TREATMENTS APPLIED TO RECYCLED CONCRETE AGGREGATES WHEN USED IN HOT-MIX ASPHALT

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ABSTRACT

The road construction industry is one of the major consumers of aggregate at the global level. The extraction of virgin aggregates entails several environmental, sociological and economic impacts. Therefore, reducing the consumption of natural aggregates is crucial to guarantee sustainable development. In this regard, in the last years, several research studies have been conducted dealing with the use of recycled concrete aggregates (RCAs) from construction and demolition wastes (C&DW) as aggregates for hot-mix asphalt (HMA). In general, from these investigations, it can be concluded that bituminous mixtures produced using partial replacement of natural aggregates with RCAs exhibit lower water resistance, which could adversely affect the durability of the HMA. To address this durability issue, in the present investigation, two simple and environmentally friendly treatments applied to the RCAs were analyzed and compared: 1) leave the mixture for 4 hours in the oven before compaction at the mixing temperature of 170 ºC and 2) pre-coat the RCA with 5% of bitumen emulsion prior to the mixing process. To evaluate the performance of HMA made with partial replacement of natural aggregate by RCA, the following measurements were conducted: the water resistance was determined by measuring the loss of indirect tensile strength, the stiffness was measured by means of the indirect tensile test (ITT) and resistance to the permanent deformation was determined by means of repeated load axial test (RLAT). Percentages of RCA of 5 %, 10%, 20% and 30% were used. Both treatments demonstrated their effectiveness in improving the water resistance of the mixtures. Moreover, the stiffness is higher in the mixtures with RCA and the rutting potential is satisfactory.

Keywords: Hot-mix asphalt, Recycled concrete aggregates, Water resistance, Treatments.

INTRODUCTION

The road construction industry is one of the major consumers of aggregate, both in Europe (*1*) and in the U.S.A. (*2*). Despite the downward trend in the construction sector since 2008, Europe consumed a total of 2.305 billion tons of natural aggregates in 2012 (*3*); while in the U.S.A., the natural aggregate future demand is estimated to be 2.7 billion tons by 2020 (*2*).

The extraction of aggregates from natural sources entails several environmental, sociological (*4*) and economical (*5*) impacts. Thus, reducing consumption of virgin aggregates for road pavement construction materials is crucial to guarantee sustainable development.

In this context, several attempts to use waste materials as aggregate have been performed: reclaimed asphalt pavement (RAP) (*6-8*), mining byproducts (*4*), asphalt shingles (*5*), or construction and demolition wastes (C&DW) are some examples of waste that have been successfully used. In particular, C&DW deserves special attention because of the huge amount that is generated at the global level and the great recycling potential of this debris (*9*), which make C&DW an excellent source for obtaining recycled aggregates. Therefore, much research on the possible applications of C&DW for road materials has emerged. In this regard, there are successful experiences on the use of recycled concrete aggregates (RCAs) from C&DW in unbound pavement layers (*10, 11*). Additionally, in recent years, new investigations have been performed dealing with the use of RCA as aggregate in hot-mix asphalt (HMA) (*12-19*).

The use of RCA in HMA exhibits a clear advantage versus its use in unbound pavement layers: asphalt is water impermeable (*17, 20*), thus avoiding dangerous leachates to the surrounding greenery (*20*). However, the difference between the RCA and the natural aggregate properties will condition the behavior of the HMA made with partial replacement of RCA. Due to the great influence of water on the durability of the mixture, performing a water sensitivity analysis is particularly important. In general, it can be concluded that the water resistance is lower in mixtures made with RCA (*12, 13, 14, 17, 18, 19*). Some researchers suggest that HMA with RCA meets the specifications relating to water sensitivity (*18, 19*), while other researchers indicate that the results are far away from the minimum national requirement (*12, 14*). Additionally, some authors stated that compliance with the national specifications depends on the percentage substitution of RCA (*13*).

To improve the moisture damage resistance of mixtures made with partial replacement of RCA, several authors have investigated the possibility of applying pretreatments. For example, Lee et al. (*21*) coated the RCA with a slag cement paste, obtaining water resistance results that are within the range of the Taiwanese requirements. Moreover, Zhu et al. (*22*) coated the RCA with a liquid silicone resin, improving the moisture damage resistance of HMA made with RCA.

In the present investigation, two simple and environmentally friendly treatments applied individually to the RCA were analyzed and compared: 1) leave the mixture for 4 hours in the oven before compaction at the mixing temperature of 170ºC (*23*) and 2) pre-coat the RCA with a 5% of bitumen emulsion prior to the mixing process (*24*). To evaluate the performance of HMA made with the partial replacement of natural aggregate by RCA, the following measurements were conducted: the water resistance was determined by measuring the loss of indirect tensile strength, the stiffness was measured by means of the indirect tensile test (ITT) and resistance to the permanent deformation was determined by means of repeated load axial test (RLAT) Percentages of RCA ranging from 5% to 30% were used.

MATERIALS AND METHODS

Materials

A base course mixture, type AC 22 base G according to the limits given by the Spanish General Technical Specifications for Road and Bridges (*25*), was chosen to conduct the investigation. Figure 1 shows the grain size distribution of the mixture.

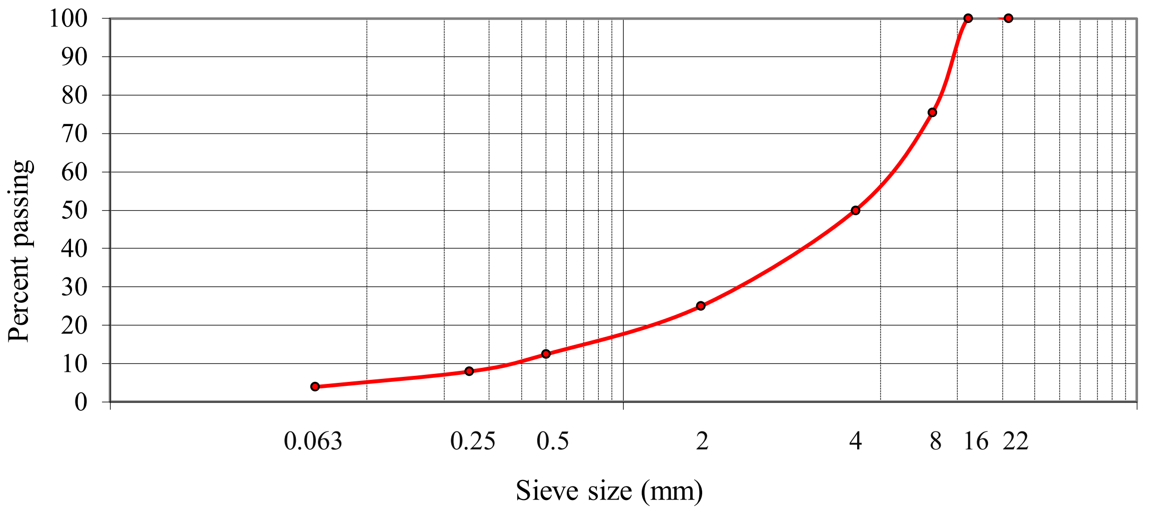


FIGURE 1 Grain size distribution of AC 22 base G.

Hornfels provided by a local supplier was used as natural aggregate. RCA (Figure 2) from the C&DW of residential buildings was supplied by a recycling site in Madrid (Spain).

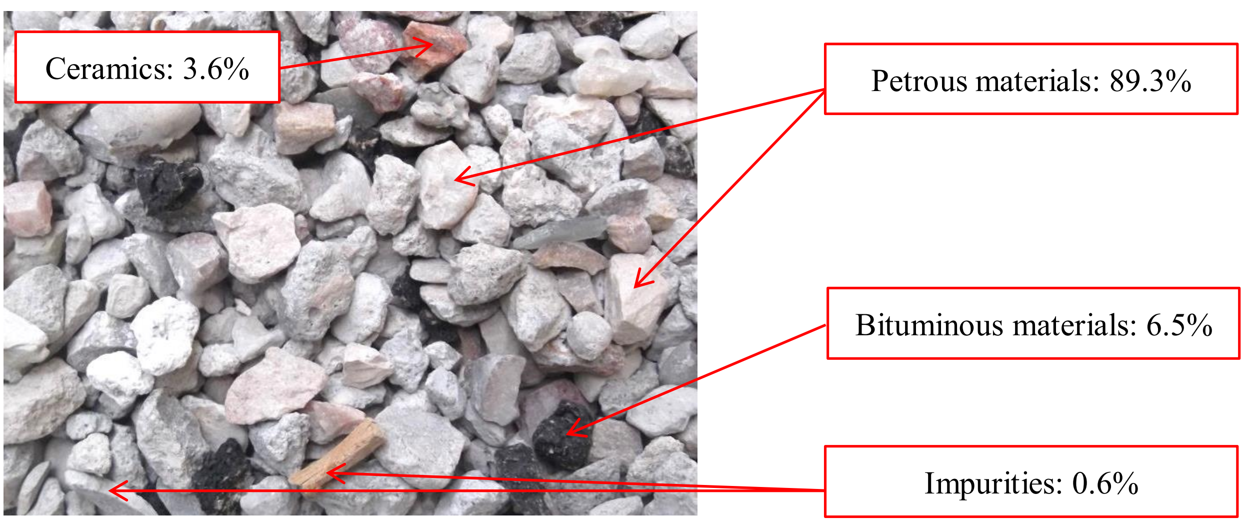


FIGURE 2 RCA used in this investigation.

The bulk specific gravity (ρa), the water absorption (W_{24}), the sand equivalent (SE) and the Los Angeles (LA) abrasion coefficient for both aggregates are presented in Table 1. Portland cement CEM II/B-M (V-L) 32.5 N was used as mineral filler.

TABLE 1 Virgin and recycled aggregates properties

Property	Hornfels	RCA	Spanish Specifications (*25*)		
			T00-T1 (*)	**T2-T3** (*)	**T4** (*)
ρa (g/cm^3)	*2.79*	*2.63*	-	-	-
WA_{24} (%)	*1.08*	*5.08*	-	-	-
SE (%)	*61*	*67*	*≥ 50*	*≥ 50*	*≥ 50*
LA (%)	*14.1*	*32*	*≤ 25*	*≤ 30*	-

(*) Traffic category T00 refers to AADHT (Annual Average Daily Heavy Traffic) ≥ 4,000
Traffic category T0 refers to 4,000 > AADHT ≥ 2,000
Traffic category T1 refers to 2,000 > AADHT ≥ 800
Traffic category T2 refers to 800 > AADHT ≥ 200
Traffic category T3 refers to 200 > AADHT ≥ 50
Traffic category T4 refers to AADHT < 50

A penetration grade bitumen B50/70 with the properties shown in Table 2 was used to manufacture the mixtures.

TABLE 2 B50/70 penetration grade bitumen properties

Property	B50/70	Spanish Specifications (*25*)
Original		
Penetration (100 g, 5 s, 25ºC), 0.1 mm	*52*	*50-70*
Softening point, ºC	*54.9*	*48-57*
Flash point, ºC	*>290*	*>235*
Density (25ºC), g/cm^3	*1.009*	*>1.0*
After rolling thin-film oven test		
Penetration (100 g, 5 s, 25ºC), 0.1 mm	*68*	*>50*
Δ Softening point, ºC	*6.5*	*≤9*

The bitumen emulsion used to coat the RCA in one of the pretreatments was an ECL-2d, that is a low setting cationic bitumen emulsion with a 61.2% of bitumen content.

Methods

Mix design

The Marshall mix design procedure according to NLT-159/86 (26), was used to manufacture the cylindrical samples. The mixing temperature was 170ºC and the compaction temperature was 165ºC. As said above, percentages of 5%, 10%, 20% and 30% of RCA by weight of total aggregate were studied. Percentages of 3.5%, 4.0% and 4.5% of bitumen by weight of total mixture were used.

Water resistance

UNE-EN 12697-12 (*27*) was used to evaluate the water resistance of HMA samples made with 5%, 10%, 20% and 30% of RCA. The samples were produced at 3.5%, 4.0% and 4.5% bitumen content for each RCA percentage. Additionally, for each RCA percentage, the two above-mentioned treatments were individually used to manufacture the mixture: 1) leave the mixture for 4 hours in the oven and 2) pre-coat the RCA with a 5% of bitumen emulsion.

For each water resistance analysis, a set of ten cylindrical Marshall samples was manufactured. Each set was subdivided into two subsets: the dry subset and the wet subset. The dry subset was kept dry at room temperature. The wet subset was vacuum saturated and then introduced in a water bath for 3 days at 40°C. After that time, both subsets were left for 2 hours at 15°C: the dry subset in air and the wet subset in water. Next, the tensile strength of the dry subset (ITS_D) and the wet subset (ITS_W) was determined. In this test, the moisture sensitivity was evaluated by measuring the loss of indirect tensile strength, expressed in terms of the tensile strength ratio (TSR):

$$TSR = \frac{ITS_W}{ITS_D} \times 100 \qquad (1)$$

TSR≥80% is required by Spanish specifications (*25*) for HMA for use in base courses.

Stiffness

The resilient modulus (M_R) of the mixtures was determined in accordance with UNE-EN 12697-26 Annex C (*27*), using a Cooper NU 14 tester (Figure 3). The test was performed in a controlled-temperature cabinet at temperatures of 0ºC, 10ºC and 20ºC.

The resilient modulus for each specimen was obtained as follows:

$$M_R = \frac{F \times (\nu + 0.27)}{z \times h} \qquad (2)$$

where M_R = the resilient modulus (MPa), F = the maximum repeated load (N), z = the horizontal recoverable deformation (mm), h = the thickness of the specimen (mm) and ν= Poisson's ratio (an assumed Poisson's ratio of 0.35 (28) was used).

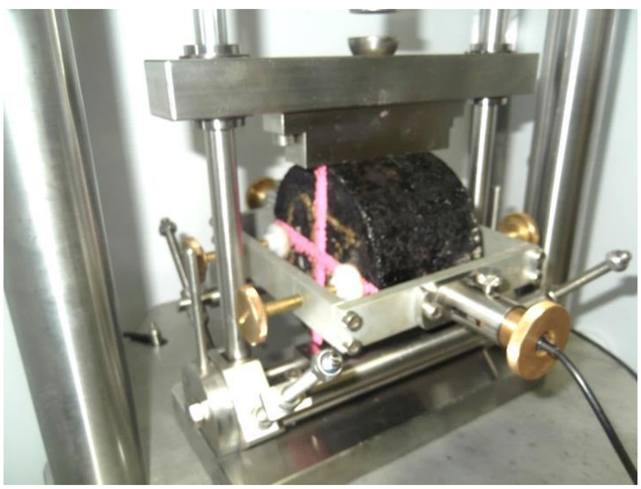


FIGURE 3 indirect tensile stiffness modulus test device.

Resistance to the permanent deformation

To evaluate the resistance of the above-mentioned mixes to the permanent deformation, the repeated-load axial test (RLAT) without confinement was conducted, following the standard 226:1996 (*29*), using a Cooper NU 14 tester (Figure 4).

To calculate the axial permanent strain, the following equation was used:

$$\varepsilon_{d(n,T)} = \frac{\Delta h}{h_0} \text{x}100 \qquad (3)$$

where $\varepsilon_{d(n, T)}$ = the axial permanent strain (in %) after n load applications at temperature T in ºC, h_0 = the initial distance between the two load platens (mm) and Δh = the axial permanent deformation (mm).

FIGURE 4 repeated-load axial test device.

RESULTS AND DISCUSSION

Mix design

Table 3 and Table 4 show the air voids (Va) and the voids in mineral aggregate (VMA) content for the two pretreatments. Also in Table 3 is included the bitumen absorption that takes place during the time the mixture is in the oven and in Table 4 is included the bitumen emulsion content by total weight of the mixture.

TABLE 3 Volumetric properties for the samples cured for 4 hours in the oven

Pretreatment	RCA (%)	Bitumen content (%)	Va (%)	VMA (%)	Bitumen absorption (%)
Leave the mixture for 4 hours in the oven before compaction at the mixing temperature of 170ºC	*5*	*3.5*	-	-	-
		4.0	*8.01*	*17.48*	*0.9*
		4.5	*6.09*	*16.86*	*0.9*
	10	*3.5*	-	-	-
		4.0	*7.98*	*17.42*	*1.1*
		4.5	10.23	20.51	-
	20	*3.5*	9.52	17.62	1.5
		4.0	4.02	13.46	1.5
		4.5	6.68	17.26	1.5
	30	*3.5*	10.39	18.38	-
		4.0	5.09	14.38	1.9
		4.5	7.22	17.63	-

"-": Not available data

TABLE 4 Volumetric properties for the samples made with RCA coated with bitumen emulsion

Pretreatment	RCA (%)	Bitumen emulsion by total weight of the RCA	Bitumen emulsion by total weight of the mixture	Bitumen content (%)	Va (%)	VMA (%)
Pre-coat the RCA with bitumen emulsion prior to the mixing process	*5*	*5%*	*0.25%*	*3.5*	6.74	15.18
				4.0	*6.18*	*15.85*
				4.5	*3.59*	*14.63*
	10		*0.50%*	*3.5*	*6.08*	*14.52*
				4.0	*4.85*	*14.55*
				4.5	3.16	14.19
	20		*1.00%*	*3.5*	6.32	14.61
				4.0	5.00	14.58
				4.5	6.39	15.84
	30		*1.50%*	*3.5*	9.28	16.19
				4.0	7.93	16.03
				4.5	5.24	14.65

Water resistance

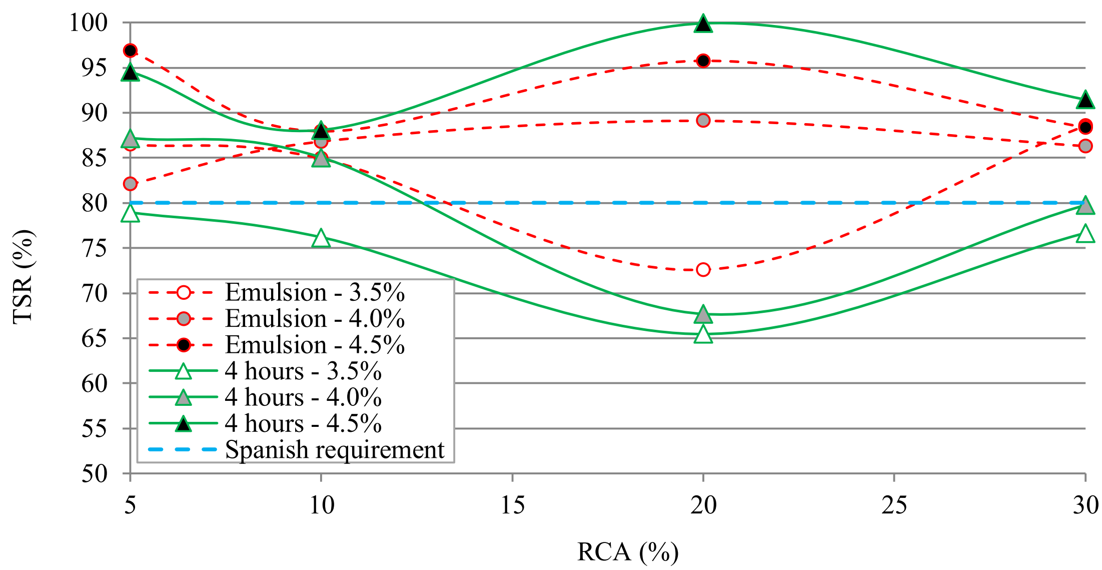
As seen in Figure 5, the TSR versus the RCA content is represented for both treatments: 4 hours of curing time in the oven and coating RCA with bitumen emulsion. Figure 5 shows that, in general, mixtures made with RCA coated with bitumen emulsion reach the minimum TSR required by Spanish standard. On the contrary, mixtures made with 4 hours of curing time in the oven only reach the minimum TSR, when the HMA is designed with an amount of binder sufficient to allow the complete absorption of the bitumen by the pores of the RCA. That is, both treatments enable mixtures with a satisfactory water resistance. Nevertheless, note that when the mixture is cured in the oven, the amount of binder should be sufficient to seal the pores and achieve the desired effect, i.e., to close the possible entryways of water. In this case, the bitumen should also be sufficient so that the binder film thickness is not too thin.

Figure 6 represents the ITS versus the RCA content for both treatments. As seen in Figure 6, mixtures made with coated RCA exhibit a more homogeneous performance, that is, more independent of the percentage of RCA and bitumen content. In addition, Figure 6 shows that with the treatment of 4 hours of curing time, the mixtures have greater indirect tensile strength in both dry and wet states.

Stiffness

Figure 7 shows the M_R versus the RCA content for the three tested temperatures for mixtures made using both treatments. As can be clearly seen, in general, mixtures cured for 4 hours in the oven exhibit higher stiffness modulus values than mixtures made with RCA coated with bitumen emulsion. The loss of volatile compounds that occur during the time that the mixtures are in the oven is mainly responsible of this performance. This tendency is more pronounced for higher test temperatures. At low temperatures the effect of the test temperature is predominant versus the use of one treatment or the other, due to the viscoplastic nature of the bitumen.
Nevertheless, mixtures made with RCA coated with emulsion exhibit values of the resilient modulus at 20ºC slightly higher than those usually obtained for mixtures AC 22 base G, probably because the emulsion penetrates onto RCA pores cause an increased resistance in the attached

mortar onto the RCA surface. In this regard, in Spain, a resilient modulus at 20ºC of 5,000 MPa is usually obtained for this type of mixture (30). As seen in Figure 7a, the tested mixtures exhibit M_R higher than 5,000 MPa. Moreover, in the case of the mixtures that have been cured for 4 hours in the oven, the value of M_R is very close to 11,000 MPa, which is the minimum value of the resilient modulus required by Spanish specifications (25) for high modulus mixtures.



(*) Emulsion – 3.5%: the mixture was manufactured with RCA coated with 5% of bitumen emulsion and 3.5% of bitumen
Emulsion – 4.0%: the mixture was manufactured with RCA coated with 5% of bitumen emulsion and 4.0% of bitumen
Emulsion – 4.5%: the mixture was manufactured with RCA coated with 5% of bitumen emulsion and 4.5% of bitumen
4 hours – 3.5%: the mixture was manufactured with 3.5% of bitumen and was cured for 4 hours in the oven
4 hours – 4.0%: the mixture was manufactured with 4.0% of bitumen and was cured for 4 hours in the oven
4 hours – 4.5%: the mixture was manufactured with 4.5% of bitumen and was cured for 4 hours in the oven

FIGURE 5 TSR versus RCA content.

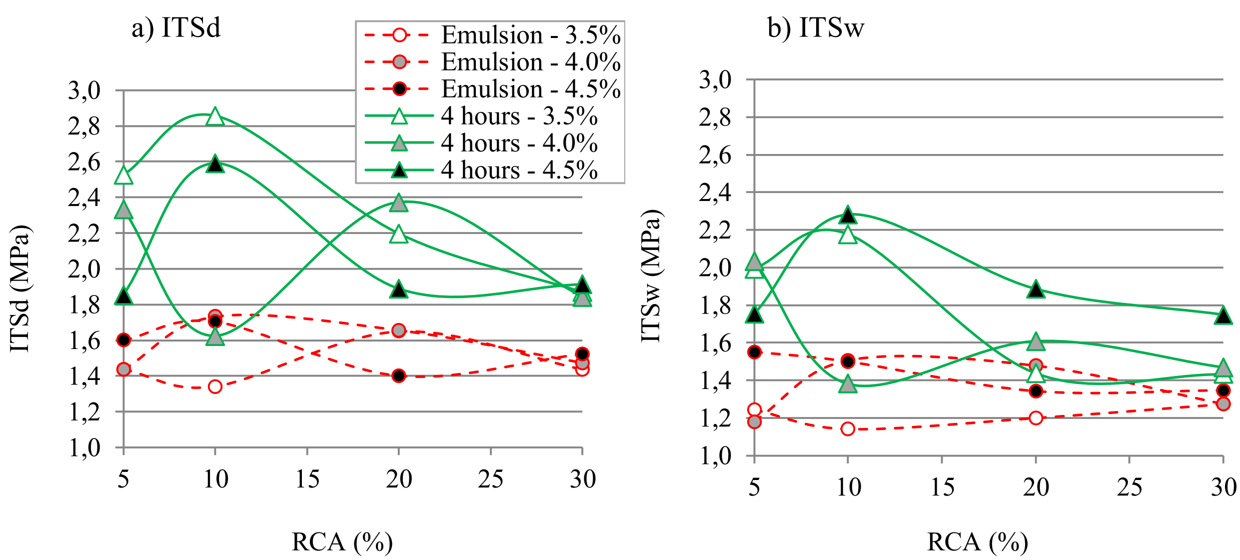


FIGURE 6 ITS versus RCA content: a) ITSd and b) ITSw.

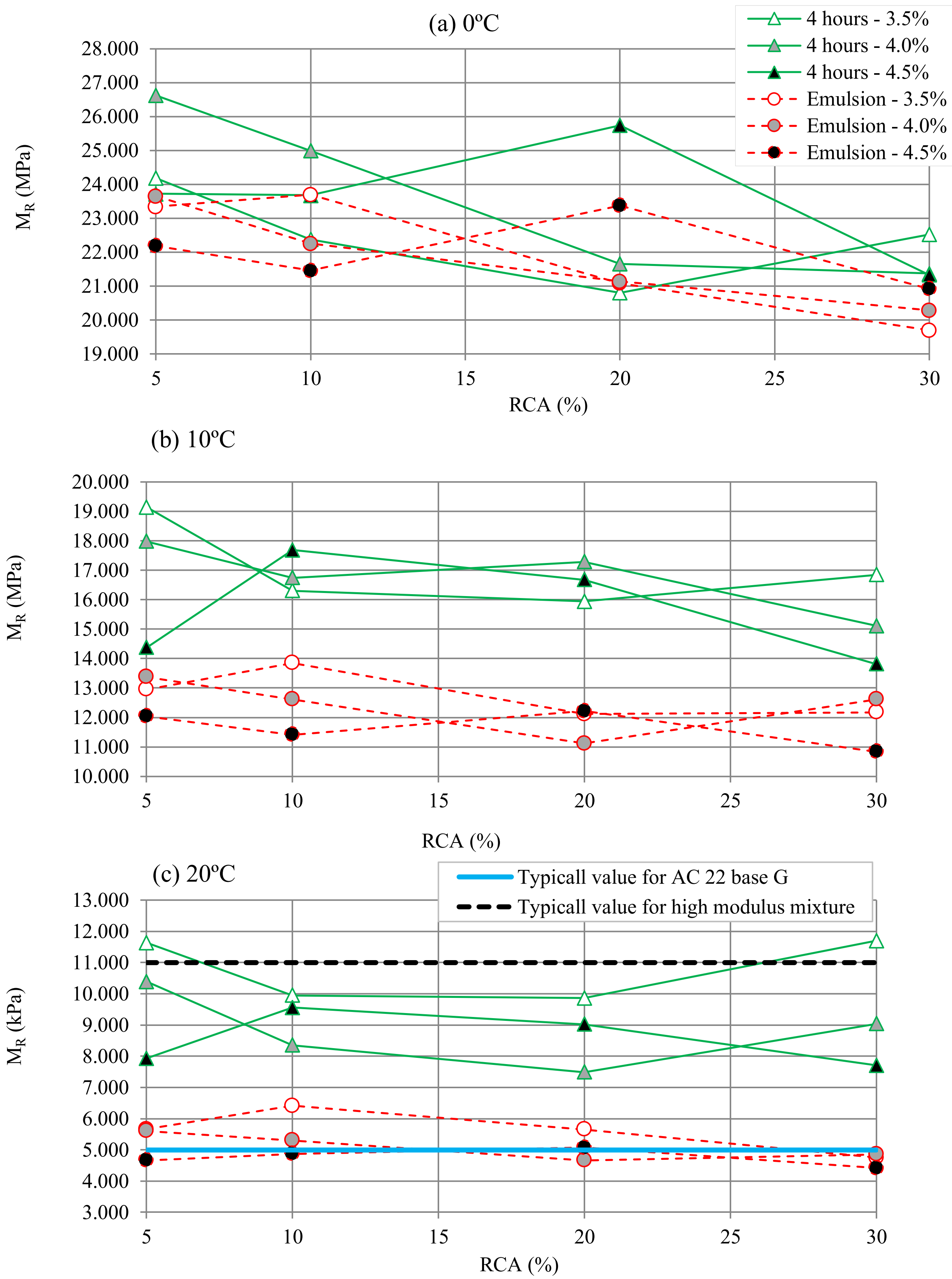


FIGURE 7 M_R versus RCA content: a) 0ºC, b) 10ºC and c) 20ºC.

A control mixture (0% RCA and no treatment) was also tested, as shown in Table 5. As can be seen, the resilient modulus for the control mixture is slightly lower than those obtained for the mixtures made with RCA coated with bitumen emulsion. Also it must be noted that the resilient modulus for the control mixture is lower than those obtained for mixtures cured for 4 hours in the oven. Same as indicated above, differences are more noticeable at 20ºC than at 0ºC.

TABLE 5 Resilient modulus for control mixture

Test temperature (0C)	**Bitumen content (%)**	**M_R (MPa)**
0	*3.5*	22,269.0
	4.0	23,065.5
	4.5	22,666.5
10	*3.5*	14,346.5
	4.0	13,391.0
	4.5	12,801.5
20	*3.5*	4,924.0
	4.0	5,309.5
	4.5	4,853.5

Resistance to the permanent deformation

The rutting potential of the mixtures is related to the permanent deformation results. The RLAT results are only useful to compare the rutting performances of the different tested mixtures because there are no requirements for this test. For this reason, a control mixture (0% RCA and no treatment) was also tested.

Figure 8 shows the accumulated permanent deformation values versus the number of loading cycles for mixtures made with both treatments and for the control mixture.

As expected, Figure 8 shows that the permanent deformation increases with the number of loading cycles for all of the tested mixtures. At the beginning of the load cycling, the mixtures exhibit rapid densification. Note that the slopes of the curves between cycles 600 and 1,800 (31) are very similar; therefore, the rapid initial densification is mainly responsible for the differences in the accumulated permanent deformation at cycle 1,800.

Nevertheless Figure 8 shows that there is no clear pattern between the final accumulated permanent deformation at cycle 1,800 and the bitumen content, the use of one or other treatment, and the RCA percentage. In this regard, it can be only concluded that the mixtures made with both treatments exhibit a final permanent deformation higher than that of the control mixture. The difficulty in compacting the RCA, which has a more roughness texture, seems to be mainly responsible of this performance. Nevertheless, the final permanent deformations are in the range of the final permanent deformations obtained by other authors (32, 33).

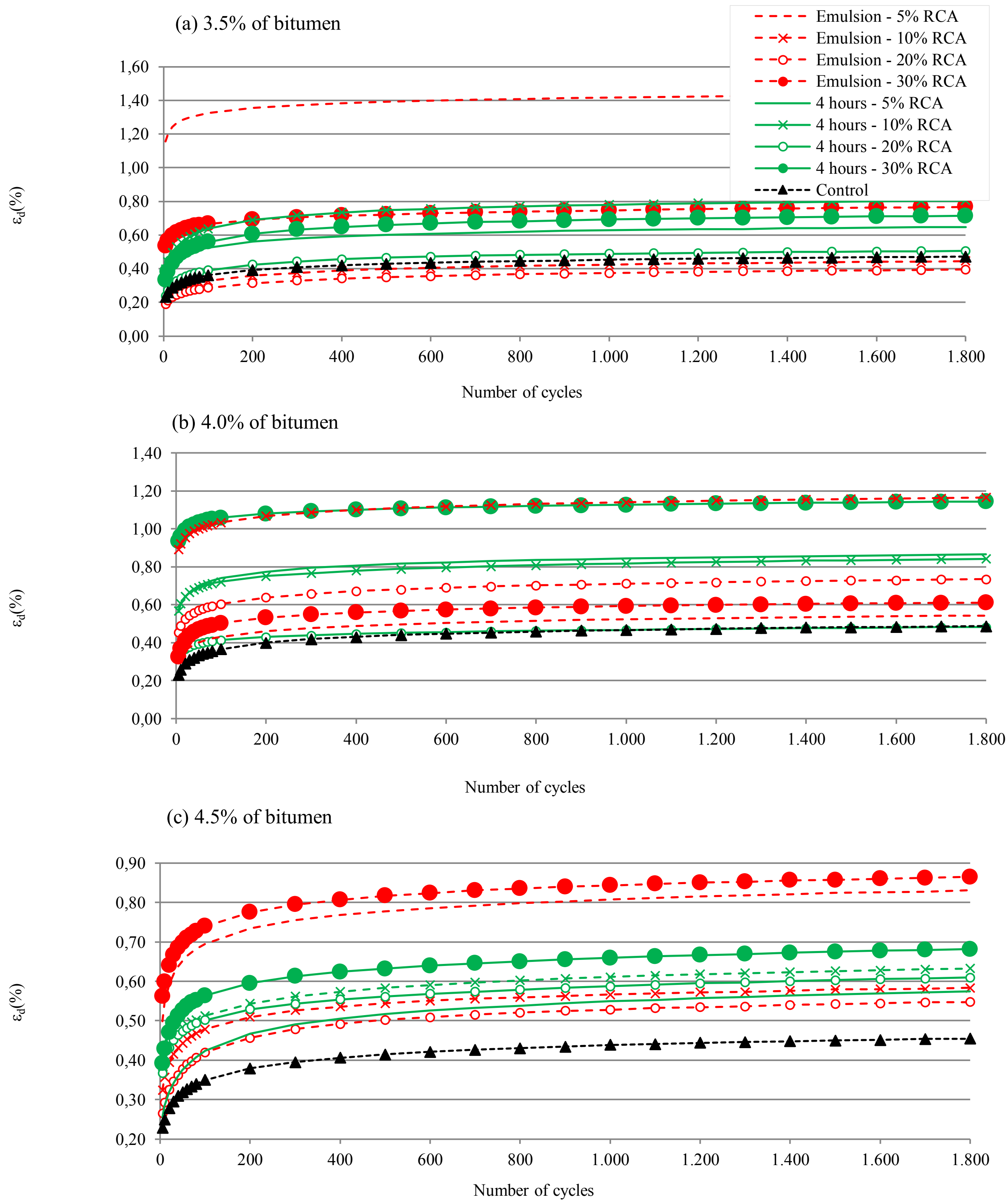


FIGURE 8 RLAT results: a) 3.5% of bitumen, b) 4.0% of bitumen and c) 4.5% of bitumen.

CONCLUSIONS

In the present investigation, two simple and environmentally friendly treatments applied to HMA made with partial replacement of RCA were evaluated. The aim of this laboratory evaluation is to improve the HMA water resistance without detriment to the other mechanical properties, such as stiffness and resistance to the permanent deformation.

The treatment that consists of coating the RCA with a 5% of bitumen emulsion prior to the mixing process leads to mixtures achieve TSR values higher than the 80% required by the Spanish specifications. Thus, this treatment was demonstrated to be effective in improving water resistance of HMA made with the partial replacement of conventional aggregate by RCA. The mixtures that were cured in the oven for 4 hours at a mixing temperature of 170ºC prior to compaction only reach or exceed this minimum TSR value when are designed with a relatively high bitumen content. That is, in this case, the binder content must be sufficient to allow its absorption by the RCA pores to eliminate possible water pathways without compromising the bitumen film thickness. Thus, the effectiveness of this treatment is dependent on the design of the bitumen content. In this regard, bitumen contents of 4.5% lead to mixtures that comply with the water sensitivity requirements.

The stiffness of the mixtures made with emulsion is slightly higher than the conventional ones, while mixtures cured in the oven are much stiffer. In this regard, this mixture displays a resilient modulus similar to those obtained for the high modulus mixtures. Nevertheless, no problem with thermal cracking is expected because at low temperatures, the viscoplastic nature of the bitumen causes that the temperature effect on resilient modulus is predominant compared to the effect of the loss of volatile compounds.

Both treatments considered in this study lead to mixtures with an adequate rutting performance, but because of the difficulty of compacting the RCA, the mixtures may undergo an initial rapid densification.

There is therefore the possibility of using any of the two treatments considered in this study. However, further investigation, particularly the performance of test sections, is required. Also it is necessary to analyze the production process and manufacture costs.

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