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PERFORMANCE OF BITUMINOUS MIXTURES INVOLVING CONSTRUCTION AND DEMOLITION WASTE

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Abstract

The incorporation of recycled concrete aggregates (RCA) from construction and demolition waste (CDW) in hot-mix asphalt (HMA) could be a way to promote sustainable construction. This paper describes a laboratory study on the use of RCA in HMA for base courses in pavements. HMA involving RCA in percentages of 0%, 5%, 10%, 20% and 30% were evaluated. To improve the moisture damage resistance of HMA made with RCA, the mixtures were cured in the oven for four hours at a mixing temperature of 170ºC, before compaction. The results indicated that the mixes made with RCA and cured for four hours in the oven loosely comply with Spanish moisture damage specifications. The results also indicated that the Marshall Stability and the moisture damage resistance are substantially improved by curing the mixture in the oven. The mixtures also exhibited an adequate resistance to permanent deformation. The results from this study were highly encouraging, although HMA with RCA requires further investigation.

Keywords: sustainable construction; recycled concrete aggregates; construction and demolition waste; hot-mix asphalt; curing time; moisture damage resistance

1. Introduction

Asphalt pavement construction is highly dependent on natural resources such as virgin aggregates and bitumen. Dust emissions, vibrations and noise are generated into the atmosphere as a result of the aggregates extraction. Also, the strong growth in the construction sector leads to the consumption of virgin aggregates that can cause the depletion of the natural resources (Ledesma et al., 2016). For these reasons during the last decades the search for new raw materials that can replace virgin aggregates in the manufacture of construction and building materials has become a major effort.

Now a day, the construction industry produces an enormous quantity of construction and demolition waste (CDW), which are often laid in landfill sites (Cardoso et al., 2016). Their disposal can cause a strong visual and scenic impact and also, the loss of areas that could be given for other land uses. In addition, uncontrolled landfilling of CDW may lead to soil and aquifer pollution.

In this regard, in order to contribute to sustainable development, several studies have been conducted dealing with the use of recycled concrete aggregates (RCA) from CDW as aggregate in hot-mix asphalt (HMA) (Cho et al., 2011; Kuo et al., 2010; Lee et al., 2012; Chen and Wong, 2013; Motter et al., 2015; Mills-Beale and You, 2010; Paranavithana and Mohajerani, 2006; Pasandín and Pérez, 2013, 2014 and 2015; Pasandín et al., 2015; Pérez et al., 2007 and 2010; Pérez et al., 2012a; Pérez et al., 2012b; Shen and Du, 2004; Shen and Du, 2005; Tam et al., 2007).

Most researchers stated that the mortar adhered to the RCA surface, which is more porous and less dense than crushed stone, appears to be the primarily responsible for the RCA's being of poorer quality than natural aggregates (Lee et al., 2012; Paranavithana and Mohajerani, 2006; Pérez et al., 2010; Pérez et al., 2012a; Tam et al., 2007).

Additionally, some authors have recommended removing impurities such as wood, rubber or gypsum, with the aim of making the RCA more homogeneous (Paranavithana and Mohajerani, 2006; Pérez et al., 2007; Pérez et al., 2012a; Pérez et al., 2012b). Moreover, the tiny fissures that appear during the crushing process (Tam et al., 2007) and the weak contact between the mortar and the aggregate (Lee et al., 2012) must also be taken into account. Differences between the properties of the RCA and those of natural aggregates prejudice the performance of HMA made with RCA.

Particularly, several studies have indicated that HMA mixes made with RCA have higher moisture damage resistance than those made with natural aggregates (Mills-Beale and You, 2010; Paranavithana and Mohajerani, 2006; Pasandín and Pérez, 2013 and 2014; Pérez et al., 2007 and 2010; Pérez et al., 2012a; Pérez et al., 2012b). However, previous research conducted with the same RCA used in this investigation (Pasandín and Pérez, 2013; Pérez et al., 2010; Pérez et al., 2012a; Pérez et al., 2012b) demonstrated that allowing the HMA to repose in the oven for an adequate amount of time at high temperature improves the HMA moisture damage resistance. Nevertheless, when the mixture is in the oven, there is significant bitumen absorption, especially into the RCA pores; thus, it is necessary to take into account not only the optimum asphalt content (OAC) but the absorbed bitumen content (Pba) and the effective binder content (Pbe), that is, the asphalt that has not been absorbed by the aggregate pores (Asphalt Institute, 1997).

The aim of the investigation is to design HMA with RCA that achieve good moisture damage resistance, as well as adequate performance, considering the effective binder content and the absorbed bitumen content. The loose mixtures were cured in the oven for four hours at mixing temperature before compaction. The moisture damage resistance and the resistance to the permanent deformation of the HMA mixes containing RCA were studied.

2. Materials and Methods

2.1. Aggregates

For manufacturing HMA, both RCA and natural aggregates were used. The RCA was supplied by a Spanish CDW recycling plant. The EN 933-11:2009/AC 2009 was followed to determine the constituents of the coarse recycled aggregates. The results indicated that the RCA was mainly composed by aggregates, concrete and other petrous materials (89.3 %). As the RCA used in this study was obtained from the demolition of residential buildings, bituminous materials (6.5 %), ceramics (3.6 %) and impurities (0.6 %) were also found. The natural aggregate used was a hornfels that was supplied by a local contractor and is typically used in HMA production in Spain. X-ray fluorescence tests were conducted to analyse the mineralogical composition of the aggregates. The results showed that both aggregates, the RCA (61.46 % SiO_2) and the hornfels (62.30 % SiO_2), were siliceous. This result indicates that both aggregates will most likely exhibit poor stripping performance.

The *Spanish General Technical Specifications for Roads and bridges (PG-3)* was used to evaluate the main properties of the RCA and the natural aggregates. As shown in table 1 (Pasandín and Pérez, 2013), the RCA had a lower bulk specific gravity (ρa) than the natural aggregates as well as a higher water absorption (W_{24}). These results are attributed to the adhered mortar on the RCA surface, which is less dense and more porous than the natural aggregate. The sand equivalent (SE) values of both aggregates complied with the specifications of the *PG-3* for HMA as a base course material. As indicated in table 1, the Los Angeles (LA) abrasion coefficient of the RCA only complied with the *PG-3* for HMA as a base course material in low-volume roads in heavy traffic category T4. On the contrary, the LA abrasion coefficient of the hornfels complied with the *PG-3* in heavy traffic category T00.

2.2. Filler and binder

The study was performed using a B50/70 penetration grade bitumen from Venezuela. The bitumen had a penetration of 52x0.1 mm (at 25 ºC, 100 g and 5 s), a softening point of 54.9 ºC, a flash point above 290 ºC and a density of 1.009 g/cm^3 (at 25 ºC). After a rolling thin-film oven test, the penetration was 68x0.1 mm and the Δ softening point was 6.5 ºC.

CEM II/B-M (V-L) 32.5 N (grey Portland cement) obtained from a commercial source was used as a mineral filler. Its Blaine surface area was of 3134 cm^2/g, and the specific gravity was 3.10 g/cm^3.

2.3. Marshall mix design

The HMA mix design was conducted following the Marshall procedure in accordance with *Spanish NLT-159/86 standard.* As shown in figure 1 (Pasandín and Pérez, 2013), a coarse aggregate blend, an AC 22 base G, was chosen in accordance with the limits given by the *PG-3*. Percentages of 0 %, 5 %, 10 %, 20 % and 30 % RCA in place of natural aggregates were studied. Following the previous studies (Pasandín and Pérez, 2013; Pérez et al., 2010; Pérez et al., 2012a; Pérez et al., 2012b), to improve the moisture sensitivity of the asphalt mixes, they were cured in an oven at the mixing temperature for 4 hours after mixing and before compaction. This made it possible for the aggregate, particularly the RCA, to absorb a greater amount of bitumen. Leaving the loose mixture in the oven helps to achieve a more complete coating, leaving no fissures through which water could penetrate. Furthermore, the absorbed bitumen reduces the porosity and thus, the water accessible voids. Moreover, the attached mortar strengthens. Thus, both less water absorption and thus better moisture damage performance are expected, as well as improved mortar resistance. The mixing temperature was 170ºC, and the compaction temperature was 160ºC. For each RCA percentage, five series of five cylindrical samples compacted with 75 blows per side were manufactured with different bitumen percentages. To compare the results, control samples, that is, samples without curing time in the oven, were also manufactured.

The optimum asphalt content was selected to achieve the maximum Marshall stability and thus, the highest traffic category possible. Additionally, the flow, air voids and voids in the mineral aggregate were chosen in accordance with the *PG-3* requirements. RCA is a porous aggregate, thus, as described above, it was interesting to determine not only the optimum asphalt content but also the effective binder content and the absorbed bitumen content. These two parameters were calculated according to the procedure given by the Asphalt Institute (1997).

2.4. Moisture damage resistance

UNE-EN 12697-12 describes the test followed to evaluate the moisture damage resistance of HMA made with RCA. To evaluate the moisture damage resistance, a series of ten cylindrical Marshall samples were prepared with optimum asphalt content and percentages of 0 %, 5 %, 10 %, 20 % and 30 % of RCA. Samples were compacted with 50 blows per face of a Marshall hammer. Five series were left in an oven at 170ºC for 4 hours after mixing, whereas the other five series were manufactured without curing time in the oven (control mixture). Each of the ten series was divided into two groups, the “dry” and the “wet” subset. The “dry” subset remained at ambient temperature, whereas the “wet” subset was saturated and introduced to a water bath at 40ºC for 3 days. After this time, both subsets were conditioned at the test temperature of 15ºC for a minimum of 2 hours in a climatic chamber. Then, the samples were subjected to a compressive load, which acts parallel to the vertical diametral plane.

The first parameter that is obtained in this test is the indirect tensile strength (ITS), both for the "dry" and the "wet" subset. The ITS is calculated according to *UNE –EN 12697-23* using the expression that follows:

$$ITS = \frac{2P}{\pi.H.d} \qquad (1)$$

where ITS = tensile strength ratio (MPa); P = the peak value of the applied vertical load (N); H = specimen height (mm); and d = specimen diameter (mm).

The second parameter is the tensile strength ratio (TSR), which provides information about the moisture damage resistance of the tested samples. The TSR is calculated according *UNE-EN 12697-12* 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 five conditioned ("wet") specimens (MPa) and ITS_D = the average tensile strength of five unconditioned ("dry") specimens (MPa). TSR≥80 % is required by *PG-3* specifications for HMA for use in base courses.

2.5. Resistance to the permanent deformation

A wheel tracking test was performed according to *UNE-EN 12697-22:2008+A1*. For each RCA percentage (5 %, 10 %, 20 % and 30 %), two prismatic specimens of 300 mm x 260 mm x 60 mm were tested. Mixtures were left in the oven for four hours at mixing temperature before compaction. Each compacted specimen was placed inside a climatic chamber at 60ºC and subjected to 10000 passages of a wheel applying a pressure of 714±10 MPa. In each specimen, the rut depth was periodically measured. The average deformation value of the two samples between cycles 5000 and 10000 was determined. For the tested mixture, the *PG-3* requires a slope between cycles 5000 and 10000 of lower than 0.07 mm/10^3 cycles).

3. Results and Discussion

3.1. Marshall mix design

The optimum asphalt content in mixture AC 22 base G made with RCA in place of natural aggregate was obtained according to the *PG-3* requirements. As shown in table 2, the OAC depends on the volume of heavy traffic involved and on the layer where the mixture is to be laid.

Figure 2 shows the curves that were drawn to obtain the OAC following the Spanish *modus operandi*, that is, unit weight (UW), Marshall Stability (S), flow (F), air voids (Va) and voids in mineral aggregate (VMA) versus bitumen content.

As appreciated in figure 2, in general, when mixtures are cured for four hours in the oven, the unit weight is lower than for the control mixture. This is most likely because the bitumen absorption that takes place during the curing time in the oven makes the compaction more difficult. Thus, the volume of the samples made with four hours of curing time will be higher than that of the control mixture.

Figure 2 also shows that the Marshall Stability is much higher for the mixtures that have been cured in the oven for 4 hours than for the control mixtures. In fact, for the mixtures cured in the oven, the Marshall Stability results are, in most cases, over 15 kN, which, as is shown in table 2, is the limit to reach the highest heavy traffic category, T00. Thus, it can be concluded that the absorption that takes place during the time that the mixture is cured in the oven improves the Marshall Stability. When the pores of the mortar are filled with bitumen, the RCA strengthens; thus, the Marshall Stability reaches higher values.

Stability provides an idea of the resistance to permanent deformation of the mixtures. Thus, in principle, it is desirable that mixtures have high Marshall Stability results. Nevertheless, it must be taken into account that excessively high stability values could lead to mixtures that are difficult to compact in the field (Murphy and Bentsen, 2001). Moreover, the *"Bituminous Concrete Mixtures, Design, Procedures and Specification for Special Bituminous Mixtures" of Pennsylvania Department of Transportation* indicates that mixtures that have excessively high stability values and too low deformation values are not desirable because their bitumen content is usually very low. Thus, the mixtures are too stiff and display a greater susceptibility to cracking under traffic. In this regard, flow analysis is a key point to determine if the mixtures manufactured with the treatment of 4 hours in the oven present abnormally high stabilities and low deformation values.

Regarding this question, figure 2 includes a graph of the Marshall flow versus the bitumen content. As observed, in general, the control mixture has greater flow values than the mixtures that have been in the oven four hours before compaction. Nevertheless, in general, for both the control mixture and the mixtures cured four hours in the oven, the flow values are in the range of values established by the Spanish specifications (table 2).

Figure 2 also represents the air void content versus the bitumen content. As shown, mixtures cured 4 hours in the oven have greater air void content than the control mixture. An excessive air void content could lead to mixtures with a low durability. Therefore, the mixtures cured 4 hours in the oven could display lower durability than the control mixture. In this regard, table 2 indicates that the *PG-3* requires an air void content ranging between 5 % and 9 %. As observed in most cases, the air void content is within these limits. Nevertheless, a mix design with higher or lower bitumen contents can lead to noncompliance for this condition.

Figure 2 also includes a graph with the voids in mineral aggregates versus the bitumen content. As shown, the voids in the mineral aggregate are higher for the mixtures cured 4 hours in the oven than for the control mixture. Higher voids in the mineral aggregate are associated with mixtures that are more flexible, more resistant to thermal cracking and with larger space to allow bitumen expansion and post compaction due to traffic during service life. In all cases, voids in mineral aggregate comply with *PG-3* (≥14 %).

From the Marshall tests, the Marshall modulus (S/F) can be obtained. This parameter provides an idea of the stiffness of the mixture. In this way, figure 3 shows the Marshall moduli versus the binder content. As shown, the Marshall modulus of the mixtures cured 4 hours in the oven is much higher than those obtained in the control mixtures. Therefore, the binder absorption stiffens the mix. Thus, mixtures cured for four hours in the oven are more resistant and have higher structural capacity than the control mixture.

The optimum asphalt content, the absorbed bitumen content and the effective binder content versus the RCA percentage are presented in figure 4. As the RCA percentage increases, the optimum asphalt content and the absorbed bitumen content also increase, whereas the effective binder content decreases. These trends can be explained by the high porosity of the mortar attached to the RCA surface, which causes bitumen absorption proportional to the RCA percentage in the HMA. As expected, this allows the mixture to perform properly. It is necessary to have a greater amount of binder, i.e., a greater optimum asphalt content is needed the higher the RCA percentage is. The high porosity of the RCA also means that the higher the RCA percentage in the mixture is, the higher the bitumen absorption is and, thus, the lower the effective binder content is. Regarding the bitumen absorption, it should be noted that the Spanish specifications do not limit its value. In contrast, in other countries, this value is limited. For example, in South Korea, a bitumen absorption up to 3.0 % is allowed (Cho et al., 2011), a value that all the tested mixtures meet.

It can also be observed that the optimum asphalt content is higher for the mixtures cured in the oven for four hours. Contrarily, the effective binder content is similar or slightly higher than that obtained for the control mixtures. This is due to the greater bitumen absorption, which, as shown in figure 4, occurs when the mixture is in the oven. Thus, to satisfy the absorption of binder by the RCA, in the case of the mixtures cured for 4 hours in the oven, a greater optimum asphalt content is required. However, as expected, although the optimum asphalt content is higher in mixtures cured in the oven, the effective binder content is notably similar in both cases, that is, for mixtures cured in the oven and for the control mixtures.

3.2. Moisture damage resistance

Figure 5 represents the indirect tensile strength for mixtures made with the optimum asphalt content for both the “wet” subset and the “dry” subset. The indirect tensile strength values in the “dry” and “wet” subsets tend to decrease, in general, with increasing RCA percentage. This is due to the nature of the RCA, with less resistance to fragmentation than natural aggregate. In figure 5, the values of the indirect tensile strength in the “dry” and “wet” subsets are higher in the case of the mixtures cured for four hours in the oven. This difference between the indirect tensile strength is considerably more pronounced in the “wet” state than in the “dry” state.

Figure 6 represents the TSR versus the percentage of RCA at the optimum asphalt content. From the analysis of figure 6, it can be concluded that the TSR is noticeably higher in the case of mixtures cured for four hours in the oven than for the control mixture. For this reason, it can be said that curing the mixtures for 4 hours in an oven is suitable to improve the water sensitivity of HMA involving RCA from CDW. As was previously shown in figure 5, this improvement is mainly given by the increased “wet” strength of the mixtures cured for four hours in the oven, that is, curing the mixtures four hours in the oven demonstrated its effectiveness in increasing the “wet” strength of mixtures cured in the oven and therefore improved the water damage resistance of such mixtures.

Figure 6 also shows that for mixtures cured in the oven, the TSR values are higher when RCA is involved in the composition of the mixture. Thus, for the 0 % RCA, the TSR values are approximately 85 %, whereas for the percentages from 5 % to 30 % RCA, the TSR values are higher than 90 % in all cases. Therefore, the pretreatment is particularly effective when RCA is involved because it is more absorbent than natural aggregate.

3.3. Resistance to the permanent deformation

Figure 7 includes the curves relating the deformation (mm) to the number of load cycles for mixtures cured 4 hours in the oven. For each RCA percentage, two samples were tested. No relation exists between the RCA percentage and the final deformation.

To facilitate the analysis of the results, the average slope between cycles 5000 and 10000 has been calculated. Table 3 includes these values. All mixtures comply with the limits given by the *PG-3* for the base course for heavy traffic categories T00 to T4. Thus, mixtures cured for four hours in the oven present adequate resistance to permanent deformation.

4. Conclusions

The following conclusions were drawn from this laboratory research:

- HMA made with RCA displays inadequate water damage resistance. RCA is primarily siliceous. Thus, the chemical affinity with bitumen may be conditioned by the RCA mineralogical composition. Moreover, the attached mortar on the RCA surface causes RCA to have a bad fragmentation resistance, which could also affect the water sensitivity of the mixtures due to the easy formation of pathways where water could penetrate.
- Curing the mixture for four hours in the oven at mixing temperature before compaction has demonstrated to be effective for improving the water resistance of mixtures made with RCA in percentages of 0%, 5%, 10%, 20% and 30%.
- This improvement is highly noticeable, particularly when the mixtures are made with RCA, due to the absorptive nature of the attached mortar. During the curing time, the aggregate, particularly the RCA, absorbs a greater amount of bitumen. Consequently, better coating is achieved, leaving no fissure through which water could penetrate. Furthermore, the absorbed bitumen reduces the porosity and thus, the water accessible voids.
- This improvement was obtained as a consequence of an increase of the “wet” indirect tensile strength of the mixtures and not at the expense of harming resistance.

- Curing the HMA made with RCA four hours in the oven leads to mixtures with high Marshall stabilities, high stiffness and an adequate resistance to permanent deformation.

These encouraging results provide a way of substituting virgin quarry aggregates by RCA in percentages up to 30% when producing HMA for road pavements base courses.

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LIST OF FIGURE CAPTATIONS

Figure 1. Gradation curve of an AC 22 base G

Figure 2. Marshall curves for AC 22 base G made with RCA

Figure 3. Marshall modulus for AC 22 base G made with RCA

Figure 4. Bitumen content for AC 22 base G made with RCA

Figure 5. Indirect tensile strength for AC 22 base G made with RCA and OAC

Figure 6. Tensile strength ratio for AC 22 base G made with RCA and OAC

Figure 7. Wheel tracking test results for AC 22 base G involving RCA and cured four hours in the oven

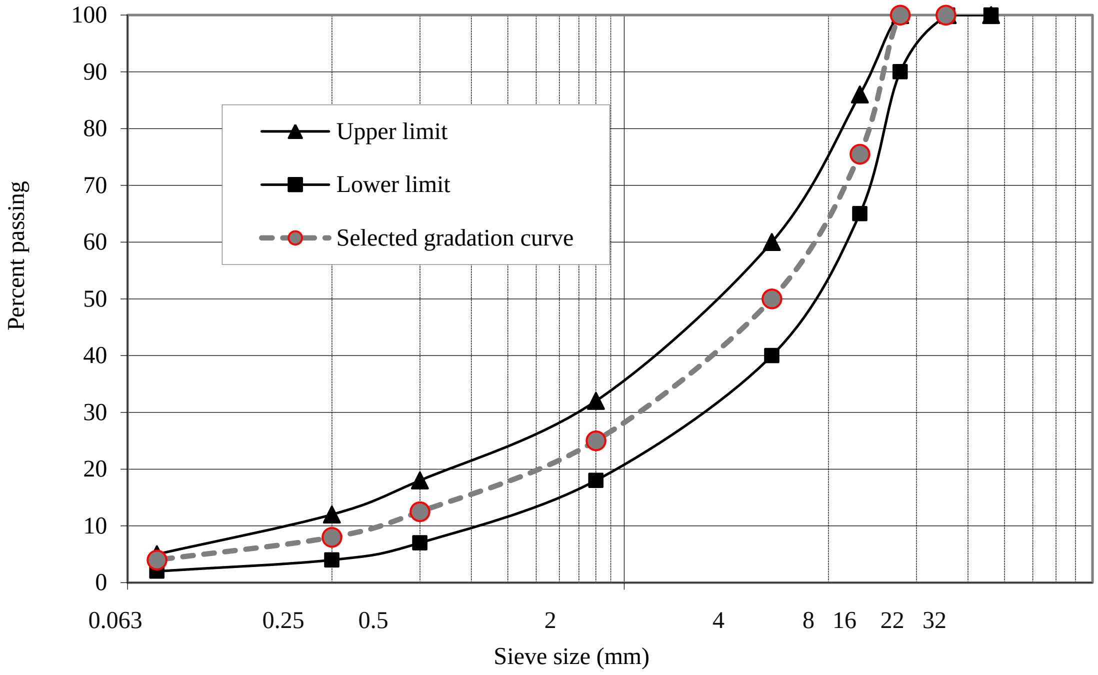

Figure 1. Gradation curve of an AC 22 base G.

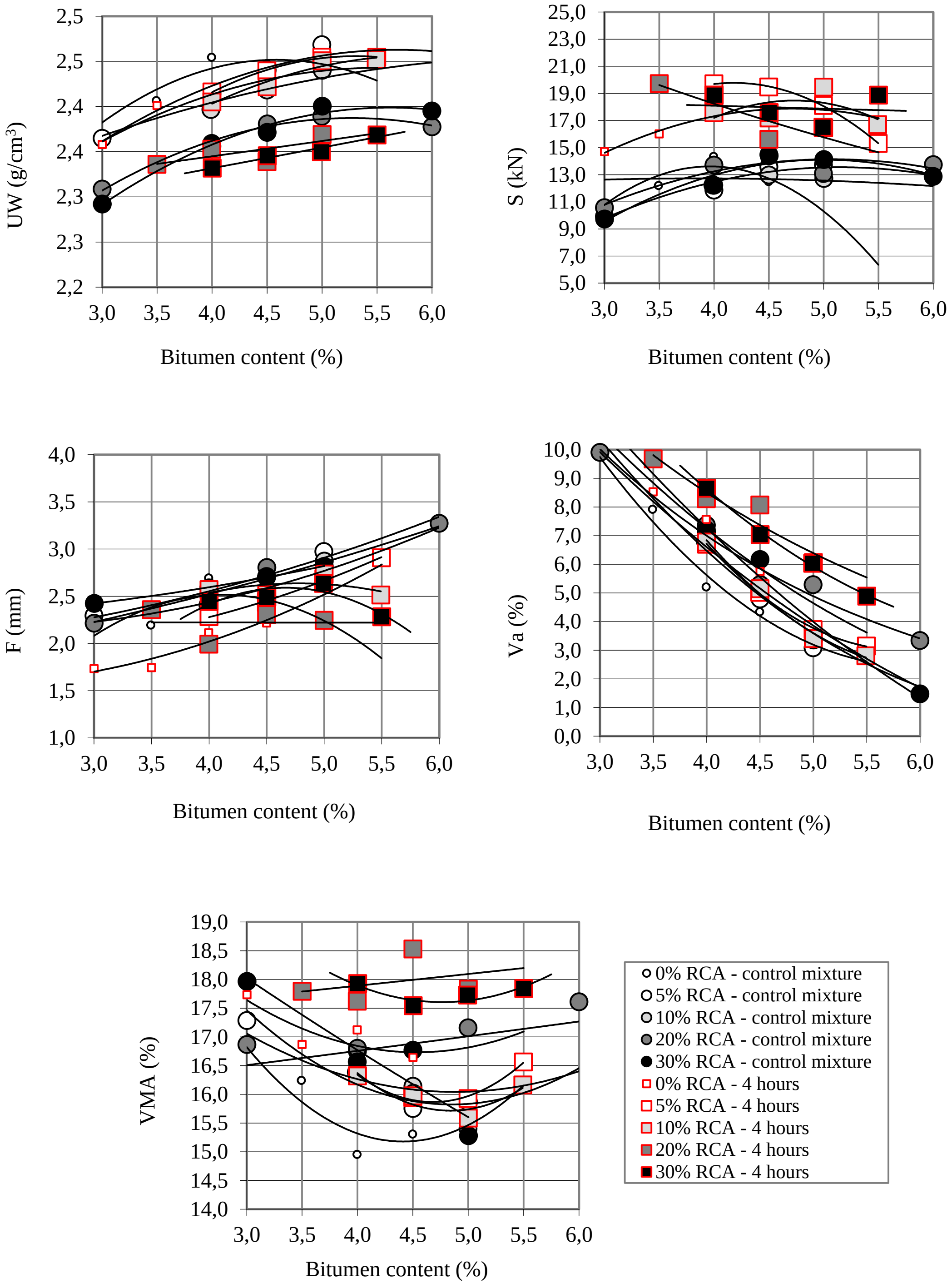

Figure 2. Marshall curves for AC 22 base G made with RCA.

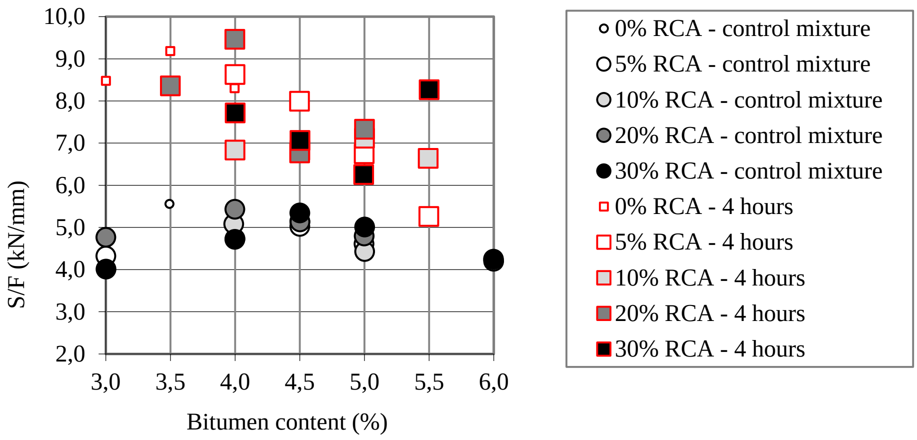

Figure 3. Marshall modulus for AC 22 base G made with RCA.

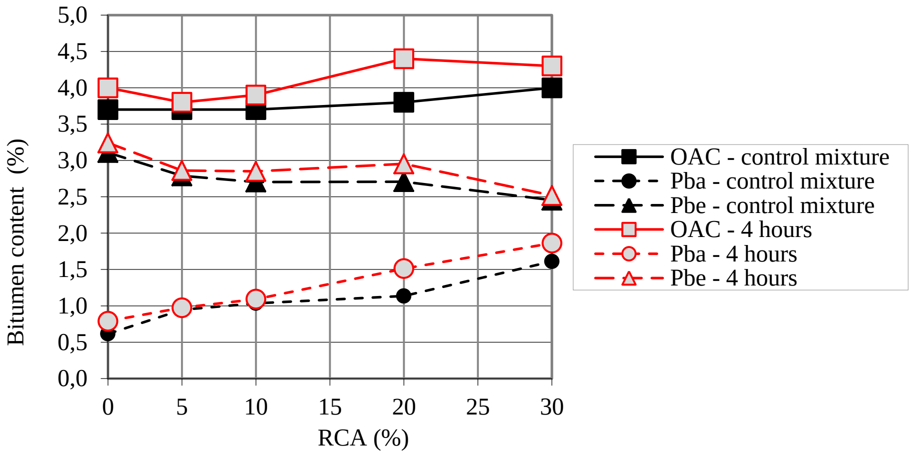

Figure 4. Bitumen content for AC 22 base G made with RCA.

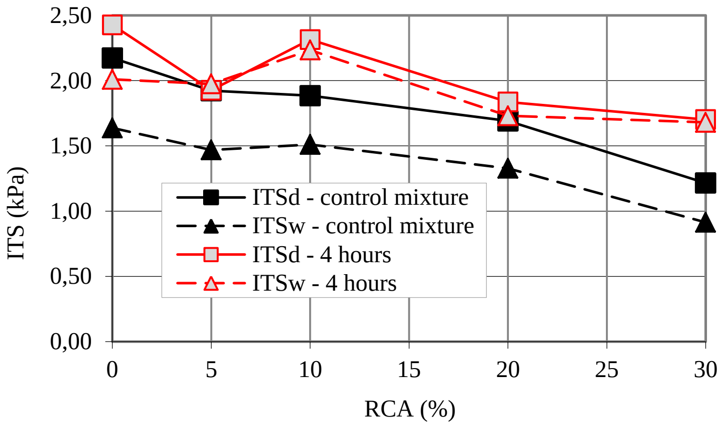

Figure 5. Indirect tensile strength for AC 22 base G made with RCA and OAC.

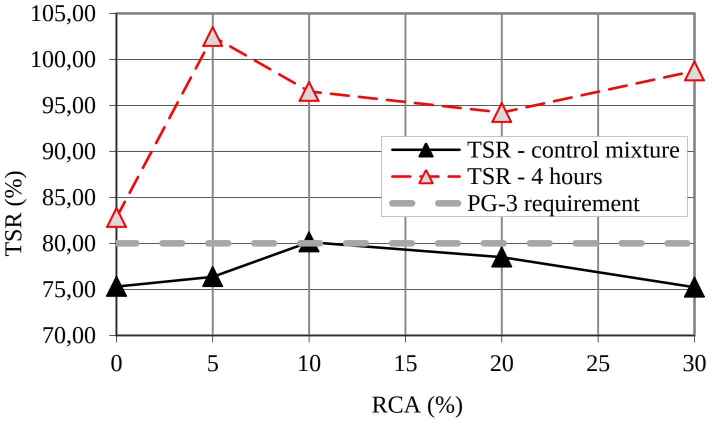

Figure 6. Tensile strength ratio for AC 22 base G made with RCA and OAC.

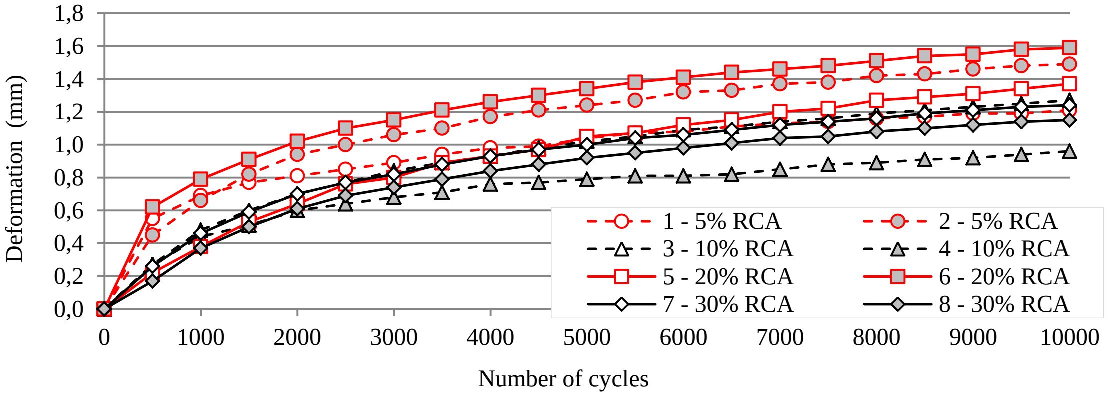

Figure 7. Wheel tracking test results for AC 22 base G involving RCA and cured four hours in the oven.

Aggregate	Standard	RCA	Hornfels	*PG-3* Specifications (*)		
				T00-T1	T3-T2	T4
ρa (g/cm^3)	EN-1097-6	2.63	2.79	-	-	-
WA_{24} (%)	EN 1097-6	5.08	1.08	-	-	-
SE (%)	EN 933-8	67	61	≥ 50	≥ 50	≥ 50
LA abrasion (%)	EN 1097-2	32	14.1	≤ 25	≤ 30	-

(*) Traffic category T00 refers to AADHT (Annual Average Daily Heavy Traffic)≥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
Traffic category T4 refers to AADHT<50

Table 1. Characterisation of aggregates.

Properties	Heavy traffic category			
	T00-T0	T1-T2	T3 and shoulder	T4
S (kN)	>15	>12.5	>10	8-12
F(mm)	2-3	2-3.5		2.5-3.5
Va (%)	5-8	6-9	5-9	-
VMA (%)	≥14			

Table 2. Mandatory mixing design criteria in Spain.

Sample	1	2	3	4	5	6	7	8
RCA (%)	5		10		20		30	
OAC (%)	3.8	3.8	3.9	3.9	4.4	4.4	4.3	4.3
Average slope (mm/10^3 load cycles)	0.04		0.04		0.06		0.05	
PG-3 specification: average slope (mm/10^3 load cycles)	≤ 0.07							

Table 3. Wheel tracking test results: average slope between cycles 5000 and 1000.