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Moisture damage resistance of hot-mix asphalt made with recycled concrete aggregates and crumb rubber

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Abstract

To guarantee sustainable construction, we investigated the reuse of construction and demolition waste (CDW) as recycled concrete aggregate (RCA) for the manufacture of hot-mix asphalt (HMA) in place of natural aggregates. The use of waste tire rubber as a bitumen modifier could be a means of improving the water resistance of these mixtures. In this investigation, moisture damage resistance of HMA for binder course, type AC 22 bin S, was analysed. Percentages of 0% (control mixture), 35% and 42% RCA were used in place of natural aggregates. Two types of bitumen have also been used: a conventional B35/50 penetration grade bitumen and BC35/50, a crumb rubber modified bitumen. Volumetric properties and water resistance were determined by means of indirect tensile tests. The results indicate that contrary to expectations, mixtures made with BC35/50 do not display better water resistance than mixtures made with B35/50. Nevertheless, a mixture made with B35/50 or BC35/50 does comply with Spanish requirements. Additionally, reversibility of moisture damage resistance was clearly demonstrated in this research. This research may help to better understand the performance of HMA made with RCA and the drawbacks of using waste tire rubber as a bitumen modifier.

Keywords: recycled concrete aggregates; crumb rubber; hot-mix asphalt; moisture damage resistance

1. Introduction

In the last several decades, the construction industry has experienced a notable growth that has caused the generation of high construction and demolition waste (CDW) (Ossa et al., 2016). CDW are one of the most voluminous and heaviest residues generated in the European Union (European Commission, 2016), as well as throughout the rest of the world. For this reason, the landfilling of these wastes has significant environmental impact, such as the occupation of large land areas with the associated visual and scenic degradation.

For these reasons and, in order to guarantee sustainable construction, the proper management of CDW is a priority. Diverse investigations have tried to reuse this waste material as recycled concrete aggregate (RCA) for the manufacture of hot-mix asphalt (HMA) in place of natural aggregates.

Despite the variability of the results, mainly due to the various origins of the RCA used, most authors agreed that the use of RCA in place of natural aggregate when manufacturing HMA leads to worse water resistance of the mixtures. In this regard, Paranavithana et al. (2006) concluded that the stripping potential of mixtures made with RCA in the coarse fraction is significantly higher. These authors attributed this behaviour to the easy separation of the mortar attached onto the RCA surface. In fact, they notice a significant change in the particle size distribution of mixtures containing RCA as a consequence of the mixing and compaction process.

Mills-Beale and You (2010) stated that as the RCA percentage increases, the moisture susceptibility of HMA also increases. Wen and Bhusal (2011) obtained an increase in the moisture susceptibility of the mixture as the RCA content grew. They attributed this performance to the higher asphalt content of mixtures made with RCA and to the crushing of RCA. Zhu et al. (2012), Pérez et al. (2012a, 2012b) and Wu et al. (2013) also confirm that the use of RCA produces HMA with lower moisture damage resistance. Ossa et al. (2016) stated that up to 20% of RCA is suitable for use in the wearing courses of urban road pavements. Percentages up to 40% of RCA will be suitable only when using anti-stripping additives. Qasrawi and Asi (2016) indicate that RCA replacement up to 50% leads to mixtures that comply with water resistance requirements. Nevertheless, these authors also stated that RCA leads to mixtures with lower stripping resistance.

To improve the water resistance of mixtures made with RCA, some researchers applied various treatments. For example, Lee et al. (2012) precoated the RCA with a slag cement paste. Zhu et al. (2012) found that precoating the RCA with a patented liquid silicon resin led to mixtures with higher water resistance than mixtures made using untreated RCA. Pasandín and Pérez (2013, 2014) tested two treatments: coat the RCA with 5% of bitumen emulsion prior to the mixing process, then keep the loose mixture in an oven for 4 hours at 170°C after mixing and before compaction. Both of them showed successful water resistance results.

Among the factors that may affect the water resistance of bituminous mixtures, binder properties play a crucial role. In particular, some investigations have demonstrated that the use of bitumen with higher viscosities improves the moisture damage resistance of HMA (Abo-Qudais and Mulqi 2005). As a consequence, when HMA is in service, the higher asphalt viscosity leads to better moisture damage resistance (Bagampadde, 2004; Xiao and Amirkhanian, 2009).

In this regard, it is interesting to note that waste tire rubber has been used in asphalt pavement since 1960s (Lo Presti, 2013) in order to promote energy savings and to reduce environmental impacts (Rodríguez-Alloza et al., 2013).

As is well known, one of the main effects of adding rubber to bitumen is that it produces an increase in its viscosity which causes the manufacturing of rubberized asphalt mixtures to need higher mixing temperatures (Rodríguez-Alloza et al., 2013; Hossain et al., 2015; Rodríguez-Alloza and Gallego, 2017).

Regarding the performance of rubberized asphalt mixtures, some investigations indicate that the use of rubberized asphalt in HMA reduces noise from tire/pavement interactions (Paje et al., 2010; Vázquez et al., 2016), is cost effective (Hicks and Epps, 2000) and reduces the rutting potential, the thermal susceptibility and the appearance of fissures (CEDEX, 2007). Additionally, waste tire rubber modified bitumen leads to mixtures with higher elasticity and resilience at higher temperatures (MFOM, 2007).

Nevertheless, despite the increased viscosity of the rubberized asphalt, its effect on the moisture damage resistance of HMA is still not clear. On one hand, some authors stated that rubberized asphalt improves water resistance (Partl et al. 2010; Hossain et al., 2015). On the other hand, Xiao and Amirkhanian (2009) stated that the use of rubberized asphalt slightly worsens HMA water sensitivity.

The potential for improving water sensitivity during its in service life suggests that the use of rubberized asphalt in the manufacture of HMA made with a partial substitution of RCA could be a successful way of increasing its water resistance, which must be investigated.

2. Aims and objectives

The aim of this investigation is to manufacture HMA with various percentages of RCA and to compare their water resistance when manufactured with conventional bitumen versus when manufactured with rubber modified bitumen.

The present research has two primary objectives:

- The first one is to strengthen the knowledge about the performance of HMA made with a partial substitution of RCA in place of natural aggregates. Particularly, the research focuses on its performance against the action of water, which is one of the most important drawbacks of these mixtures. This first objective could be useful to those researchers who are currently focused on the study of this type of bituminous mixtures.

- The second objective is to check whether the use of rubberized asphalt may improve the water sensitivity of HMA made with a partial substitution of RCA. As a result of the technical literature review, a potential of improving water resistance of these mixtures by using rubberized asphalt has been detected. This second objective could be useful not only for researchers but for a large number of construction industry actors, particularly those who currently use or recommend the use of this type of bitumen. In this regard, this research can help to deepen the knowledge of the advantages and disadvantages of rubberized asphalt.

3. Materials and Methods

3.1. Aggregates

In this investigation, RCA and natural aggregate were used. The RCA (figure 1a) came from the demolition of diverse residential housing in Madrid (Spain) and was supplied by a CDW recycling plant. A local contractor supplied the natural aggregate (figure 1b) that is a limestone which is typically used in HMA production in Spain due to its expected adequate water sensitivity.

Figure 1. Aggregates used in this investigation: a) fraction 8/16 mm of RCA, with an 89.3% mix of concrete, stone or similar material and b) fraction 2/4 mm of limestone used as natural aggregate.

The main properties of the RCA and limestone were evaluated according to the Spanish General Technical Specifications for Roads, usually known as PG-3 (MFOM, 2015). Table 1 summarizes the results of this characterization.

Table 1. Characterization of RCA and natural aggregates.

Aggregate		RCA	Limestone	PG-3 Specifications (*)		
				T00-T1	T3-T2	T4
ρa (g/cm^3)	0/2 mm	2.693	2.720	-	-	-
	2/4 mm	2.675	2.709			
	4/8 mm	2.645	2.686			
	8/16 mm	2.630	2.688			
	16/22.4 mm	2.605	2.686			
WA_{24} (%)	0/2 mm	7.467	1.404	-	-	-
	2/4 mm	5.772	2.351			
	4/8 mm	5.065	1.473			
	8/16 mm	4.376	1.671			
	16/22.4 mm	4.088	1.631			
SE (%)		67	59	≥ 55	≥ 55	≥ 55
FI (%)		8	15	≤ 20	T2, T31 ≤ 20 T32≤ 30	≤ 30
LA abrasion (%)		32	26	≤ 25	≤ 35	-

(*) 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 T31 refers to 200>AADHT ≥100
Traffic category T32 refers to 100>AADHT ≥50
Traffic category T4 refers to AADHT<50

As was expected, when comparing both aggregates, the RCA presented a lower bulk specific gravity (ρa) (AENOR, 2014) as well as higher water absorption (W_{24}) (AENOR, 2014), particularly in the finest fraction. The attachment of mortar onto the RCA surface and the higher mortar content in the finest fractions (de Juan and Gutiérrez, 2009) are mainly responsible for this low value. The flakiness index (FI) (AENOR, 2012a) and the sand equivalent (SE) (AENOR, 2012b) of both types of aggregate complied with the Spanish Specifications for all traffic categories. The Los Angeles (LA) abrasion coefficient (AENOR, 2010a) only complies with T3 and T2 heavy traffic categories.

3.2. Bitumen

A B35/50 penetration bitumen was chosen to prepare the HMA test pieces. The B35/50 had a penetration of 41x0.1 mm at 25°C and a softening point of 53°C.

The same bitumen, modified with waste tire rubber (figure 2), BC35/50, was also used. To prepare the BC35/50, a B50/70 sample of 600 g was heated in an oil bath at 180ºC and then 10% by weight of rubber was added. This mixture was blended for 60 minutes at 4,000 rpm at a constant temperature of 180ºC. The resultant BC35/50 had a penetration of 38x0.1 mm at 25°C and a softening point of 64°C.

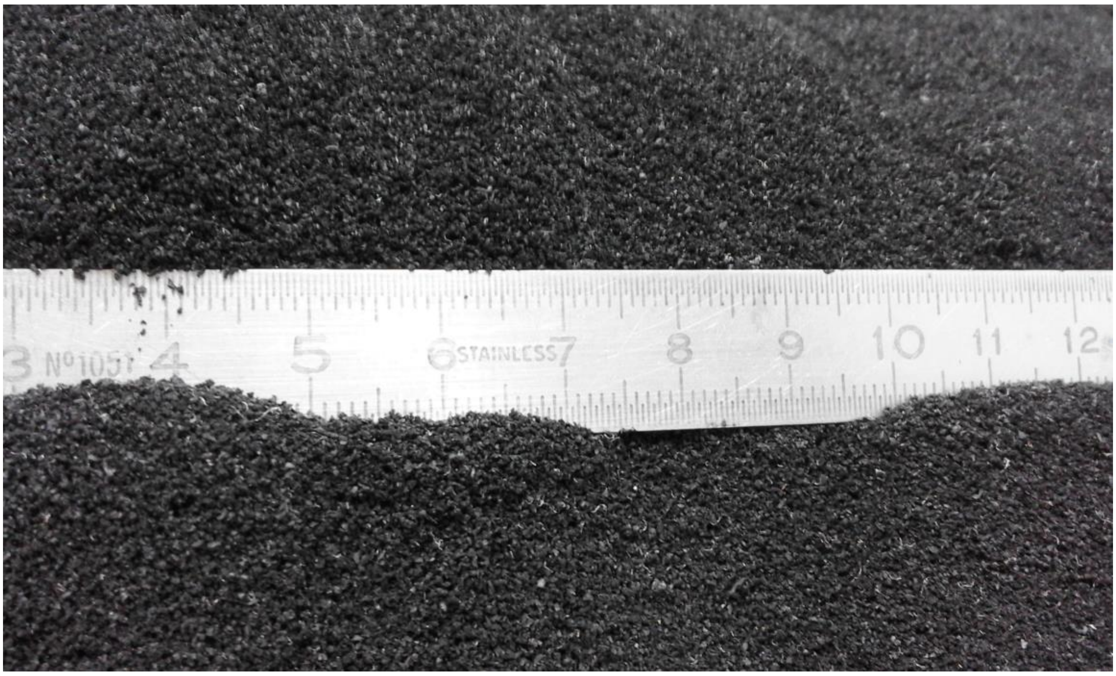

Figure 2. Waste tire rubber.

The viscosity of B35/50 and BC35/50, determined by using a Brookfield rotational viscometer (AENOR, 2010c), can be seen in figure 3. As was expected, BC35/50 displays higher dynamic viscosities.

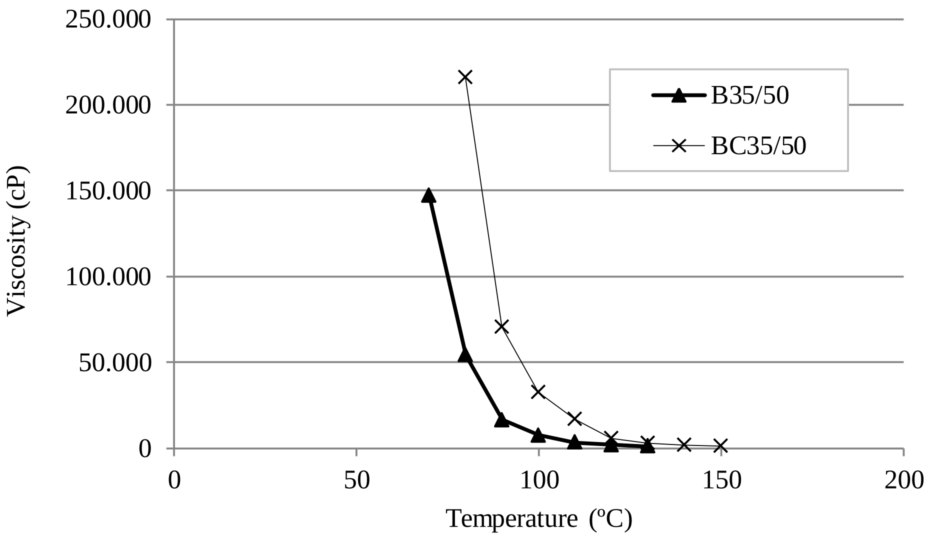

Figure 3. Bitumen dynamic viscosity.

3.3. Specimen preparation

The HMA aggregate gradation, corresponding to AC 22 bin S (figure 4), for road pavement binder course was chosen according to the gradations limits given by PG-3 (MFOM, 2015).

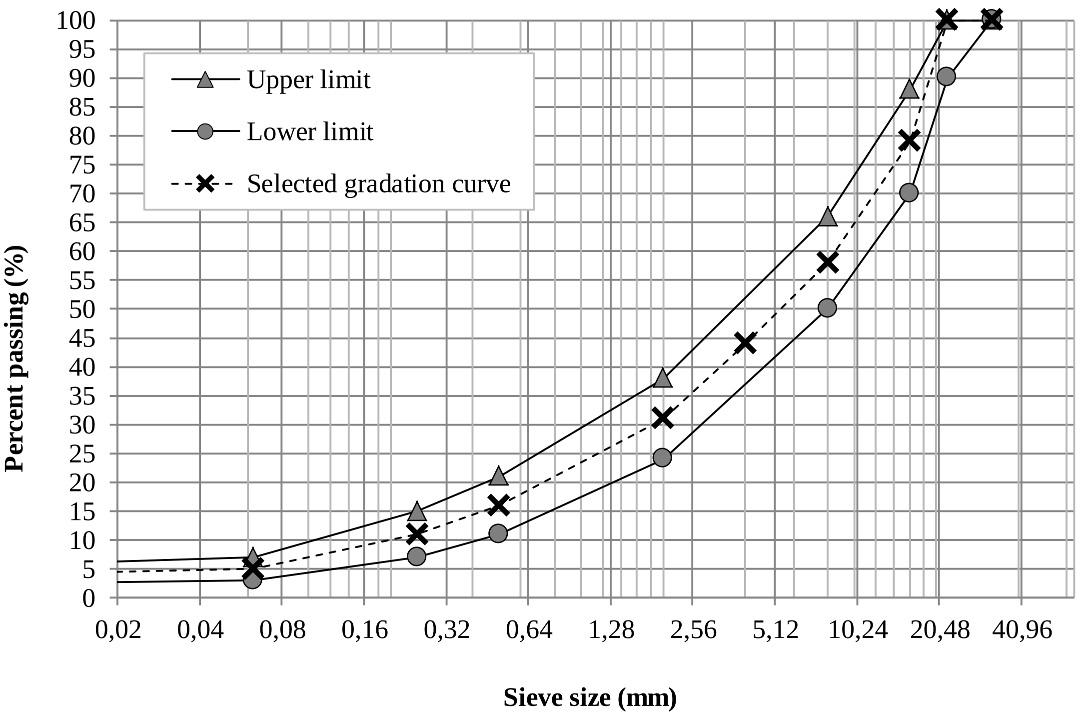

Figure 4. Gradation curve of AC 22 bin S.

The volumetric properties and the water resistance were evaluated on Marshall specimens manufactured according to NLT-159/86 (MOPT, 2002). The aggregates were heated for 8 hours at 175ºC before mixing and compaction. The B35/50 was heated for 3 hours at the temperature of 165ºC and the BC35/50 was heated for the same time at the temperature of 170ºC. The mixing and compaction temperature was 140ºC for mixtures made with B35/50 and 145ºC for mixtures made with BC35/50.

Percentages of 0%, 35% and 42% of RCA in place of natural aggregates were tested on cylindrical asphalt specimens 101.6 mm in diameter and 63.5 mm in height. Bitumen content from 4.25% up to 6.00% of the total weight of the mixture was analysed for each RCA percentage, both with B35/50 and BC35/50.

3.4. Volumetric properties

It is highly important to analyse the volumetric properties of mixtures described above because these properties are crucial in the design of bituminous mixtures. In fact, volumetric properties are closely related to HMA performance (Mallick and El-Korchi, 2009). In this regard, some authors stated that air voids (Va) may be the main source of moisture damage (Terrel and Al-Swailmi, 1994; Varveri et al., 2014). Moreover, higher air void content leads to mixtures with lower fatigue life (Ma et al., 2016) and less durability (Choubane et al., 1998). Additionally, recent investigations concluded that air voids could affect heat transfer (Hassn et al., 2016) and self-healing via induction and infrared heating (Gómez-Meijide et al., 2016).

In this regard, the PG-3 (MFOM, 2015) requires Va ranging from 4% to 6% for the heavy traffic categories T00 and T0 and from 4% to 7% for the heavy traffic categories T1 to T4. For these reasons, air voids were calculated according to UNE-EN 12697-8 (AENOR, 2003) as follows:

$$Va = \frac{\rho_m - \rho_b}{\rho_m} \times 100 \qquad (1)$$

where ρ_b= bulk specific gravity by the saturated surface dry (SSD) water displacement method according to UNE-EN 12.697-6 (AENOR, 2012c) applied on cylindrical Marshall samples compacted with 50 blows per face and ρ_m= maximum specific density according to UNE-EN 12.697-5 (AENOR, 2010b) applied on loose mixtures.

3.5. Water resistance

Moisture damage is one of the most important drivers of asphalt pavement distress (Kakar et al., 2015). Due to its importance, UNE-EN 12697-12 (AENOR, 2009) was used to evaluate the water resistance of the HMA. In this test, a series of eight cylindrical Marshall samples each, compacted with 50 blows per face, were manufactured.

According to the above mentioned standard, and with the aim of analysing the effect of the moisture, each series was subdivided into two subsets: the “dry subset” and the “wet subset”. The “dry subset,” (figure 5a) was kept on a horizontal surface at room temperature, while the “wet subset,” was saturated and held in a water bath for 3 days at 40°C (figure 5b).

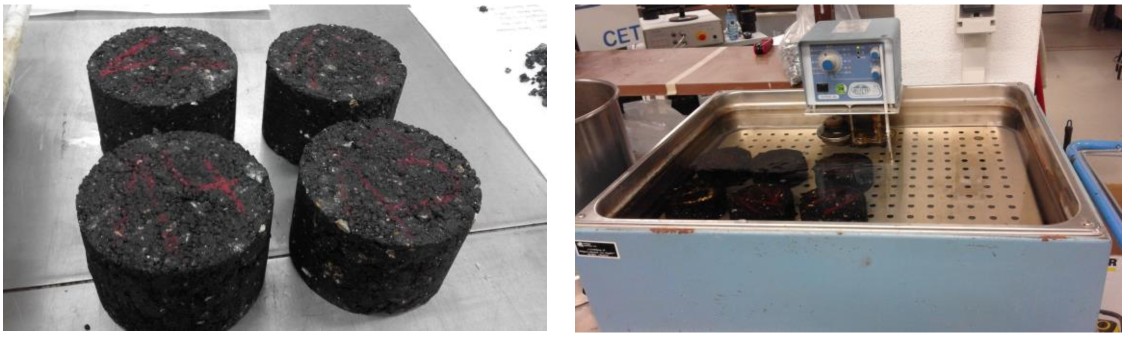

Figure 5. Water resistance test: a) “dry” subset at room temperature and b) “wet” subset in a water bath at 40°C.

Next, both subsets were left for a minimum of 2 hours at 15°C with the “dry subset” in air and the “wet subset” in water.

After that step, the tensile strength ratios (TSR) of the specimens in each set were determined as follows:

$$TSR = \frac{ITS_W}{ITS_D} \times 100 \qquad (2)$$

where TSR = the tensile strength ratio (%), ITS_W = the average tensile strength of the four conditioned (wet) specimens (MPa), and ITS_D = the average tensile strength of the four unconditioned (dry) specimens (MPa). TSR≥80% is required by the PG-3 (MFOM, 2015) specifications for an AC 22 bin S.

A total of 46 series, that is, 368 specimens, were tested in order to analyse the water resistance of each RCA percentage, each bitumen content and both types of bitumen, B35/50 and BC35/50.

The optimum bitumen content for each RCA percentage and each bitumen type is the minimum that achieves the 80% of TSR required by the PG-3 (MFOM, 2015), complying with air void (Va) requirements.

3.6. Reversible moisture damage resistance

Several authors have found that stiffness degradation due to moisture damage is reversible after re-drying the mixtures (Apeagyei et al., 2016). Thus, it is interesting to determine if tensile strength degradation due to moisture damage is also reversible after drying the bituminous mixtures. For this reason, 36 specimens were manufactured at the optimum bitumen content, that is, 6 for each RCA percentage (0%, 35% and 42%) and for B35/50 and BC35/50 and were conditioned similarly to the "wet" subset, described above. However, before breaking them at 15°C, they were dried at room temperature for several days until the mass remained constant.

4. Results and Discussion

4.1. Volumetric properties

Figure 6 shows the bulk specific gravity by the SSD method versus the bitumen content for each RCA percentage. As seen, mixtures made with B35/50 display higher bulk specific densities than mixtures made with BC35/50 for the same binder content and the same RCA percentage. These results highlight that the higher viscosity of BC35/50 makes compaction more difficult.

Moreover, higher RCA percentages lead to lower bulk specific densities for all bitumen content and for B35/50 and BC35/50. It is clear that the greater RCA roughness also makes compaction more difficult. It should also be kept in mind that the lower density of the RCA causes a lower final density of the mixture. In addition, the increased bitumen absorption by the RCA results in a lower amount of effective binder (Pasandín and Pérez, 2013), which also hinders compaction.

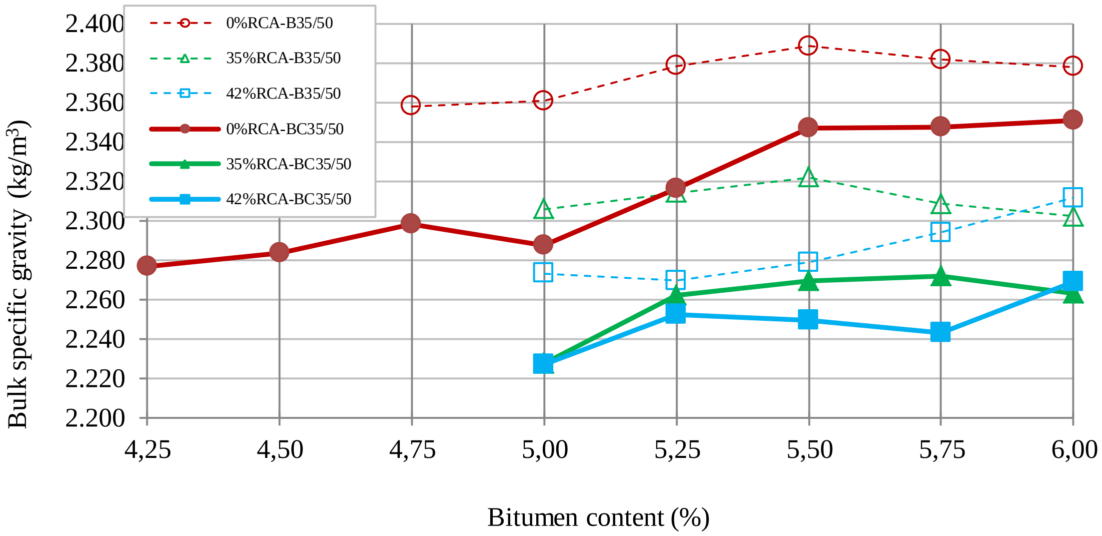

Figure 6. Bulk specific gravity by the SSD method versus the bitumen content, for each RCA percentage. Mixtures made with B35/50 and BC35/50.

As a consequence of the subjective methodology employed to determine the bulk specific gravity, it was necessary to include an ANOVA analysis. In this regard, three one-way ANOVA analyses were performed to analyze the influence of RCA content, bitumen content and type of bitumen in the bulk specific gravity. The dependent variable was the bulk specific gravity. The factors were the RCA content (0%, 35% and 42%), bitumen percentage (5.00%, 5.25%, 5.50%, 5.75% and 6.00%) and the bitumen type (B35/50 and BC35/50). Both, bulk specific gravity and the three factors, were quantitative variable.

The results of the ANOVA analyses indicate that the RCA content ($p=0.000$) and bitumen type ($p=0.000$) are statistically significant for a 95% confidence interval ($p<0.05$). Nevertheless, the bitumen content ($p=0.795$) is not statistically significant. That is, the statistical analysis confirms the above mentioned results.

Figure 7 shows the maximum specific density versus the bitumen content for each RCA percentage. For 42% RCA, this figure shows that mixtures made with B35/50 display a higher maximum specific density than mixtures made with BC35/50 for all bitumen content. For 35% RCA, figure 7 shows that mixtures made with B35/50 display a higher maximum specific density than mixtures made with BC35/50 for the lower bitumen content (5.00% and 5.25%).

For the higher bitumen content (5.50%, 5.75% and 6.00%) a reversing trend is observed. Finally, for 0% RCA, maximum specific density is, in general, slightly higher for mixtures made with B35/50 than for mixtures made with BC35/50. From this behaviour, it can be inferred that as the RCA percentage increases, the amount of B35/50 that is absorbed by the RCA also increases but not the amount of BC35/50. The latter is more viscous; thus, its absorption by the RCA is more complicated. The higher heating temperature to which it was subjected (170 ° C for BC35/50 and 165 ° C for B35/50) does not cause the absorption of BC35/50 to match that of B35/50.

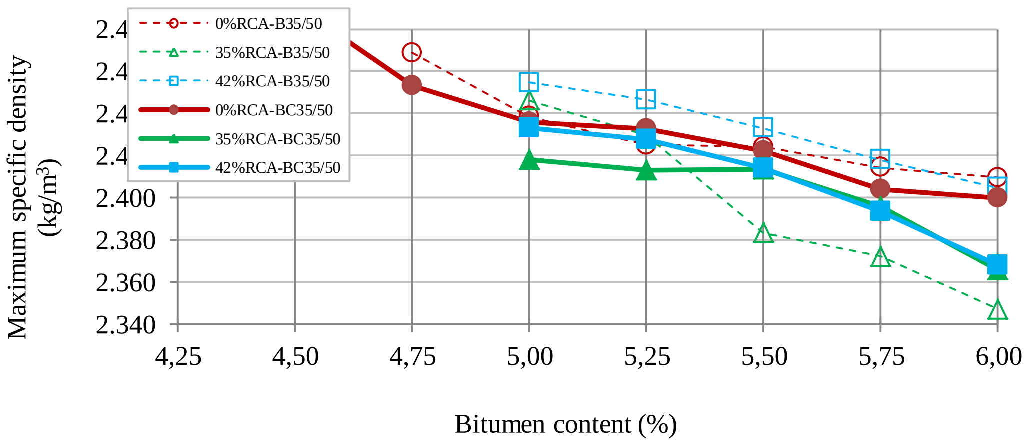

Figure 7. Maximum specific density versus the bitumen content, for each RCA percentage. Mixtures made with B35/50 and BC35/50.

Figure 8 shows the air voids versus the bitumen content for each RCA percentage. As seen in this figure, in general, air void content is higher in mixtures made with BC35/50 for all RCA percentages and all bitumen content. The higher viscosity of BC35/50, which hinders HMA compaction, appears to be mainly responsible for this performance. In general, it is expected that HMA with higher air void content yield worse water resistance results.

Nevertheless, it must be noted that for mixtures made with 0% RCA, differences between air voids in mixtures with BC35/50 and in mixtures with B35/50 are much less marked than for mixtures made with 35% and 42% RCA. In these two cases bitumen absorption plays a crucial role.

Thus, on the one hand, the RCA have higher binder absorption than the natural aggregates. On the other hand, the BC35/50 has higher viscosity than the B35/50. Therefore, the bitumen absorption by the RCA will be much more marked in the case of B35/50. Hence, the differences in air void content between mixtures made with B35/50 and those made with BC35/50, will be less marked as the RCA percentage increases. In this regard, the greater absorption of B35/50 by the RCA compensates the greater difficulty in compacting the mixtures manufactured with BC35/50.

For the binder course studied in this research, PG-3 (MFOM, 2015) requires Va ranging from 4% to 6% for T00 and T0 heavy traffic categories and from 4% to 7% for T1 to T4 heavy traffic categories. Figure 8 also shows these limits and the mixtures that are compliant with Va specifications:

- For T00 to T0 and T1 to T4: 0%RCA made with 4.75% of B35/50 and 5.25% of BC35/50; 35% RCA made with 5.00% and 5.25% of B35/50 and with 5.50%, 5.75% and 6.00% of BC35/50; 42% RCA made with 5.75% of B35/50 and with 6.00% of BC35/50.

- Only for T1 to T4: 0% RCA made with 4.75% and 5.00% of BC35/50; 35% RCA made with 5.25% of BC35/50; 42% RCA made with 5.50% of B35/50 and with 5.50% and 5.75% of BC35/50.

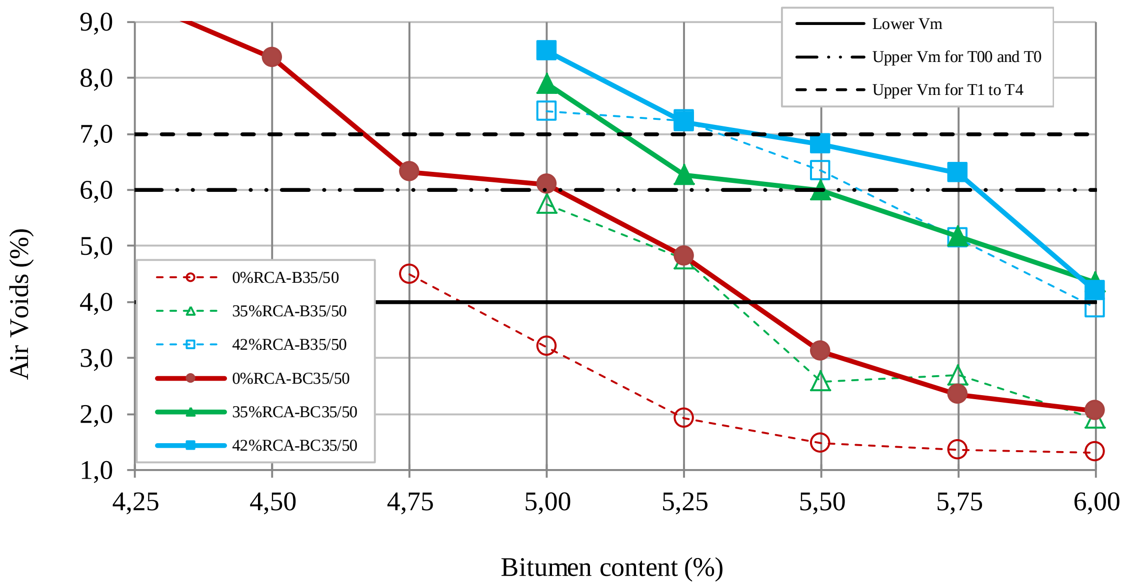

Figure 8. Air voids versus the bitumen content, for each RCA percentage. Mixtures made with B35/50 and BC35/50.

Figure 8 also shows that, as was expected, higher RCA percentages lead to higher air void content. Taking into account these results, bitumen absorption seems to be proportional to the RCA mass. Some authors stated that bitumen absorption is proportional to the aggregate mass for some aggregates but for other aggregates this presumption is not necessarily true (Liu et al., 2014).

4.2. Water resistance

Table 2 and table 3 show, respectively, the tensile strength of the dry (ITSd) and wet (ITSw) specimens in MPa, for all RCA percentage and all bitumen content.

Table 2. Tensile strength of dry specimens (MPa).

	0% RCA		35% RCA		42% RCA	
	B35/50	BC35/50	B35/50	BC35/50	B35/50	BC35/50
4.25	2.59	1.94				
4.50	2.89	2.39				
4.75	2.55	1.98				
5.00	2.68	2.10	2.52	1.88	2.62	1.57
5.25	2.76	2.25	1.77	2.08	2.59	1.89
5.50	2.52	2.41	2.39	2.09	1.99	2.07
5.75	2.38	2.46	2.47	2.35	2.57	2.28
6.00	2.34	2.24	2.68	2.29	2.19	2.26

Table 3. Tensile strength of wet specimens (MPa).

	0% RCA		35% RCA		42% RCA	
	B35/50	BC35/50	B35/50	BC35/50	B35/50	BC35/50
4.25	1.78	1.49				
4.50	2.03	1.59				
4.75	2.04	1.47				
5.00	2.24	1.68	1.71	1.35	1.99	1.35
5.25	2.22	1.85	1.47	1.60	1.83	1.53
5.50	2.04	2.08	1.82	1.79	1.58	1.58
5.75	2.20	1.99	1.84	1.58	2.08	1.70
6.00	2.11	1.84	1.95	1.69	1.43	1.82

In general, ITSd (Table 2) is higher for mixtures made with B35/50 than for mixtures made with BC35/50 for all RCA percentages and for all of the tested bitumen content. There are some exceptions to this trend, such as 0% RCA and 5.75% of bitumen, 35% RCA and 5.25% of bitumen and 42% RCA and 5.50% and 6.00% of bitumen. The same trend can be observed for ITSw (Table 3). In this case, there are also some exceptions, such as 0% RCA and 5.50% of bitumen, 35% RCA and 5.25% of bitumen and 42% RCA and 6.00% of bitumen.

Moreover, in general, as RCA content grows, the tensile strength of dry and wet specimen decreases, but only for mixtures made with BC 35/50. For mixtures made with B35/50 this trend is not clear. Maybe it is due to the absorbent nature of RCA. These aggregates absorb the B35/50 much better than the BC35/50, due to the greater viscosity of the latter. The absorption of B35/50 by the RCA probably homogenizes its performance.

In this regard, it is interesting to note that the heterogeneity of the RCA may affect the water resistance results. Particularly, RCA contain not only concrete fragments and aggregates but other materials (eg. asphalt, ceramic and gypsum), which can be prejudicial to the water resistance of HMA. The bitumen absorption by the RCA particles may aid to homogenize its performance when used in HMA manufacture. As stated above, due to the lower viscosity of the B35/50, it is better absorbed by the RCA particles than the BC35/50, which contributes to homogenize RCA performance to a greater extent.

Table 4 shows the tensile stress ratio (TSR) for all the RCA percentages and all bitumen content. The PG-3 (MFOM, 2015) requires a TSR equal to or greater than 80% for binder course mixtures. In table 4, bold numbers indicate those mixtures that comply with PG-3 requirements, and shaded cells indicate the optimum binder content. The optimum binder content has been chosen as the minimum bitumen content that complies with air void and TSR requirements.

As seen, higher RCA content leads to mixtures with higher optimum bitumen content, due to the absorptive nature of the RCA. Moreover, mixtures made with BC35/50 have higher optimum binder content than mixtures made with B35/50, for the same RCA percentage.

Hence, contrary to initial expectations, mixtures made with BC35/50 display lower moisture damage resistance than mixtures made with B35/50 for all RCA percentages, since they need higher bitumen content to achieve the same results than mixtures made with B35/50.

The higher viscosity of BC35/50 could explain this performance. On the one hand, it is more difficult to cover the entire aggregate surface during the mixing process with higher viscosity bitumen. This phenomenon has been observed during laboratory manufacture. On the other hand, as stated in section 3.1., the higher viscosity of rubberized asphalt, hinders HMA compaction, leading to mixtures with higher air void content and, thus, worse water resistance.

Table 4. Tensile stress ratio (%) for mixtures made with 0%, 35% and 42% RCA and B35/50 or BC35/50.

	0% RCA		35% RCA		42% RCA	
	B35/50	BC35/50	B35/50	BC35/50	B35/50	BC35/50
4.25	68.90	76.84				
4.50	70.39	66.61				
4.75	**80.24**	74.05				
5.00	**83.45**	**80.09**	67.75	71.75	76.11	**85.97**
5.25	**80.29**	**82.10**	**83.23**	77.05	70.91	**80.82**
5.50	**81.05**	**86.48**	76.43	**85.85**	79.68	76.66
5.75	**92.42**	**81.02**	74.60	67.26	**80.95**	74.69
6.00	**90.13**	**82.16**	72.82	73.56	65.63	**80.30**

4.3. Volumetric properties at the optimum bitumen content

It is interesting to analyse the volumetric properties at the optimum bitumen content. Figure 9 shows the bulk specific gravity (kg/m^3) by the SSD method for mixtures made with 0%, 35% and 42% RCA and B35/50 and BC35/50 at the optimum bitumen content. Figure 10 shows the maximum specific density (kg/m^3) for mixtures made with 0%, 35% and 42% RCA and B35/50 and BC35/50 at the optimum bitumen content.

As seen in figure 9, bulk specific gravity is higher for mixtures made with B35/50, because as mentioned earlier, it is easier to compact mixtures made with B35/50 than mixtures made with BC35/50, due to the higher viscosity of the latter. The same trend can be observed for the maximum specific density in figure 10. The higher optimum bitumen content of mixtures made with BC35/50 could explain this phenomenon. The bitumen has lower density than the aggregates, and for this reason, mixtures made with higher bitumen content display lower maximum density.

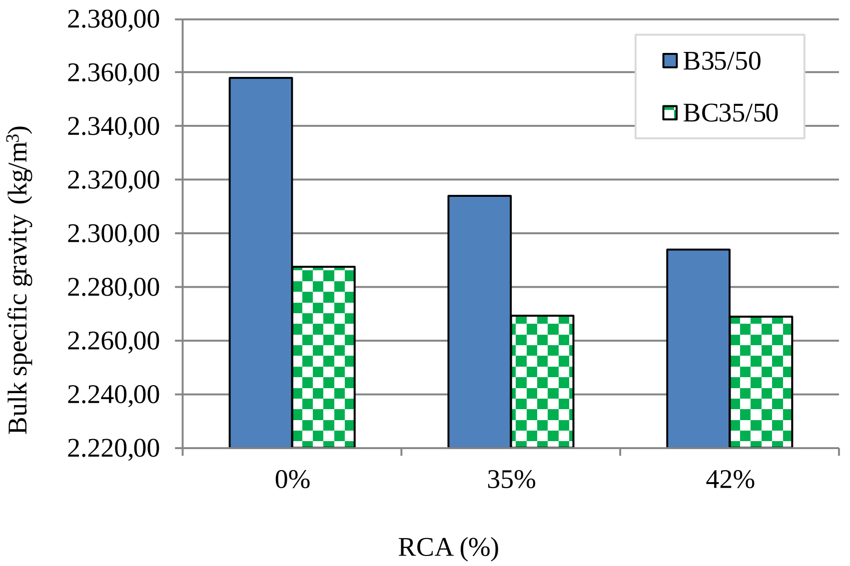

Figure 9. Bulk specific gravity for mixtures made with 0%, 35% and 42% RCA. Mixtures made with B35/50 and BC35/50 at the optimum bitumen content.

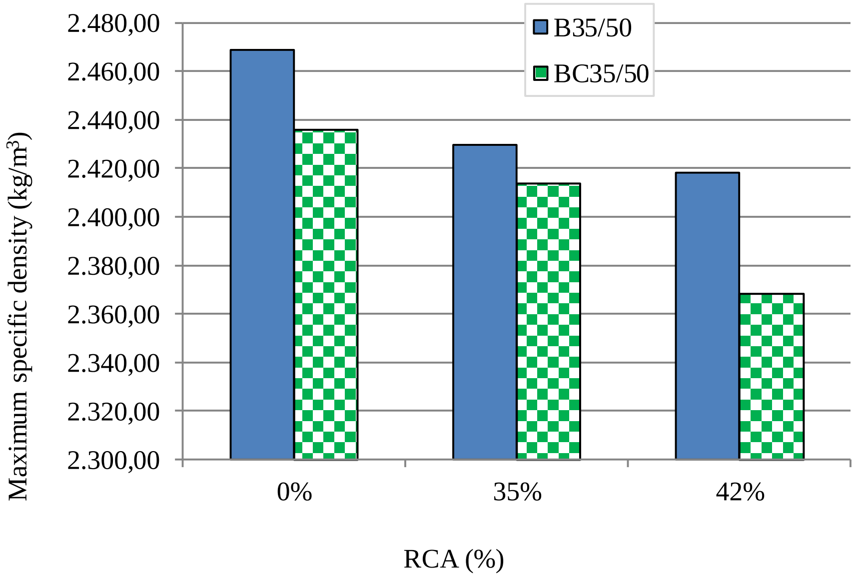

Figure 10. Maximum specific density for mixtures made with 0%, 35% and 42% RCA. Mixtures made with B35/50 and BC35/50 at the optimum bitumen content.

Moreover, figures 9 and 10 show that as the RCA percentage increases, the density decreases. The lower RCA density compared with that of natural aggregate could explain this trend. Additionally, in the case of the bulk specific gravity, there is another reason that could explain this trend: the RCA hinders compaction due to its rough surface.

Figure 11 shows the air void content for mixtures made with 0%, 35% and 42% RCA and B35/50 and BC35/50 at the optimum bitumen content.

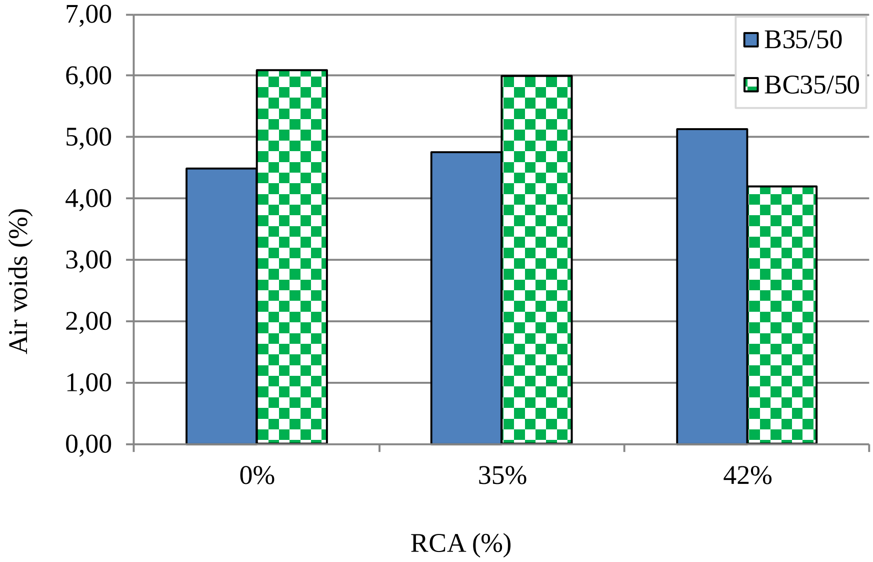

Figure 11. Air void content of mixtures made with 0%, 35% and 42% RCA. Mixtures made with B35/50 and BC35/50 at the optimum bitumen content.

In general, mixtures made with BC35/50 display a higher percentage of air voids despite optimum bitumen content being higher for these mixtures. As noted earlier, BC35/50 exhibits a higher viscosity, which hinders sample compaction. The higher B35/50 absorption by the RCA causes the differences in air void content to be less marked as higher the RCA percentage is. It must be noted, that, as said before, the higher air void content could also explain the lower water resistance of mixtures made with BC35/50 compared with mixtures made with B35/50.

4.4. Reversible moisture damage resistance

For each RCA percentage, three samples were manufactured with the optimum bitumen content, for B35/50 and for BC35/50. Thus, as mentioned before, a total of 36 samples were tested. These samples were conditioned similarly as the “wet” subset. However, before breaking them at 15°C, these samples were dried at room temperature for 56 days until their mass remained constant. Records indicate that during this period of time, the daily temperatures ranged from 21.5°C to 26.7°C. Additionally, records show that the relative humidity of the air ranged from 21% to 40% over these 56 days.

Figure 12 shows the TSR (%) obtained for mixtures made with the optimum bitumen content of B35/50 and BC35/50 following the conventional water sensitivity analysis procedure (series B35/50 and BC35/50, respectively). Figure 12 also shows the TSR (%) obtained for mixtures made with the optimum bitumen content of B35/50 and BC35/50 that were dried at constant mass at room temperature before breaking them at 15°C in order to analyse the reversible moisture damage resistance (series B35/50R and BC35/50R, respectively).

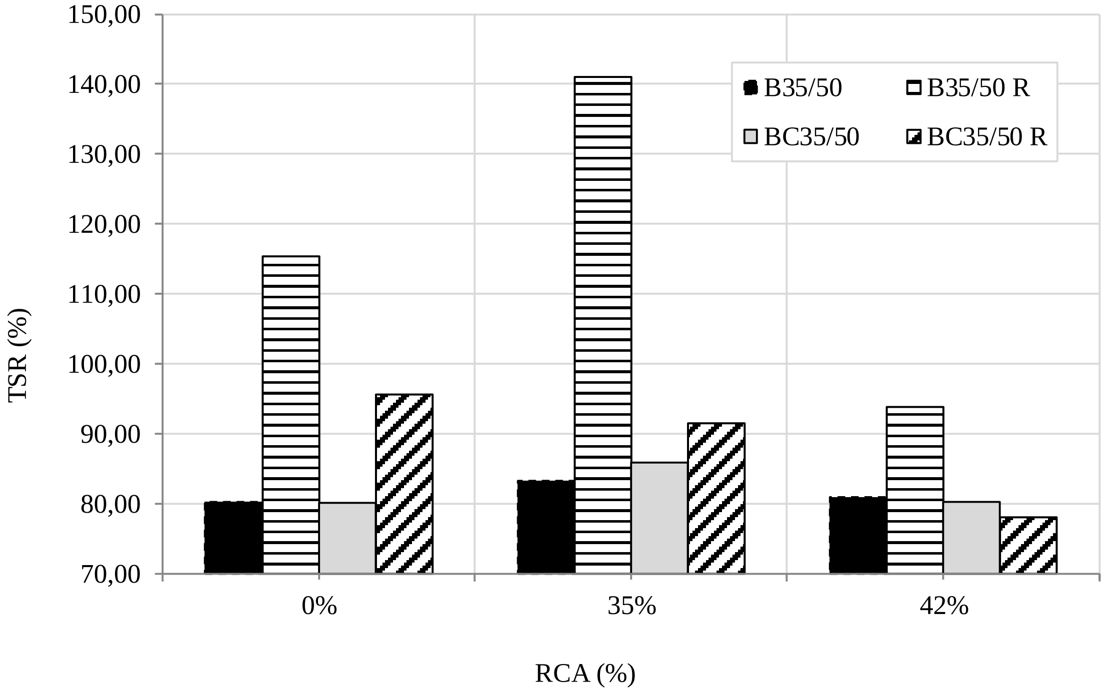

Figure 12. TSR (%) of mixtures made at the optimum bitumen content with B35/50 and BC35/50. Comparison between mixtures tested following the conventional water resistance process vs samples tested in order to analyse reversible moisture damage resistance.

As seen in figure 12, the TSR of mixtures made in order to determine the reversibility of moisture damage resistance is higher than that obtained for mixtures that followed the conventional process. Thus, the reversibility of moisture damage resistance is clearly demonstrated. Nevertheless, it is important to note that this reversibility is more evident in mixtures made with B35/50 than in mixtures made with BC35/50. Again, the B35/50 seems to be more appropriate than the BC35/50 in order to guarantee the water resistance of HMA made with RCA over its in service life.

5. Conclusions

In this research, the moisture damage resistance of HMA, type AC 22 bin S for binder course made with 0%, 35% and 42% of RCA was analysed. For this analysis, two types of bitumen were used: conventional B35/50 and crumb rubber modified BC35/50. As a result, the following conclusions were drawn:

- Higher RCA content leads to mixtures with higher optimum bitumen content, due to the absorptive nature of the RCA. Moreover, mixtures made with BC35/50 have higher optimum bitumen content than mixtures made with B35/50, due to the higher viscosity of the former, which hinders the total coverage of the aggregate during mixing and the HMA compaction.

- At the optimum bitumen content, all of the mixtures presented air void percentages ranging between 4% and 7%. Therefore, the mixtures comply with the Spanish specifications for air void content. Nevertheless, in general, mixtures made with BC35/50, display higher air void content. The higher viscosity of BC35/50 hinders sample compaction, which could explain this trend.

- Mixtures made at the optimum bitumen content display adequate water resistance. In this regard, all of these mixtures display TSR≥80%, as required by the Spanish specifications. It must be noted that contrary to initial expectations, mixtures made with BC35/50 display a slightly lower water resistance, since they need higher bitumen content in order to comply with the requirements. This performance could be explained by two main reasons. On the one hand, the higher air void content of mixtures made with BC35/50 provides these mixtures with a larger surface area accessible to water. On the other hand, the higher viscosity of BC35/50 hinders the total coverage of the aggregate during mixing and makes that it is easier for water to penetrate into the aggregate.

- In general, tensile strength, in dry and wet condition, is higher for mixtures made with B35/50. Moreover, in general, as RCA content increases, the tensile strength of dry and wet specimens decrease but only for mixtures made with BC35/50. The RCA absorbs B35/50 considerably more effectively than BC35/50, due to the greater viscosity of the latter. The absorption of B35/50 by the RCA probably strengthens the RCA and homogenizes its performance.

- Reversibility of moisture damage resistance was clearly demonstrated in this research. Nevertheless, it is important to note that this reversibility is more evident in mixtures made with B35/50 than in mixtures made with BC35/50.

This study is a preliminary investigation focused on the moisture damage resistance of HMA made with RCA and rubberized asphalt. Further investigation is needed in order to analyze the resistance to the permanent deformation, stiffness and fatigue of such mixtures. Also, the analysis of volumetric properties, taking the asphalt absorption into account, could be of great interest.

This research could be helpful in two ways. Firstly, to further understand the performance of HMA made with RCA which could be primarily useful for the researchers who are currently focusing their efforts on this subject. Secondly, a deeper understanding of the drawbacks of using waste tire rubber as a bitumen modifier may be useful for all the actors involved in the road pavement construction sector.

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