Performance of hot-mix asphalt involving recycled concrete aggregates

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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 road 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 4 hours at a mixing temperature of 170ºC, before compaction. The results indicated that the mixes made with RCA and cured for 4 hours in the oven loosely fulfil the 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: recycled concrete aggregates; construction and demolition waste; hot-mix asphalt; curing time; moisture damage resistance; absorbed bitumen content; effective binder

1. Introduction

Asphalt pavement construction is highly dependent on natural resources such as natural aggregates and bitumen. Dust emissions, vibrations and noise are generated into the atmosphere as a result of the virgin aggregates extraction. Also, the strong growth in the construction sector leads to the consumption of natural 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 (Spanish Ministry of the Presidency, 2008). In addition, uncontrolled landfilling of CDW may lead to soil and aquifer pollution (Spanish Ministry of the Presidency, 2008).

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) (Chen and Wong 2013, Cho et al. 2011, Daquan et al. 2018, Kuo et al. 2010, Mills-Beale and You 2010, Motter et al. 2015, Paranavithana and Mohajerani 2006, Pasetto and Baldo, 2004, Shen and Du 2004, 2005, Tam et al. 2007, Zhang et al. 2016).

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, Tam et al. 2007).

Also, the acidic nature of the RCA must be considered when the RCA is used for the manufacture of hot-mix asphalt, due to this acidic nature is related with the poor interfacial bond between RCA and bitumen (Pan et al. 2015).

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).

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 lower moisture damage resistance than those made with natural aggregates (Mills-Beale and You 2010, Paranavithana and Mohajerani 2006, Pérez et al. 2010, Qasrawi and Asi 2016). Other authors indicate that this lower moisture damage resistance only occurs for some RCA percentages. In this regard, Daquan et al. (2018) stated that bituminous mixtures made with RCA percentages ranging from 50% to 60%, lead to mixtures with lower water resistance than those made without RCA.

However, some RCA treatments appear to be successful when used to improve the performance of the mixtures made with partial replacement of RCA (Lee et al., 2012, Pan et al. 2015, Pasandín and Pérez 2014, Qiu et al. 2014, Tam et al. 2007, Wong et al. 2007). Particularly, previous research conducted with the same RCA used in this investigation (Pasandín and Pérez 2013) 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 but the absorbed bitumen content and the effective binder content, that is, the asphalt that has not been absorbed by the aggregate pores (Asphalt Institute 1997).

Moreover, deeper analysis are required for a better understanding of this treatment.

2. Aims and scope

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.

In this regard to achieve a proper performance, the loose mixtures were cured in the oven for 4 hours at mixing temperature before compaction.

Marshall mix design was used in order to determine the optimum bitumen content, taking into account the absorbed and the effective binder content.

In order to deepen the performance of this mixtures, the moisture damage resistance and the resistance to the permanent deformation of the HMA mixes containing RCA were studied.

Percentages of 0%, 5%, 10%, 20% and 30% of RCA were used in place of natural aggregates. As a consequence of the low resistance to the fragmentation of the RCA used in this investigation, its highly absorptive nature, and its expected low moisture damage resistance, percentages of RCA greater than 30% were not considered (Pasandín and Pérez, 2013).

3. Materials and Methods

3.1. Aggregates

For manufacturing HMA, both RCA and natural aggregates were used. The RCA was supplied by a Spanish CDW recycling plant. The UNE-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 RCA had a bulk specific gravity (ρa) of 2.63 g/cm^3 while the natural aggregates presented a ρa of 2.73 g/cm^3. The water absorption (W_{24}) of RCA was 5.08% while the W_{24} of the virgin aggregates was 1.08%. That is, the ρa of the RCA was 3.7% lower than that of the natural aggregate and the W_{24} of the RCA was 370,4% higher than that of the hornfels. These results are attributed to the adhered mortar on the RCA surface, which is less dense and more porous than the natural aggregate.

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 indicated in table 1, the sand equivalent (SE) values of both aggregates complied with the specifications of the PG-3 for HMA as a base course material. 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.

3.2. 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 softening point increased 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 3,134 cm^2/g, and the specific gravity was 3.10 g/cm^3.

3.3. 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, 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.

As is well known, the AASHTO R30 standard states that the asphalt concrete mixtures must be 4 h in the oven at 135ºC before compaction in order to simulate the short term aging. Even though the Spanish PG-3 does not include this requirement, in this research, to improve the moisture sensitivity of the asphalt mixes and to simulate the short term aging, 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).

3.4. 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. In this case, to have the action of water into account, the 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 room 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:

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

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:

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

where TSR = the tensile strength ratio (%), $\mathrm{ITS_W}$ = the average tensile strength of five conditioned (“wet”) specimens (MPa) and $\mathrm{ITS_D}$ = 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.

3.5. 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 4 hours at mixing temperature before compaction.

Each compacted specimen (figure 2) was placed inside a climatic chamber at 60ºC and subjected to 10,000 passages of a wheel applying a pressure of 714±10 kPa. In each specimen, the rut depth was periodically measured. The average deformation value of the two samples between cycles 5,000 and 10,000 was determined. For the tested mixture, the PG-3 requires a slope between cycles 5,000 and 10,000 of lower than 0.07 mm/10^3 cycles).

4. Results and Discussion

4.1. Marshall mix design

The optimum asphalt content (OAC) 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.

Figures 3 to 7 show the curves that were drawn to obtain the OAC, 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 3, in general, when mixtures are cured for 4 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 4 hours of curing time will be probably higher than that of the control mixture.

Figure 3 also shows that, as was expected, as the RCA percentage grows, the UW decreases. The lower bulk specific gravity of the RCA is mainly responsible for this performance.

Figure 4 shows that the Marshall Stability is higher for the mixtures that have been cured in the oven for 4 hours than for the mixtures without curing time in the oven. 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. The bitumen ageing that takes place during the curing time, could also contribute to this performance.

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 (PennDOT, 2003) 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 5 includes a plot of the Marshall flow versus the bitumen content. As observed, in general, mixtures without curing time in the oven have greater flow values than the mixtures that have been in the oven 4 hours before compaction. Nevertheless, in general, for both the mixtures without curing time and the mixtures cured 4 hours in the oven, the flow values are in the range of values established by the Spanish specifications (table 2).

Figure 6 represents the Va versus the bitumen content. As shown, mixtures cured 4 hours in the oven have greater air void content than the mixtures that have not been cured in the oven. 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 mixtures without curing time. 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 7 includes a plot with the VMA versus the bitumen content. As shown, the voids in the mineral aggregate are, in general, higher for the mixtures cured 4 hours in the oven than for mixtures without curing time.

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 8 shows the Marshall modulus versus the binder content. As shown, the Marshall modulus of the mixtures cured 4 hours in the oven is higher than those obtained in the mixtures manufactured without curing time. Therefore, the binder absorption stiffens the mix. Also, as said above the bitumen ageing that takes place during the curing time could stiffen the mix. Thus, mixtures cured for 4 hours in the oven are more resistant and have higher structural capacity than the mixtures without curing time.

As can be seen in figures 3 to 8, the RCA content seems not to affect the Marshall results, except in the case of the unit weight.

The OAC, the absorbed bitumen content (Pba) and the effective binder content (Pbe) versus the RCA percentage are presented in figure 9. As the RCA percentage increases, the OAC and the Pba also increase, whereas the Pbe 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.

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). As can be seen in figure 9 all the tested mixtures meet this value.

It can also be observed that the OAC and the Pba are higher for the mixtures cured in the oven for 4 hours than for the control mixtures. Moreover, the differences between the OAC and the Pba results are more noticeable when the RCA percentages are high (20% and 30%) than when the RCA percentages are low (0%, 5% and 10%).

In contrast, the Pbe is similar or only slightly higher than that obtained for the control mixtures for all RCA percentages.

These trends are due to the greater bitumen absorption, which, as shown in figure 9, mainly occurs when the mixture is in the oven and when the mixture is made with high RCA percentages (20% and 30%). Thus, to satisfy the absorption of binder by the RCA, in the case of the mixtures cured for 4 hours in the oven, greater OAC is required, as shown in figure 9.

4.2. Moisture damage resistance

Figure 10 represents the indirect tensile strength for mixtures made with the OAC 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 10, the values of the indirect tensile strength in the “dry” and “wet” subsets are higher in the case of the mixtures cured for 4 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 11 represents the TSR versus the percentage of RCA at the OAC. From the analysis of figure 11, it can be concluded that the TSR is noticeably higher in the case of mixtures cured for 4 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 10, this improvement is mainly given by the increased “wet” strength of the mixtures cured for 4 hours in the oven, that is, curing the mixtures 4 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 11 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.

4.3. Resistance to the permanent deformation

Figure 12 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 5,000 and 10,000 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 4 hours in the oven present adequate resistance to permanent deformation.

Nevertheless, it is interesting to take into account that, as be seen in table 3, the slopes are higher for the higher RCA percentages (20% and 30%). It is probably due to the higher bitumen content of these mixtures.

5. **Conclusions**

In this research HMA made with 0%, 5%, 10%, 20% and 30% of RCA were analyzed and compared with similar mixtures that were left in the oven for 4 hours at the mixing temperature before their compaction. The optimum bitumen content by the Marshall procedure was obtained for all the mixtures. Also, their moisture damage resistance and their resistance to the permanent deformation at the optimum bitumen content were studied. The following conclusions were drawn from this laboratory research:

- The RCA not only has higher water absorption than natural aggregate, but also higher bitumen absorption.

- Furthermore, it has been found that this absorption increases when the mixture is cured in the oven for 4 hours before compaction. This is more noticeable for higher percentages of RCA in the mixture (20% and 30%).
- Therefore, to satisfy this absorption, the optimum asphalt content increases with the percentage of RCA and is higher for mixtures that have been cured for 4 hours in an oven than for mixtures that have not undergone this curing process.
- Nevertheless, it must be said that the effective binder content, is not affected by the RCA percentage and the curing time as the OAC.
- In general, 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 4 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 this aggregate.
- 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 4 hours in the oven leads to mixtures with high Marshall stabilities, high stiffness and an adequate resistance to permanent deformation.
- Nevertheless, it has been found that RCA percentages (from 0% to 30%) do not affect the Marshall results.

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. However, further investigation is needed. In this regard it is particularly important to study the fatigue life of the mixtures, the rheology of the bitumen before and after the curing time of the mixture in the oven, and how can be implemented at a full-scale the pretreatment of 4 hours in the oven. A simple storage system in asphalt plants that maintains the temperature of mixtures made with RCA without increased consumption of fossil fuels could be the solution for this question.

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Figure captions

Figure 1. Gradation curve of an AC 22 base G (Pasandín and Pérez, 2013)

Figure 2. Wheel tracking sample compaction by using the roller compactor

Figure 3. Unit Weight versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA

Figure 4. Marshall Stability versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA

Figure 5. Marshall flow versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA

Figure 6. Air voids versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA

Figure 7. Voids in mineral aggregate versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA

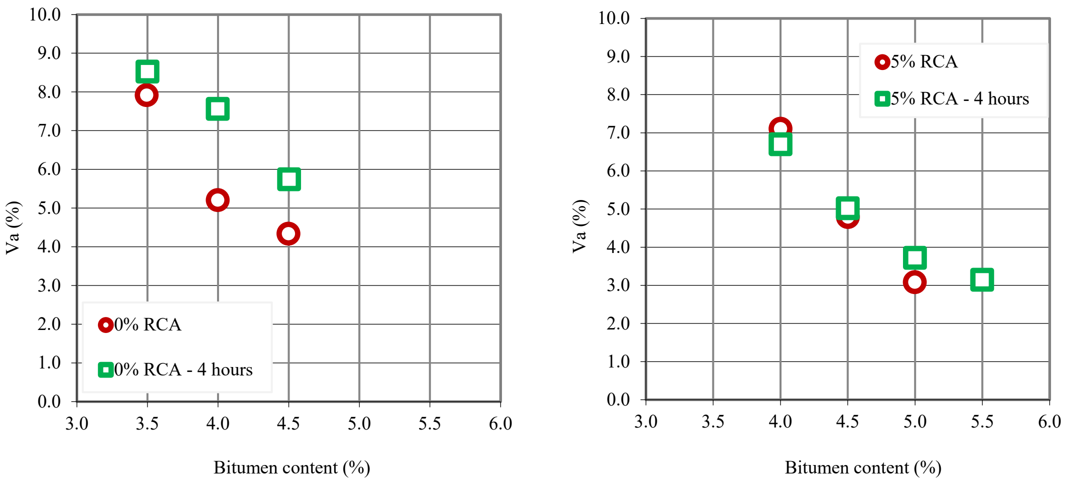
Figure 8. Marshall modulus for AC 22 base G made with RCA versus bitumen content.

Figure 9. Bitumen content for AC 22 base G made with RCA.

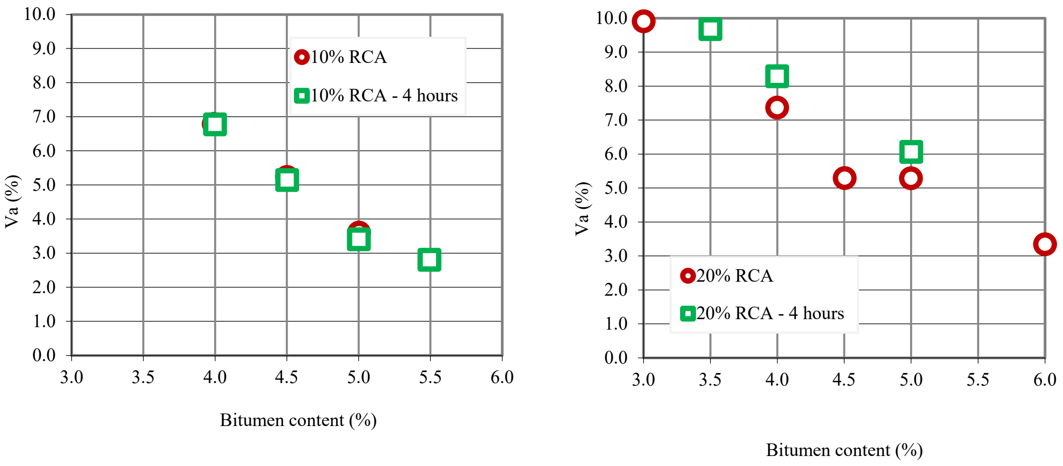
Figure 10. Indirect tensile strength for AC 22 base G made with RCA and OAC.

Figure 11. TSR for AC 22 base G made with RCA and OAC.

Figure 12. Wheel tracking test results for AC 22 base G involving RCA and cured four hours in the oven.


a) 0% RCA

b) 5% RCA


c) 10% RCA

d) 20% RCA

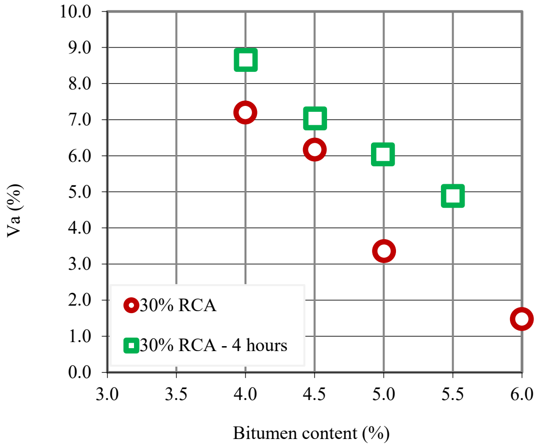

e) 30% RCA

Figure 6. Air voids versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA

Figure 2. Wheel tracking sample compaction by using the roller compactor

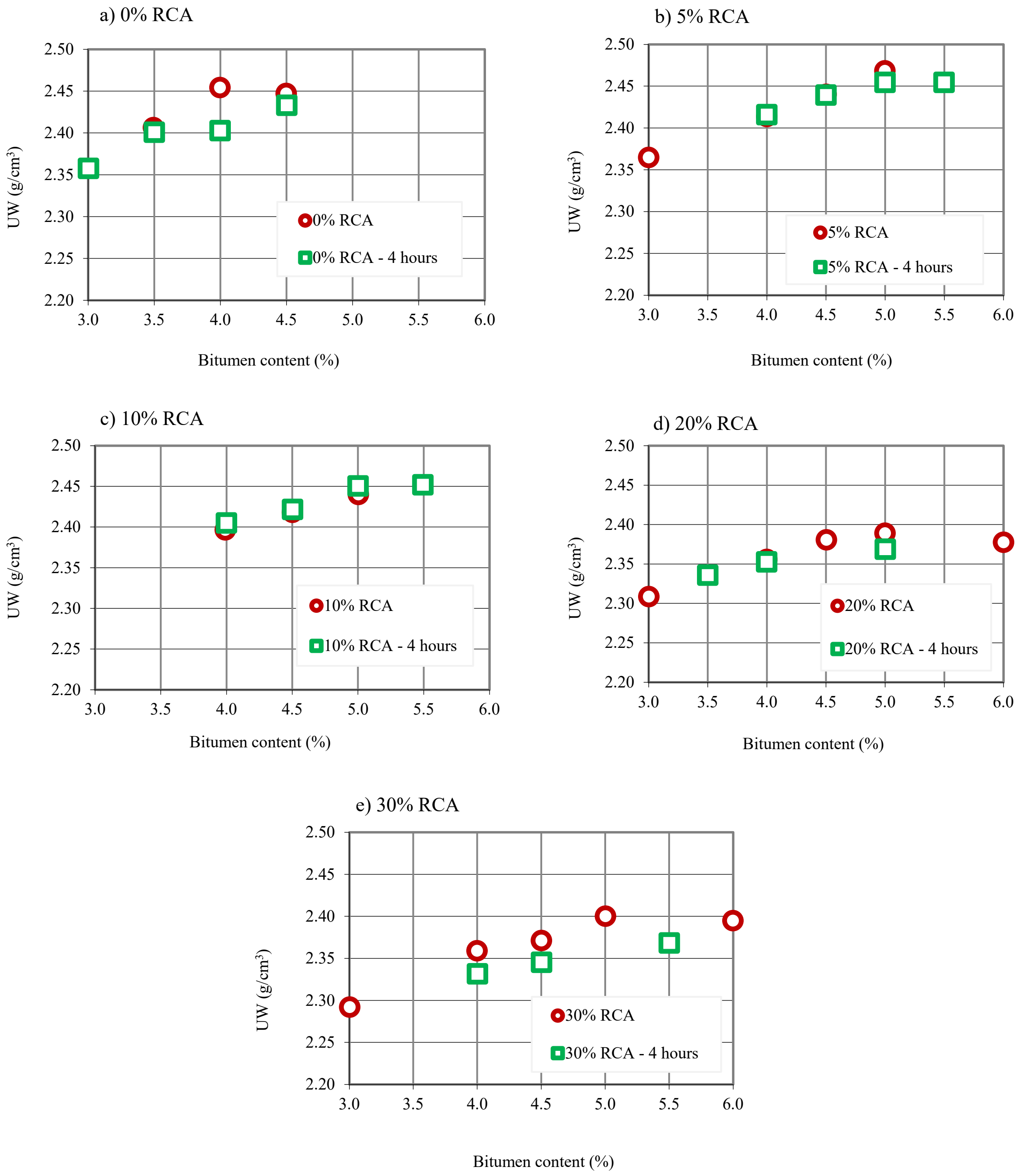


Figure 3. Unit Weight versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA

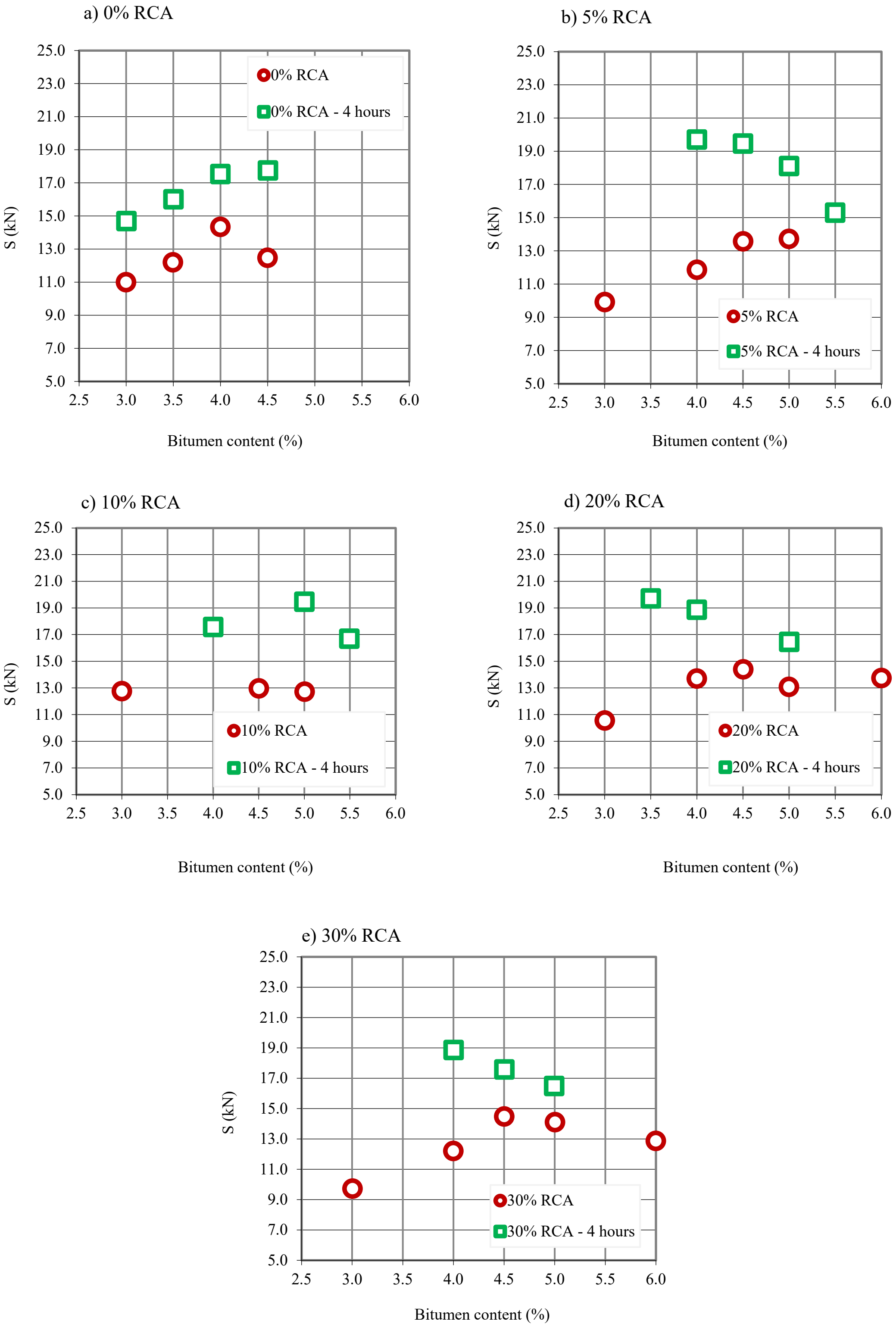


Figure 4. Marshall Stability versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA

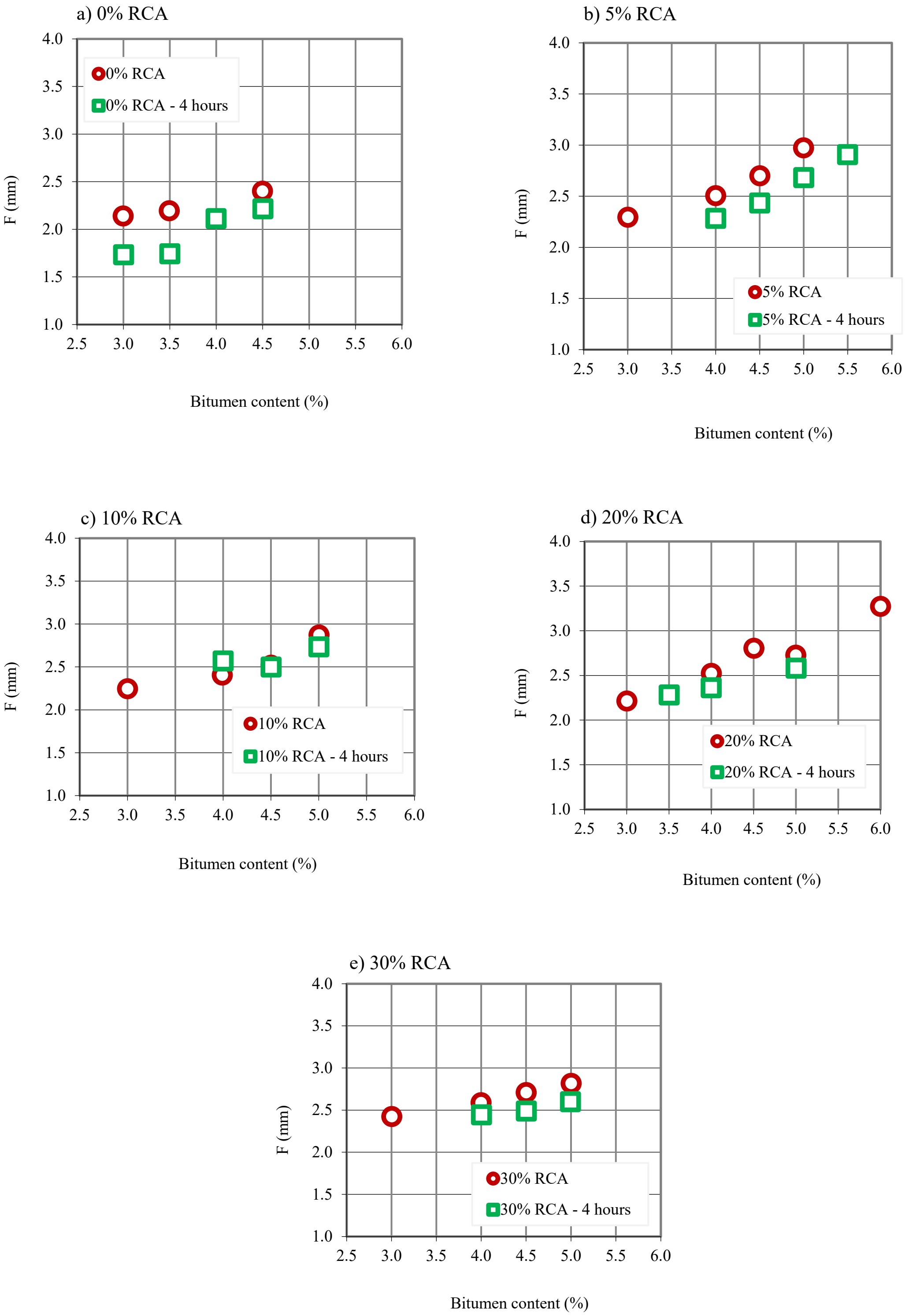


Figure 5. Marshall flow versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA

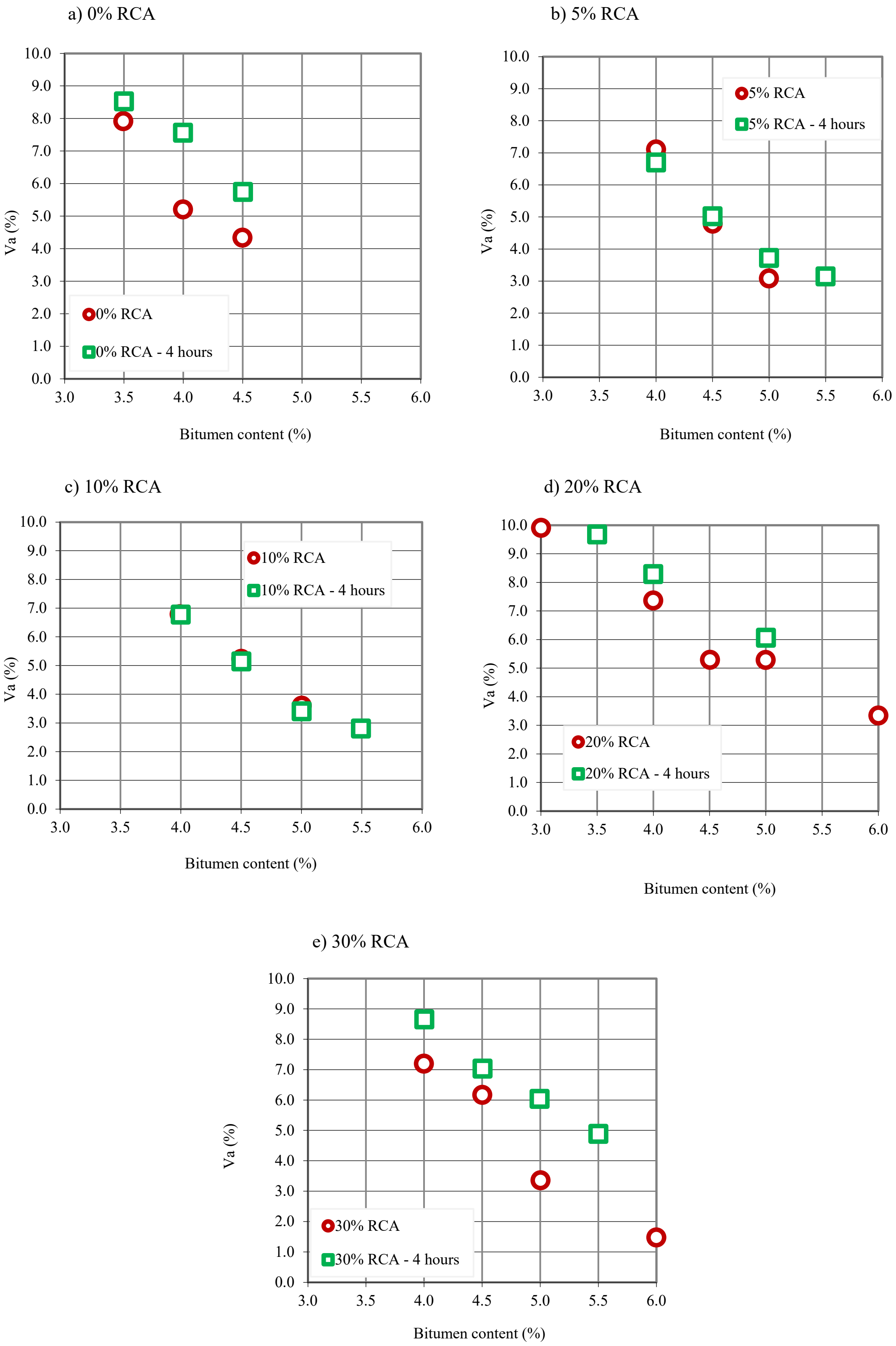
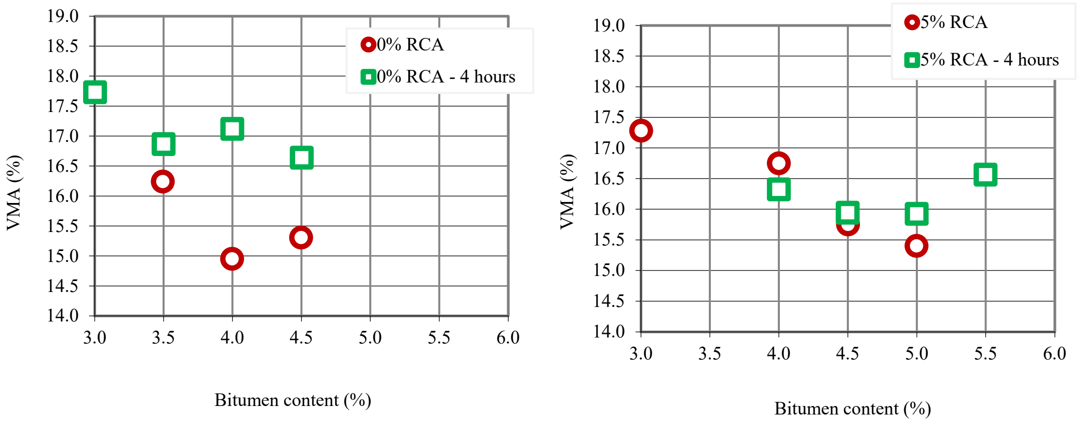
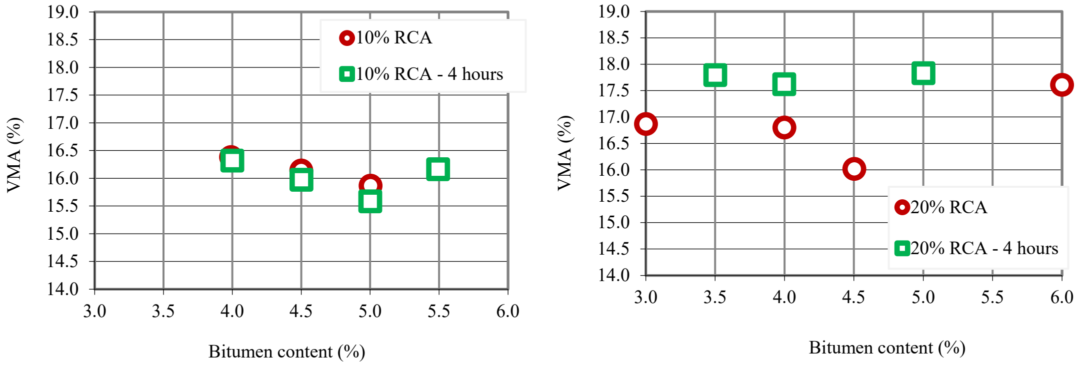


Figure 6. Air voids versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA



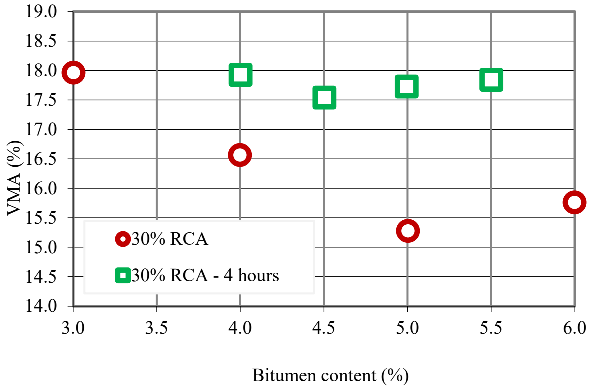
a) 0% RCA

b) 5% RCA



c) 10% RCA

d) 20% RCA



e) 30% RCA

Figure 7. Voids in mineral aggregate versus bitumen content: a) 0% RCA, b) 5% RCA, c) 10% RCA, d) 20% RCA and e) 30% RCA

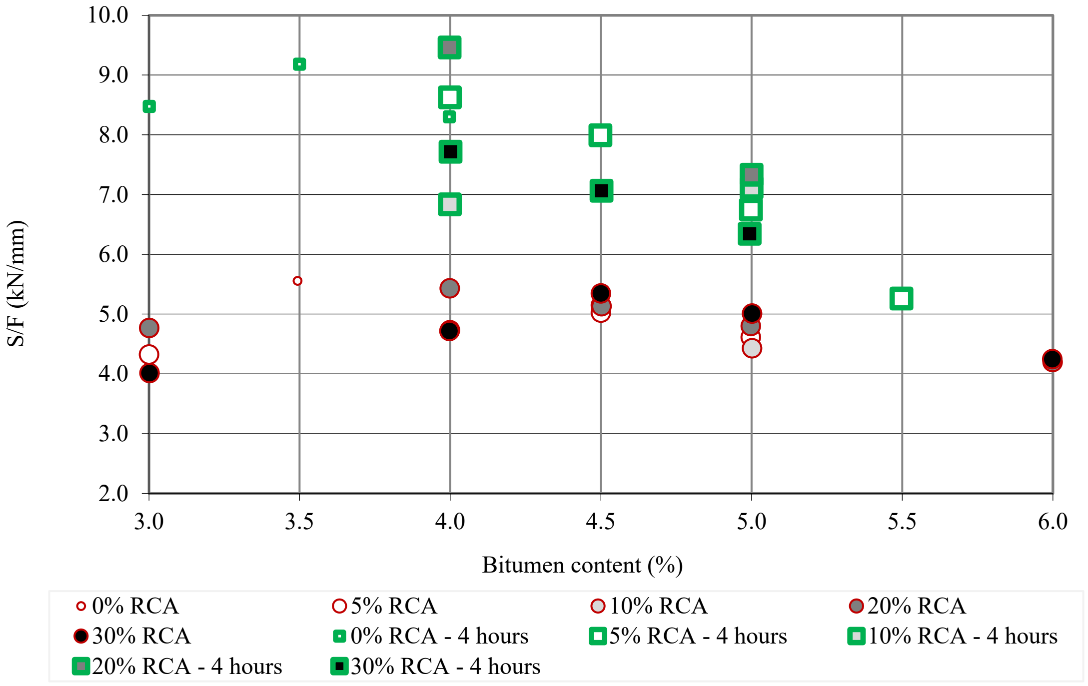
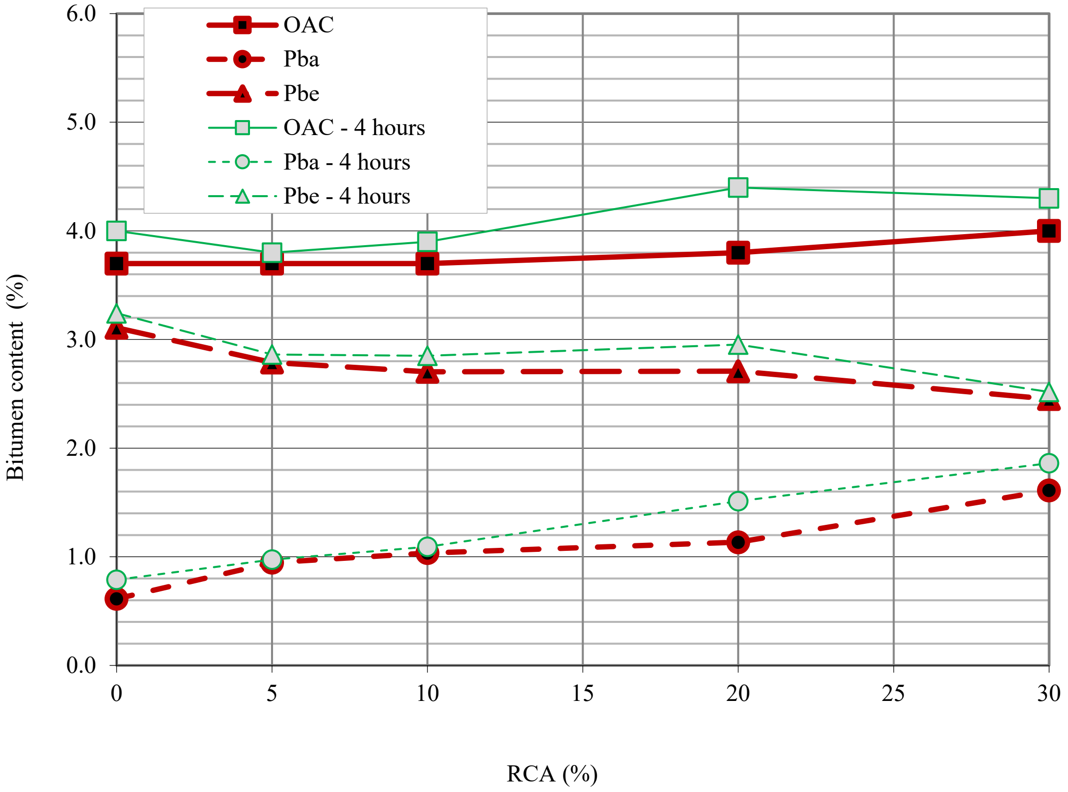


Figure 8. Marshall modulus for AC 22 base G made with RCA versus bitumen content.



OAC=Optimum Asphalt Content
Pba=Absorbed bitumen content
Pbe=Effective bitumen content

Figure 9. Bitumen content for AC 22 base G made with RCA.

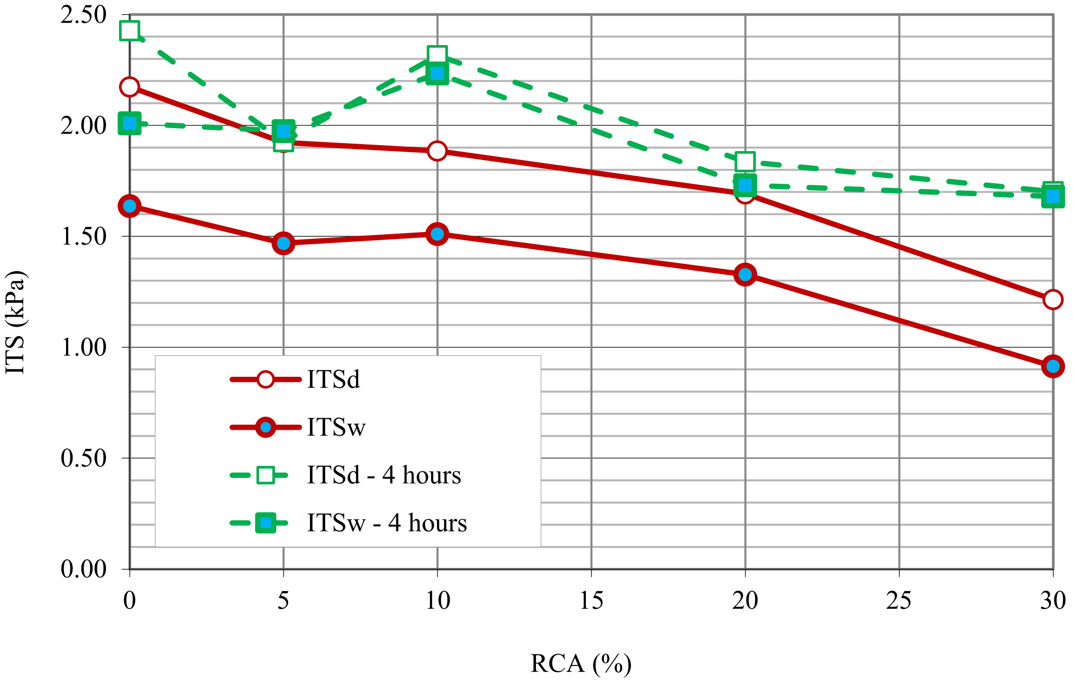


Figure 10. Indirect tensile strength for AC 22 base G made with RCA and OAC.

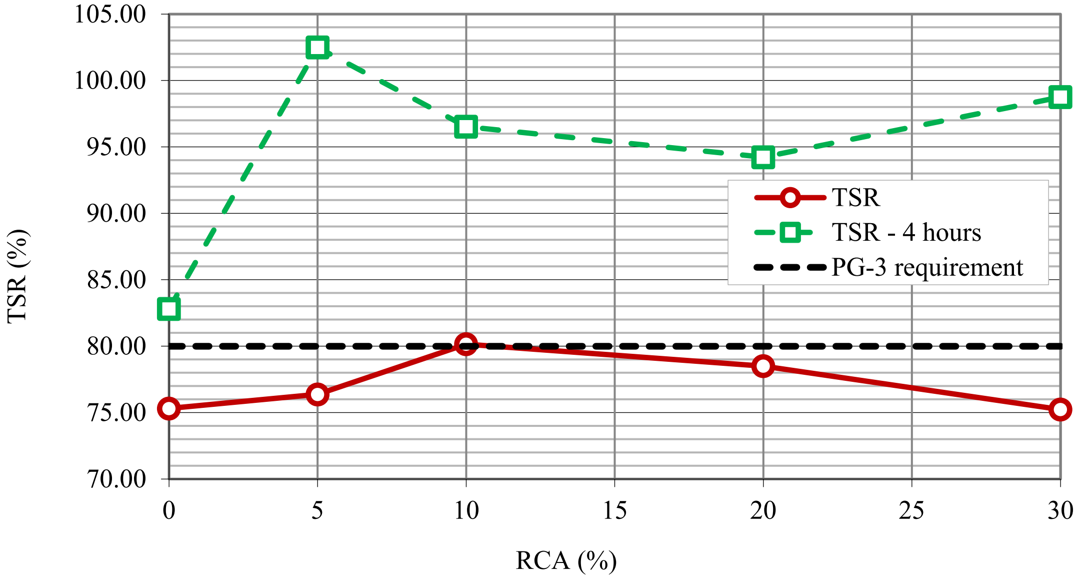


Figure 11. TSR for AC 22 base G made with RCA and OAC.

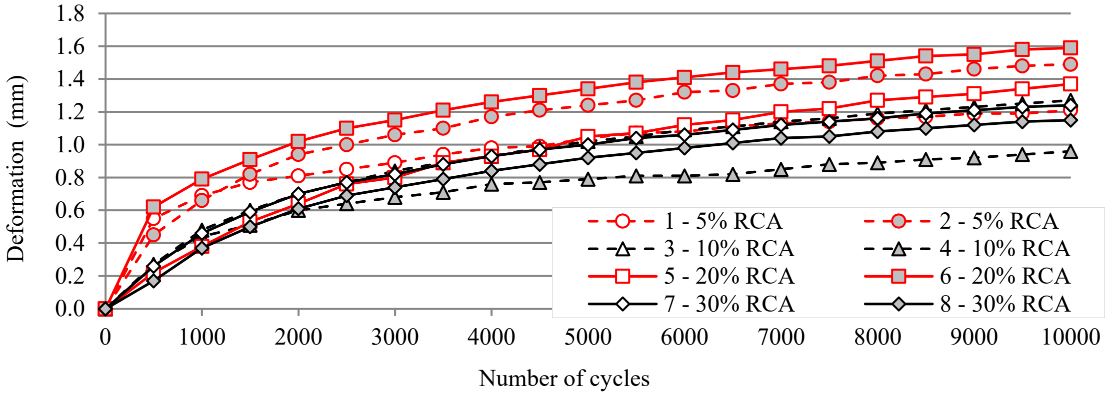


Figure 12. Wheel tracking test results for AC 22 base G involving RCA and cured four hours in the oven.

Property	Standard	RCA	Hornfels	PG-3 Specifications (*)		
				T00-T1	T3-T2	T4
Sand Equivalent (%)	UNE-EN 933-8	67	61	≥ 50	≥ 50	≥ 50
Los Angeles abrasion coefficient (%)	UNE-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. PG-3 specifications of aggregates.

Properties	Standard	Heavy traffic category			
		T00-T0	T1-T2	T3 and shoulder	T4
Stability (kN)	NLT-159/86	>15	>12.5	>10	8-12
Flow (mm)	NLT-159/86	2-3	2-3.5		2.5-3.5
Air voids (%)	UNE-EN 12697-8	5-8	6-9	5-9	-
Voids in mineral aggregate (%)	UNE-EN 12697-8	≥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 (UNE-EN 12697-22:2008+A1) results: average slope between cycles 5000 and 1000.