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Technical suitability of wet or dry processing of a dense rubberized warm asphalt mixture

A.M. Rodríguez-Alloza [a] ✉, F. Giuliani [b], J. Gallego [c]

a. Departamento de Ingeniería Civil, Náutica y Marítima, Universidad de La Laguna (ULL), (San Cristóbal de La Laguna, Spain)
b. Dipartimento di Ingegneria e Architettura, Università degli Studi di Parma, (Parma, Italy)
c. Departamento de Ingeniería del Transporte, Urbanismo y Territorio, Universidad Politécnica de Madrid (UPM), (Madrid, Spain)
✉: arodrial@ull.es

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ABSTRACT: Warm mix asphalt (WMA) and crumb rubber modified asphalt in the field of asphalt paving have been demonstrated to be green technologies for producing environmentally friendly pavement. However, limited research has assessed the behaviours of mixtures including both technologies. This study performed research aligned with environmental considerations and sustainability to examine the design and manufacturing of dense asphalt mixtures incorporating a crumb-rubber modifier through a wet or dry process and a specific vegetable additive for WMA technologies. The results indicated that, when rubber is added through a wet process, and a WMA vegetable additive is incorporated, the mixture can be manufactured and compacted at temperatures approximately 25 °C below that of the control mixture, while keeping the mechanical properties within the specifications.

KEYWORDS: Rubber; Warm mix asphalt; Dense asphalt mixture; Compactability; Water sensitivity.

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RESUMEN: *Idoneidad técnica de una mezcla semicaliente densa con caucho introducido por vía húmeda o vía seca.* Las mezclas semicalientes y las mezclas con caucho son técnicas en el campo de la pavimentación asfáltica que han demostrado ser tecnologías sostenibles y respetuosas con el medio ambiente. Sin embargo, la investigación dedicada al comportamiento de las mezclas que incluyen ambas tecnologías es limitada. Esta investigación está alineada con consideraciones ambientales y de sostenibilidad: el diseño y la fabricación de la mezcla asfáltica densa incorpora caucho tanto por la vía húmeda o vía seca, y un aditivo vegetal específico de la tecnología de mezclas semicalientes. De los resultados obtenidos se ha demostrado que, cuando se añade el caucho por vía húmeda, la mezcla se puede fabricar y compactar a temperaturas del orden de 25 ºC por debajo de la temperatura de la mezcla de control gracias a la adición del aditivo vegetal para mezclas semicalientes seleccionado mateniéndose las propiedades mecánicas dentro de las especificaciones.

PALABRAS CLAVE: Caucho; Mezcla semicaliente; Mezcla densa; Compactabilidad; Sensibilidad al agua.

1. INTRODUCTION

Because of global warming and climate change, a major challenge faced by society is the efficient use of energy and the corresponding need to decrease greenhouse gas emissions. In fact, the Paris agreement has addressed the mitigation, adaptation, and financing of greenhouse gas emissions from the year 2020. Currently, the circular economy model is gaining prominence in all areas of society, particularly in the construction and maintenance of roads. Therefore, the pavement industry has developed warm mix asphalt (WMA) technology methods to decrease the manufacturing and compaction temperatures of asphalt mixtures (1-5). WMA offers unique environmental benefits by decreasing energy consumption, as well as economic benefits in terms of fuel cost and hauling distance. Appropriate WMA technologies can provide several technical benefits: energy and resource savings due to lower mixing temperatures; improved working conditions to achieve lower emissions of fumes, aerosols and odour at both plants and work sites; faster reopening of new traffic surfaces; and lower production and laying temperatures to decrease thermal aging of the bitumen.

Asphalt mixtures with rubber provide better performance than conventional asphalt mixtures, through increasing the resistance to rutting, fatigue, thermal cracking and aging. Two systems are used to incorporate rubber and WMA additives into the asphalt mixture. In the wet process, the bitumen is first mixed with the WMA, and the rubber modifier is then added. This binder is subsequently mixed with aggregate. In the dry process, the bitumen, WMA additive, rubber modifier and aggregates are mixed simultaneously (6, 7).

However, the use of crumb rubber in asphalt mixtures increases the mixing and compaction temperatures because the modification of the binder by the rubber increases the viscosity and requires higher working temperatures to achieve proper densification of the mixture (8). Using WMA technology in combination with rubberized binders may provide a practical solution to alleviate this problem, but minimal effects on the volumetric and mechanical properties of these types of mixtures should be ensured. Hence, this topic should be further analysed to determine the effects of warm additives on the performance of rubberized asphalt mixtures.

According to a literature review, the influence of the manufacturing temperatures of mixtures with rubber in the wet process with two different WMA additives (Sasobit and Aspha-min) has indicated that the production temperature can be decreased while maintaining an adequate air void content (9). Another study with highly rubber modified binders has demonstrated the benefits of incorporating waxes as WMA additives, which improve the resistance to permanent deformation and fatigue, slightly worsen the water sensitivity and do not affect the stiffness modulus of asphalt mixtures (10). In addition, workability and mechanical property characterization of asphalt rubber mixtures modified with various warm mix asphalt additives (Evotherm-DAT, Evotherm-3G, Sasobit, paraffin wax and Aspha-min) has demonstrated that the working temperature can be decreased without affecting the compactability of the mixtures (11). Nevertheless, the rutting resistance of the mixture has been found to be negatively affected for all additives except a Fisher-trop wax. The effects on water sensitivity, stiffness and fatigue characteristics have been found to depend on the additive, and to show slight differences with respect to the control mixture. Recent evaluation of foamed warm mix asphalt mixtures containing crumb rubber has indicated that the manufacturing temperature can be decreased by 17 °C with respect to that of the hot mix asphalt mixture with crumb rubber. The foamed rubberized asphalt binder and mixture, compared with conventional rubberized asphalt binder and mixture, exhibit better low-temperature performance and fatigue resistance, but inferior high-temperature performance (12). The addition of Sasobit to asphalt mixtures containing crumb rubber in a dry mixing process has been found to improve workability and compactability, and decrease the compaction temperature approximately 15 °C, without negatively affecting the rutting and cracking resistance (13). When slag is included as an aggregate in a rubberized warm asphalt mixture, the stiffness in mixtures with wax is slightly higher, and no significant differences have been observed in the resistance to fatigue, although this resistance appears to decrease when the wax is added; moreover, WMA additive has been found to worsen water sensitivity (14). In addition, the incorporation of reclaimed asphalt pavement to the rubberized mixture increases the mixture's stiffness; however, WMA mitigates that increase. Furthermore, the addition of reclaimed asphalt pavement has an adverse effect on the resistance to fatigue and reflective cracking of the mixtures, which is magnified with the use of WMA (15). In the dry process, the rubber must interact with the binder and partially modify it. This interaction depends on the temperature, among other factors. Recently Shen et al. (13) have reported that temperatures above 160 °C are recommended to achieve proper reaction or digestion of rubber in the bitumen in mixtures in the dry process.

In summary, although the above-mentioned mechanical properties have been studied for rubberized warm asphalt mixtures, the literature has recommended further investigation of the proper decrease in temperature. Moreover, comparisons between the wet or dry processes for these types of mixtures have not been extensively investigated. Therefore, this investigation was aimed at increasing knowledge regarding the mechanical characteristics of rubberized warm mixtures and evaluating the suitability of WMA additives to decrease working temperatures without compromising the volumetric and mechanical properties of the mixtures.

2. MATERIALS AND PROCEDURES

This study was performed on a dense graded asphalt mixture incorporating a WMA additive and rubber with wet or dry processes. In the following sections, the materials are presented and described.

2.1 Bitumen and aggregates

To manufacture the rubberized warm asphalt mixtures, a 50/70 penetration bitumen, a porphyric material as a coarse aggregate and limestone sand (<2 mm in size) were used. All fractions were washed to ensure that they were essentially free of dust. The mineral powder was calcium carbonate. These types of aggregates and binders are commonly used in the wearing course for moderate traffic, and in the binder course for moderate and high traffic in Spanish roads.

2.2 Crumb rubber and the WMA additive

Rubber powder was obtained from end-of-life tyres through grinding at room temperature; this process is the most widespread procedure used in Spain. For the base binder, 50/70 penetration bitumen was used in the production of 35/50 modified bitumen incorporating 10% rubber according to the weight of the base bitumen. The rubber gradation is presented in Table 1.

Table 1. Rubber gradation.

Sieve (mm) (EN 933–2)	**Passing (%)**
2	100
1.5	100
1	100
0.5	94.1
0.25	23.7
0.125	3.7

The WMA selected for this study was Noburbur® ThErmo+, a liquid additive with surfactant properties that allows manufacturing temperatures to be decreased. It has vegetable origin, is thermo-resistant, remains stable in storage and improves the adhesiveness of the aggregate with the binder. It is formulated with natural compounds that are not classified as hazardous. The dose of WMA additive was 0.5% the weight of the base bitumen.

2.3 Binder preparation

In the rubberized warm mixtures manufactured with the wet process, the WMA additive was first added to the bitumen and stirred for 15 minutes at 140 °C and 900 rpm. Then the temperature was increased to 185 °C, and the rubber was incorporated and stirred for 45 minutes at 4000 rpm. The composition of this binder was 100 parts of 50/70 + 0.5 parts of WMA additive + 10 parts of rubber. In the dry process, the rubber was added as an aggregate; hence, rubber did not need to be added to the base binder. In this case, the WMA additive was also first added to the net bitumen and stirred for 15 minutes at 140 °C and 900 rpm, and the composition of the binder was 100 parts of 50/70 + 0.5 parts of WMA additive.

In both cases, the dose of additive (0.5% the weight of the base bitumen) was established on the basis of the manufacturer's recommendations for rubberized materials. Of note, the term warm refers to the production temperature of the asphalt mixture. Nevertheless, the rubber modified binders were previously produced at 185 °C, the standard temperature.

2.4 AC16 S asphalt mixture

To perform the investigation, we used a dense graded AC16 S mixture. Sizes larger than 2 mm were porphyric in nature, whereas smaller sizes were of limy origin, including the calcium carbonate filler. The resulting granulometry for both the wet and dry processes is presented in Table 2. The rubber content used in the dry process was the same as that used in the wet process, and the grading curve was not modified.

Table 2. Grading curve of the AC16S mixture.

Sieve (mm)	22	16	8	4	2	0.5	0.25	0.063
Resulting curve	100.0	100.0	60.0	43.0	32.0	17.0	12.1	5.2

The optimum content of binder in both reference mixtures was selected to achieve an air void content of approximately 5%. This intermediate air void content was selected with the intention of maintaining a reasonable range for this parameter in the subsequent tests, because at lower temperatures, the air void content might have increased, depending on the effectiveness of the WMA additive. The volumetric properties of the reference mixtures are presented in Table 3.

Table 3. Volumetric properties of reference mixtures.

	Standard	Wet process	Dry process
Production temperature (°C)	-	165	170
Binder content (% aggregate weight)	-	5.0	5.0
Maximum density (g/cm^3)	EN 12697-5	2.499	2.497
Bulk density (g/cm^3), SSS, 75 blows/side	EN 12697-5	2.378	2.375
Air void content (%)	EN 12697-8	4.84	4.89

Knowing in advance that the digestion of the rubber would be more difficult in the dry process, to promote rubber digestion and to make the results more comparable in the investigation, five grades were higher for the dry process than the wet process mixtures.

3. METHODS

From the reference production temperature, the manufacturing temperatures were varied in steps of 20 °C, and the resulting bulk density (EN 12697-6), air void content (EN 12697-8), compactability-temperature curve with a gyratory compactor (EN 12697-10), water sensitivity (EN 12697-12) at 15 °C and resistance to plastic deformation with the wheel tracking test (EN 12692-22) at 60 °C were determined. The main goal was to evaluate the suitability of the WMA additive to decrease the working temperatures without compromising the volumetric and mechanical properties of the mixture.

In the wet process, the manufacturing temperature for the reference mixture was 165 °C, and the rubberized warm mixtures were manufactured at 145 °C and 125 °C. In the dry process, the manufacturing temperature for the reference mixture was 170 °C, and the rubberized warm mixtures were manufactured at 150 °C and 130 °C. A scheme of the work conducted during the investigation is shown in Figure 1.

The thresholds that the laboratory test results were required to satisfy came from the Spanish specifications for dense grade asphalt mixtures (11). The water sensitivity (ITSw/ITsd) was required to reach a value of 85% or 80% for mixtures to be set in the wearing or the binder course, respectively. For the wheel-tracking test, the wheel tracking slope (WTS) was required to be lower than 0.07 mm/1000 cycles.

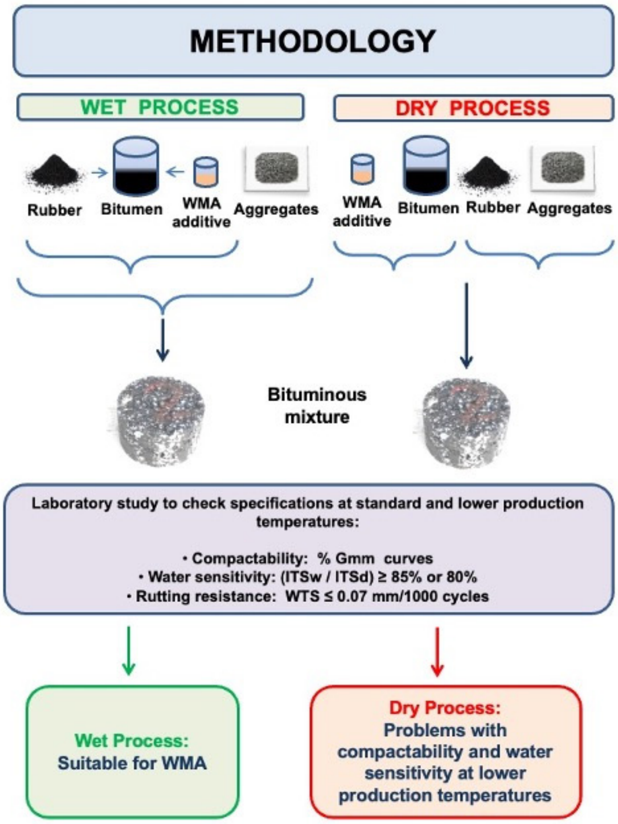

Figure 1. Graphical abstract of the investigation.

4. RESULTS AND DISCUSSION

4.1 Results for the wet process mixtures

The following sections present the tests performed for mixtures with rubber incorporated with a wet process.

4.1.1 Compaction energy

In this study, most tests were performed on cylindrical specimens manufactured with a gyratory compactor (EN 12697-31). However, Spanish regulations include specifications for specimens manufactured with a Marshall compactor (EN 12697-30), which indicate that for an AC16 S mixture, the compaction energy must be 75 blows on each side. Therefore, we first determined the number of rotations that needed to be applied by the gyratory compactor to reach the density achieved with 75 blows on each side by using a Marshall compactor. For this purpose, three specimens were compacted per study point, with 120, 140 or 160 rotations. Figure 2 presents the bulk density (saturated surface-dry, SSD) of the specimens according to the number of rotations. The bulk density of 2.387 g/cm^3 (corresponding to 75 blows on each side) was reached after approximately 130 rotations. Therefore, this number of rotations was selected as a reference for the wet-process mixes.

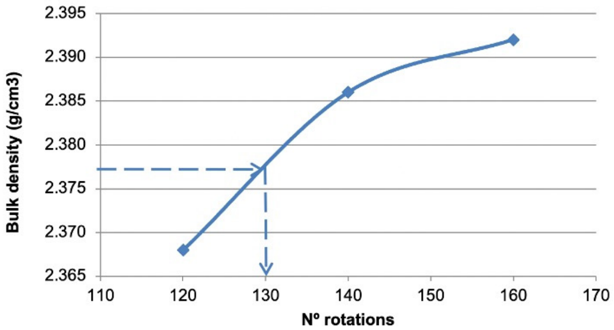

Figure 2. Evolution of bulk density (SSD) with the number of rotations for mixtures manufactured with the wet process.

4.1.2 Compactability

Likewise, a compactability study was performed with a gyratory compactor, and the manufacturing temperatures were varied to determine whether the WMA additive allowed for the same levels of densification to be maintained despite the decrease in production temperatures. These results are presented in Figure 3.

As can be seen in Figure 3, the reference mixture, the rubberized mixture without the WMA additive, was manufactured at 165 °C. Mixtures with additive, manufactured at 165 °C and at 145 °C, both were located above the reference curve. Thus, the WMA additive facilitated the densification of the mixture with sufficient efficiency that the manufacturing temperature could be decreased more than 20 °C. However, the densification of the mixture manufactured at 125 °C, was lower than that of the reference mixture. Thus, in terms of compactability and volumetric properties of bituminous mixtures with the wet process, the additive allowed the manufacturing temperature to be decreased approximately 30 °C. However, because the mechanical properties might have been worsened, testing of the water sensitivity and the resistance to plastic deformation were performed.

4.1.3 Water sensitivity

The water sensitivity of the mixtures was evaluated through the indirect tensile test, before and after immersion. We first determined the compaction energy that needed to be applied to the specimens for this test. When the specimens were manufactured with 75 blows/side with a Marshall compactor, the water sensitivity specimens were compacted with 50 blows/side. Decreasing the compaction energy subjects specimens to more critical conditions: the density decreases, the air void content increases, and the asphalt mixture is ultimately more vulnerable to the action of water.

However, for compaction with a gyratory compactor, insufficient evidence was available to establish the magnitude of the energy decrease that needed to be applied. Because in surface layers manufactured with AC type mixtures, the compaction reaches 98% of the reference (75 blows/side), in this investigation, the number of rotations was decreased so that the densi-

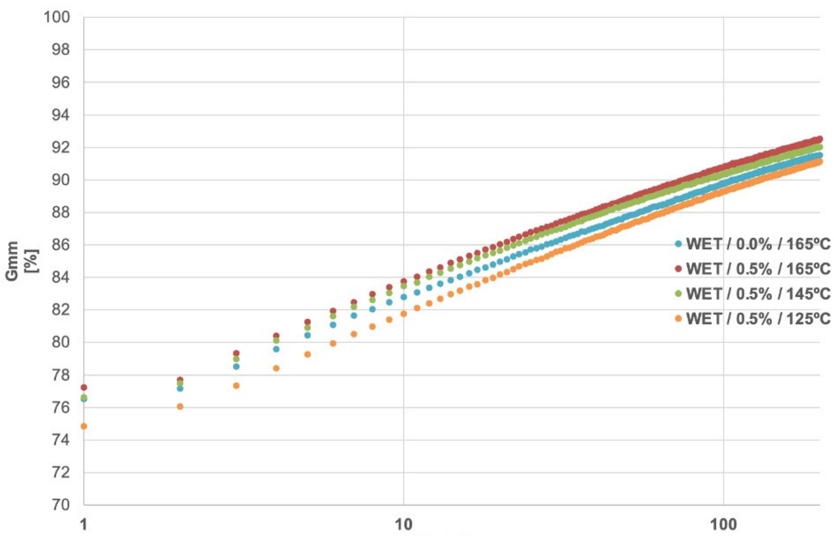

Figure 3. Compactability of mixtures manufactured by the wet process.

Table 4. Water sensitivity of mixtures manufactured with the wet process.

Manufacturing temperature (°C)	Compaction temperature (°C)	Additive (%)	Condition	Bulk density (g/cm³)	Air void content (%)	ITS (MPa)	ITSR (%)
165	155	0.0	Dry	2.341	6.32	2.13	91
			Wet	2.346	6.12	1.94	
165	155	0.5	Dry	2.349	6.00	2.12	93
			Wet	2.350	5.96	1.97	
145	135	0.5	Dry	2.349	6.00	1.86	87
			Wet	2,343	6.24	1.62	
125	115	0.5	Dry	2.327	6.88	1.71	70
			Wet	2.321	7.12	1.20	

ty for the reference mixture decreased approximately 1–2%. In this case, the 130 established rotations were decreased to 100 rotations. Thus, the reference mixture (without additive and manufactured at 165°C), decreased in density from 2.387 g/cm³ to 2.344 g/cm³, or 1.5%. The immersion conditions were 72 hours at 40 °C. All specimens, both dry and submerged, were finally tested at 15 °C. The results obtained are presented in Table 4 and Figure 4.

Decreasing the temperature resulted in more effective water attack, although the increase in the air void content did not exceed 1%. Hence, the additive allowed for a decrease of temperature in terms of densification, but the adhesiveness between the binder and the aggregates appeared to lose quality, as indicated by the decrease in the ITSR parameter while the manufacturing temperature was decreased.

ITSR values ≥ 85% for the surface layer and ≥ 80% for the intermediate layer are usually required. Therefore, decreasing the manufacturing temperature below 145 °C for surface layers and above 140 °C for intermediate layers is not advisable (Figure 4).

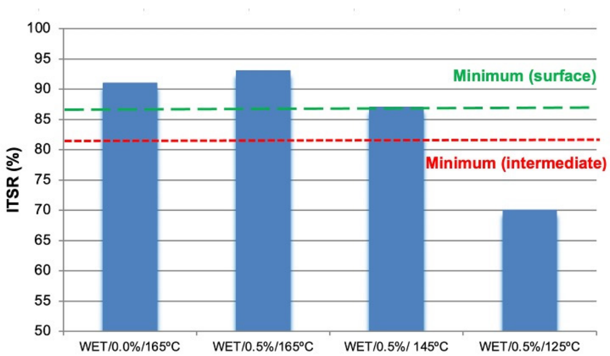

Figure 4. Water sensitivity of mixtures manufactured by the wet process.

4.1.4 Resistance to permanent deformation

The addition of the WMA additive at 165 °C did not appear to introduce marked differences in the resistance to plastic deformation. However, for the mixtures incorporating the additive, as the manufacturing temperature decreased, the bituminous mixture became more prone to plastic deformation. The mixture manufactured at 125 °C (Figure 5) already exceeded the maximum of WTS air = 0.07 mm/1,000 cycles allowed for AC16 S mixture subjected to the wheel tracking test, according to Spanish specifications (PG-3). Therefore, decreasing the manufacturing temperature below approximately 135 °C would not be reasonable; otherwise, the mixture could experience rutting. This result may relate to the decrease in density, as shown in Table 4, at a 125 °C working temperature, thus making the mixtures more prone to post-compaction and resulting in a deeper track during the testing.

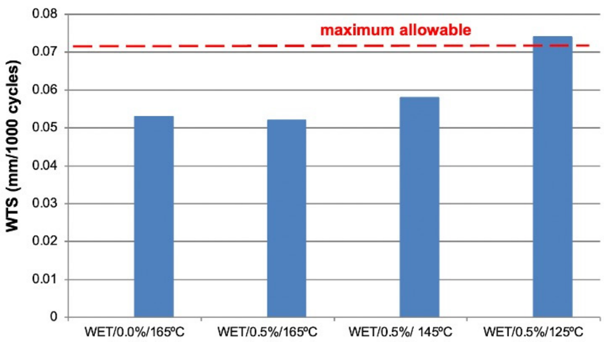

Figure 5. Deformation resistance of mixtures manufactured with the wet process.

4.2 Dry process mixtures

The following sections present the tests performed on mixtures with rubber incorporated with the dry process.

4.2.1 Compaction energy

As explained before, we first established the number of rotations that needed to be applied in the gyratory compactor to reach a density similar to the Marshall compaction energy with 75 blows/side. Figure 6 shows the bulk density (SSD) of the specimens for the indicated rotations. The apparent density of 2.375 g/cm³ (corresponding to 75 blows/side) was reached with approximately 120 rotations. Therefore, this number of rotations was selected as a reference for the compaction of dry process mixtures.

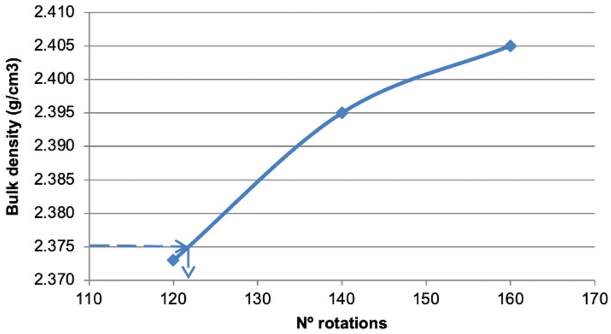

Figure 6. Evolution of bulk density (SSD) with the number of rotations for mixtures manufactured with the dry process.

This energy was lower than that of wet process mixes, for which 130 rotations had been established. This result might have been because the gyratory compactor, as a result of its kneading effect, performed better than the Marshall compactor in addressing the compaction difficulties caused by the rubber particles incorporated by the dry process.

4.2.2 Compactability

For the wet process, a compactability study was performed with the gyratory compactor. The reference mixture (without additive and manufactured at 170 °C) was studied, as well as mixtures with the WMA additive manufactured at temperatures of 170, 150 and 130 °C (Figure 7).

The results obtained did not indicate a clear trend, but the decrease in temperature from 170 to 150 and 130 °C resulted in lower densities than that of the 170 °C reference mixture. As shown in Figure 8, the reference mixture with no additive and produced at 170 °C, was reached by only the mixture with additive at 170 °C. Nevertheless, as soon as the production temperature decreased to 150 and 130 °C, the densification curves, respectively, decreased, thus indicating an inefficient compaction process.

These results might have been because the rubber particles needed to be digested in the bituminous mixture in the dry process (in the wet process, they were already digested in the binder). Because digestion requires high temperatures, above 160 °C (10), the mixtures produced herein by the dry process at 150 and 130 °C had not sufficiently digested the rubber particles and therefore remained in an elastic condition, thereby hindering the compaction and densification of the bituminous mixtures.

This finding is in line with results from previous research indicating that, when rubber is added, if the compaction temperature is not sufficiently high, the use of rubberized mixes results in inadequate volumetric properties (higher air voids and uneven density distribution) and poor short-term and long-term performance, because of uncertain factors (16).

4.2.3 Water sensitivity

The test conditions were the same as those described in Section 4.3 for the study of wet process mixtures. However, the compaction conditions of

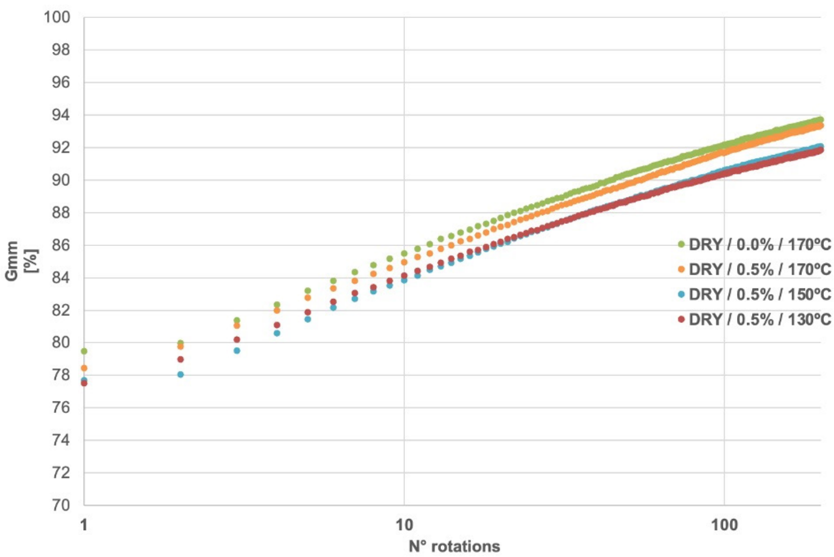

Figure 7. Compactability of mixtures manufactured with the dry process.

Table 5. Water sensitivity (dry process).

Manufacturing temperature (°C)	Compaction temperature (°C)	Additive (%)	Condition	Bulk density (g/cm^3)	Air void content (%)	ITS (MPa)	ITSR (%)
170	160	0.0	Dry	2.338	6.37	1.72	88
			Wet	2.342	6.21	1.51	
170	160	0.5	Dry	2.348	5.97	1.67	91
			Wet	2.349	5.93	1.52	
150	140	0.5	Dry	2.323	6.97	1.49	61
			Wet	2.319	7.13	0.91	
130	120	0.5	Dry	2.313	7.37	1.11	55
			Wet	2.320	7.09	0.61	

the specimens differed. In this case, the compaction reference was 120 rotations in the gyratory compactor. The density obtained for the reference mixture with that energy level was 2.375 g/cm^3. As in the case of the wet process mixtures, we determined the number of rotations after which the density decreased to no more than 98% of the reference to be 90 rotations, with a bulk density of 2.340 g/cm^3, 98.5% of the reference. Therefore, all water sensitivity specimens were compacted with 90 rotations in the gyratory compactor. The results obtained are presented in Table 5.

In terms of resistance to the action of water, the manufacturing temperatures could not be decreased (Figure 9), despite the incorporation of the WMA additive. Even for a temperature of 150 °C, the ITSR was far from the 80% usually required for an intermediate layer and the 85% required for a surface layer (11).

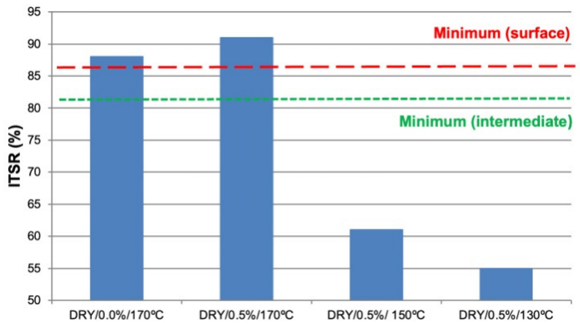

Figure 8. Water sensitivity of mixtures manufactured by the dry process.

This result was attributed to the lack of digestion of the rubber particles, because of the need for higher temperatures for the dry process (10, 12). In short, the selected WMA additive, which might have had other effects, did not promote the digestion of the rubber particles, which remained in an elastic state among the aggregates. Therefore, compaction was difficult, and the rubber-bitumen interface did not achieve sufficient affinity and, consequently, became vulnerable to water attack.

To overcome this situation, three alternatives can be suggested: a decrease in the rubber particle size, which in this case was <0.5 mm, to smaller particles, as reported by Da Silva et al. (15) ; the selection of rubber pretreated to facilitate the digestion; or a decrease in rubber content, which was 1% of the mixture by weight. These solutions would decrease the digestion time at standard temperature and probably allow for the working temperatures to be decreased.

Although this aspect is previously undescribed, according to the protocol for compaction in a gyratory compactor (EN 12697-31), the bituminous mixture must remain in an oven at the compaction temperature for 2 hours, within the mould. In short, all studied mixtures, including those incorporating dry rubber, underwent 2 hours of digestion in an oven (12). However, this treatment did not solve the compactability and water sensitivity problems. Hence, these problems do not appear to be addressable by increasing the digestion time if the manufacturing temperatures are not increased as well (contrary to the objectives of this investigation). The feasibility of using rubberized WMA mixtures with rubber with the dry process, at least with the additive selected for this study, does not appear to be ensured, on the basis of the results in this investigation. Additional research is needed.

4.2.4 Resistance to permanent deformation

Regarding the resistance to plastic deformation, the addition of the WMA additive at the reference temperature (170 °C) did not appear to introduce appreciable differences. In contrast, in the mixtures incorporating the additive, decreasing the manufacturing temperature resulted in no significant changes in the resistance to ruts (Fig. 10), because for all temperatures, the values obtained were below WTS air = 0. 07 mm/1,000 cycles, the maximum allowed for this type of bituminous mixture by the Spanish specifications (11). The manufacturing temperatures could feasibly be decreased, although this hypothesis was already rejected because of compactability reasons and vulnerability to water attack.

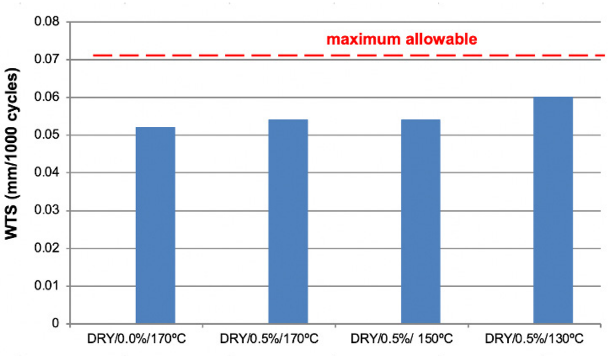

Figure 9. Resistance to permanent deformation of mixtures manufactured with the dry process.

5. CONCLUSIONS

The following conclusions can be drawn from the research performed:

- The incorporation of the additive used in this study (dose 0.5% the weight of the base bitumen) allowed for a decrease in the manufacturing temperature of the mixtures with rubber incorporated with a wet process, from the reference temperature of 165 °C to approximately 140 °C, while maintaining similar volumetric properties, as well as resistance to water and plastic deformation meeting the Spanish specifications for dense graded asphalt mixtures used in surface and intermediate layers.
- However, the use of the additive was not effective for mixtures with rubber incorporated with the dry process. When the temperature decreased below the reference temperature, the compaction was deficient, as displayed in the compactability curves. Moreover, the rubber-bitumen contact was clearly weakened, as shown by worsening of the water sensitivity. These results might have been associated with insufficient digestion of the rubber particles in the bituminous mixture, owing to the lowering of the working temperature. Therefore, the option of using WMA mixtures with rubber incorporated with a dry process does not appear viable with this additive.

Owing to the lack of digestion of the rubber particles under low working temperatures, WMA mixtures with rubber incorporated with a dry process, indicated that new solutions are needed. Among possible solutions, the use of catalysers of the digestion process, pre-treated easily digestible rubbers, or simply finer rubber gradations may overcome the problems with the dry process reported herein. All these issues are topics for further investigation.

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AUTHOR CONTRIBUTIONS:

Conceptualization: A.M. Rodríguez-Alloza, J. Gallego, F. Guliani. Data curation: A.M. Rodríguez-Alloza, J. Gallego, F. Guliani. Formal analysis: A.M. Rodríguez-Alloza. Funding acquisition: A.M. Rodríguez-Alloza. Investigation: A.M. Rodríguez-Alloza, F. Giuliani, J. Gallego. Methodology: A.M. Rodríguez-Alloza, F. Giuliani, J. Gallego. Project administration: A.M. Rodríguez-Alloza. Resources: A.M. Rodríguez-Alloza. Software: A.M. Rodríguez-Alloza. Validation: A.M. Rodríguez-Alloza, F. Giuliani, J. Gallego. Visualization: A.M. Rodríguez-Alloza. Writing, original draft: A.M. Rodríguez-Alloza, J. Gallego, F. Giuliani. Writing, review editing: A.M. Rodríguez-Alloza.

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