

# MECHANICAL PROPERTIES OF HOT-MIX ASPHALT MADE WITH RECYCLED CONCRETE AGGREGATES COATED WITH BITUMEN EMULSION

A.R. Pasandín <sup>a,\*</sup> and I. Pérez <sup>a</sup>

<sup>a</sup>Universidade da Coruña, E. T. S. I. Caminos, Canales y Puertos, Campus de Elviña s/n, 15071. A Coruña, Spain

\* Corresponding author. Tel.: +34-981167000. Fax: +34-981167170

E-mail addresses: [arodriguezpa@udc.es](mailto:arodriguezpa@udc.es) (A.R. Pasandín), [iperez@udc.es](mailto:iperez@udc.es) (I. Pérez)

## Abstract

The incorporation of recycled concrete aggregates (RCA) in hot-mix asphalt (HMA) could be a way to promote sustainable construction. To date, several investigations have examined the use of this type of waste material in HMA. Several researchers have observed that due to the action of water, the use of this material proved to have insufficient durability. In this investigation, a laboratory characterisation of HMA made with RCA from construction and demolition waste (CDW) for base layers in road pavements was conducted. Percentages of 5%, 10%, 20% and 30% of RCA in place of natural aggregates were analysed. To improve the water resistance of the mixes, the RCA were coated with 5% of bitumen emulsion prior to the mixing process. The results indicated that the mixes comply with the Spanish water resistance specifications required for base layers. The stiffness, permanent deformation and fatigue of the mixtures were also studied. The results indicated that HMA made with RCA coated with bitumen emulsion exhibited mechanical properties similar to those obtained for conventional mixtures.

*Keywords: hot-mix asphalt; recycled concrete aggregates; bitumen emulsion; water resistance; mechanical properties*

## 1. Introduction

Several investigations examining the use of recycled concrete aggregates (RCA) from construction and demolition waste (CDW) in hot-mix asphalt (HMA) have been conducted in recent years to pursue sustainable development. In these investigations, the mortar attached to the RCA surface caused the properties of RCA to be different from those of natural aggregates [1-6]. Thus, the performance of HMA made with RCA will be different from that of conventional HMA.

After a review of the technical literature, we observed that the results of the research were quite variable. Particularly, the water resistance of HMA made with RCA is a property about which there is a wide disparity of opinions: some authors affirm that HMA made with RCA present an adequate water resistance performance [7-10]; nevertheless, other authors see the need to limit the percentage of RCA [11] and / or treat the RCA prior to manufacturing HMA [12-14] to achieve a satisfactory water resistance of such mixtures. In this regard, Lee et al. [12] used a slag cement paste to coat the RCA, obtaining moisture damage results within the Taiwanese range of specification requirements. In addition, Zhu et al. [13] showed that RCA coated with a liquid silicone resin improved the water resistance of HMA made with RCA. Moreover, Pasandín and Pérez [14] found that leaving the mixture in the oven for four hours at a mixing temperature before compaction improves the water resistance of HMA made with RCA.

In addition to providing these conclusions regarding water resistance, the review of the technical literature allows us to confirm that other HMA properties are affected by the use of RCA in place of natural aggregates. In this way, some researchers have stated that HMA made with RCA are stiffer than conventional mixes [9, 14-15], while others suggest the opposite [11, 16]. The resistance to permanent deformation has also been studied. In this sense, most investigators stated that HMA made with RCA exhibit a permanent deformation performance similar to [14, 16] or better than [2, 7-8, 10] that of conventional mixes. On the contrary, other researchers indicate that despite meeting these specifications, the resistance to permanent deformation decreases as the percentage of RCA in the mix increases [11]. The fatigue life of HMA containing RCA is the mechanical property that has been least studied in the literature. The few studies conducted on this topic indicate that the fatigue life of HMA made with RCA is similar to [14, 15, 17] or better than [10] that obtained for conventional mixtures.

This paper presents a laboratory study on the water resistance and mechanical properties of HMA made with RCA from CDW for base layers on road pavements. The aim of the investigation is to design HMA with RCA that achieves an adequate water resistance performance and satisfactory mechanical properties. To achieve these objectives, RCA were coated with a bitumen emulsion prior to the mixing process. On the one hand, it is expected that

due to the action of bitumen emulsion, the RCA pores become obstructed, preventing the entry of water and therefore improving the mixture's resistance to moisture damage. Conversely, a better chemical affinity between the RCA coated with a bitumen emulsion and the bitumen is expected, thus preventing the mixture from suffering from stripping. The water resistance, stiffness, resistance to permanent deformation and fatigue life of the mixtures were analysed.

## **2. Materials and Methods**

### **2.1. Basic materials**

#### *2.1.1. Aggregates*

In this investigation, RCA and natural aggregates were used. The RCA were obtained from the waste generated during the demolition of residential buildings in Madrid (Spain). The EN-933-11 [18] was followed to determine the constituents of RCA. The results showed that concrete and petrous materials constituted 89.3% of the mass of the RCA. The remainder of the constituents were bituminous materials (6.5%), ceramics (3.6%) and impurities (0.6%) such as wood, rubber or gypsum. These impurities were manually removed before the manufacture of RCA to avoid dispersions in the results. A hornfels supplied by a local contractor was used as natural aggregate. The mineralogical compositions of the RCA and the natural aggregates were determined using X-ray fluorescence tests. The results indicated that both the RCA (61.46% SiO<sub>2</sub>) and the hornfels (62.30% SiO<sub>2</sub>) are siliceous aggregates. Consequently, both of them were expected to exhibit an inadequate resistance to water damage.

As seen in table 1 [14], the RCA and natural aggregate properties were evaluated according to the Spanish General Technical Specifications for Roads, also known as PG-3 [19]. The results indicate that, as expected, the RCA had a lower bulk specific gravity ( $\rho_a$ ) than the hornfels as well as higher water absorption ( $W_{24}$ ). The mortar attached to the RCA surface is mainly responsible for the RCA's behaviour. The sand equivalent (SE) of the RCA and the hornfels complied with the PG-3 for HMA as a base layer material. The Los Angeles (LA) abrasion coefficient was determined for recycled and natural aggregates. As seen in table 1, the RCA's LA only complied with the PG-3 for HMA as a base layer material in low-volume roads in heavy traffic category T4, while the LA of the natural aggregate complied with the PG-3 for

HMA as a base layer material in roads in heavy traffic category T00. As seen in figure 1, the LA abrasion coefficient of a mix of RCA and natural aggregate was also determined. The results showed that for RCA percentages up to 58.5%, the resulting LA (RCA + natural aggregate) complied with the PG-3 (LA<25%) for HMA as a base layer material in roads in heavy traffic category T00.

### *2.1.2. Binder, bitumen emulsion and filler*

A B50/70 penetration grade bitumen from Venezuela was chosen in this investigation. Its engineering properties are presented in table 2 [14]. To coat the RCA before the mixing process, a bitumen emulsion type ECL-2d was used. ECL-2d is a slow-setting cationic asphalt emulsion that has a bitumen content of 61.2%.

Grey Portland cement (CEM II/B-M (V-L) 32.5 N) was used as mineral filler. Its specific gravity was equal to 3.10 g/cm<sup>3</sup> and its Blaine surface area was equal to 3,134 cm<sup>2</sup>/g.

## **2.2. Testing program**

### *2.2.1. Specimen preparation*

The HMA aggregate gradation, corresponding to an AC 22 base G (figure 2) [14], was chosen according to the gradations limits given by the PG-3 [19].

The water resistance and mechanical properties were evaluated on Marshall specimens compacted with 75 blows per face according to NLT-159/86 [20]. Cylindrical asphalt specimens of 101.6 mm in diameter and 63.5 mm in height were manufactured with the bitumen content of 3.5%, 4.0% and 4.5% of the total weight of the mixture.

Percentages of 5%, 10%, 20% and 30% of RCA in place of hornfels were used. Following previous research [6, 17] and with the aim of producing environmentally friendly materials, a maximum replacement ratio of 30% of RCA was chosen, because the high absorptive nature of RCA [14] can lead to excessive bitumen consumption. As a consequence of the higher mortar content of the RCA fine fraction, which negatively affects the properties of RCA [4], the replacement of RCA was made in the coarse fraction. In addition, in the coarse fraction, it is easier to remove the impurities by hand. The 8/16 mm coarse fraction (replacement of 5%,

10%, 20% and 30%) and the 4/8 mm coarse fraction (replacement of 30%) were chosen. Due to the heterogeneity of the RCA, it was not considered appropriate to include RCA in coarser fractions. As previously mentioned, RCA was coated with a bitumen emulsion to improve the water resistance of the HMA. A 5% of ECL-2d in total weight of the mass of the RCA was used, because it is the bitumen emulsion percentage that reached the best bond results in the affinity test conducted prior to the performance of this research [21]. As shown in table 3, as a consequence of the bitumen emulsion coating, the bitumen content of the HMA increases.

### 2.2.2. Water resistance

To evaluate the stripping potential of HMA made with RCA, the UNE-EN 12697-12 [22] was followed. In this test, the loss of indirect tensile strength, expressed in terms of the tensile strength ratio (TSR), was determined. A set of 10 cylindrical Marshall samples is subdivided into two subsets with 5 specimens in each subset. The “dry” subset was kept at room temperature, while the “wet” subset was saturated and was held in a water bath for 3 days at 40°C. After that time, the specimens of each subset were left a minimum of 2 hours at 15°C: the “dry” subset in air and the “wet” subset in water. The tensile strength of the two subsets was then determined.

Four RCA percentages (5%, 10%, 20% and 30%) were evaluated. The samples were produced at bitumen contents of 3.5%, 4.0% and 4.5% for each RCA percentage. As previously mentioned, the RCA were coated with a 5% of bitumen emulsion. Emulsion breaking occurs prior to the HMA mixing process. Cylindrical specimens were compacted with 50 blows on each side. The stripping potential of the mixture was evaluated as follows:

$$TSR = \frac{ITS_w}{ITS_D} \times 100 \quad (1)$$

where TSR = the tensile strength ratio (%),  $ITS_w$  = the average tensile strength of the “wet” subset (MPa) and  $ITS_D$  = the average tensile strength of “dry” subset (MPa).  $TSR \geq 80\%$  is required by PG-3 specifications [19] for HMA to be used in base layers.

### 2.2.3. Stiffness

To analyse the influence of the use of RCA coated with bitumen emulsion on HMA stiffness, the UNE-EN 12697-26 Annex C [23] was followed. To determine the resilient modulus of the HMA, the indirect tensile stiffness modulus test (ITSM) using a Cooper NU 14 tester was conducted. In this test, after ten conditioning haversine pulses, five haversine test pulses were applied along the vertical diameter of a cylindrical Marshall specimen. The haversine wave had a rise time of  $124 \pm 4$  ms and a repetition period of  $3 \pm 0.1$  seconds. The maximum applied load was selected to produce a maximum horizontal strain of 0.005% of the sample diameter. The test procedure was repeated in a perpendicular diameter. The average stiffness of the five test pulses from the two tested diameters was recorded as the stiffness modulus of the HMA specimen.

Marshall samples compacted at 75 blows on each side at bitumen contents of 3.5%, 4.0% and 4.5% for each RCA percentage (5%, 10%, 20% and 30%) were tested. The resilient modulus for each specimen was obtained in a climatic chamber at temperatures of 0°C, 10°C and 20°C, as follows:

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

where  $M_R$  = the resilient modulus (MPa),  $F$  = the maximum repeated load (N),  $z$  = the horizontal recoverable deformation (mm),  $h$  = the thickness of the specimen (mm) and  $v$  = Poisson's ratio (an assumed Poisson's ratio of 0.35 for all of the test temperatures [23] was used).

Spanish specifications [19] have no requirements for a conventional mixture in terms of its resilient modulus.

#### *2.2.4. Resistance to permanent deformation*

To evaluate the resistance to permanent deformation of HMA made with RCA coated with a bitumen emulsion, a repeated load axial test (RLAT) without confinement was conducted, following DD 226:1996 [24]. In this test, the same Marshall specimens used in the indirect tensile stiffness modulus test were used. Each specimen was held at a test temperature of 30°C in a climate chamber overnight and then was placed between two load platens. First, the Cooper NU 14 tester machine preloaded each specimen with a conditioning load equivalent to 10kPa of

axial stress for  $600 \pm 6$  s. Afterward, each sample was subjected to 1,800 load cycles. Axial square repeated load pulses with a pulse width of 1 s and a rest period of 1 s were applied. Stress level of  $100 \pm 2$  kPa was selected according to the standard test procedure. To calculate the axial permanent strain, the following equation was used:

$$\varepsilon_{d(n,T)} = \frac{\Delta h}{h_0} \times 100 \quad (3)$$

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

### 2.2.5. Fatigue life

The fatigue life of RCA coated with a bitumen emulsion was evaluated using the repeated indirect tensile fatigue test (ITFT), following UNE-EN 12697-24 Annex E [25], using a Cooper NU 14 tester. In this controlled-stress fatigue test, cylindrical samples are subjected to repeated haversine loads along a vertical diameter. Marshall specimens at the bitumen content of 3.5%, 4.0% and 4.5% were compacted at 75 blows per side. For every RCA content (5%, 10%, 20% and 30%), a minimum of three specimens were tested at each of three constant stress levels (150 kPa, 200kPa and 250 kPa were chosen). The tests were conducted at a reference temperature of 20°C in a climate chamber. To obtain regression equations for fatigue life, the Whöler equation was used:

$$\varepsilon_0 = k \cdot Nf^{-n} \quad (4)$$

where  $Nf$  = the number of load cycles to fatigue failure, k and n = material constants obtained from the ITFT and  $\varepsilon_0$  = the initial tensile horizontal strain at the centre of the specimen in  $\mu\epsilon$ . During ITFT, a combination of permanent deformation and fatigue mechanisms occur [26]. In this regard, two failure criteria were used to determine the fatigue resistance: the total number of load cycles to complete the splitting of the specimen along the vertical plane or the total number of cycles to the 10% vertical deformation of the specimen along the vertical plane, whichever came first.

### 3. Test results and Discussion

#### 3.1. Water resistance

Table 4 shows the results of the indirect tensile strength in a dry (ITS<sub>d</sub>) and wet state (ITS<sub>w</sub>) versus the RCA percentage for samples made with 3.5%, 4.0% and 4.5% of binder content. In figure 3, the tensile strength ratio (TSR) versus the RCA content for samples made with 3.5%, 4.0% and 4.5% of binder content are plotted. As was expected, table 4 shows that the ITS<sub>w</sub> is lower than the ITS<sub>d</sub>, which indicates that water affects the HMA resistance. Nevertheless, as can be observed in figure 3, in general, TSR values are over 80%, which is the minimum value required by the PG-3 for base layers of road pavements. There is only one exception: the samples with 20% of RCA and 3.5% of bitumen content did not comply with this requirement. This exception could be explained by the usual dispersions of this test. Thus, as can be observed, coating the RCA with a 5% of bitumen emulsion leads to mixtures with a satisfactory moisture damage resistance in accordance with the specifications of the Spanish government. It must be noted that the bitumen content seems to have no influence on the water resistance. This surprising result could be explained by the reduced bitumen content range tested (between 3.5% and 4.5%).

As said before, the properties of the RCA differ from the properties of natural aggregate mainly due to the mortar attached to the RCA surface. The attached mortar is more porous than a natural aggregate and thus, as seen in section 2.1.1., the water absorption of RCA is greater than the water absorption of the natural aggregates. The attached mortar also leads to aggregates with a worse fragmentation resistance, as seen in section 2.1.1., due to the weak contact between the original aggregate and the mortar [5]. In addition to the siliceous nature of RCA, these two properties are mainly responsible for the bad expected water resistance of RCA. However, figure 3 and table 4 show that there is not a relationship between the RCA percentage and the TSR values or the ITS values. Thus, this result demonstrates that the treatment of coating the RCA with a bitumen emulsion improves the RCA properties and makes their performance similar to that of the natural aggregates. Indeed, the coating treatment obstructs the mortar



pores, preventing water pathways and also strengthens the mortar, preventing further fragmentation that could lead to creating new pathways for water.

A two-way and a three-way analysis of variance (ANOVA) were conducted. The first ANOVA was carried out to determine the effect of the RCA percentage (5%, 10%, 20% and 30%) and the bitumen content (3.5%, 4.0% and 4.5%) on the TSR. The second ANOVA was conducted to determine the effect of the RCA percentage (5%, 10%, 20% and 30%), the bitumen content (3.5%, 4.0% and 4.5%) and the state (wet or dry) on the ITS. This model confirms the aforementioned results. In this regard, the first ANOVA indicates that the RCA percentage is not statistically significant at the 95% confidence level ( $p=0.953>0.05$ ). In addition, the bitumen content ( $p=0.194>0.05$ ) does not have a statistically significant influence on the TSR. The second ANOVA results also confirm that the bitumen content ( $p=0.051>0.05$ ) and the RCA percentage ( $p=0.517>0.05$ ) are not statistically significant, thus, as was expected, they will not affect the indirect tensile strength of the mixture. Nevertheless, the state is statistically significant ( $p=0.001<0.05$ ), thus, as was expected, ITS is influenced by the state (wet or dry) of the samples.

### **3.2. Volumetric properties**

It is also important to analyse the compliance of volumetric properties of such mixtures with the PG-3, that is, air voids ( $V_a$ ) and voids in the mineral aggregate (VMA). As seen in table 5, most of the mixtures reach compliance with PG-3 as a base layer material in roads in heavy traffic categories T00 to T4. However, there are some exceptions: mixtures with 20% of RCA and 4.0% of bitumen content and mixtures with 30% of RCA and 4.5% of bitumen content have an air void content too low to reach compliance with PG-3 in heavy traffic category T1. In addition, mixtures with 5% of RCA and 4.5% of bitumen content and 10% of RCA and 4.0% and 4.5% of bitumen content only reach compliance with PG-3 in the lower heavy traffic category T4 due to a low air void content. In addition, mixtures with 30% of RCA and 3.5% of bitumen content are only apt for base layers of pavement in heavy traffic category T4 due to excessive air void content. As can be observed, HMA made with RCA coated with a bitumen emulsion has, in general, adequate volumetric properties to reach compliance with the highest

heavy traffic categories. Nevertheless, we must take into account that too low or too high bitumen contents could lead to mixtures that are only apt for a base layer in pavements in the lower heavy traffic category. Thus, the bitumen content must be carefully selected.

Two two-way ANOVA have been conducted to analyse the effect of the RCA percentage and the bitumen content on the volumetric properties  $V_a$  and  $V_{MA}$ . The first ANOVA results indicate that the RCA percentage ( $p=0.088>0.05$ ) is not statistically significant in the air void content, but the bitumen content ( $p=0.045<0.05$ ) is statistically significant. These results confirm the aforementioned conclusion: the bitumen content must be adequate to reach compliance with PG-3 air void requirements. The second ANOVA results confirm that the RCA percentage ( $p=0.295>0.05$ ) and the bitumen content ( $p=0.692>0.05$ ) are not statistically significant in  $V_{MA}$ .

### **3.3. Stiffness**

As mentioned before, Spanish specifications have no requirements for the acceptance of a conventional mixture in terms of its resilient modulus ( $M_R$ ), so this modulus is only useful to compare the performance of the different mixtures tested in this laboratory research. For this reason, a control mixture (RCA without treatment) has also been tested. Table 6 shows the results obtained for HMA produced with 3.5%, 4.0% and 4.5% of bitumen content and with 0% to 30% of RCA percentage.

The HMA type AC 22 base G used in Spain has a typical mean resilient modulus of 5,000 MPa at 20°C [27]. Table 6 shows that the resilient modulus values of HMA made with RCA coated with a bitumen emulsion were slightly higher than 5,000 MPa or approximately this value at 20°C, which indicates that the studied mixtures will behave similarly to conventional mixtures.

In table 6, we can also appreciate that the tested mixtures are slightly stiffer than the control mixture. As seen in table 6, this conclusion is extended to 10°C and 0°C. Thus, it can be concluded that coating the RCA with a bitumen emulsion slightly stiffens the mixture.

Table 6 also shows that, as was expected, the resilient modulus of HMA made with RCA is dependent on the test temperature: the mixtures were stiffer at lower temperatures. In Spain, a winter resilient modulus 1.5 times higher than the mean value at 20°C is often adopted [27]. The

resilient modulus of HMA with RCA coated with a bitumen emulsion at 0°C is 3.7 to 4.7 times higher than that at 20°C, while at 10°C, the resilient modulus is 2.1 to 2.6 times higher.

Nevertheless, the control mixture displays the resilient modulus at 0°C 3.6 to 5.3 times higher than that at 20°C, while at 10°C, the resilient modulus is 2.0 to 2.9 times higher than that at 20°C. Therefore, the resilient modulus of HMA made with RCA exhibits much more dependence on in-service temperatures than typical conventional mixtures do. Nevertheless, coating RCA with a bitumen emulsion reduces the range of variation between the resilient modulus at 20°C and the resilient modulus at 0°C and 10°C, making the performance of the mixtures more homogeneous.

Moreover, there is no clear pattern between RCA content and the resilient modulus of mixtures without treatment (control mixture), possibly due to the heterogeneity of the RCA used.

However, the resilient modulus of mixtures made with RCA coated with a bitumen emulsion seems to slightly decrease as the RCA percentage grows. Again, coating the RCA with a bitumen emulsion demonstrates that it makes the mixture performance more homogeneous.

A four-way ANOVA was conducted to determine the effect of the RCA percentage (0%, 5%, 10%, 20% and 30%), test temperature (0°C, 10°C and 20°C), bitumen content (3.5%, 4.0% and 4.5%) and the presence or absence of a coating treatment on HMA made with RCA stiffness ( $M_R$ ). As expected, in view of the test results obtained, the ANOVA confirms that the temperature ( $p=0.000<0.05$ ) and the RCA percentage ( $p = 0.007<0.05$ ) are significant. ANOVA analysis also indicates that the use of the coating treatment is significant ( $p=0.026<0.05$ ), while the bitumen content is not significant ( $p=0.563$ ). On the basis of the ANOVA, we can deduce that the dominant factor in specimen stiffness is test temperature, but a variation in the RCA percentage will also affect the stiffness of the mixture. In addition, ANOVA confirms that coating the RCA with a bitumen emulsion leads to HMA with higher stiffness. The short bitumen content range analysed seems not to influence the stiffness results.

#### **3.4. Resistance to permanent deformation**

The permanent deformation results are related to the rutting potential of the mixtures. There are no requirements for the acceptance of conventional mixtures in terms of RLAT results, so this

test is only useful to compare the performance of the different mixtures analysed in this laboratory research. For this reason, a control mixture (RCA without treatment) has also been tested. Figure 4 shows the accumulated permanent deformation values versus the number of loading cycles for HMA made with RCA coated with a bitumen emulsion and for HMA made with RCA without treatment (control mixture). It is well known that HMA permanent deformation occurs mainly due to densification (a decrease in the air void content causing a volume change) and plastic flow (aggregates and binder being gradually moved without a volume change) [28]. As seen in figure 4, the permanent deformation of HMA made with RCA occurs mainly due to densification. Plastic flow did not occur, so the specimens did not fail during the tests.

Figure 4 also shows that a linear relationship exists between the axial permanent strain and the number of load cycles between cycles 600 and 1,800 [29]. The slope of the line reflects the trend of the axial permanent deformation such that larger slopes indicate less resistance to permanent deformation [29]. As table 7 shows, the slopes of the lines between cycles 600 and 1,800 are very similar and do not show any trend between the creep curve slope and the RCA percentage or the bitumen content. It is expected that higher bitumen contents produce mixtures with greater susceptibility to plastic deformation [7]. As said before, in the case of the mixtures made with RCA, this trend does not exist, possibly due to the great bitumen absorption into the RCA pores that takes place.

As was expected, figure 4 also shows that the permanent deformation increases with the number of loading cycles for all the tested mixtures. It must be noted that at the beginning of the load cycling, the mixtures exhibit rapid densification. However, as stated above, the slopes between cycles 600 and 1,800 are very similar for all the tested percentages of RCA, and the different amounts of this rapid initial densification in the different mixes are mainly responsible for the differences in the accumulated permanent deformation at cycle 1,800. As seen in figure 4, there is no clear pattern between the final accumulated permanent deformation at cycle 1,800 and the RCA percentage. It could be explained by the heterogeneity of the RCA used in this investigation. Nevertheless, for all of the RCA percentages tested, the HMA mixtures exhibited

ultimate permanent deformation levels lower than those that conventional mixtures exhibit. For example, Santagata et al. [30] obtained values of the final strain between 0.4% and 1.1% at 1,800 load cycles for HMA made with various binders, while Aschuri et al. [31] obtained values of approximately 1.3% for conventional mixtures. As figure 4 shows, all of the studied mixtures had final axial permanent strain values lower than 1.1% at 1,800 cycles except for the mixtures made with 5% and 10% of RCA coated with a bitumen emulsion. These two exceptions are clearly due to the dispersion of the RLAT test. Thus, the control mixture and the mixtures with RCA that have been coated with a bitumen emulsion will perform well against rutting.

One three-way ANOVA was conducted to determine the effect of the RCA percentage (0%, 5%, 10%, 20% and 30%), the bitumen content (3.5%, 4.0% and 4.5%) and the use of treatment or not on the creep curve slope between cycles 600 and 1,800. As was expected, the ANOVA results show that the RCA percentage ( $p=1.000>0.05$ ), the bitumen content ( $p=1.000>0.05$ ) and the use of treatment or not ( $p=1.000>0.05$ ) do not have a significant effect on permanent deformation.

Another three-way ANOVA was conducted to determine the effect of the RCA percentage (0%, 5%, 10%, 20% and 30%), the bitumen content (3.5%, 4.0% and 4.5%) and the use of treatment or not on the cumulative permanent deformation at cycle 1,800. The ANOVA results show that the RCA percentage ( $p=0.209>0.05$ ), the bitumen content ( $p=0.228>0.05$ ) and the use of treatment or not ( $p=0.091>0.05$ ) do not have a significant effect on permanent deformation.

Again, the statistical analysis confirms the observed results.

### **3.5. Fatigue life**

Controlled-stress tests are adequate to evaluate the fatigue life of thick asphalt pavement layers with high stiffness [32]. Thus, the slightly high stiffness of HMA made with RCA coated with a bitumen emulsion justifies the use of ITFT. As seen in figure 5, the indirect tensile fatigue test ends when a sample is fractured by a diametral plane and split into two parts (figure 5a) or when the vertical deformation is more than 10% of the specimen diameter (figure 5b). Most samples

were split into two parts (figure 5a), therefore, we can conclude that fatigue mechanisms were predominant in the failure of all the HMA samples tested.

Figure 6 shows the initial horizontal strain versus the number of cycles to failure at 20°C on a logarithmic scale for the mixtures made with 4% of bitumen content. The same figure shows the fatigue equation of the control mixture (0% of RCA and the optimum Marshall bitumen content) for comparison with the fatigue equations obtained for the mixes tested in this investigation. As seen in figure 6, the mixtures made with RCA perform similarly to each other in fatigue. Again, this result can be explained by the use of bitumen emulsion: coating the RCA with a bitumen emulsion makes the performance of the mixture more homogeneous.

In general, it can be said that HMA made with RCA coated with a bitumen emulsion exhibit a similar fatigue life to the control mixture. Moreover, in figure 6, we can see that the RCA percentage does not affect the results. Again, it demonstrates that coating the RCA with a bitumen emulsion prior to the mixing process make the performance of HMA more homogeneous.

#### **4. Conclusions**

HMA made with 5%, 10%, 20% and 30% RCA in the 4/8 mm and/or 8/16 mm coarse fractions of the aggregate gradation have been studied. To improve their water resistance, the RCA were coated with a 5% of bitumen emulsion prior to the mixing process. The following conclusions are drawn from this laboratory characterisation:

- There are three major reasons why the HMA made with RCA display poor water resistance. The first reason is the siliceous nature of the RCA used in this investigation, which reduces the recycled aggregate's chemical affinity with the binder. The second reason is the porous nature of the mortar attached to the RCA surface, which provides the recycled aggregates high water absorption. The third reason is the high LA abrasion coefficient of RCA, which is a weakness of HMA and could lead to the creation of fissures through which water could penetrate the mixture.
- Coating the RCA with a 5% of bitumen emulsion and waiting for the breaking of the bitumen emulsion prior to the HMA mixing process improves the water resistance of

the mixtures made with RCA. In this way, due to the action of the bitumen emulsion, the RCA pores become obstructed, preventing the entry of water and, therefore, improving the resistance of the mixture to moisture damage. Moreover, the bitumen emulsion achieves a better chemical affinity between the RCA and the bitumen, thereby preventing the mixture from suffering from stripping. Indeed, the coating treatment strengthens the mortar, preventing further fragmentation that could lead to the creation of new pathways for water.

- In this regard, the tested mixtures exhibited a notably good stripping performance. HMA made with RCA coated with a bitumen emulsion complied with Spanish specifications for use in pavement base layers in road construction.
- Coating the RCA with a bitumen emulsion makes the performance of the mixture more homogeneous.
- The tested HMA mixtures containing RCA coated with the emulsion exhibited resilient moduli values very similar to those of the conventional mixtures. It must also be noted that increased RCA percentages lead to a slight decrease in the HMA stiffness.
- The results of the tests of the resistance to permanent deformation indicate that HMA made with RCA exhibit good rutting performances that are similar to those of conventional mixtures.
- Additionally, the fatigue life of HMA made with RCA coated with a bitumen emulsion is similar to that of conventional mixtures.
- The results of this investigation are satisfactory. However, HMA made with RCA requires further investigation. In this regard, other natural aggregates should be tested to generalize the conclusions. Moreover, Marshall parameters, such as stability and flow, could bring very interesting results. Additionally, using the Superpave mix design method would lead to new conclusions that could be compared with those obtained using the Marshall mix design method.

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Figure 1  
LA of a mixture of RCA and hornfels

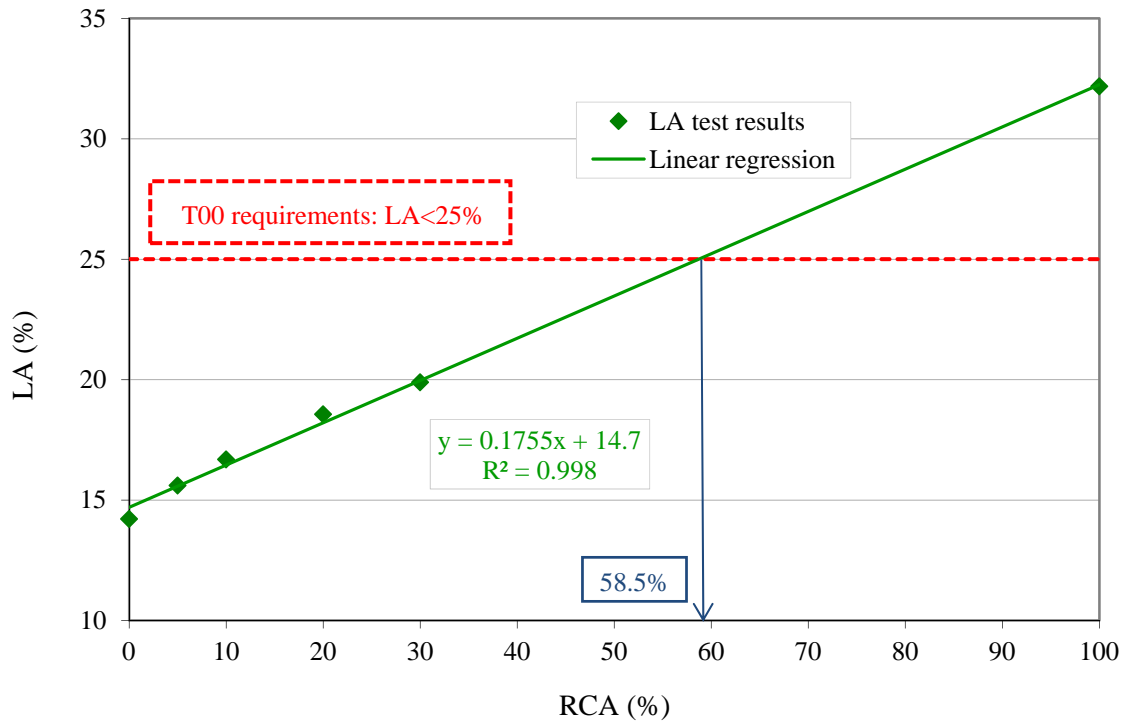


Figure 2  
Gradation curve of an AC 22 base G

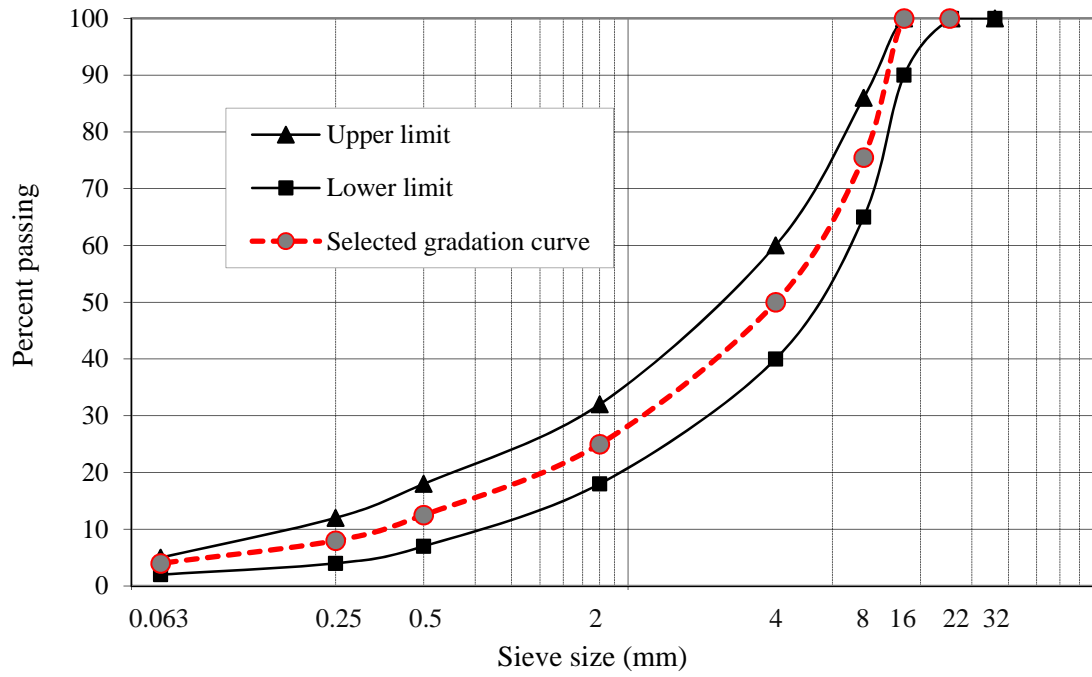


Figure 3  
Tensile strength ratio of HMA made with RCA coated with bitumen emulsion

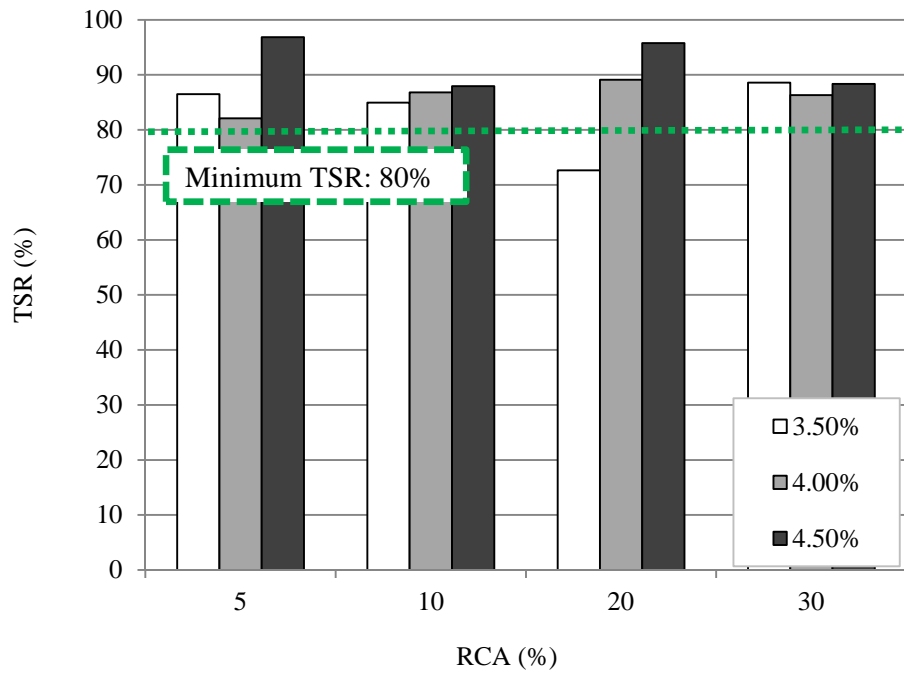


Figure 4

Permanent deformation versus the number of cycles of HMA made with RCA coated with a bitumen emulsion: a) 3.5% of bitumen content, b) 4.0% of bitumen content and c) 4.5% of bitumen content

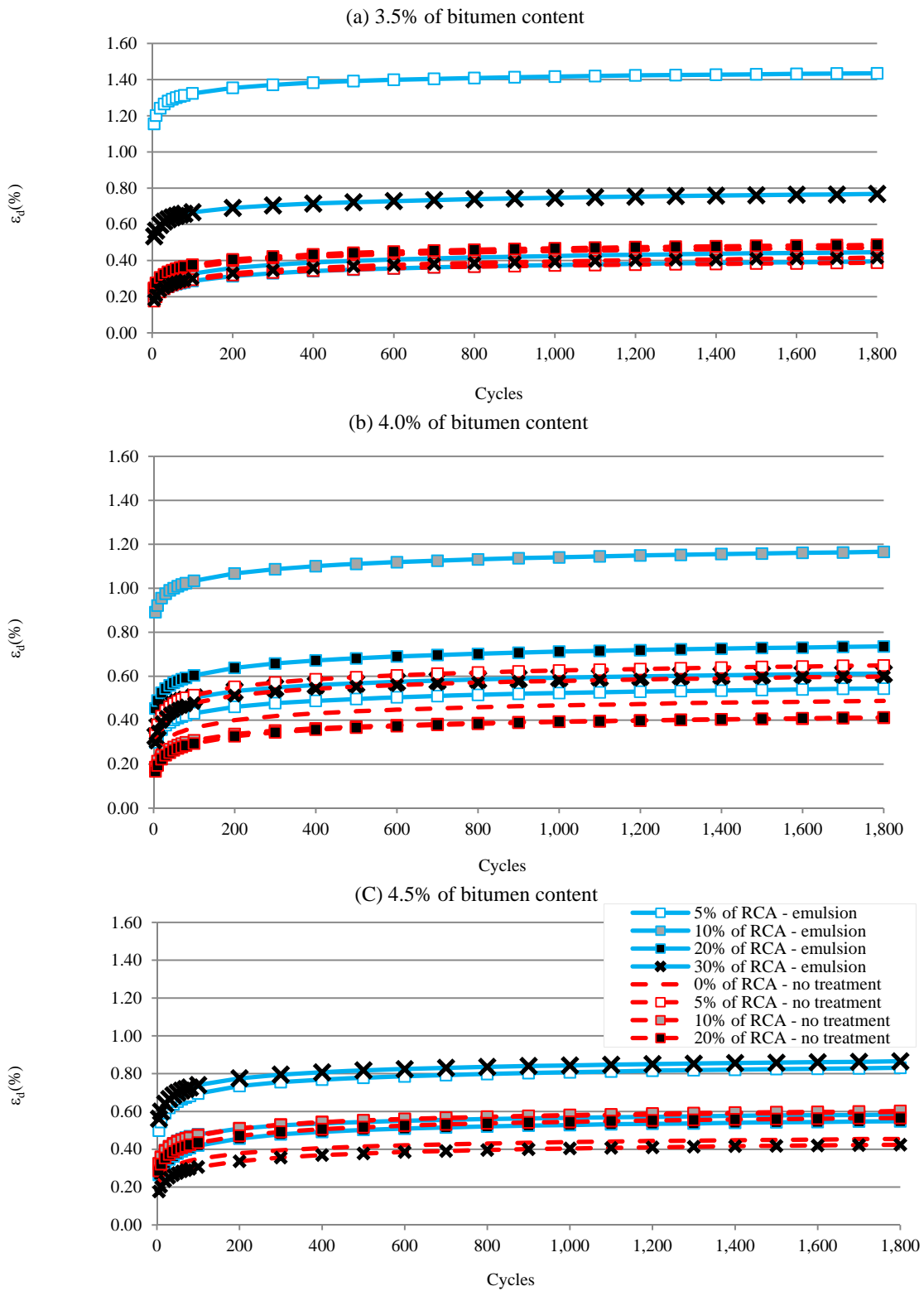


Figure 5

ITFT failure patterns: (a) Sample fractured by a diametral plane and split into two parts and (b) Permanent vertical deformation more than 10% of sample diameter

(a) Sample fractured by a diametral plane and split into two parts



(b) Permanent vertical deformation more than 10% of sample diameter



Figure 6  
 Fatigue life of HMA made with RCA coated with a bitumen emulsion

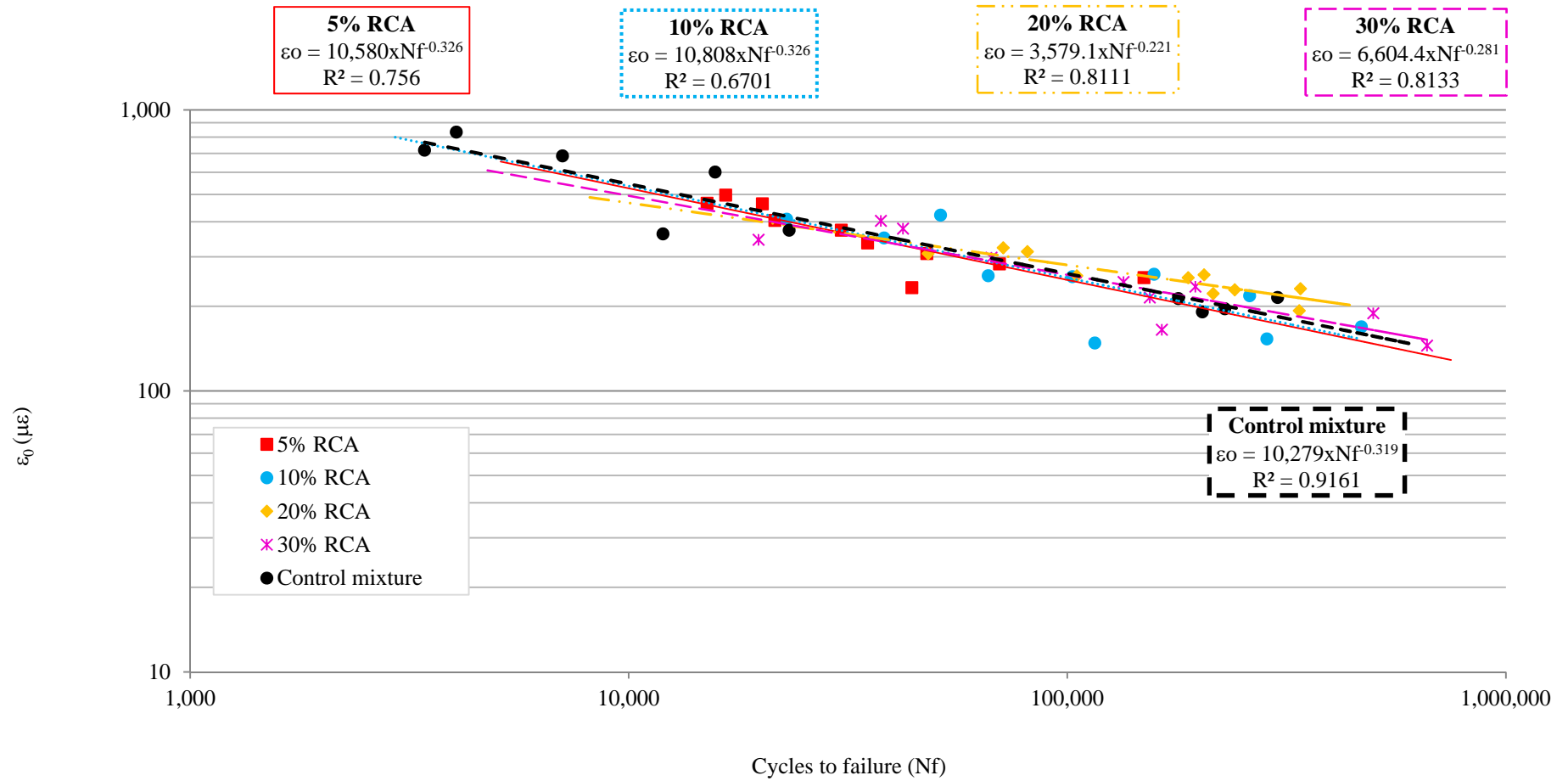


Table 1  
Characterisation of aggregates

Aggregate	Standard	RCA	Hornfels	PG-3 Specifications (*)		
				T00-T1	T3-T2	T4
$\rho_a$ (g/cm <sup>3</sup> )	EN-1097-6	2.63	2.79	-	-	-
WA <sub>24</sub> (%)	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

Traffic category T4 refers to AADHT < 50



Table 2  
Properties of asphalt cement

Test	Standard	B50/70	PG-3 specification
<b>Original</b>			
Penetration (100 g, 5 s, 25°C), 0.1 mm	NLT-124	52	50-70
Softening point, °C	UNE-EN 1427	54.9	48-57
Flash point, °C	ISO 2592	>290	>235
Density (25°C), g/cm <sup>3</sup>	NLT-122	1.009	>1.0
<b>After rolling thin-film oven test</b>			
Penetration (100 g, 5 s, 25°C), 0.1 mm	NLT-124	68	>50
Δ Softening point, °C	NLT-125	6.5	≤9

Table 3

Bitumen content increase as a consequence of coating RCA with bitumen emulsion

<b>RCA (%)</b>	<b>Bitumen emulsion content (by total weight of RCA)</b>	<b>Bitumen emulsion content (by total weight of mixture)</b>	<b>Bitumen content increase (by total weight of mixture)</b>
0		0.00%	0.000%
5		0.25%	0.153%
10	5%	0.50%	0.306%
20		1.00%	0.612%
30		1.50%	0.918%

Table 4

Indirect Tensile strength of HMA made with RCA coated with bitumen emulsion

RCA (%)	ITS <sub>D</sub> (MPa)			ITS <sub>w</sub> (MPa)		
	Pb (%) (*)					
	3.5	4.0	4.5	3.5	4.0	4.5
5	1.438	1.436	1.601	1.243	1.179	1.550
10	1.342	1.734	1.705	1.140	1.505	1.499
20	1.651	1.657	1.402	1.199	1.477	1.343
30	1.437	1.475	1.525	1.273	1.273	1.347

(\*) Pb = bitumen content (total weight of the mixture)

Table 5

Volumetric properties of HMA made with RCA coated with a bitumen emulsion

RCA (%)	Pb (%)	VMA (%)	PG-3 specification for VMA (%)	Va (%)	PG-3 specification for Va (%)			
					T00-T0	T1-T2	T3	T4
5	3.5	15.18	≥ 14%	6.74	5-8	6-9	5-9	-
	4.0	15.85		6.18				
	4.5	14.63		3.59				
10	3.5	14.52		6.08				
	4.0	14.55		4.85				
	4.5	14.19		3.16				
20	3.5	14.61		6.32				
	4.0	14.58		5.00				
	4.5	15.84		6.39				
30	3.5	16.19		9.28				
	4.0	16.03		7.93				
	4.5	14.65		5.24				

Table 6  
Stiffness of HMA made with RCA coated with bitumen emulsion and RCA without treatment

Test temperature (°C)	Pb (%) / RCA (%)	$M_R$ (MPa)									
		RCA coated with bitumen emulsion					RCA without treatment				
		0	5	10	20	30	0	5	10	20	30
0	3.5	-	23,342.5	23,697.0	21,089.5	19,703.5	22,269.0	19,958.5	19,586.0	20,415.0	20,313.5
	4.0	-	23,650.5	22,259.0	21,143.0	20,289.0	23,065.5	20,961.0	21,328.0	21,629.0	20,882.5
	4.5	-	22,187.5	21,463.5	23,381.0	20,924.0	22,666.5	22,585.5	21,681.5	21,184.5	22,349.0
10	3.5	-	12,949.5	13,851.5	12,119.0	12,177.5	14,346.5	10,638.5	10,399.0	11,888.5	11,207.0
	4.0	-	13,377.0	12,618.0	11,115.5	12,615.0	13,391.0	12,049.0	11,565.5	11,860.5	10,868.0
	4.5	-	12,042.5	11,412.5	12,220.5	10,840.0	12,801.5	12,859.0	14,154.5	12,170.0	13,534.5
20	3.5	-	5,660.5	6,409.0	5,654.5	4,748.0	4,924.0	3,786.5	4,167.5	5,629.5	5,663.0
	4.0	-	5,609.0	5,301.0	4,665.5	4,858.0	5,309.5	4,485.0	4,648.5	4,940.5	4,267.0
	4.5	-	4,664.0	4,869.0	5,067.5	4,413.5	4,853.5	4,749.5	5,390.0	4,817.5	5,086.5

Table 7

Creep curve slopes between cycles 600 and 1,800 ( $10^{-6}\mu\text{m}/\text{cycle}$ )

RCA (%) / Bitumen content	RCA coated with bitumen emulsion			RCA without treatment		
	3.5%	4.0%	4.5%	3.5%	4.0%	4.5%
0	-	-	-	30	33	28
5	29	33	38	26	38	32
10	34	39	27	28	28	35
20	33	38	32	32	33	33
30	33	31	35	34	33	32