aged as a result of exposure to the environment during its service life, as expected. In light of these results, the recovered bitumen can be classified as a hard bitumen of type B15/25. The use of bitumen emulsion as a binder for HWMA could help compensate for the aged RAP bitumen, thus improving the workability and compactability of the mixture [6].

The grain size distribution [25] of the recovered aggregates is shown in Figure 2.

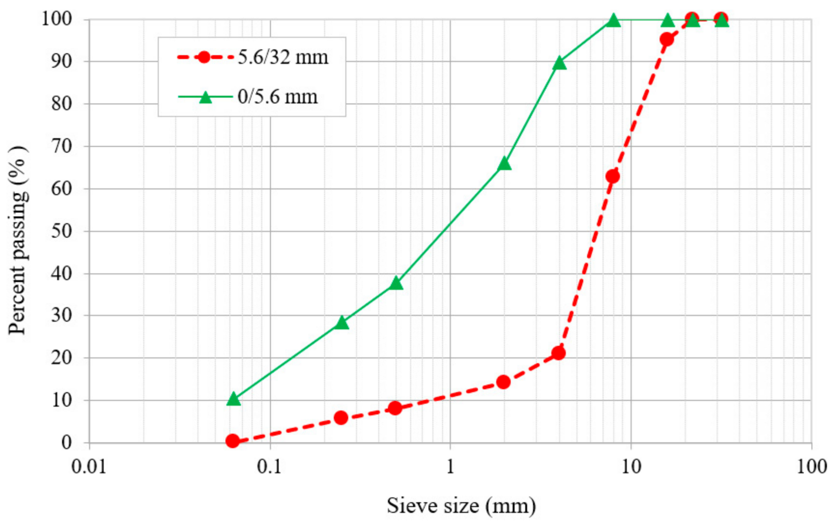


Figure 2. Grain size distributions of the recovered aggregates.

The grain size distribution of the recovered aggregate plays a crucial role in the design of the HWMA. This is because the mixing temperatures are generally higher than the ring and ball softening point of the residual RAP binder. Therefore, during the mixing process of the HWMA, the bituminous material will crumble. For this reason, when RAP percentages above 15% are used, the grain size distribution of the recovered aggregate should also be considered [19].

2.1.3. Bitumen Emulsion

A C69B3 cationic medium setting bitumen emulsion was chosen to prepare the control HWMA (0% RAP) and a C67B3 cationic medium setting bitumen emulsion was selected to prepare the high-RAP HWMA specimens. Their main properties are summarized in Table 5.

Table 5. Properties of bitumen emulsions.

Properties	Standard	C69B3	C67B3
Breaking value (filler Forshammer)	EN 13075-1 [26]	70–155 g	
Bitumen content (by water content)	EN 1428 [27]	67–71%	65–69%
Recovered oil distillate from bitumen emulsions by distillation	EN 1431 [28]	≤2%	
Efflux time by the efflux viscometer (4 mm, 40 °C)	EN 12846-1 [29]	5–70 s	40–100 s
Storage stability by sieving (0.5 mm sieve size)	EN 1429 [30]	≤0.1%	
Settling tendency (7 d)	EN 12847 [31]	≤5%	≤10%
Adhesivity	EN 13614 [32]	≥90%	

2.2. *Specimen Preparation*

2.2.1. Type of HWMA

Given the size distribution of the different fractions supplied for the natural aggregate, for the control HWMA (0% RAP), a mixture of type AC 16 surf S was chosen (Figure 3) with the following percentages of natural aggregate:

- 45% of the 0/4 mm fraction;
- 15% of the 0/4 mm fraction (clean);
- 9% of the 6/12 mm fraction; and
- 31% of the 10/16 mm fraction.

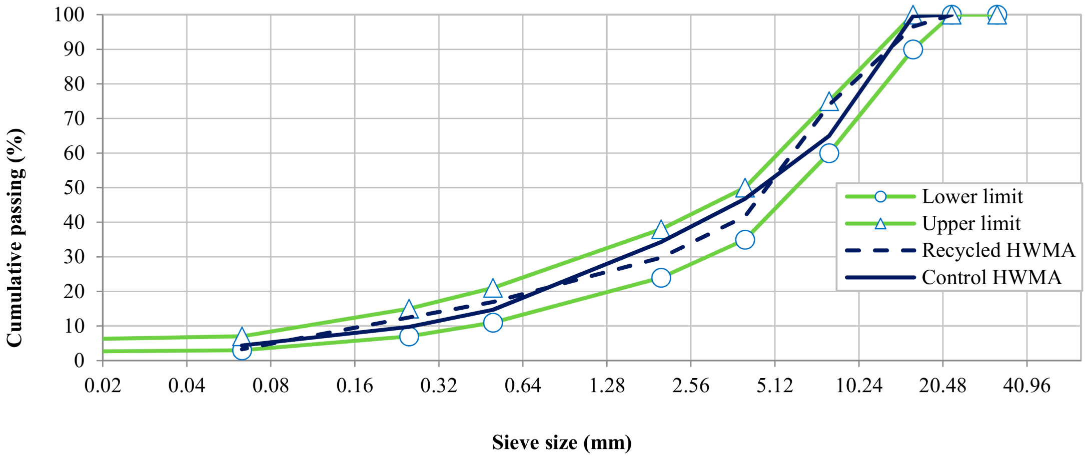


Figure 3. Grain size distributions of the control HWMA and high-RAP HWMA.

Given the recovered grain size distribution of the RAP, and because the aim was to investigate a mixture for a surface course, a high-RAP HWMA of type AC 16 surf S (Figure 3) was manufactured. For this purpose, 30% by mass of the 0/5.6 mm fraction and 70% of the 5.6/32 mm fraction were used.

The obtained grain size distributions for the control and high-RAP HWMAs are shown in Figure 3. As shown, the particle size distributions are within the lower and upper limits specified by the ATEB [19] for this type of mixture.

2.2.2. Minimum Residual Binder Content

Taking into account the aggregate density, the ATEB [19] sets a minimum residual binder content of 4.15% for the control mix and 4.8% for the high-RAP HWMA. In addition, it should be noted that the same publication states that for high-RAP HWMA, the emulsion must provide a minimum of 1.5% of the residual binder, with the rest being provided by the aged RAP binder.

As previously mentioned, the fine fraction of RAP (0/5.6 mm) comprised 7.3% of the binder and the coarse fraction (5.6/32 mm) accounted for 3.7%. In addition, the high-RAP HWMA was composed of 70% fine fraction and 30% coarse fraction. Therefore, with the combination of the selected RAP fractions, a residual binder content of 4.78% was assumed in the mix. In other words, the minimum value of 1.5% provided by the emulsion was taken as the minimum content of the new residual binder for the high-RAP HWMA.

2.2.3. Mixing Time and Temperature

For HWMA made with a bitumen emulsion, manufacturing temperatures lower than 100 °C are recommended [19]. For this reason, the aggregates are usually heated to between 100 °C and 110 °C, whereas the bitumen emulsion is usually heated to between 60 °C and 80 °C [19]. To determine the most suitable temperatures for both the aggregates and the bitumen emulsion, loose-mixture specimens were manufactured with different aggregate and bitumen emulsion heating temperatures following NLT-145 [33]. Thus, for aggregates heated to 100 °C and 110 °C, the bitumen emulsion was heated to 60, 70, and 80 °C. The loose mixtures were manufactured at the minimum binder content, which was 1.5% of the residual binder for the high-RAP HWMA and 4.15% for the control mixtures. The most suitable temperatures were determined visually.

Mixing times between 60 s and 120 s are suitable, according to the ATEB [19]. To determine the most suitable mixing time in the tests described above, the coating was visually analyzed after mixing times of 1 and 2 min.

2.2.4. Compaction Energy

Compaction of both the control mix and the high-RAP HWMA was carried out under the following conditions:

- Type of compaction: gyratory;
- Internal rotation angle: 0.82°;
- Consolidation pressure: 600 kPa;
- Speed: 30 rpm;
- Compaction temperature: 80 °C (the loose mixture is left to condition for 30 min at this temperature before being fed into the gyratory compactor); and
- Mold diameter: 100 mm diameter molds were used for the AC 16 surf S.

In addition, it was necessary to determine the most suitable number of turns for compaction with the gyratory compactor according to EN 12697-31 [34].

2.2.5. Curing Time

Before conducting the tests, the compacted HWMA samples were left for 3 d in an oven at 50 °C to accelerate their maturation.

2.3. Volumetric Properties

The Spanish standards consider eight traffic categories: Traffic category T00 refers to annual average daily heavy traffic (AADHT) ≥ 4000, traffic category T0 refers to 4000 > AADHT ≥ 2000, traffic category T1 refers to 2000 > AADHT ≥ 800, traffic category T2 refers to 800 > AADHT ≥ 200, traffic category T3 refers to 200 > AADHT ≥ 50, and traffic category T4 refers to AADHT < 50.

For HWMA surface course mixes, the air void content (Va) should be between 4% and 6% for heavy traffic categories T1 and T2. The ATEB [19] allows this value to be decreased to 3% for HWMA with 100% RAP based on previous experience. For T3, T4, and shoulders, the void content in HWMA should be between 3% and 5%.

To determine the Va, standard EN 12697-8 [35] was followed, such that:

$$Va = \frac{\rho_m - \rho_b}{\rho_m} \times 100 \tag{1}$$

where ρ_m is the maximum density obtained by the volumetric procedure in water according to standard EN 12697-5 [36], and $]\rho_b$ is the apparent density obtained based on the dry saturated surface (SSD) procedure for compacted specimens in standard EN 12697-6 [37]. Both ρ_m and ρ_b for HWMA should be determined after 3 d of curing in an oven at 50 °C.

2.4. Moisture Damage Resistance

To determine the water sensitivity of the mixtures, an indirect traction test after immersion was carried out in accordance with the EN 12697-12 standard [38].

For this test, a series of six cylindrical compacted specimens was manufactured with 67% of the turns [19]. After manufacture, the specimens were left to cure for 3 d at 50 °C in an oven.

The series was then divided into two groups: the dry group and the wet group. The dry group was left to air-dry at room temperature on a flat surface, whereas the wet group was saturated and then the specimens were placed in a water bath at 40 °C for 3 d. Then, both groups were conditioned for a minimum of 2 h at the test temperature of 15 °C and broken under indirect traction, yielding the following index:

$$\mathrm{TSR} = \frac{\mathrm{ITS_W}}{\mathrm{ITS_D}} \times 100 \tag{2}$$

where TSR is the tensile stress ratio (%), $\mathrm{ITS_W}$ is the average indirect tensile strength of the wet specimens (MPa), and $\mathrm{ITS_D}$ is the average indirect tensile strength of the dry specimens (MPa). A TSR ≥ 85% is required by the specifications for HWMA [19].

2.5. Stiffness

The stiffness was analyzed following the procedure described in Annex C of standard EN 12697-26 [39], which describes the indirect traction test on cylindrical specimens (IT-CY). The NU 14 servo-pneumatic machine from Cooper was used for this purpose. Cylindrical specimens compacted with the number of turns previously determined in the gyratory compactor were placed in the indirect test jig.

A dynamic load was applied in the form of a half-sine wave. The pulse repetition period was 3 ± 0.1 s and the maximum load was selected to achieve a maximum transitory horizontal deformation of 0.005% of the specimen diameter (5 m). The rise time measured between the start of the impulse and the maximum load was set at 124 ± 4 ms. A total of 10 conditioning pulses were applied, followed by five load pulses. The stiffness modulus for each of the five load pulses was obtained using the following expression [39]:

$$M_R = \frac{F \times (\nu + 0.27)}{z \times h} \tag{3}$$

where M_R is the resilient modulus (MPa), F is the maximum applied load (N), z is the horizontal deformation (mm), h is the sample thickness (mm), and v is the Poisson's ratio (a value of 0.35 was adopted for all temperatures [39]).

The test was carried out in a climatic chamber at 20 °C.

2.6. Resistance to Permanent Deformation

Standard EN 12697-22 [40] was followed to analyze the resistance to permanent deformation of both the control mixture and the 100% recycled mixture. The small-size device was used by applying procedure B in air at 60 °C and with a duration of 10,000 cycles. A load of 714 ± 10 N was applied. The frequency was 26.5 ± 1.0 cycles every 60 s. The 260 × 300 mm rectangular specimens were compacted by a plate compactor using controlled energy. The average thickness of the specimens was 60 mm.

2.7. Fatigue

To determine the fatigue behavior of the control mixture (0% RAP and optimum residual binder) and 100% recycled mixture (100% RAP and optimum residual binder), the indirect tensile fatigue test procedure (ITFT) described in Annex E of standard EN 12697-24: 2006 + A1 [41] was carried out. Cylindrical specimens compacted with the number of turns previously determined in the gyratory compactor were placed in the indirect traction jig.

This was a controlled tension test, in which a half-single repeated load was applied. The loading time was 0.1 s and the rest time 0.4 s.

Two failure criteria were used: the number of load cycles until the diametric deformation of the specimen reached 10% of its initial diameter, and the number of load cycles until the specimen broke into two parts. The first of the two failure criteria was adopted.

For bituminous mixtures, the fatigue law is usually of the following type (Wöhler curve):

$$\varepsilon = A.N^{-b} \tag{4}$$

where N is the number of load cycles, A and b are parameters that define the Wöhler curve (obtained experimentally), and ε is the unit tensile deformation in the lower fiber of the bituminous mix.

To obtain the fatigue laws, three stress levels were tested with a minimum of three specimens per level and a total of 10 specimens per law. The tests were carried out in a climatic chamber at 20 °C.

3. Results and Discussion

3.1. Mixing Time and Temperature

After visual examination, the temperatures listed in Table 6 were selected as the most suitable for the mixing process. Furthermore, from the same visual examination, it was concluded that in both cases, i.e., for both the high-RAP HWMA mixture (Figure 4) and the control HWMA, a mixing time of 2 min was necessary to achieve a complete coating. As can be seen, for the high-RAP HWMA, the bitumen emulsion temperature was 20 °C lower than that of the control mixture. This is probably due to the bitumen attached to the RAP, which reduces the roughness of the aggregate, thus facilitating the coating process.

Table 6. Selected mixing temperatures for the aggregate and bitumen emulsion.

Mixture	Aggregate Temperature (°C)	Bitumen Emulsion Temperature (°C)
AC 16 surf S (high-RAP HWMA)	110	60
AC 16 surf S (control HWMA)	110	80

Figure 4. Detail of the appearance of the high-RAP HWMA with 1.5% residual binder after 2 min of mixing, with an aggregate temperature of 110 °C and an emulsion temperature of 60 °C.

3.2. Compaction Energy

Based on experience, the ATEB [19] indicates that HWMA mixtures without RAP are usually compacted with between 90 and 150 turns. Therefore, the air voids (*Va*) in the mixture were first determined following the procedure described in Section 2.3 for specimens manufactured with 4.15% and 4.75% residual binder in the mixture and compacted with 90, 120, and 150 turns. The voids were determined after 3 d of curing in an oven at 50 °C. The obtained air voids are listed in Table 7.

Table 7. Air voids (*Va*) (%) for control HWMA manufactured with 90, 120, and 150 turns of the gyratory compactor.

Residual Binder (%)	Number of Turns of the Gyratory Compactor		
	90	**120**	**150**
4.15	8.77	8.71	7.55
4.75	7.74	6.96	5.34

Because the air voids must be between 4% and 6% [19] for AC 16 surf S, compacting with 150 turns of the gyratory compactor was selected as the most suitable.

In contrast, the ATEB [19] indicates that for high-RAP HWMA, 65 cycles may be sufficient to study the mechanical characteristics. Therefore, for residual binder contents provided by the bitumen emulsion of 1.5%, 2.0%, 2.5%, 2.75%, and 3.0%, the air voids (*Va*) were determined following the procedure described in Section 2.3. The results obtained are listed in Table 8.

Table 8. Air voids for the high-RAP HWMA manufactured with 40 and 65 turns of the gyratory compactor.

Residual Binder (%)	Number of Turns	*Va* (%)
1.5	40	7.69
	65	6.10
2.0	40	6.96
	65	5.60
2.5	40	4.97
	65	5.00
2.75	40	5.79
	65	3.90
3.0	40	3.86
	65	3.70

In light of these results and given that the air voids should be between 4% and 6%, 65 turns was selected as the most appropriate condition.

That is, for the high-RAP HWMA, a number of turns lower than that of the control mixture was selected (65 vs. 150). This is attributed to the bitumen attached to the RAP, which reduces the friction within the aggregates, thus facilitating their compaction.

3.3. Volumetric Properties

Table 9 lists the bulk specific gravity (ρ_b), maximum density (ρ_m), and air void content (*Va*) for both the control mix and the high-RAP HWMA with varying residual binder content provided by the bitumen emulsion. As can be seen, for the high-RAP HWMA, the emulsion content providing a residual binder content of 2% to 2.5% yields an appropriate air void percentage. In the case of the control mix, the first emulsion content that yields an adequate air void content is that with 4.75% residual binder.

Table 9. Volumetric properties of the high-RAP HWMA (65 turns) and control HWMA (150 turns).

Residual Binder Provided by the Bitumen Emulsion (%)	High-RAP HWMA			Control HWMA		
	ρ_b (Mg/m^3)	ρ_m (Mg/m^3)	*Va* (%)	ρ_b (Mg/m^3)	ρ_m (Mg/m^3)	*Va* (%)
1.50	2.3316	2.4832	6.1	-	-	-
2.00	2.3229	2.4606	5.6	-	-	-
2.50	2.3230	2.4450	5.0	-	-	-
2.75	2.3400	2.4343	3.9	-	-	-
3.00	2.3386	2.4293	3.7	-	-	-
4.15	-	-	-	2.4414	2.6409	7.55
4.55	-	-	-	2.4564	2.6207	6.27
4.65	-	-	-	2.4575	2.6178	6.12
4.75	-	-	-	2.4680	2.6073	5.34

It should be noted that many repetitions were necessary to obtain the volumetric properties, particularly with the high-RAP HWMA, as significant dispersion was observed.

Again, these results show the greater ease of compacting the high-RAP HWMA, since with a lower number of turns, similar air voids to that of the control mixture are achieved, with a lower residual binder content.

3.4. Water Sensitivity

For the control mixture, the moisture damage resistance was analyzed with the first binder content that satisfied the desired volumetric properties. In other words, the test was carried out with 4.75% residual binder (*Va* = 5.34%). The specimens were manufactured with 67% of the 150 turns (100 turns), obtaining a TSR of 98.1%, which is higher than the 85% required by the standard for AC 16 surf S. This emulsion content, which provided a residual binder content of 4.75%, was therefore adopted as the optimum binder content for the HWMA control mixture.

For the high-RAP HWMA, the specimens were manufactured with 67% of the 65 turns (44 turns). The moisture damage resistance results are summarized in Table 10. As can be seen, only the emulsion contents providing 2.0% and 3.0% residual binder yield a TSR above 85%, as required in the specification for AC 16 surf S [19].

Table 10. Moisture damage resistance results for the high-RAP HWMA.

Residual Binder Provided by the Bitumen Emulsion (%)	Total Residual Binder (%)	*Va* (%)	TSR (%)
1.50	6.21	6.1	-
2.00	6.68	5.60	87.69
2.50	7.16	5.0	68.87
2.75	7.40	3.9	76.59
3.00	7.64	3.7	88.84

In light of these results, it can be concluded that the optimum binder content that guarantees compliance with the water sensitivity and provides suitable volumetric properties is that which provides a residual binder content of 2.0%.

3.5. Resistance to Permanent Deformation

Table 11 summarizes the wheel tracking test results for the control mixture and the high-RAP HWMA. Particularly, this table lists the rut depth, proportional rut depth (PRDair), and creep slope (WTSair) in the range of 5000 to 10,000 load cycles.

Table 11. Wheel tracking test results.

	Control HWMA	High-RAP HWMA
Rut depth, $d_{10.000}$ (mm)	1.81	0.89
PRDair (%)	3.01	1.49
WTSair (mm/10^3 cycle)	0.09	0.04

There are no specifications for HWMA in terms of resistance to permanent deformation. Nevertheless, taking into account the specifications of the PG-3 for HMA for surface course type AC 16 surf S (article 542) [42] listed in Table 12, the control mixture would serve for T2, T3, and shoulders in the hot zone, and T1, T2, T3, and shoulders in the middle and warm zones. Following the same criteria, the high-RAP HWMA could be used for T1, T2, T3, T4, and shoulders in the warm, medium, and temperate zones. Therefore, in the hot zone, the high-RAP HWMA without rejuvenators seems to have better resistance to permanent deformation than the control mixture.

Table 12. Wheel tracking test specifications for HMA type AC 16 surf S, WTSair, and PRDair [39].

Thermal Zone	T00 and T0	T1	T2	T3 and Shoulder	T4
Hot	≤0.07	≤0.07	≤0.07 (*)	≤0.10 (**)	-
Temperate	≤0.07	≤0.07 (*)	≤0.10 (**)	≤0.15	-
Warm	≤0.10	≤0.10 (**)	≤0.10 (**)	-	-

(*) Higher values may be accepted if WTSair ≤ 0.10 and PRDair ≤ 5% simultaneously. (**) Higher values may be accepted if WTSair ≤ 0.15 and PRDair ≤ 5% simultaneously.

Figure 5 shows two of the tested specimens following the conduction of the tests. It can be seen that the rut is more pronounced in the control mixture (Figure 5a) than in the high-RAP HWMA

(Figure 5b), which emphasizes the conclusion that the control mixture is more susceptible to permanent deformation. The use of RAP, i.e., aggregates coated with aged bitumen that are therefore stiffer, seems to be the main cause of this behavior.

(**a**) (**b**)

Figure 5. Wheel tracking test samples: (**a**) control mixture (0% RAP) and (**b**) high-RAP HWMA (100% RAP).

3.6. *Stiffness*

Table 13 lists the resilient modulus results for the control HWMA and the high-RAP HWMA.

Table 13. Stiffness of the control HWMA and high-RAP HWMA.

Mixture	Resilient Modulus (MPa)
Control HWMA	2888
High-RAP HWMA	4216

In Spain, there are no technical specifications regarding the value of the resilient modulus for HWMA, and thus this test is used to compare the mixtures. In this sense, as can be seen in Table 13, the high-RAP HWMA without rejuvenators presents a resilient modulus that is 45.98% higher than that of the control HWMA. These results are in accordance with those obtained for the permanent deformation and fatigue behavior, as lower stiffness is generally associated with mixtures having greater susceptibility to permanent deformation but longer fatigue life. In addition, these results were expected because in the absence of rejuvenators, the bitumen in the high-RAP HWMA is a hard bitumen (B15/25). It must also be taken into account that the asphalt composition influences the stiffness as well as other properties [43,44]. In the case of the high-RAP HWMA, not only does the bitumen provided by the emulsion intervene, but also the attached bitumen.

3.7. *Fatigue*

Figure 6 shows the initial strain (εo) versus the final number of cycles (N) for both the control HWMA and high-RAP HWMA. The equations for the fatigue laws obtained through linear regression are also included in the figure.

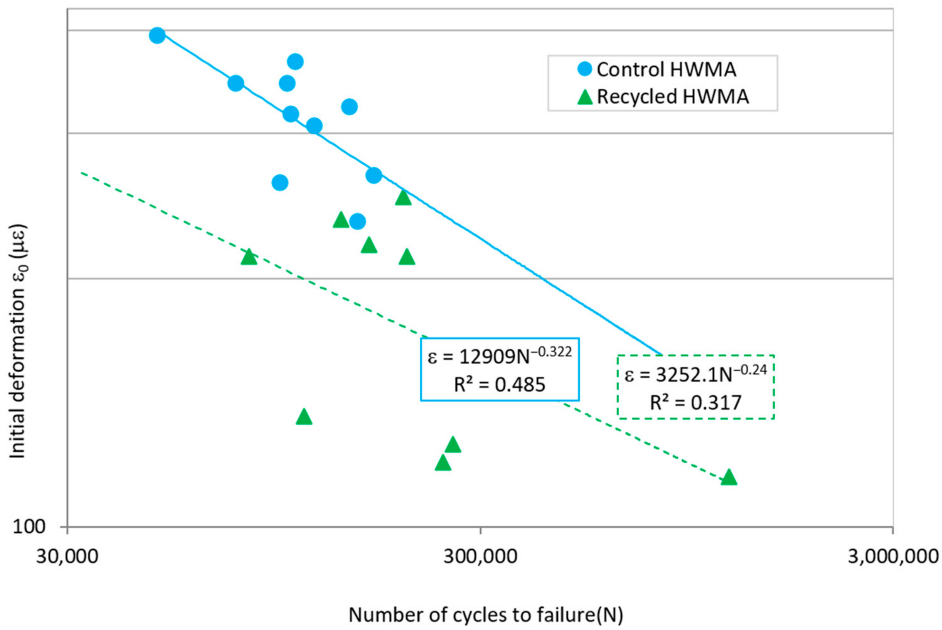
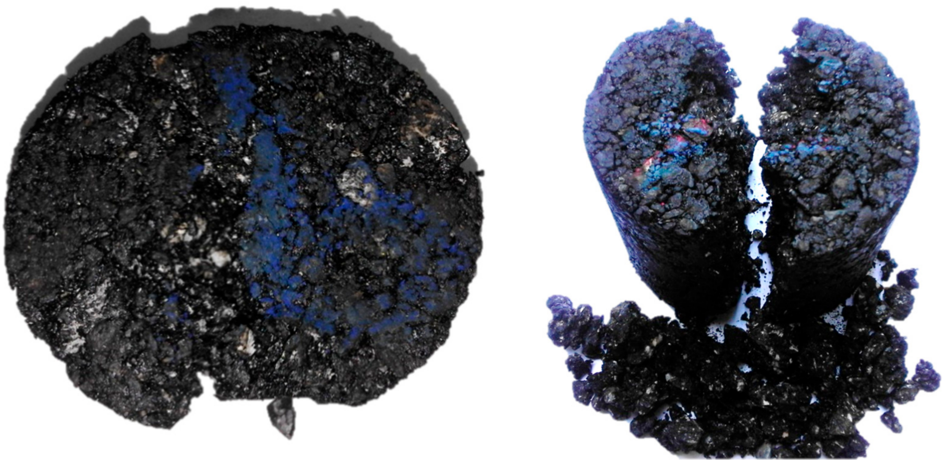


Figure 6. Fatigue life of the control HWMA and high-RAP HWMA.

As can be seen, the fatigue life is much longer for the control mixture than for the high-RAP HWMA without rejuvenators. For example, using the fatigue laws, for an initial deformation of 200 με, the number of cycles to failure for the control mixture is 275% higher than for the high-RAP HWMA. For an initial deformation of 300 με, the number of cycles to failure for the control mixture is 477% higher than for the high-RAP HWMA. Again, the aged bitumen that coats the RAP seems to be mainly responsible for this performance, due to its inadequate fatigue performance [45,46].

It should be noted that the obtained regressions are not very good because of the significant dispersion in the results, as shown in Figure 6. That regression for the control mix is slightly better, probably because greater dispersion is introduced with the use of RAP rather than natural aggregate.

It is interesting to note that in the case of the control mix, during the execution of the fatigue test, the tested samples failed mostly through fracture by a diametric plane. However, as illustrated in Figure 7a, there were some test pieces in which excessive deformation was also observed.



(**a**) (**b**)

Figure 7. Specimens after fatigue testing: (**a**) detail of a fatigue-broken control mix specimen in which permanent deformation failure was predominant over fatigue failure and (**b**) detail of a 100% hardened recycled-mix specimen with numerous loose particles after fatigue breakage.

In contrast, as shown in Figure 7b, in all cases of the high-RAP HWMA, the fatigue-tested specimens fractured through a vertical diametric plane, separating the specimen into two parts. Thus, the predominant failure mechanism was fatigue rather than permanent deformation.

This is consistent with the permanent deformation resistance results, which clearly showed that the control mixture was more sensitive to permanent deformation than the high-RAP mixture.

In addition, it can be clearly seen (Figure 7b) that in the high-RAP HWMA specimens, numerous particles of binder-impregnated aggregate were detached during breakage, probably because these specimens contained less of the new bitumen emulsion than the control mixture.

4. Conclusions

In this study, the performance of two HWMA mixtures was compared in the laboratory. Both an HWMA entirely manufactured with natural quarry siliceous aggregates and an HWMA manufactured using 100% RAP as an aggregate without rejuvenators were analyzed. In other words, the performance of a control mixture was compared with the performance of a high-RAP HWMA. From the results of the present study, the following conclusions can be drawn:

During the manufacturing process, it was necessary to heat the bitumen emulsion of the control HWMA at 80 °C, whereas for the high-RAP HWMA, the bitumen emulsion was heated at 60 °C. Moreover, the control mixture was compacted using 150 turns of the gyratory compactor, whereas for the high-RAP HWMA, only 65 turns were used. This is attributed to the bitumen attached to the aggregate, which reduces the friction within the aggregates, thus facilitating their compaction.

In addition, for the control mixture, it was necessary to add a bitumen emulsion content that provided 4.75% residual binder; however, for the recycled mixtures, it was necessary to add a bitumen emulsion that provided 1.5% residual binder. Thus, high-RAP HWMA without rejuvenators can be manufactured using a lower bitumen content, less heating energy, and less compaction energy than the control HWMA. These energy and material savings could promote sustainable development.

The water sensitivity of the mixtures was adequate in both the control and high-RAP HWMA cases.

The aged bitumen contained in the RAP led to the high-RAP HWMA having higher stiffness than the control mixture. Particularly, the high-RAP HWMA displayed a resilient modulus at 20 °C that was 45.98% higher than that of the control mixture (2.888 MPa for the control mixture versus 4.216 MPa for the recycled mixture).

This stiffening was mainly responsible for the better permanent deformation resistance of the high-RAP HWMA in any weather situation. In fact, for both temperate, warm, and hot zones, the mixture made with 100% RAP would be suitable up to a T1 heavy traffic category (2000 > AADHT ≥ 800). In contrast, the control mix could only cope with these traffic demands in the case of warm and temperate climates, but not in hot areas.

After an analysis of the fatigue resistance of both mixtures, it can be concluded that a lower fatigue life is expected for the high-RAP HWMA without rejuvenators. The greater stiffness of this mixture is also the main cause of this behavior. However, it should be noted that during the fatigue analysis, strong dispersion of the results was observed, and thus it would be prudent to further investigate this property in future studies.

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