EFFECT OF AGEING TIME ON PROPERTIES OF HOT-MIX ASPHALT CONTAINING RECYCLED CONCRETE AGGREGATES

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Abstract

This study describes a laboratory evaluation on the effect of ageing time on the primary properties of hot-mix asphalt (HMA) containing recycled concrete aggregates (RCA) from construction and demolition waste (CDW). The mixtures were left in an oven for 0 hours, 2 hours and 4 hours at the mixing temperature prior to compaction. The volumetric properties, stiffness and resistance to the permanent deformation of HMA containing 0%, 5%, 10%, 20% and 30% RCA instead of natural aggregate were studied. The results showed that increasing the ageing time of HMA containing RCA increased the number of air voids, the stiffness at ambient temperature and the initial permanent deformation.

Keywords: hot-mix asphalt, recycled concrete aggregate, ageing time, properties

1. Introduction

In recent years, the use of recycled concrete aggregates (RCA) from construction and demolition waste (CDW) as coarse aggregates in hot-mix asphalt (HMA) has been studied as a sustainability practice. These studies have produced encouraging but widely differing results. However, the great variability in the results is not surprising. In these different studies, RCA was combined with natural aggregates and bitumens of different types; thus, different performances were to be expected. However, although a substantial contingent of the studies used RCA from the demolition of structures formed exclusively of concrete (e.g., concrete pavements) [1, 2], other studies used RCA from the demolition of residential buildings [3, 14] or natural disaster debris [13]. In the latter two cases, the quality of the original concrete was sufficiently different to negatively affect the performance of the mixtures. Furthermore, the RCA contained concrete fragments as well as other materials (e.g., ceramic and gypsum), which may also have affected the results.

In the literature, various authors have recommended that RCA should be treated prior to manufacturing HMA [11, 13-14] to produce mixtures with good water resistance. Consequently, Lee et al. [11] coated RCA with a slag cement paste and obtained water resistances within the range of the Taiwanese specification requirements. Laboratory results by Zhu et al. [13] also showed that RCA coated with a liquid silicone resin improved moisture damage resistance. Pasandín and Pérez [14] found that mixtures containing RCA that were left in the oven for 4 hours at the mixing temperature before compaction complied with the Spanish moisture damage resistance specifications.

The Superpave mix design short-term ageing procedure for paving mixtures simulates the ageing that takes place during the plant mixing phase, transportation and construction of pavement [15]. In the Superpave mix design method, the loose mixture is usually left in the oven at 135 ºC for 4 hours [15]. The short-term ageing process used in the Superpave mix design method is similar to the last treatment (mixtures left in the oven for four hours at the mixing temperature) mentioned above but has a different purpose, i.e., to improve the moisture damage resistance [14]. The RCA absorbs bitumen, which enables the binder to coat the entire aggregate surface, leaving no fissures through which water can penetrate, thereby reducing the porosity and the water-accessible voids at the same time [14]. The bitumen absorbed by the pores of the mortar attached to the surface of RCA also strengthens the mortar and, thus, the RCA [14]. However, it is well known that while the mixture is in the oven, oxidation and loss of volatile fractions occurs within the bitumen, resulting in bitumen hardening [16]. The aforementioned discussion shows that this treatment improves the moisture damage properties of HMA made with recycled concrete aggregates and also modifies the volumetric properties and service performance of these materials. Thus, the effect of the bitumen absorption and bitumen hardening on the properties of HMA containing RCA should be investigated.

In this study, we analyse the volumetric properties, stiffness and resistance to permanent deformation of HMA containing RCA from CDW as a base course material. To investigate the effect of the ageing time, asphalt mixes were left in the oven after mixing and before compaction for 0 hours, 2 hours and 4 hours at the mixing temperature. Increasing the curing time was expected to cause the aggregate, particularly RCA, to absorb more bitumen. Increasing the ageing time was also expected to increase the loss of volatile compounds. Therefore, increasing the ageing time in the oven was predicted to increase the mortar resistance and change the volumetric properties and performance of HMA containing RCA. Mixtures containing 0% (control mixture), 5%, 10%, 20% and 30% of RCA were tested. To produce environmentally friendly materials, the RCA replacement was limited to 30%, because the high absorption capacity of RCA for bitumen [14] can lead to excessive bitumen consumption.

2. Materials and methods

2.1. Basic materials

2.1.1. Aggregates

Two types of aggregates were used in this study: RCA and natural aggregate. The RCA (figure 1) were supplied by a CDW recycling plant in Madrid (Spain). The RCA composition was as follows: 89.3% stone, mortar, concrete or similar materials; 6.5% bituminous materials and 3.6% ceramics. Figure 1 shows that 0.6% of impurities, such as gypsum plaster, wood, metals and crystal, were carefully removed. Hornfels, which was supplied by a local contractor, was used as the natural aggregate. X-ray fluorescence tests (XRF) have shown that RCA (61.46% of SiO_2) and hornfels (62.30% of SiO_2) are siliceous aggregates. Moreover, X-ray diffraction tests (XRD) have shown that RCA and hornfels contain quartz in their mineralogical composition. Quartz is known to adhere poorly to the binder [17]. For all of these reasons, both aggregates, i.e., RCA and hornfels, were expected to exhibit poor moisture damage resistance.

The properties of the RCA and the natural aggregate were evaluated following the Spanish General Technical Specifications for Roads, which is also known as PG-3 [18]. The results are summarised in table 1 [14]. As expected, RCA had a lower bulk specific gravity (ρa) than the natural aggregate and a higher water absorption (W_{24}) because of the mortar attached to the RCA surface. The sand equivalent (SE) values of the RCA and the natural aggregate complied with the PG-3 for HMA as a base course material. However, note that the Los Angeles abrasion coefficient (LA) for RCA exceeded the PG-3 specifications; thus, the RCA are only suitable for the lighter heavy traffic categories. In contrast, the LA for natural aggregates was adequate for all of the heavy traffic categories.

2.1.2. Binder and filler

A B50/70 penetration bitumen from Venezuela was chosen to prepare the HMA specimens. The B50/70 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, a density of 1.009 g/cm^3 (at 25 ºC), a penetration following a rolling thin-film oven test of 68x0.1 mm and a Δ softening point following a rolling thin-film oven test of 6.5 ºC. Grey Portland cement (CEM II/B-M (V-L) 32.5 N) was obtained from a commercial source for use as a mineral filler. The cement had a Blaine surface area of 3,134 cm^2/g and a specific gravity of 3.10 g/cm^3.

2.2. Test program

2.2.1. Specimen preparation

A continuous grading HMA for a base course type material, AC 22 base G (figure 2) [14], was chosen to comply with the gradation limits given by the PG-3 [18]. The HMA had a maximum aggregate size of 22 mm and a 4% filler content.

As previously stated, the samples were manufactured using 0% (control mixture), 5%, 10%, 20% and 30% RCA instead of hornfels. Impurities in the RCA coarse fraction can be most easily removed by hand. Note that when HMA is produced on an industrial scale, the impurities are removed by magnetic separation, water-floatation or air-sieving [19], thereby avoiding the inconvenient use of manual methods. Moreover, the RCA fine fraction has a higher mortar content than the RCA coarse fraction, which negatively impacts the RCA properties [20]. For all of these reasons, RCA replaced the natural aggregate for the coarse fractions of 8/16 mm (at replacement contents of 5%, 10%, 20% and 30%) and 4/8 mm (at a replacement content of 30%). In this study, the RCA was heterogeneous and was therefore not considered in the coarser fractions.

Experimental tests were conducted on Marshall specimens that were compacted with 75 blows per face according to NLT- 159/86 [21]. Asphalt specimens of 101.6 mm in diameter and 63.5 mm in height were manufactured with binder contents of 3.5%, 4.0% and 4.5% of the total weight of the mixture. The mixtures were left in the oven at the traditional mixing temperature (170 ºC) for 0 hours, 2 hours and 4 hours after mixing and before compaction.

2.2.2. Volumetric properties

The volumetric properties of the HMA samples, i.e., the content of the air voids (Va), the voids in the mineral aggregate (VMA), and the voids filled with asphalt (VFA), were obtained. The bulk specific density (ρb) was measured using the saturated surface dry (SSD) water displacement method, and the maximum specific density (ρm) was measured according to UNE-EN 12.697-5 [22]. These values were used to calculate the volumetric properties of the asphalt specimens according to UNE-EN 12.697-8 [23].

In defining the volumetric properties, the effective binder content (Pbe) (or the binder percentage not absorbed by the aggregate) and the absorbed binder (Pba) (or the binder percentage absorbed by the pores of the aggregate) must be considered. In the European standards, the bitumen absorption is calculated by allowing for a specified tolerance in determining the voids in the mineral aggregate, so as not to overestimate the void fraction. In contrast, both the effective (Pbe) and absorbed (Pba) binder content can be determined in U.S. legislation. This distinction is particularly important for porous aggregates, such as RCA, which can absorb a large amount of bitumen. Therefore, both the effective binder content (Pbe) and the absorbed binder content (Pba) [24] were determined in this study. The voids in mineral aggregate (VMAabs) and the voids filled with asphalt (VFAabs) were then recalculated by accounting for the absorbed bitumen (Pba) [24].

2.2.3. Stiffness

In the design of flexible pavements and the analysis of HMA performance, it is essential to determine the HMA stiffness, because it is directly related to the ability of the material to distribute traffic loads [25].

In the present study, the HMA stiffness was determined by measuring the resilient modulus in indirect tensile mode following UNE-EN 12697-26 Annex C [26]. This non-destructive test involves applying compressive loads in a vertical diametral plane of Marshall specimens. The HMA resilient modulus was determined using a Cooper NU 14 testing machine with an indirect tensile device (figure 3). A repeated haversine load wave with an impulse repetition period of 3±0.1 seconds and a rise time of 124±4 ms was applied. The maximum load was selected to achieve a maximum horizontal strain of 0.005% for the specimen diameter. The tests were conducted at temperatures of 0ºC, 10ºC and 20ºC.

The resilient modulus test was performed after 10 conditioning pulse cycles and 5 load pulse cycles, and the resilient modulus was determined using the following equation:

$$M_R = \frac{F \times (\nu + 0{,}27)}{z \times h} \quad (1),$$

where M_R=resilient modulus (MPa); F=maximum applied load (N); z=horizontal deformation (mm); h=sample thickness (mm) and ν=Poisson´s ratio (a Poisson ratio of 0.35 was assumed for different temperatures [26]).

2.2.4. Resistance to permanent deformation

The resistance to permanent deformation was determined using a repeated load axial test (RLAT) without confinement, following DD 226:1996 [27]. The same Marshall specimens were used as in the resilient modulus test. The specimens were left overnight at a test temperature of 30ºC and then placed between two load platens (figure 4). A pre-load of 10 kPa was applied for 600±6 s. The samples were then subjected to 1,800 load applications. The test was performed under the following conditions: an axial stress of 100±2 kPa, a load application period of 1 s and a rest period of 1 s. The axial permanent strain was calculated using the following equation:

$$\varepsilon_{p(n,T)} = \frac{\Delta h}{h_0} x100 \quad (2),$$

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

4. Test results and discussion

4.1. Volumetric properties

Volumetric properties have widely used in the design of bituminous mixtures. These properties are related to the HMA performance [28]. A high air voids content results in a fast ageing process and a less durable mixture [29]. The Spanish requirements for the HMA air voids (Va) content are given in table 2.

A high number of voids in mineral aggregate (VMA) content of mixtures is desirable in some applications to provide greater flexibility and more space for bitumen expansion and post-compaction from traffic during the service life and to allow for the binder content to vary during HMA production in the mixing plant [30]. PG-3 requires a voids in mineral aggregate value of over 14% [18].

Voids filled with asphalt (VFA) are also related to HMA durability. A low voids filled with asphalt content can result in a HMA with low durability [31], particularly when these materials have a low effective binder content. The Spanish specifications do not place requirements on voids filled with asphalt.

Figures 5 and 6 show the volumetric properties of HMA versus the RCA content (0%, 5%, 10%, 20% and 30%). The graphs correspond to mixtures with binder contents of 3.5%, 4.0% and 4.5% and ageing times of 0 hours, 2 hours and 4 hours. The voids in mineral aggregate (figure 5) and the voids filled with asphalt (figure 6) were calculated in two ways: neglecting the bitumen absorption (VMA, VFA) and including the bitumen absorption (VMAabs, VFAabs). As previously stated, the Pba and Pbe values were used to calculate VMAabs and VFAabs. The Pba and Pbe values are shown in table 3. The greater the curing time, the higher was the bitumen absorption and therefore, the lower was the effective binder content. Also, the higher the RCA percentage, the higher was the bitumen absorption and thus, the lower was the effective binder content. That is, the curing time allowed the aggregate to absorb more binder, particularly, the RCA.

Figures 5a, b and c show that the air voids content (Va) increased with the RCA content. This trend can be explained as follows: mortar attached to the RCA surface increased the roughness of the RCA, which made it more difficult to compact the mixture. In general, a higher ageing time also increased the air voids content. This trend reflected the absorbent character of the RCA. Note that this trend was not as clearly observable for a lower binder content (figure 5a) as for the bitumen contents of 4.0% (figure 5b) and 4.5% (figure 5c). This result was observed because the bitumen could not completely fill the RCA pores in the time that the mixture remained in the oven at the lower binder content. Table 2 shows that for the range of bitumen contents tested (3.5% to 4.5%), the mixtures had air voids contents that generally complied with the Spanish specifications for all of the heavy traffic categories; however, the binder content should be carefully selected among these limits so as not to affect the durability of the mixture.

As expected, the voids in mineral aggregate (VMA) followed the same trend as the air voids (Va): the RCA content increased with the VMA content. However, figures 5a, b and c show that when the binder absorption was accounted for, the voids in mineral aggregate (VMAabs) tended to slightly decrease or remain constant as the RCA content increased. This result highlights the absorbent character of the RCA. Figures 5a, b and c show the overestimate in the voids in mineral aggregate content that results from neglecting binder absorption. However, the voids in mineral aggregates content of the mixtures exceeded the 14% limit specified by the Spanish specifications when binder absorption was both included and neglected. The limit was not exceeded for the highest RCA contents (20% and 30%). For this reason, higher RCA substitution rates should not be used at the binder contents tested. Note that the voids in mineral aggregate did not appear to be affected by the binder content, because the binder content exhibited two contradictory effects: increasing the bitumen content increased the volume occupied by the bitumen in the mixture, while also facilitating compaction, thereby decreasing the air voids content of the mixture.

Figures 6a to c clearly show that the VFA decreased as the RCA content increased. Once again, this trend shows that the presence of RCA increased the binder absorption. This trend was particularly noticeable for binder contents at which the RCA pores were completely filled by the bitumen over the ageing time in the oven. That is, the trend was more clear for higher binder contents (figures 6b and c). Moreover, as expected, figures 6a, b and c show that the voids filled with asphalt content decreased as the ageing time increased because of the increased bitumen absorption that occurred while the mixture was left in the oven before compaction. Figures 6b to 6c also show that neglecting the binder absorption resulted in an overestimate of the voids filled with asphalt content, as for the voids in mineral aggregate.

Table 4 shows the results from five three-way ANOVA analyses, which were performed to determine the effects of the RCA content, the bitumen content and the ageing time on the volumetric properties. The volumetric property (Va, VMA, VMAabs, VFA and VFAabs) was the dependent variable in each case. For the five ANOVA analyses, the three factors were the RCA content (0%, 5%, 10%, 20% and 30%), the bitumen content (3.5%, 4.0% and 4.5%) and the ageing time (0 hours, 2 hours and 4 hours). Both the volumetric properties and factors were quantitative variables.

The results of the ANOVA analysis showed that the RCA content, the bitumen content and the ageing time were statistically significant for a 95% confidence interval ($p<0.05$) for Va, VFA and VFAabs. That is, the statistical analysis confirmed the aforementioned result, i.e., the RCA content, the bitumen content and the ageing time significantly affected the air voids content and the voids filled with asphalt content. However, the bitumen content was not statistically significant for VMA (p=0.170) and VMAabs (p=0.253). This result was expected because, as mentioned above, no significant differences in the voids in mineral aggregate content were observed for different binder contents. The RCA content (p=0.218) also did not have a statistically significant effect on the VMAabs. This result was also expected, because increasing the RCA content caused the VMAabs to decrease slightly or remain constant, as previously stated.

4.2. Stiffness

There is no standard in the Spanish specifications for the resilient modulus of a mixture. PG-3 [18] only requires a resilient modulus higher than 11,000 MPa for high modulus bituminous mixtures. AC 22 base G is not a high modulus mixture; thus, the stiffness results were only used for comparison.

Figure 7 shows the resilient modulus (M_R) for the HMA containing RCA that was cured in the oven before compaction for 0 hours, 2 hours and 4 hours. Typical resilient modulus values at 20ºC for mixtures similar to that used in this study are approximately 5,000 MPa [33]. Therefore, the tested mixtures should attain this value at 20ºC. Figure 7a shows that at 20ºC, the resilient modulus of the mixtures that were in the oven for 0 hours was approximately 5,000 MPa. Thus, with 0 hours of curing time, the mixtures containing RCA performed similarly to a conventional HMA. However, different results were obtained for mixtures that were left in the oven for 2 hours and 4 hours. The HMA with 2 hours of ageing time (figure 7b) had a resilient modulus that ranged between 5,000 MPa and 10,000 MPa, which was higher than that of conventional mixtures. The mixtures that remained in the oven for 4 hours (figure 7c) exhibited higher stiffnesses, with resilient moduli that even reached 11,000 MPa, which is the minimum value required by the PG-3 for high modulus mixtures. Therefore, we can clearly see that increasing the ageing time increased the stiffness of the mixture. As the ageing time increased, the binder absorption also increased, which appeared to be the primary cause for the stiffening of the mixture. The aggregate was strengthened by introducing bitumen into its pores, resulting in stiffer mixtures. The loss of volatile bitumen compounds because of curing in the oven should be considered, because the resulting hardening affects the stiffness of the mixture.

Figures 7a, b and c shows that in the resilient modulus tests at 10ºC and 0ºC, the stiffness of the mixture increased with the ageing time. However, the lower the testing temperature, the less dramatic was the increase in the stiffness. Thus, analysing the results at 0ºC shows that for 0 hours of curing time (figure 7a), the resilient modulus ranged between 20,000 MPa and 25,000 MPa. The resilient modulus was slightly higher for 2 hours of curing time (figure 7b) but also ranged between 20,000 MPa and 25,000 MPa. The resilient modulus increased slightly for 4 hours of ageing time (figure 7c) and even exceeded 25,000 MPa in some cases but never reached 30,000 MPa. That is, ageing appeared to soften the effect of the temperature. This result was probably because of the loss of volatile bitumen compounds during the ageing in the oven. Increasing the ageing time in the oven would result in further loss of volatile compounds; therefore, the stiffening of the bitumen as the temperature decreases should be less significant.

Given the results in figure 7, we verified that the binder content (3.5%, 4.0% and 4.5%) did not affect the resilient modulus. At 0°C only, the resilient moduli obtained for 3.5% binder were generally inferior to those obtained with 4.5% binder. Similarly, the RCA content did not appear to affect the resilient modulus. The RCA contents used were low (i.e., between 0% and 30%); therefore, the RCA content did not have a remarkable effect on the mixture stiffness. The ageing time in the oven and the testing temperature were the predominant factors that affected the mixture stiffness.

Table 5 shows the results from a four-way ANOVA analyses that was conducted to determine the effects of the RCA content (0%, 5%, 10%, 20% and 30%), the bitumen content (3.5%, 4.0% and 4.5%), the test temperature (0ºC, 10ºC and 20ºC) and the ageing time (0 hours, 2 hours and 4 hours) on the resilient modulus. As expected, the ANOVA results confirmed that the test temperature ($p \leq 0.0001$) and the ageing time ($p \leq 0.0001$) significantly affected the resilient modulus, whereas the RCA content ($p=0.234>0.05$) and the bitumen content ($p=0.052>0.05$) did not have statistically significant effects. Thus, varying the test temperature or the ageing time will affect the HMA stiffness.

4.3. Resistance to permanent deformation

RLAT results are typically presented as the evolution of cumulative permanent axial strain versus the number of applied cycles. In this study, the obtained creep curves (figure 8) only exhibited two of the three stages that are usually observed: the primary and the secondary stages. The tertiary stage was not observed for any case. The flex point, which is usually used to identify the mixture failure [33], was also not observed. This result was probably obtained for two reasons: the applied axial stress was relatively small, and the number of applied cycles was too few to cause specimen failure [34]. For these reasons, two parameters were used to quantify the resistance to permanent deformation: the cumulative permanent axial strain at the end of the test and the average slope of the creep curve [35]. Note that various researchers [34] have shown that a linear relationship exists between the cumulative permanent axial strain and the number of load applications between 600 and 1,800 cycles. Figure 8 shows a linear relationship between these cycles in the present study; thus, the slope of the average creep curve was calculated between 600 and 1,800 cycles.

There are no specifications for these two parameters; therefore, the analysis was conducted to compare the resistance to permanent deformation among the tested mixtures.

Figure 9 shows the cumulative permanent axial strain at the 1,800th cycle versus the RCA content for mixtures that were cured in the oven for 0 hours, 2 hours and 4 hours with bitumen contents of 3.5% (figure 9a), 4.0% (figure 9b) and 4.5% (figure 9c). Figure 9 shows that the mixtures that were left in the oven for 4 hours and 2 hours generally showed higher cumulative permanent axial strains at the 1,800th cycle than that of the control mixture (0 hours). Nevertheless, in all of the cases studied, the final axial permanent strain was similar to that obtained by other authors for conventional mixtures. For example, Santagata et al. [33] obtained permanent axial strains at the 1,800th cycle between 0.4% and 1.1% for HMA manufactured with different bitumen contents. Aschury et al. [34] obtained permanent axial strain values of approximately 1.3% for conventional HMA. Except for some isolated cases, all of the specimens tested exhibited permanent strain values below 1.3% for the 1,800th cycle.

Figure 10 shows the average slope of the creep curve between 600 and 1,800 cycles versus the RCA percentage for HMA containing 3.5% binder (figure 10a), 4.0% binder (figure 10b) and 4.5% binder (figure 10c). The slope of the creep curve between 600 and 1,800 cycles can be used to estimate the strain rate of deformation after the densification that occurs at the primary stage. Thus, the higher the slope, the higher the strain rate and the lower the resistance to permanent deformation. The control mixture (0 hours of ageing) generally exhibited lower creep curve slopes than those obtained for the mixtures that were left in the oven for 2 and 4 hours. The HMA that was manufactured with 2 and 4 hours of ageing time exhibited the highest final deformations and the highest average creep slopes and thus, a lower resistance to permanent deformation: this result contradicted the result that these mixtures exhibited the highest stiffnesses. However, these results could be explained by the higher air voids content of these mixtures. Note that only the densification mechanism was active in the primary and secondary stages of the creep curve, whereas shear deformation was not operational in these stages. Thus, the RLAT results only showed that the HMA containing RCA for 2 hours and 4 hours of ageing time exhibited a greater initial densification and did not show an inadequate resistance to permanent deformation. Moreover, the cumulative permanent axial strain at the 1,800th cycle showed that these mixtures behaved similarly to conventional mixtures and thus had an adequate rutting performance.

The results in figures 9 and 10 also motivated us to verify that the binder content did not affect the resistance to permanent deformation. This result was probably obtained because of the contradictory effects of this parameter. Increasing the binder content usually leads to greater permanent deformation; however, a higher binder content also leads to greater absorption and thus, to the stiffening of the mixture. The RCA content also did not appear to affect the permanent deformation, probably because of the low RCA contents used in this study.

Table 6 shows the results from two three-way ANOVA analyses that were conducted to investigate the effects of the RCA content, the bitumen content and the ageing time on the resistance to permanent deformation. In each case, the dependent variable was the cumulative permanent axial strain at the 1,800th cycle and the average slope of the creep curve between 600 and 1,800 cycles. For the two ANOVA analyses, the three factors were the RCA content (0%, 5%, 10%, 20% and 30%), the bitumen content (3.5%, 4.0%

and 4.5%) and the ageing time (0 hours, 2 hours and 4 hours). The cumulative strain, the slope of the creep curve and factors were quantitative variables.

First, the ANOVA results confirmed the aforementioned results: the ageing time ($p=0.02<0.05$) significantly affected the cumulative permanent axial strain at the 1800^{th} cycle and thus, the resistance to permanent deformation, whereas the RCA content ($p=0.362>0.05$) and the bitumen content ($p=0.667>0.05$) did not have statistically significant effects.

Second, the ANOVA results re-confirmed that the ageing time ($p=0.030<0.05$) significantly affected the average slope of the creep curve and thus, the resistance to permanent deformation, whereas the RCA content ($p=1.0>0.05$) and the bitumen content ($p=1.0>0.05$) did not have statistically significant effects.

5. Conclusions

An AC 22 base G containing 0%, 5%, 10%, 20% and 30% of RCA with a 8/16 mm fraction was fabricated using the Marshall method with bitumen contents of 3.5%, 4.0% and 4.5%. The mixtures were left in the oven at the mixing temperature for 0 hours, 2 hours and 4 hours before compaction. The volumetric properties, stiffness and resistance to permanent deformation were evaluated in this laboratory study. The following conclusions were drawn from this study.

- The attached mortar on the RCA surface enabled these aggregates to absorb a large amount of bitumen during HMA manufacture. The laboratory results showed that the bitumen absorption increased with the RCA content and the ageing time. This result highlights both the absorptive character of RCA and that the ageing time promoted bitumen absorption onto the RCA pores.

- The attached mortar caused the RCA roughness. This roughness appeared to be the primary reason for why mixture compaction was more difficult. The air voids content increased with the RCA content for this reason.
- To ensure that the voids in mineral aggregate content and voids filled with asphalt content were not overestimated, the absorbed bitumen was accounted for in calculating the volumetric properties. Neglecting the bitumen absorbed onto the RCA pores could result in a HMA that does not comply with the volumetric properties requirements and thus, exhibits low durability.
- Ageing caused mixture stiffening. Thus, the HMA containing RCA that was left in the oven for 4 hours before compaction exhibited a resilient modulus similar to those required for high modulus mixtures in the Spanish specifications.
- HMA containing RCA for 2 hours or 4 hours of ageing time were stiffer at the ambient temperature (20ºC) than the control mixture (0 hours of ageing time) at the same temperature. However, no performance problems are anticipated for these mixtures at low temperatures (0ºC).
- HMA containing RCA exhibited an adequate resistance to permanent deformation, whether the mixtures remained in the oven for 0 hours, 2 hours or 4 hours. However, mixtures manufactured with ageing times of 2 hours and 4 hours exhibited higher initial densifications because of their higher air voids content.

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Figure 1
Details of impurities in the 8/16 mm RCA fraction used in this study

Figure 2
Gradation curve for AC 22 base G

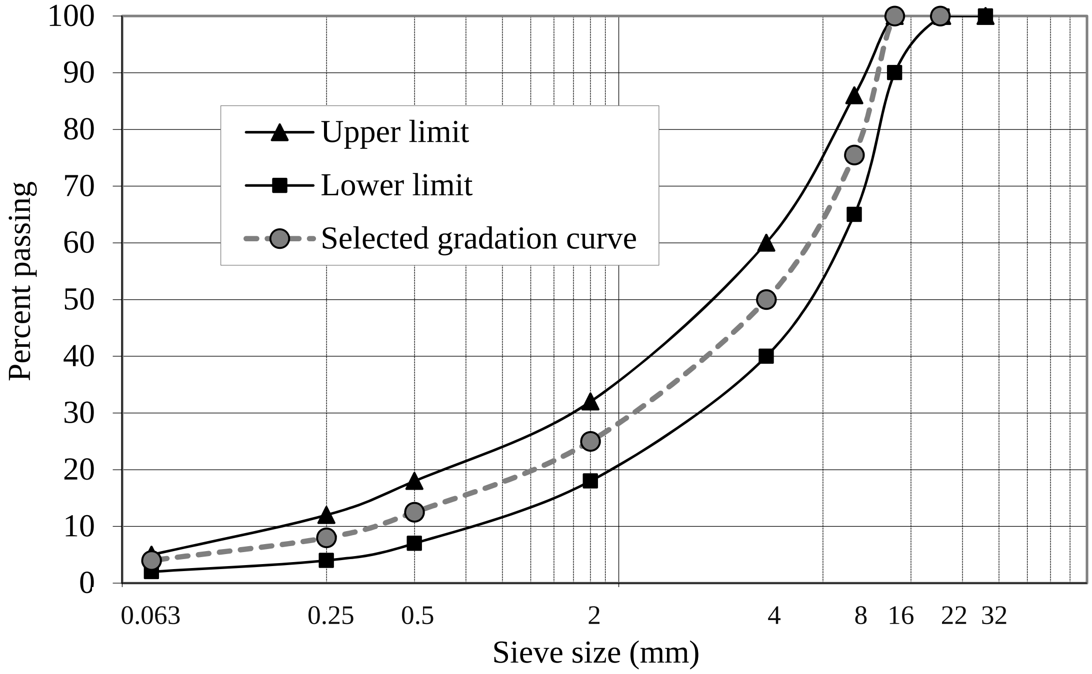


Figure 3
Resilient modulus jig test

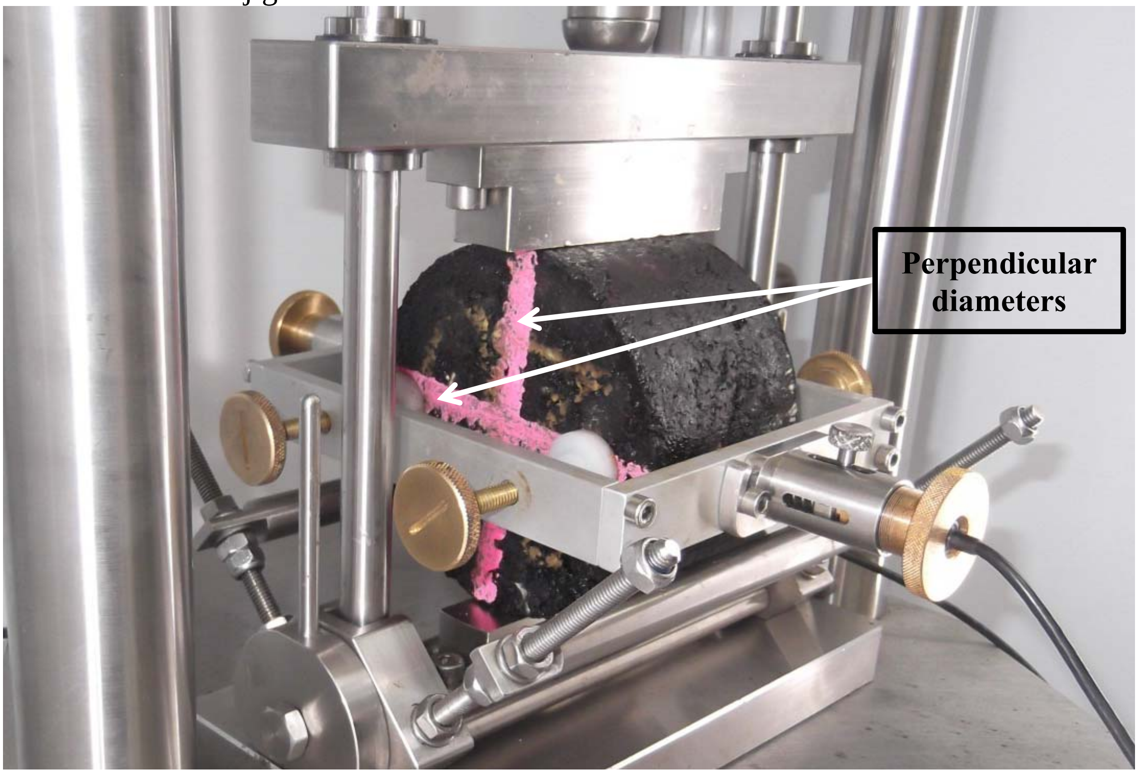


Figure 4
Permanent deformation jig test

Figure 5

Voids in mineral aggregate content and air voids content for HMA containing RCA: a) Va, VMA and VMAabs (3.5% binder), b) Va, VMA and VMAabs (4.0% binder) and c) Va, VMA and VMAabs (4.5% binder)

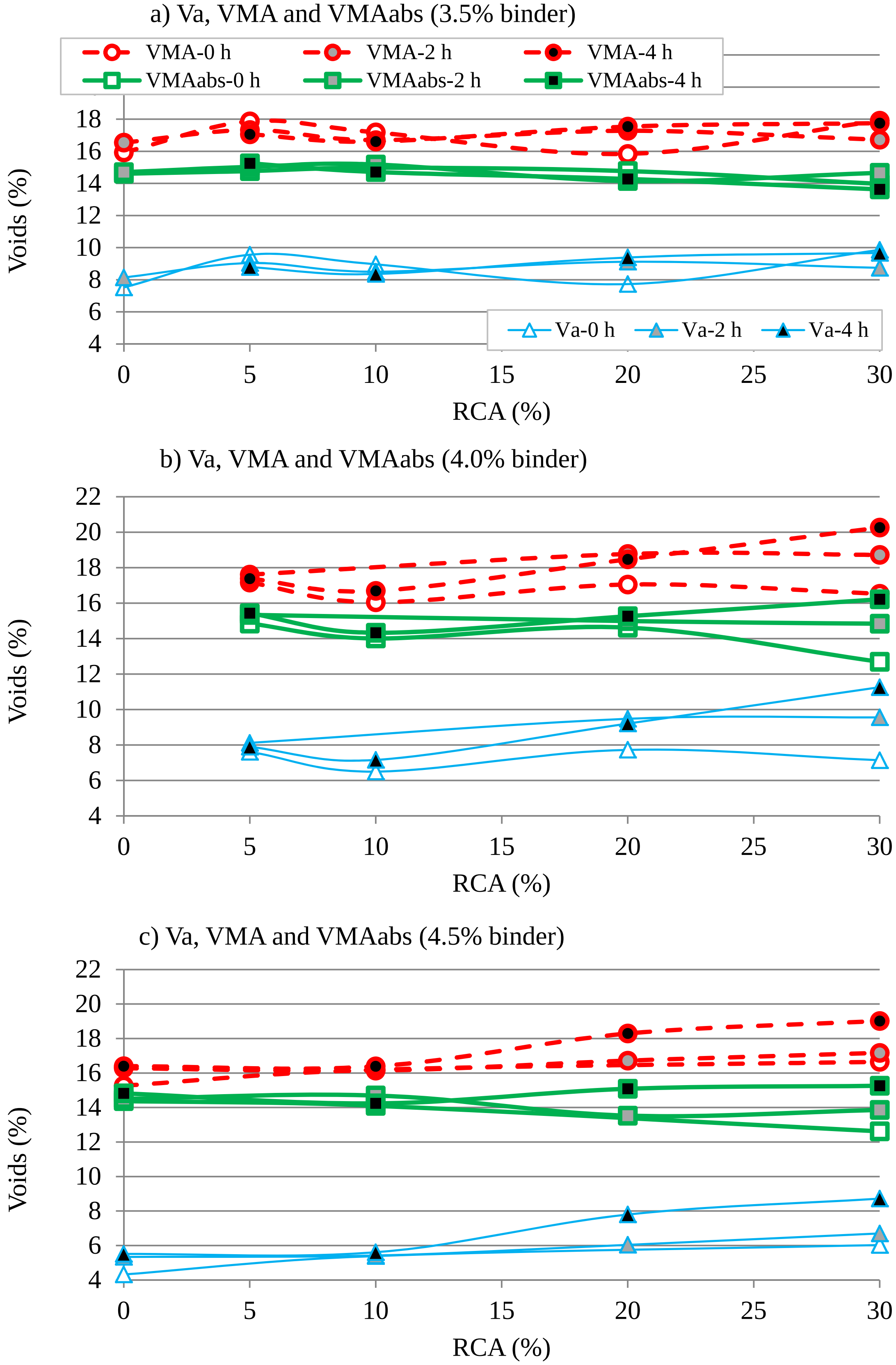


Figure 6
Voids filled with asphalt content of HMA containing RCA: a) VFA and VFAabs (3.5% binder), b) VFA and VFAabs (4.0% binder), c) VFA and VFAabs (4.5% binder)

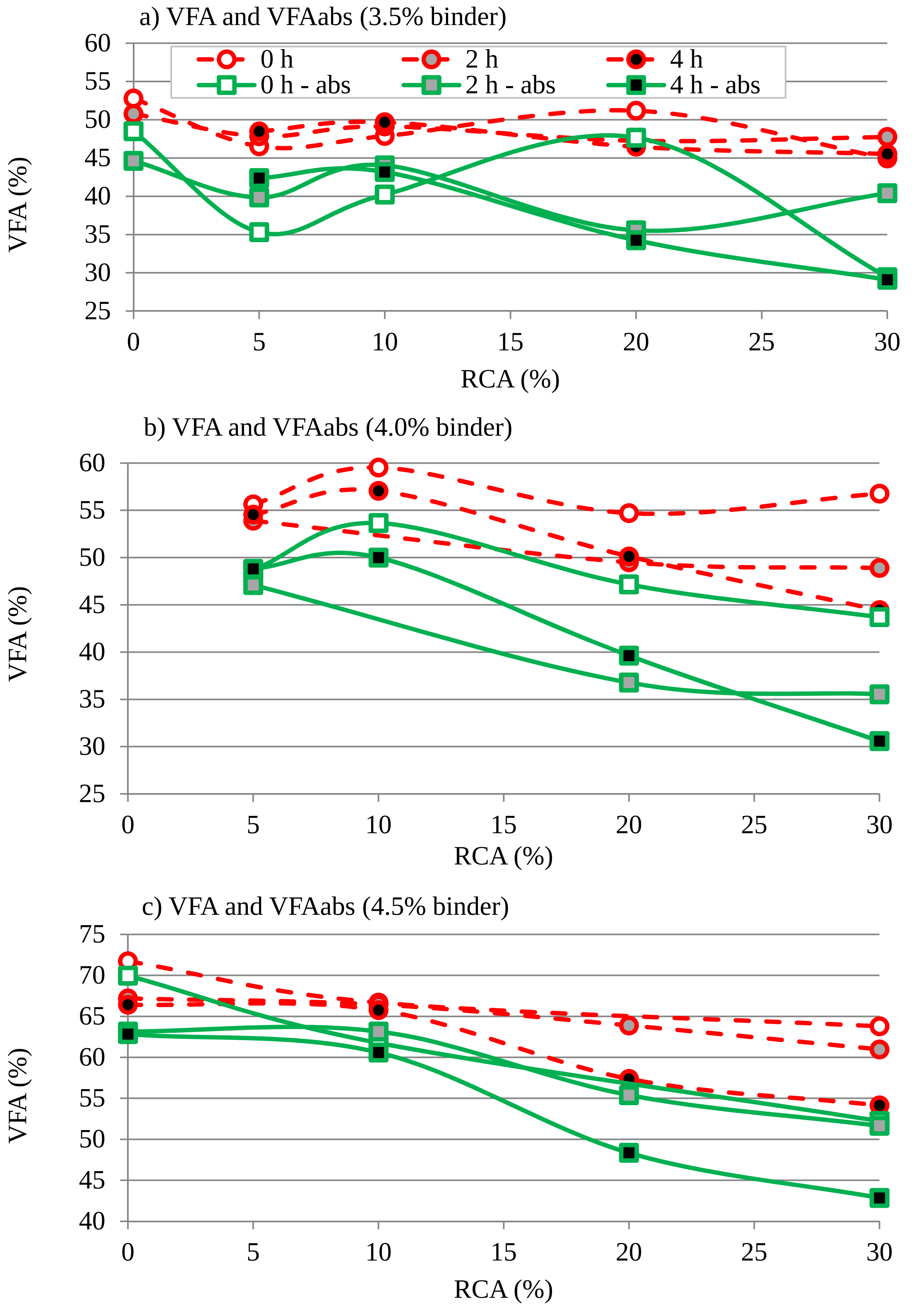


Figure 7
Resilient modulus versus RCA content for different ageing times: a) 0 hours, b) 2 hours and c) 4 hours

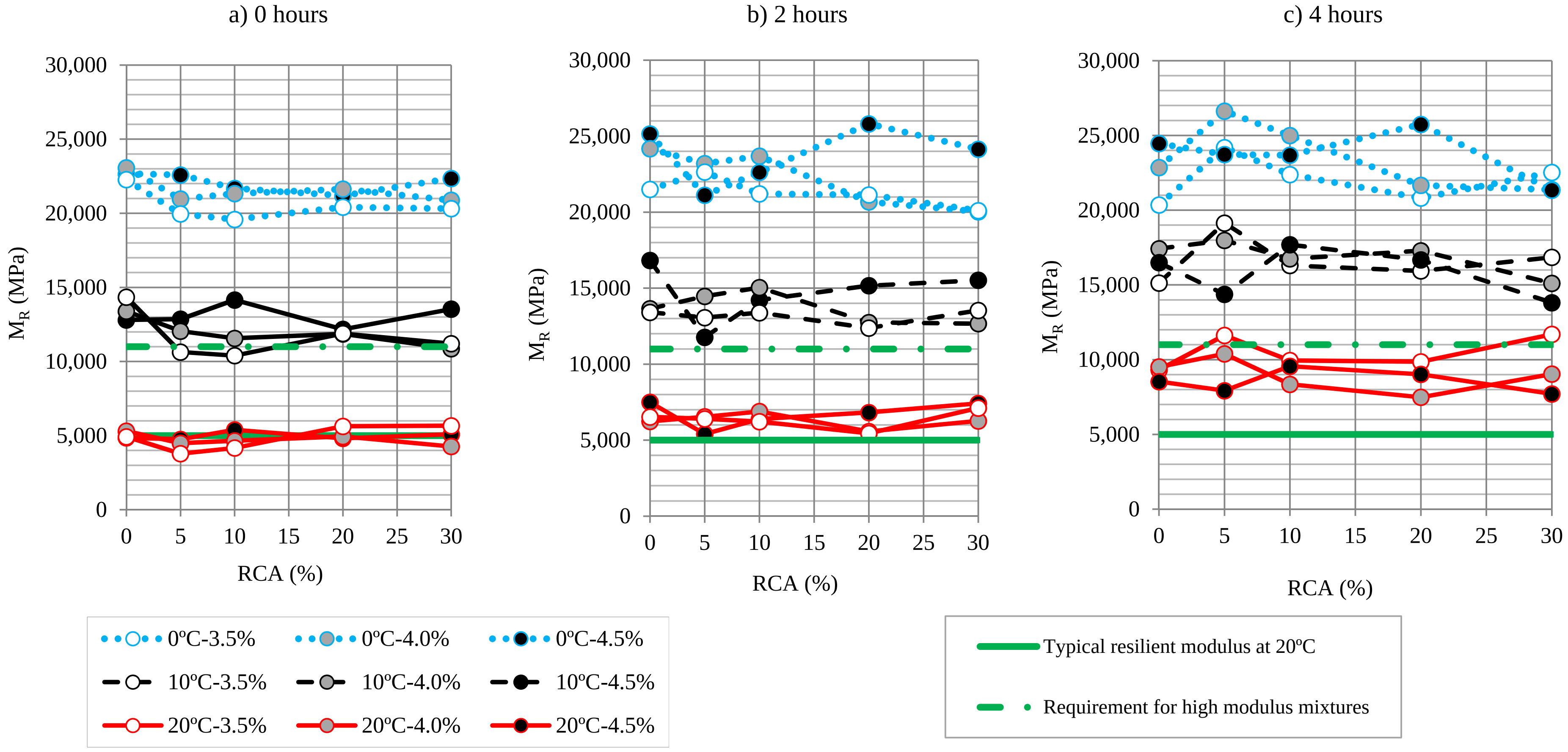
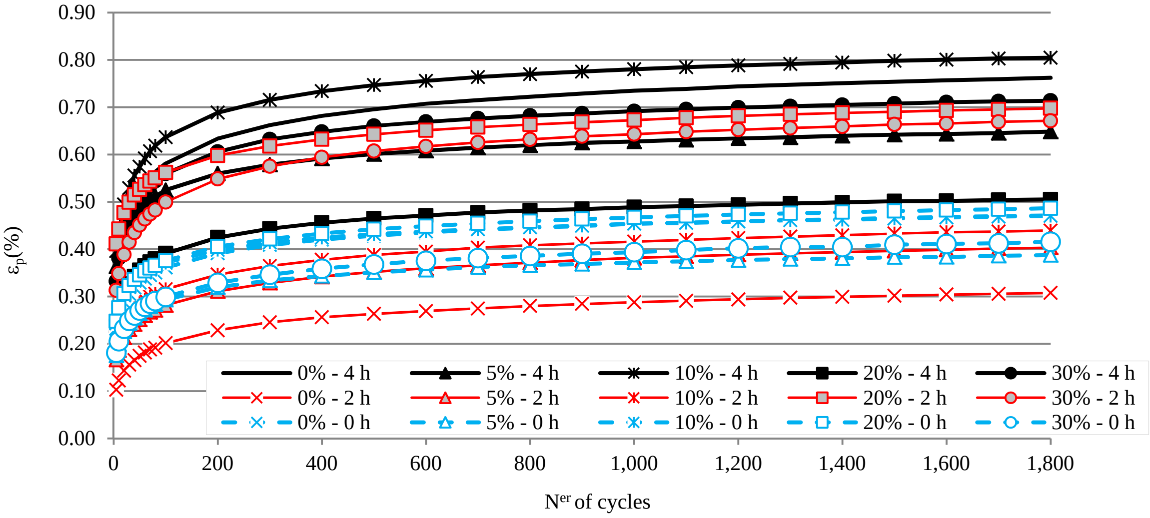
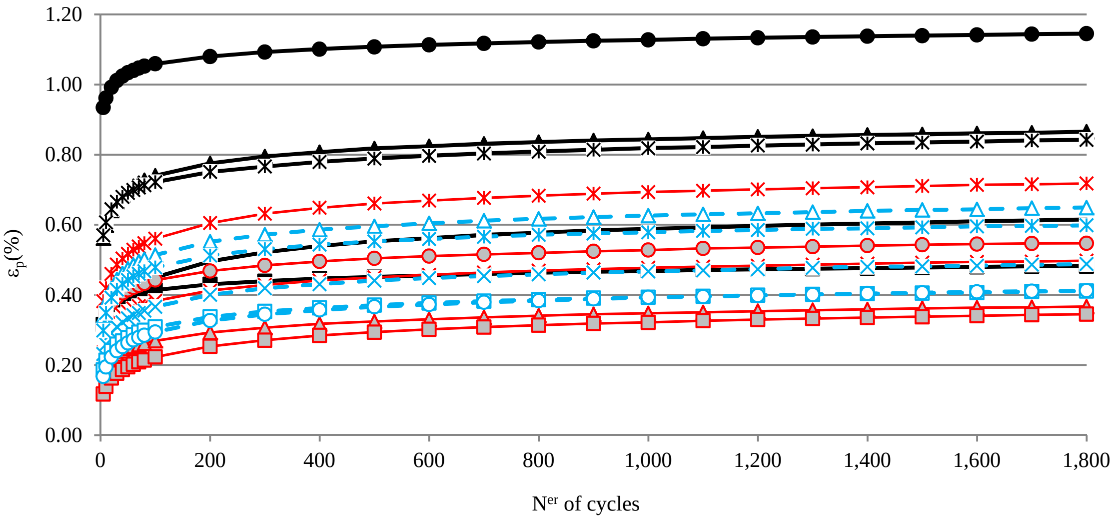


Figure 8
RLAT results: creep curves for mixtures containing RCA (0%, 5%, 10%, 20% and 30%), curing times of 4 hours (4 h), 2 hours (2 h) and 0 hours (0 h) and a) 3.5% bitumen, b) 4.0% bitumen and c) 4.5% bitumen

a) 3.5% bitumen



b) 4.0% bitumen



c) 4.5% bitumen

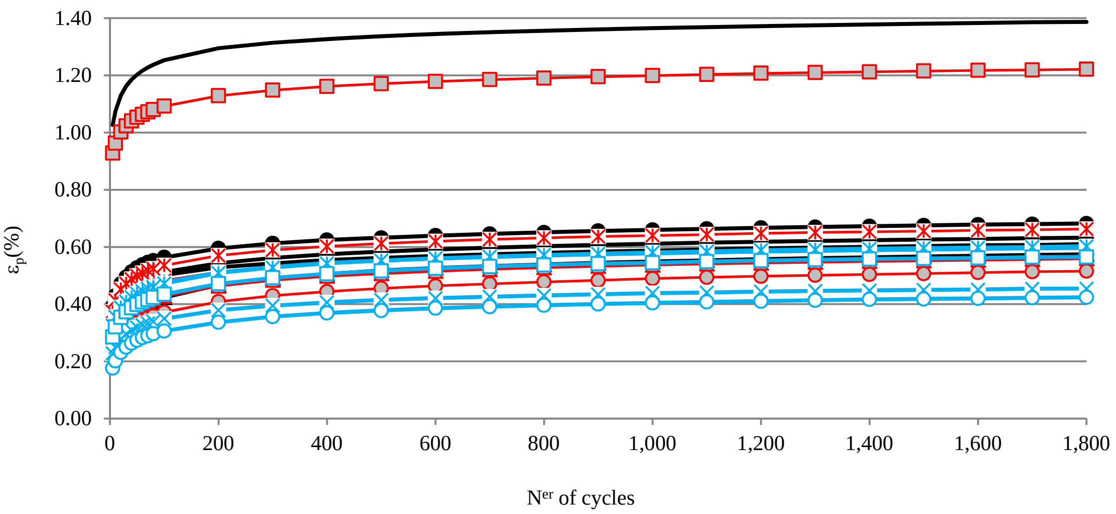


Figure 9
RLAT results: cumulative permanent axial strain at 1,800th cycle for mixtures made with a) 3.5% bitumen, b) 4.0% bitumen and c) 4.5% bitumen

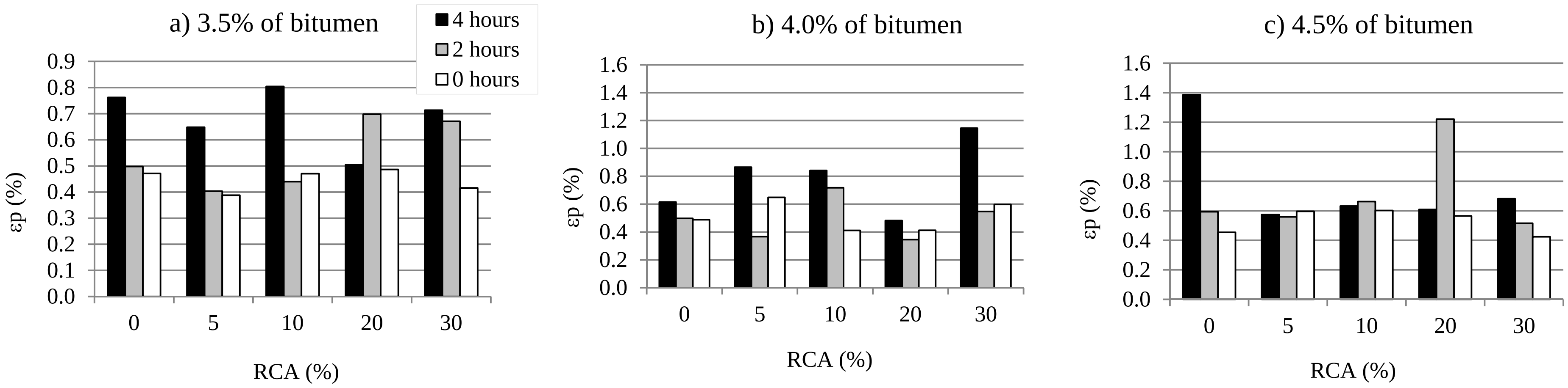


Figure 10
RLAT results: slope of creep curve between 600 and 1,800 cycles for mixetures with ageing times of a) 0 hours, b) 2 hours and c) 4 hours

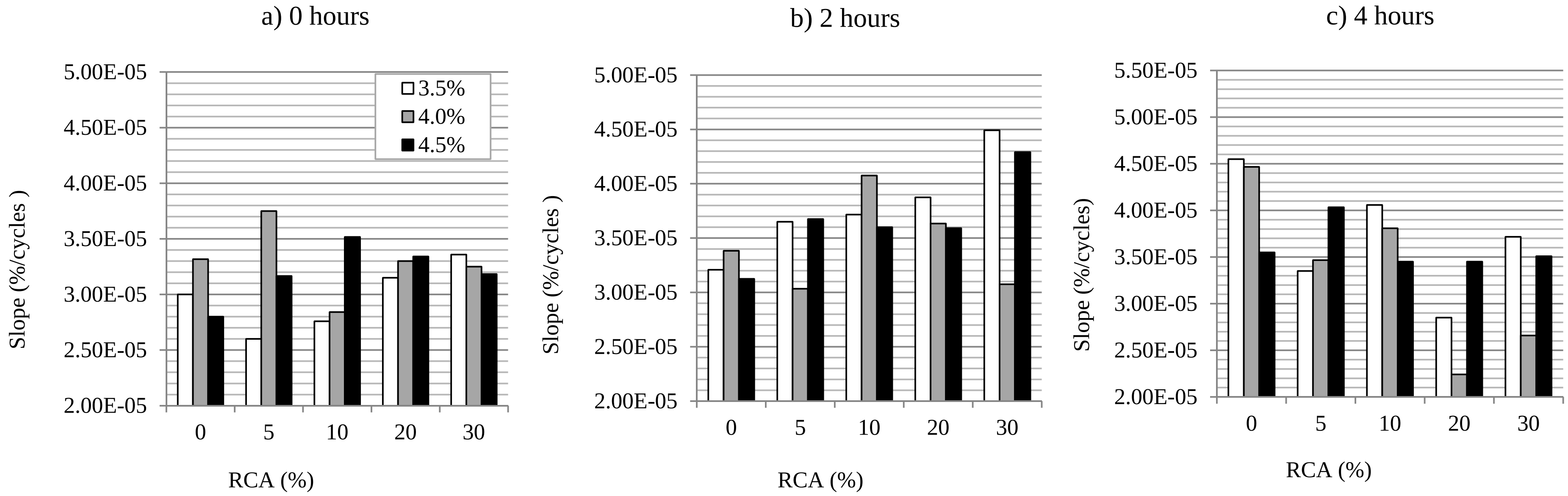


Table 1
Properties of RCA and hornfels

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)≥4,000;
Traffic category T0 refers to 4,000>AADHT ≥2,000;
Traffic category T1 refers to 2,000>AADHT ≥800;
Traffic category T2 refers to 800> AADHT ≥200;
Traffic category T3 refers to 200>AADHT ≥50 and
Traffic category T4 refers to AADHT<50

Table 2

Requirements for air voids content for AC 22 base G

	PG-3 Specifications (*)			
	T00-T0	T1-T2	T3	T4
Va (%)	5-8	6-9	5-9	-

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

Table 3

Bitumen absorption for a) Pba and b) Pbe

a) Pba

Curing time		4 hours			2 hours			0 hours		
Bitumen (%)		3.5	4.0	4.5	3.5	4.0	4.5	3.5	4.0	4.5
RCA (%)	0	0.818	0.794	0.766	0.871	0.632	0.820	0.646	0.600	0.462
	5	0.855	0.942	0.939	1.086	1.062	0.715	1.403	1.094	0.867
	10	0.899	1.107	1.017	0.751	1.436	0.689	1.021	0.984	1.006
	20	1.534	1.528	1.514	1.474	1.763	1.463	0.529	1.182	1.025
	30	1.912	1.951	1.806	1.018	1.825	1.549	1.830	1.797	1.883

b) Pbe

Curing time		4 hours			2 hours			0 hours		
Bitumen (%)		3.5	4.0	4.5	3.5	4.0	4.5	3.5	4.0	4.5
RCA (%)	0	2.711	3.238	3.768	2.659	3.393	3.717	2.877	3.424	4.059
	5	2.675	3.096	3.604	2.452	2.981	3.817	2.146	2.949	3.672
	10	2.633	2.937	3.529	2.776	2.622	3.842	2.514	3.056	3.540
	20	2.020	2.533	3.055	2.078	2.307	3.102	2.990	2.865	3.521
	30	1.655	2.127	2.776	2.517	2.248	3.021	1.734	2.275	2.702

Table 4
ANOVA results: effects of RCA content, bitumen content and ageing time on the volumetric properties for a) Va, b) VMA, c) VMAabs, d) VFA and e) VFAabs

a) Va

Source of Variation	SS (*)	DF (*)	MS (*)	F	p-value
MAIN EFFECTS					
A: RCA content	16.034	4	4.009	6.267	0.001
B: bitumen content	40.842	2	20.421	31.927	0.000
C: ageing time	6.260	2	3.130	4.894	0.015
RESIDUAL	17.270	27	0.640		
TOTAL	80.406				

b) VMA

Source of Variation	SS (*)	DF (*)	MS (*)	F	p-value
MAIN EFFECTS					
A: RCA content	10.345	4	2.586	4.269	0.006
B: bitumen content	2.113	2	1.057	1.891	0.170
C: ageing time	5.290	2	2.645	4.735	0.017
RESIDUAL	15.085	27	0.559		
TOTAL	32.833				

c) VMAabs

Source of Variation	SS (*)	DF (*)	MS (*)	F	p-value
MAIN EFFECTS					
A: RCA content	2.533	4	0.633	1.544	0.218
B: bitumen content	1.186	2	0.593	1.445	0.253
C: ageing time	3.221	2	1.611	3.926	0.032
RESIDUAL	11.077	27	0.410		
TOTAL	18.017				

d) VFA

Source of Variation	SS (*)	DF (*)	MS (*)	F	p-value
MAIN EFFECTS					
A: RCA content	227.683	4	56.921	8.641	0.000
B: bitumen content	1,352.586	2	676.293	102.662	0.000
C: ageing time	72.904	2	36.452	5.533	0.010
RESIDUAL	177.864	27	6.588		
TOTAL	1,831.037				

e) VFAabs

Source of Variation	SS (*)	DF (*)	MS (*)	F	p-value
MAIN EFFECTS					
A: RCA content	1,014.066	4	253.517	14.869	0.000
B: bitumen content	1,737.314	2	868.657	50.949	0.000
C: ageing time	115.214	2	57.607	3.379	0.049
RESIDUAL	460.336	27	17.049		
TOTAL	3,326.930				

(*) SS: sum of squares; DF: degrees of freedom and MS: mean square

Table 5
ANOVA results: effects of RCA content, bitumen content, test temperature and geing time on the resilient modulus

Source of Variation	SS	DF	MS	F	p-value
MAIN EFFECTS					
A: RCA content	1.047E+07	4	2.618E+06	1.413	0.234
B: bitumen content	1.152E+07	2	5.760E+06	3.033	0.052
C: test temperature	5.378E+09	2	2.689E+09	1,415.429	0.000
D: ageing time	2.744E+08	2	1.372E+08	72,209.000	0.000
RESIDUAL	2.356E+08	124	1.900E+06		
TOTAL	5.910E+09				

Table 6
ANOVA results showing effects of RCA content, bitumen content and ageing time on the resistance to permanent deformation: a) cumulative permanent axial strain at 1,800th cycle and b) average creep slope between cycles 600 and 1,800 cycles

a) Cumulative permanent axial strain at 1,800th cycle

Source of Variation	SS	DF	MS	F	p-value
MAIN EFFECTS					
A: RCA content	0.063	4	0.016	1.127	0.362
B: bitumen content	0.011	2	0.006	0.411	0.667
C: ageing time	0.224	2	0.112	8.008	0.002
RESIDUAL	0.433	31	0.014		
TOTAL	0.731				

b) Average creep slope between 600 and 1,800 cycles

Source of Variation	SS	DF	MS	F	p-value
MAIN EFFECTS					
A: RCA content	0.000	4	0.000	0.000	1.000
B: bitumen content	0.000	2	0.000	0.000	1.000
C: ageing time	1.907E-10	2	9.535E-11	3.881	0.030
RESIDUAL	8.846E-10	36	2.457E-11		
TOTAL	1.075E-9				