Wordcount: 8523 words (including title page, tables and figure captions)

RECYCLED CONSTRUCTION AND DEMOLITION WASTE IN COLD ASPHALT MIXTURES: EVOLUTIONARY PROPERTIES

B. Gómez-Meijide [a,*], *I. Pérez* [a] *and A.R. Pasandín*[a]

[a]*E.T.S.I. Caminos, Canales y Puertos, Universidade da Coruña. Campus de Elviña s/n, 15071. A Coruña, Spain*
**Corresponding author. Tel.: +34-981167000. Fax: +34-981167170*
E-mail addresses: breixo.gomez.meijide@udc.es (B. Gómez Meijide), iperez@udc.es (I. Pérez),
arodriguezpa@udc.es (A.R. Pasandín)

Abstract

The use of Cold Asphalt Mixtures (CAM) usually results in financial and environmental saving, while decreasing pollution and occupational hazards. However, they require a length of curing time to reach their full potential. Regarding ecological and financial implications, CAM can be further improved when produced with 100% recycled materials from Construction and Demolition Waste (CDW). In this paper, the evolutionary properties of CAM with CDW were studied in terms of stiffness growth and water loss and the results were compared with conventional control mixes. Among other conclusions, the results showed that although CAM with CDW lost water during longer curing periods, higher stiffness can be obtained with CDW than with Natural Aggregates (NA) at any curing time.

Keywords: *emulsion-treated material; cold asphalt mixture; indirect tensile stiffness modulus; construction and demolition waste; recycled aggregate*

Highlights

Curing properties of Cold Asphalt Mixtures (CAM) were studied
CAM with Construction and Demolition Waste Aggregates (CDWA) were tested
CDWA mixes are stiffer than control mixes at any curing time
Optimal bitumen contents change with the curing processes
CDWA mixes are suitable for a wider range of stiffness requirements

---

[1] CDW: Construction and Demolition Waste
[2] CAM: Cold Asphalt Mixtures
[3] HMA: Hot Mix Asphalt
[4] CDWA: Construction and Demolition Waste Aggregates
[5] NA: Natural Aggregates
[6] ITSM: Indirect Tensile Stiffness Modulus

1. Introduction

Due to the massive use of minerals as raw materials (Krausmann et al., 2009), the building industry is one of the largest material consumers, responsible for 24% of global material extractions (Bribían et al., 2010). These activities are related to environmental impacts, such as damage to landscape and health, disruption of ecosystems and contamination of soil, water, and air (Blankendaal, 2014). Thanks to an increased awareness of these problems, different policies were adopted (e.g., the Directive 2010/31/EU) and research on this field was encouraged towards more sustainable building and construction techniques (Pacheco-Torgal, 2014). In the last decades, there has been a growing interest in construction materials with low embodied energy, both natural (Wang et al., 2014) and unconventional construction materials (Ashour et al., 2011), which help reducing the exploitation rate of nonrenewable resources (Milutiene et al., 2012). Examples of these materials in civil engineering are the earth plasters (Melià et al., 2014) and the permeable pavement systems made of Construction and Demolition Waste (CDW[1]) (Rahman et al., 2015).

In road pavement engineering, Cold Asphalt Mixtures (CAM[2]) are bituminous materials which are normally made by mixing cold aggregates with an asphalt emulsion and water. Unlike Hot Mix Asphalt (HMA[3]), and due to the fact that CAM can be produced at low temperatures, large amounts of aggregates and bitumen do not require heating. Therefore, the use of CAM usually results in financial and environmental saving, while decreasing pollution and occupational hazards.

As far as the ecological and financial implications are concerned, CAM can be further improved when produced with 100% recycled materials from Construction and Demolition Waste Aggregates (CDWA[4]). Research on HMA with recycled aggregates from waste materials has experienced extensive and growing success recently (Bhusal et al., 2011; Chen et al., 2011; Liu et al., 2012; Mills-Beale and You, 2010; Modarres et al, 2015; Paranavithana and Mohajerani, 2006; Pérez et al., 2010; Pérez et al., 2012; Wong et al., 2007), thus reinforcing this new approach within pavement engineering. To a lesser extent, and although more research in this regard is necessary, different studies on CAM with recycled aggregates can also be found at present (Gómez-Meijide and Pérez, 2014b; Gómez-Meijide et al., 2015; Modarres and Ayar, 2014).

From a mechanical point of view, CAM can be stored at room temperature until lay-down and are sufficiently flexible to withstand traffic loads without cracking when high-quality subgrade is not used. Thus, CAM are particularly suitable for the construction and maintenance of low/medium-traffic roads in rural areas that are distant from asphalt plants.

However, in recent decades, several drawbacks have resulted in the inferior consideration of CAM when compared to HMA (Thanaya et al., 2009) and the lack of a performance-based mix design procedure has prevented many agencies from promoting its use. The required length of time to reach full strength and the potential premature distress caused by rainfall water intrusions seem to be the most likely and main disadvantages in this regard (Brown and Needham, 2000). After lay-down, the development of the binder and mastic cohesion, the binder-aggregate adhesion and the mixture shear strength take place, what hinders the efforts to study the effect of the material and/or the process-related variables—e.g., moisture conditions—on its mechanical properties (Khalid and Monney, 2008). Thus, CAM are described as evolutive materials (Serfass et al., 2004) and, therefore, the understanding of the development of their strength while in service still remains incomplete (Doyle et al., 2013).

Although their curing processes are still subject to controversy, many authors have studied the performance of CAM and other materials stabilized with bitumen emulsions (Oruc et al., 2007; Rutherford et al., 2014). For example, Jenkings et al. (2007) predicted a behavior which first involved a 6-to-18-month “Curing Phase” characterized by growing stiffness caused by the moisture reduction and densification of the layer. According to Ebels (2008) and Jenkings and Yu (2009), in this phase the behavior of the material is similar to that of an unbound granular material.

This paper is aimed at studying in depth both the stiffness of CAM with CDWA and control mixes with Natural Aggregates (NA[5]), as well as its variation after different lengths of curing time at room temperature, in order to determine whether these aggregates affect CAM in a detrimental way or they can be considered as a feasible alternative to NA.

The Indirect Tensile Stiffness Modulus (ITSM[6]) and the weight loss of the specimens made with 80 different combinations of bitumen and water contents were also studied, what enabled the discovery of changes in the optimal contents over time, as well as to determine the end of the curing processes from two different points of view: the end of the stiffness growth and the end of the water loss of the samples.

Among other conclusions, the results showed that CAM with CDW have higher practical potential. Thus, although they lost water during longer curing periods (compared to mixes with NA), higher stiffness can be obtained with CDW than with NA at any curing time, including at early stages. Furthermore, it was found that the development of the stiffness during the curing time clearly depends on the binder content of the mix, being this a factor not considered by the methods normally used to design CAM.

2. Material and method

2.1 Materials used

To determine if the curing processes of the mixes are affected by the type of aggregate used to produce the CAM, and, more in particular, by their volumetric properties—e.g. water absorption—, two notably different sources of aggregate were selected. First, a common Spanish hornfels, which is a metamorphic siliceous aggregate obtained from a natural quarry (hereafter, natural aggregate or NA), was used to produce control mixes. Second, a 100% recycled aggregate from construction and demolition waste (hereafter CDWA) was used for a wide range of combinations of bitumen and water contents. Concrete and mortar, as well as natural aggregates (mostly granite), compose the main part of this aggregate; what makes it absorb much more water than NA. In addition, other impurities such as ceramic, metal pieces, gypsum, plastic and glass were also found (Figure 1). Other important properties of these two types of aggregates are listed in Table 1 below.

Among the aggregate gradations recommended by the Spanish Technical Association of Bituminous Emulsions (ATEB), the dense and continuously graded GE1 type was selected for all the specimens in this research. However, in all types of CDWA, the amount of medium and fine particles tended to increase after the mixing and compaction processes. Therefore, the initial gradation was more closely adjusted to the lower limit, whereas the final gradation was proven to be between the upper and lower limits (Figure 2).

The binder was a cationic bitumen emulsion (60% bitumen content) with 100 pen. grade-base bitumen.

2.2 Laboratory testing program

2.2.1 Mixture production

Nowadays, there are numerous methods for the design of CAM, such as the Modified Hveem Method or the Marshall Method for asphalt-aggregate cold-mixture design, as well as many empirical formulas (Asphalt Institute, 1997). In some countries, the first step of the applied traditional methods consists in determining the optimal water content in accordance with the Modified Proctor test (UNE 103-501). Then, and in order to find both the optimal water and bitumen/emulsion contents, samples with this optimal water content but different bitumen/emulsion contents are subsequently made, tested and analyzed. In Spain, for example, it is common to use Immersion-Compression tests (NLT 162) or Indirect Tensile Strength tests (UNE EN 12697-23). Therefore, the optimal water and bitumen contents can be understood in this case as those which are supposed to produce mixtures with the best possible mechanical properties. However, none of these methods takes into account the changes in these optimal contents over the curing time.

All these methods establish an artificial curing time in the oven which is most likely based on the assumption that, after this curing time, the curing processes will be stabilized and the optimal contents will no longer vary. To check whether this hypothesis is correct, the experimental part was designed as follows: a series of different binder contents was selected and for each of them, the same series of water contents was linked, obtaining a matrix of different combinations of binder-water contents. For each combination, a number of specimens were produced. For mixes with NA, 3 specimens were a satisfactory quantity but due to the higher heterogeneity of recycled aggregates, this number had to be increased to 5 for mixes with CDWA. The studied mechanical property was the stiffness, since the tests are non-destructive and the same samples could be repeatedly tested after different curing times. Thus, a clear relationship between stiffness, bitumen/water contents and time could be found. The series of bitumen and water contents were extended until the stiffness showed a peak value surrounded by decreasing trends with higher and lower bitumen/water contents. In the end, 20 different mixes with NA were enough (5 water contents x 4 bitumen contents) but with CDWA, up to 60 mixes were necessary to reach the mentioned objective (10 water contents x 6 bitumen contents).

The mixing and compaction processes were performed following a new protocol developed by the authors of this paper and published in Gómez-Meijide and Pérez (2014a). Thus, and according to this method, 1,550 g of the CDWA and 1,875 g of the NA (it was necessary to make this adjustment in order to maintain the volume of the samples as the study involved the use of aggregates with different specific gravities) were dried, batched in accordance with the aforementioned gradation and mixed with pre-wetting water for 30 sec; what helped to avoid the loss of fine particles during the mechanical mixing. Then, the bitumen emulsion and the remaining water were added and mixed for 90 sec (the time needed to obtain satisfactory coating). Compaction was achieved by applying a static axial compaction effort of 21 MPa for 2 min after a 1-min preload of 1 MPa, as indicated in the Spanish Standards NLT-161 and NLT-162. As a result, 101.6 mm diameter x 101.6 mm high cylindrical specimens were produced and subsequently cut using a radial saw blade until 101.6 mm diameter x 50 mm high cylindrical specimens were obtained.

In order to reach a sufficient level of stiffness to perform both the aforementioned cuts and the first ITSM tests, an artificial and accelerated curing time was applied. Nevertheless, and with regard to this very last aspect, it should be borne in mind that the equivalence between this artificial curing time and the real one still remains unclear. Many authors have studied the curing processes of CAM using different laboratory conditioning regimes, such as two days at 60ºC (Kishore Kumar et al., 2008; Yan et al., 2010), three days at 40ºC (Kim and Lee, 2006), and three days at 60ºC (Bowering and Martin, 1976). However, it is significantly complicated to set the equivalence between these artificial curing times and the real ones that might be observed in an actual road. Thus, and as compiled in Doyle et al. (Doyle et al., 2013), some authors such as Ruckel et al. (1983) have reached the conclusion that curing the specimens for three days at 40ºC is equivalent to one-month under real conditions, whereas the Asphalt Academy (2002) suggests a match of a six-month period of in situ conditioning. Acott (2000) equated a three-day conditioning time at 60ºC with a notably broad span under real conditions which ranges from 23 to 200 days, whereas Maccarrone (1994) increased this time to one year.

In view of this great variation, and in order to meet the ATEB recommendations, an artificial curing time of 3 days at 60ºC in an air-ventilated oven was selected among all the aforementioned options. However, it should be borne in mind that the equivalent to the real curing time in an actual road still remains unclear. After this artificial curing time, the specimens were stored at a laboratory room temperature (20±2ºC) with a relative humidity of 30-40% for 18 more months (Figure 3).

2.2.2 Water and bitumen contents

As mentioned throughout the introduction of this study, CAM are, in general, more flexible than HMA, what can be an advantage to withstand traffic loads when high-quality subgrade is not used. In this paper, and in view of their paramount importance in order to better understand the curing processes and their development, the authors will study, among other aspects, which combinations of water and bitumen contents produce the peak stiffness at each curing time. However, it is important to point out that these contents cannot be labeled as “optimal”, since they may not necessarily be the best ones for every use (although they, in fact, could, as is the case with a stiff base layer). Hence, from this point on, the use of the terms “main water content” and “main bitumen content” was preferred.

Unless specified otherwise, “water content” will refer, hereafter, to the initial water content in the mixture during the mixing process, the amount of water provided by the emulsion and the added water. It was necessary to analyze a long series of water contents (up to 36%) to finally determine the main water content at each curing time. Although after the compaction and curing processes all mixes tended to lose most of their initial water, the highest contents studied in this paper lacked any kind of practical application to road construction itself. Nevertheless, they allowed us to find a trend which indicated that the main contents, as well as the other ones, increased over time.

After the artificial curing process in an air-ventilated oven, all the samples were stored at room temperature and weighed after 0 (right after artificial curing), 6, 12 and 18 months. Finally, the specimens were dried in a ventilated oven until they reached a constant weight. The weight difference led to the determination of the water content of every sample at each curing time. Thus, the end of the curing process, in terms of the water loss of the samples, could be studied.

2.2.3 Indirect tensile stiffness modulus

Since the stiffness of bituminous mixes is related to the capacity of the material to distribute traffic loads, it can be considered as a synthetic indicator of their structural properties. Therefore, and for the purposes of this piece of research, the ITSM was assessed after different storage periods from the end of artificial curing process in an air-ventilated oven (0 or right after the artificial curing, 6, 12 and 18 months). The environment conditions were controlled in order to study the curing process with regard to the growth in stiffness.

The ITSM test was performed in accordance with the Standard EN 12697-26, Annex C. Five semi-sinusoid impulses with a total duration of 3 s —which consisted of a rise time of 124 ms and a visco-elastic deformation recovery— were applied and studied by controlling the deformation (5 µm). Five or three specimens (depending on the source of the aggregate) per bitumen/water content were tested with an assumed Poisson ratio of 0.35. The final value for each water and bitumen content was calculated as the average value of the 5 or 3 specimens.

All ITSM tests were performed in a climatic chamber at 20ºC. This temperature was selected in order to minimize the alteration of the curing processes during the storage of the samples. Although the storage temperature was notably similar, a 4-hour conditioning period in the chamber was applied to guarantee a test temperature of 20±0.5ºC, as stipulated in the aforementioned Standard EN 12697-26, Annex C.

3. Results

3.1 Weight loss of the specimens

In this section, the curing time (which was considered to be the time in which the specimens progressively lost weight) was studied and analyzed. This water loss, which was due to the evaporation of both interstitial water and a small portion of the volatile compounds of the binder which might have remained after the 3-day artificial curing process, is shown in Tables 2 and 3 below for CDWA and NA mixes, respectively.

As it can be observed, CDWA mixes considerably lost more water by the end of the 6 and 12-month periods than NA mixes. This trend was noticeable even in mixes with identical initial bitumen and water contents, but with a different type of aggregate. For instance, when the mixtures with CDWA and 9% water content were analyzed after 0 and 6 months, the water content of the mix with 4% bitumen content moved from 1.56% to 0.78% (thus showing a water loss of 3.4 g in 6 months). As for the mix with 5% bitumen content, it decreased from 2.24% to 0.83% (7.7 g water loss). With regard to NA mixtures, however, the mixes with 4% and 5% bitumen content dropped from 0.34% to 0.13% (0.9 g water loss) and from 0.79% to 0.20% (5.2 g water loss), respectively.

Thus, this result indicates that the higher level of stiffness showed by CDWA mixes is not related to shorter curing times or a greater tendency to expel the interstitial water at room temperature. In fact, after the first 6 months, almost all NA mixes had practically stopped losing weight (values between ± 1 g), whereas some CDWA mixes had lost more than 15 g and, some of them, had even lost a noticeable amount of water in the second 6-month period (for example, the CDWA mix with 8% bitumen and 36% water contents had lost 5.8 g during this period, moving from 1.43% to 1.29%).

In addition, some common features were also found in both types of aggregates. First, it was observed that the water content at each curing time barely depended on the initial amount of water added to the mix during the mixing process. Second, it was also found that the greater the bitumen content of a mix, the longer the time losing weight. One possible explanation for this behavior could be the obstruction of the water-filled voids caused by the coating of the bitumen, thus making more difficult for them to release water.

A two-way analysis of variance (ANOVA) was conducted to statistically confirm the effect of both the initial water and the bitumen contents added during the mixing process on the residual water content after different curing times. In the ANOVA setting, the variance of each variable is partitioned into components attributable to different sources of variation, providing a statistical test of whether or not the means of several groups are equal. The test assumes the independence, normality and homogeneity of the variances of the residuals. Therefore, besides independence (which is clearly satisfied by the studied variables), the normality and homogeneity of the variances had to be first checked by means of Shapiro-Wilk and Levene tests respectively. In case that at least one variable affected the results with statistical significance, the Tukey's post hoc test was applied in order to compare results in pairs and find between which values exist or not exist a significant difference.

In general, it was found that both contents were statistically significant for each curing time at the 99% confidence level, being all p-values lower than 0.001. The only exception found in this study was related to the case of the water at a 0-month curing time, where the initial water was not significant and showed a p-value of 0.889. As for the mixes with NA, no significant water influence was found, since all the water contents at each curing time were very low and similar since the beginning of the test.

Furthermore, a three-way ANOVA was also carried out to determine the effect of the initial water and bitumen contents, as well as of the curing time, on the residual water content at each curing time. The test showed that all parameters were statistically significant. A Tukey's test was conducted in order to obtain a pairwise comparison of the results, being especially interesting the fact that the water contents at each curing time were not significantly different for 6 and 12-month curing times (what consequently meant that the weights of the samples were stable after 6 months). Therefore, the curing time needed to reach full curing conditions, in terms of water loss, was statistically confirmed to be at 6 months.

3.2 Indirect tensile stiffness modulus

In this section, the curing time was understood as the time in which the stiffness of the mixes progressively increased until it reached a stabilized value.

As previously mentioned, an artificial and accelerated curing time of 3 days at 60ºC in an air-ventilated oven was applied in order to reach a sufficient level of stiffness to cut the samples and perform the first ITSM tests without damaging the specimens. After obtaining these first results, the samples were stored at room temperature for months. The results of all these ITSM tests performed with the same samples of CDWA and NA mixes after 6, 12 and 18 months are respectively shown in Tables 4 and 5 (numerically) and in Figures 4 and 5 (graphically) below.

First, it is noticeable that the level of stiffness strongly depended on the bitumen content, whereas it was barely related to the water content. At the initial time (0 months), ITSM peak values were found in CDWA and NA mixes with 5% and 4% bitumen contents, respectively. With regard to the main water content (as previously defined), NA mixes tended to reach higher ITSM values with low water contents, whereas CDWA mixes showed higher values with 15-27% water contents.

Considering that CDWA mixes contain more water than NA mixes, it is paradoxical for the stiffness of CDWA mixes to be generally higher at 0 months. For example, the highest ITSM was 2,537 MPa for NA mixes and 4,024 MPa for CDWA mixes, what obviously meant an increase of 59%.

In addition, it was also observed that the level of stiffness increased in a non-uniform way over the curing time (Tables 6 and 7). Although the largest increments tended to be caused by intermediate water contents (15-27% for CDWA mixes and 6-12% for NA mixes), the increase in stiffness undoubtedly depended on the bitumen content. Thus, higher bitumen contents corresponded to a larger increase in stiffness over the curing time. After 6 months, the ITSM of CDWA mixes with only 3% bitumen content increased by approximately 14%. However, the same mixes with 8% bitumen content increased by over 100%, i.e., they doubled their stiffness. After the next 6 months (12 months in total), and although the increase had not been that strong, some of the mixes with 8% bitumen content increased to almost 150% (in cumulative terms), whereas the mixes with 3% bitumen content barely increased to 20%. This result indicated that, in the second period of 6 months, the mixes with higher bitumen contents experienced the fastest increase with regard to their level of stiffness. The same result was obtained for NA mixes. After 6 months, the stiffness of the mixes with 2% bitumen content increased by approximately 10%, whereas some of the mixes with 5% bitumen content became more than 100% stiffer. As observed in the second 6-month period, the same trend was confirmed and mixes such as 6% water-5% bitumen content increased to approximately 150% (in cumulative terms).

After 18 months, it was observed that the level of stiffness of both CDWA and NA mixes was practically the same as the value registered after 12 months (in some cases even a bit lower). Only in mixes with the highest bitumen content, marginal growths in the level of stiffness, normally below 5%, were found. Thus, a 12-month period was considered to be the total time needed to reach full curing conditions. In addition, both mixes not only needed the same time to get fully cured, but also recorded similar increases in the level of stiffness, with peak values of almost 150% for the highest bitumen contents in both cases.

It was also observed that the times at which the mixes stopped losing weight and those at which the level of stiffness stopped increasing were not exactly the same. The aging of the residual bitumen after the end of water loss could be an explanation for this stiffening behavior, which also supports, to a great extent, the predicted 6-to-18-month growing stiffness phase after which the stiffness progressively falls again (Jenkings et al., 2007).

In addition to these considerations, it can also be said that, in general, CDWA mixes were stiffer than NA mixes at any time. For instance, the peak ITSM values of CDWA mixes and NA mixes were 6,169 MPa and 3,389 MPa after 6 months and 6,811 MPa and 3,580 MPa after 12 months, respectively. This result indicates that, by substituting the NA for the CDWA in the CAM, stiffness raised to 59% immediately after the artificial curing time, whereas, after 6 and 12 months, this increase was 82% and 90%, respectively. Therefore, and as it has previously been stated in Gómez-Meijide and Pérez (2014b), replacing a common NA by this type of recycled aggregate increases the potential stiffness of CAM. Besides, it has also been observed that the differences between both mixes increased over the curing time and that CDWA mixes could reach higher stiffness levels than NA mixes. Furthermore, and due to the fact that the stiffness of the mixes with the highest bitumen contents increased more than that of the mixtures with lower contents, the main contents tended to be progressively displaced toward higher bitumen contents. Therefore, the main bitumen content, which is usually obtained in the lab after a normal testing program with an artificial curing time of 2 or 3 days at 40ºC or 60ºC, can no longer be considered to be the main content since it changes over the curing time.

For instance, in Figure 6 below it can be seen how, after the artificial curing time of 3 days at 60ºC (t=0 months), CDWA mixes showed a main bitumen content of 5%. However, after 6, 12 and 18 months at room temperature, this 5% stiffness did not increase in the same way as that in 6% and 7% mixes when changing the main bitumen content from 5% to 7%. A similar trend was noticed with regard to the NA, since the most significant growths were observed in mixes with the highest bitumen content (5%). In this case, however, the initial ITSM for mixes with 5% bitumen content were so low at t=0 that, even when registering top increases, they could not reach the values of the mixes with 4% bitumen content (although they surpassed the values for mixes with 3% bitumen content). As a result, when too high stiffness is not desirable (typical case when working with CAM) it is advisable to use low bitumen contents, since high contents tend to produce strong increases in stiffness.

A three-way ANOVA was conducted to determine the effect of the initial water content, bitumen content and curing time on the ITSM for CAM with CDWA. The results showed that, statistically speaking, all of them were significant at the 99% confidence level (p_{water}<0.001, $p_{bitumen}$<0.001 and p_{time}<0.001). The p-values obtained for the intersections were also significant, with the exception of the water-time intersection, which was not significant even at the 95% confidence level ($p_{water*bitumen}$0.001, $p_{bitumen*time}$<0.001 and $p_{water*time}$=0.573>0.05). Tukey's post-hoc tests showed that all curing times produced significantly different ITSM values, except for the periods of 12 and 18 months (p=0.606>0.05). Thus, the end of the curing process after 12 months could be statistically verified according to the growth in stiffness.

Similar results were observed for NA mixes. The bitumen content, water content and curing time were all of them, as well as the intersections (except for, again, the water-time intersection), statistically significant at the 99% confidence level (p_{water}<0.001, $p_{bitumen}$<0.001, p_{time}<0.001, $p_{water*bitumen}$<0.001, $p_{bitumen*time}$<0.001 and $p_{water*time}$=0.098>0.05). Tukey's post-hoc tests confirmed, again, that the end of the curing process corresponded to a 12-month curing time, since all ITSM values were significantly different except for the 12 and 18-month periods (p=0.055>0.05).

Finally, the same previous ANOVA tests were repeated, but changing the initial water contents for the water contents at each curing time (Tables 2 and 3), in order to assess whether the water content at each curing time also affected the level of stiffness at that exact moment. The previous conclusions about curing times were reaffirmed, but, in this case, the amount of water at each curing time was statistically non-significant (p=0.871 for CDWA mixes). Taking into account that these water contents were stabilised after the first 6-month period while the ITSM kept growing for a longer time, it seems logical to think that the former did not affect the latter in any significant way.

At the same time, the fact that the initial water content in the mixing process did affect the results of ITSM tests clearly indicates that it might be closely related to a better compaction or a delay in the asphalt emulsion setting during mixing and/or compaction. As explained in other publications (Gómez-Meijide and Pérez, 2014b), it seems that, due to the great water absorption of CDWA mixes, it is necessary to add a huge amount of water during the mixing process in order to avoid the premature setting of the asphalt emulsion and the formation of clots, which can lead to a deficient coating of the aggregates during the mixing and compaction processes. When the aggregate is not that absorbent (as is the case with NA), this premature setting does not take place and, therefore, the presence of large amounts of water becomes detrimental to CAM and their curing processes. For this reason, lower main water contents for NA mixes were also studied in this piece of research.

The practical point of view of all the previous considerations is that mixes with CDWA need, in general, higher water and bitumen contents in order to obtain good mix designs. Thus, they needed a minimum 9% water content to avoid the premature setting of the asphalt emulsion. Mixes with CDWA stiffer than mixes with NA can be obtained with bitumen contents higher than 4%, while softer mixes can be obtained with lower contents. In case that high stiffness is desired, higher bitumen contents (up to 6%-7%) can be used. Otherwise, it is advisable to limit bitumen contents to 4%-5% (values just similar to the main contents obtained with NA), since higher contents involve strong increases over the curing time. In addition, the use of CDW as aggregates in CAM involves raw material savings, reductions in landfilling and other environmental impacts and, as it was explained, it can even improve some properties of CAM, compared to ordinary mixtures with NA.

4. Conclusions

This paper studies the feasibility of improving the environmental aspects of CAM by using recycled waste materials as recycled aggregates. This feasibility was analyzed focusing on their curing properties. After examining all these considerations, the following conclusions were drawn:

1. In general, CDWA mixtures are stiffer than NA mixes at any curing time, reaching values more typical of HMA. Furthermore, their increasing rate of stiffness is higher over the curing time when compared to that of NA mixes.

2. Stiffness growth required the same amount of time to reach full curing conditions for both CDWA and NA mixes. Thus, the incorporation of the CDWA did not affect negatively the length of the curing time from the point of view of stiffness.

3. The source of the aggregate clearly affected the remaining amount of interstitial water in the samples after the compaction process. A high-absorption aggregate, such as CDWA, significantly retains more water, what increases the length of the water loss process.

4. Although a certain correlation exists, the times at which the mixes stopped losing weight and those at which the level of stiffness stopped increasing were not exactly the same. The aging of the residual bitumen after the end of water loss could be an explanation for this stiffening behavior.

5. In general, higher bitumen contents correspond to a greater increase in stiffness over the curing time. This aspect, which led to a rise in the main bitumen content toward higher values, was more noticeable in CDWA mixes. Although no standard design methods have been found in this regard, this consideration should be taken into account in long-term road projects. Therefore, further research on this aspect is still needed.

6. If desired, stiffer mixes can be obtained with CDWA than with NA and with bitumen contents higher than 4%, what can be understood as a greater potential that CDWA offer. However, as far as CAM are concerned, “stiffer” does not necessarily mean “better”. Thus, in case that more flexible pavements are desired, it would be enough just limiting the bitumen content to 4%, what would also reduce both economic and ecological costs.

In view of the previous conclusions, and focusing on the stiffness and curing processes, adding a waste material, such as CDWA, into the CAM did not produce any detrimental effect, although new aspects must be taken into account when designing the mixture. In some cases, it even provided CAM with greater potential and better properties. The obtained mixes showed no negative impacts on their rheo-mechanical properties, while they have better ecological and economic features. The results found in this piece of research, have demonstrated the great potential CAM with CDWA can reach, encouraging further research on this topic.

Acknowledgements

The authors of this paper would like to acknowledge the funding from both the project BIA2010-17751 and the scholarship FPI (ref. BES-2011-044377) from the Spanish Ministry of Economy and Competitiveness. Furthermore, the authors wish to express their most sincere gratitude to the GESTAN Group and ECOASFALT for respectively providing them with the CDWA and the bitumen emulsion which were generously donated for this piece of research.

References

Ashour, T., Georg, H., Wu, W., 2011. An experimental investigation on equilibrium moisture content of earth plaster with natural reinforcement fibres for straw bale buildings. Appl. Therm. Eng. 31, 293-303.

Asphalt Academy, 2002. Interim Technical Guideline: The design and use of foamed bitumen treated materials. Technical Guideline TG2. Asphalt Academy, Pretoria, South Africa.

Asphalt Institute, 1997. Asphalt Cold Mix Manual. Manual Series No. 14 (MS.14), third ed. Asphalt Institute, Lexington, KY, USA.

Bhusal, S., Li, X., Wen, H., 2011. Evaluation of effects of recycled concrete aggregate on volumetrics of hot-mix asphalt. Transportation Research Record: Journal of the

Transportation Research Board, No. 2205, Transportation Research Board of the National Academies, Washington DC, 36–39.

Blankendaal, T., Schuur, P.,Voordijk, H., 2014. Reducing the environmental impact of concrete and asphalt: a scenario approach. J. Clean. Prod. 66, 27-36.

Bowering, R.H., Martin, C.L, 1976. Foamed bitumen production and application of mixtures evaluation and performance of pavements. Proceedings of Association of Asphalt Paving Technologists. 45, 453-477.

Bribián, I.Z., Capilla, A.V., Usón, A.A, 2010. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco efficiency improvement potential. Build. Environ. 46, 1133-1140.

Brown, S.F., Needham, D, 2011. A study of cement modified bitumen emulsion mixtures. Proceedings of the Association of Asphalt Paving Technologists 2000. 69, 92-116.

Chen MZ, Lin JT, Wu SP. Potential of recycled fine aggregates powder as filler in asphalt mixture. Constr. Build. Mater. 25, 3909-3914.

Doyle, T.A., McNally, C., Gibney, A., Tabakovic, A., 2013. Developing maturity methods for the assessment of cold-mix bituminous materials. Constr. Build. Mater. 38, 524-529.

Ebels, L.J., 2008. Characterisation of material properties and behaviour of cold bituminous mixtures for road pavements. University of Stellenbosch, PhD thesis, South Africa.

Gómez-Meijide, B., Pérez, I., 2014. A proposed methodology for the global study of the mechanical properties of cold asphalt mixtures. Mat. Des. 57, 520-527.

Gómez-Meijide, B., Pérez, I., 2014. Effects of the use of construction and demolition waste aggregates in cold asphalt mixtures. Constr. Build. Mater. 51, 267-277.

Gómez-Meijide, B., Pérez, I., Airey, G., Thom, N., 2015. Stiffness of cold asphalt mixtures with recycled aggregates from construction and demolition waste. Constr. Build. Mater. 77, 168–178.

Jenkins, K.H., Long, F.M., Ebels, L.J., 2007. Foamed bitumen mixes=shear performance? Int. J. Pavement Eng. 8, 85-98.

Jenkins, K.H., Yu, M., 2009. Cold-recycling techniques using bitumen stabilization: Where is this technology going? ASCE Geotechnical Special Publication.191–200.

Jenkins, K.J., 2000. Mix design considerations for cold and half-warm bituminous mixes with emphasis on foamed bitumen. University of Stellenbosch, PhD thesis, South Africa.

Khalid, H.A., Monney, O.K., 2008. Moisture damage potential of cold asphalt. Int. J. Pavement Eng. 10(3), 11-318.

Kim, Y., Lee, H.D., 2006. Development of mix design procedure for cold in-place recycling with foamed asphalt. J. Mat. Civ. Eng. 18, 116-124.

Kishore Kumar, C., Amar Kumar, D.S.N.V., Amarantha Reddy, M., Sudhakar Reddy, K., 2008. Investigation of cold in-place recycled mixes in India. Int. J. Pavement Eng. 9, 265-274.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K-H., Haberl, H., Fischer-Kowalski, M., 2009. Growth in global materials use, GDP and population during the 20th century. Ecol. Econ. 68(10), 2696-2705.

Liu, Y., Han, S., Zhang, Z., Xu, O., 2012. Design and evaluation of gap-graded asphalt rubber mixtures. Mat. Des. 35, 873-877.

Maccarrone, S., 1994. Cold asphalt systems as an alternative to hot mix. In Asphalt Review: presented at the 9th AAPA international Asphalt conference. Australian Asphalt Pavement Association, Australia, 19-24.

Melià, P., Ruggieri, G., Sabbadini, S., Dotelli, G., 2014. Environmental impacts of natural and conventional building materials: a case study on earth plasters. J. Clean. Prod. 88, 179-186.

Mills-Beale, J., You, Z., 2010. The mechanical properties of asphalt mixtures with recycled concrete aggregates. Constr. Build. Mater. 24, 230-235.

Milutiene, E., Staniskis, J.K., Krucius, A., Auguliene, V., Ardickas, D., 2012. Increase in buildings sustainability by using renewable materials and energy. Clean Technol. Environ. Policy. 14, 1075-1084.

Modarres, A., Ayar, P., 2014. Coal waste application in recycled asphalt mixtures with bitumen emulsion. J. Clean. Prod. 83, 263-272.

Modarres, A., Rahmanzadeh, M., Ayar, P., 2015. Effect of coal waste powder in hot mix asphalt compared to conventional fillers: mix mechanical and environmental impacts. J. Clean. Prod. 91, 262-268.

Oruc, S., Celik, F., Akpinar, M.V., 2007. Effect of Cement on Emulsified Asphalt Mixtures. J. Mat. Eng. Perform. 16(5), 578-583.

Pacheco-Torgal, F., 2014. Eco-efficient construction and building materials research under the EU framework programme horizon 2020. Constr. Build. Mater. 51, 151-162.

Paranavithana, S., Mohajerani, A., 2006. Effects of recycled concrete aggregates on properties of asphalt concrete. Resour. Conserv. Recycl. 48, 1-12.

Pérez, I., Gallego, J., Toledano, M., Taibo, J., 2010. Asphalt mixtures with construction and demolition debris. Proceedings of the Institution of Civil Engineers 163, 165-174.

Pérez, I., Pasandín, A., Medina, L., 2012. Hot mix asphalt using C&D waste as coarse aggregates. Mat. Des. 36, 840-846.

Rahman, M.A., Imteaz, M.A., Arulrajah, A., Piratheepan, J., Disfani, M., 2015. Recycled construction and demolition materials in permeable pavement systems: geotechnical and hydraulic characteristics. J. Clean. Prod. 90, 183-194.

Ruckel, P.J., Acott, S.M., Bowering, R.H., 1983. Foamed-asphalt paving mixtures: preparation of design mixes and treatment of test specimens. Transportation Research Record: Journal of the Transportation Research Board, No. 911. Transportation Research Board of the National Academies, Washington DC, 88-95.

Rutherford, T., Wang, Z., Shu, X., Huang, B., Clarke, D., 2014. Laboratory investigation into mechanical properties of cement emulsified asphalt mortar. Constr. Build. Mater. 65, 76-83.

Serfass, J.P., Poirier, J.E., Henrat, J.P., Carbonneau, X., 2004. Influence of curing on cold mix mechanical performance. Mat. Struct. 37, 365-368.

Technical Association of Bituminous Emulsions (ATEB). Gravel-emulsion specifications. http://www.ateb.es/pdf/PLI_GRAVA.pdf. Accessed March 2014.

Thanaya, I.N.A., Zoorob, S.E., Forth, J.P., 2009. A laboratory study on cold-mix, cold lay emulsion mixtures. Proceedings of the Institution of Civil Engineers. 162, 47-55.

Wang, E., Shen, Z., 2013. A hybrid data quality indicator and statistical method for improving uncertainty analysis in LCA of complex system e application to the whole-building embodied energy analysis. J. Clean. Prod. 43, 166-173.

Wong, Y.D., Sun, D.D., Lai, D., 2007. Value-added utilization of recycled concrete in hot-mix asphalt. Waste Manag. 27, 294-301.

Yan, J., Ni, F., Yang, M., Li, J., 2010. An experimental study on fatigue properties of emulsion and foam cold recycled mixes. Constr. Build. Mater. 24, 2151-2156.

Table 1. Characterization of Recycled and Natural Aggregates

Property	**Recycled aggregate**	**Natural aggregate**
Flakiness Index (UNE EN 933-3)	4.5%	19.8%
Crushed particles (UNE EN 933-5)	89%	94%
Sand equivalent (UNE EN 933-8)	77	78
Los Angeles coefficient (UNE EN 1097-2)	38	14
Bulk specific gravity (UNE EN 1097-6)	2.64 t/m^3	2.78 t/m^3
Dry specific gravity (UNE EN 1097-6)	2.23 t/m^3	2.74 t/m^3
SSD specific gravity (UNE EN 1097-6)	2.39 t/m^3	2.75 t/m^3
Absorption (UNE EN 1097-6)	7.0%	0.5%

Table 2. Water content at each curing time (% of the Dry Aggregate Weight) of the CAM with 100% of CDWA after Different Curing Times (Standard Deviations in subscript)

Bitumen content	**Initial water content in the mixing process**									
	9%	**12%**	**15%**	**18%**	**21%**	**24%**	**27%**	**30%**	**33%**	**36%**
Immediately after artificial curing time										
3%	$1.42_{\pm0.22}$	$1.49_{\pm0.21}$	$1.47_{\pm0.28}$	$1.50_{\pm0.32}$	$1.48_{\pm0.44}$	$1.28_{\pm0.30}$	$1.25_{\pm0.11}$	$1.42_{\pm0.16}$	$1.39_{\pm0.21}$	$1.44_{\pm0.27}$
4%	$1.56_{\pm0.27}$	$1.83_{\pm0.25}$	$1.79_{\pm0.26}$	$1.63_{\pm0.39}$	$1.54_{\pm0.35}$	$1.52_{\pm0.32}$	$1.40_{\pm0.23}$	$1.38_{\pm0.32}$	$1.47_{\pm0.39}$	$1.45_{\pm0.41}$
5%	$2.24_{\pm0.29}$	$2.22_{\pm0.23}$	$2.17_{\pm0.25}$	$2.28_{\pm0.28}$	$2.39_{\pm0.24}$	$2.25_{\pm0.28}$	$2.30_{\pm0.17}$	$2.20_{\pm0.42}$	$2.09_{\pm0.41}$	$2.01_{\pm0.64}$
6%	$2.86_{\pm0.32}$	$2.80_{\pm0.21}$	$2.35_{\pm0.24}$	$2.42_{\pm0.26}$	$2.59_{\pm0.30}$	$2.84_{\pm0.24}$	$2.91_{\pm0.07}$	$2.83_{\pm0.33}$	$2.69_{\pm0.36}$	$2.62_{\pm0.30}$
7%	$2.90_{\pm0.34}$	$2.91_{\pm0.26}$	$2.86_{\pm0.24}$	$2.79_{\pm0.21}$	$2.90_{\pm0.24}$	$3.10_{\pm0.25}$	$3.22_{\pm0.21}$	$3.15_{\pm0.43}$	$2.75_{\pm0.41}$	$2.73_{\pm0.52}$
8%	$3.10_{\pm0.20}$	$2.98_{\pm0.21}$	$2.91_{\pm0.20}$	$2.82_{\pm0.17}$	$3.17_{\pm0.27}$	$3.57_{\pm0.28}$	$3.74_{\pm0.29}$	$3.88_{\pm0.28}$	$3.60_{\pm0.23}$	$3.51_{\pm0.19}$
After artificial curing time + 6 months at room temperature										
3%	$0.71_{\pm0.03}$	$0.72_{\pm0.02}$	$0.70_{\pm0.03}$	$0.74_{\pm0.03}$	$0.70_{\pm0.03}$	$0.75_{\pm0.03}$	$0.88_{\pm0.02}$	$0.86_{\pm0.03}$	$0.72_{\pm0.02}$	$0.68_{\pm0.02}$
4%	$0.78_{\pm0.02}$	$0.66_{\pm0.03}$	$0.67_{\pm0.02}$	$0.69_{\pm0.01}$	$0.64_{\pm0.01}$	$0.72_{\pm0.02}$	$0.94_{\pm0.03}$	$0.95_{\pm0.04}$	$0.84_{\pm0.03}$	$0.80_{\pm0.03}$
5%	$0.83_{\pm0.02}$	$0.70_{\pm0.02}$	$0.63_{\pm0.03}$	$0.66_{\pm0.02}$	$0.70_{\pm0.02}$	$0.79_{\pm0.03}$	$1.03_{\pm0.03}$	$1.08_{\pm0.04}$	$1.00_{\pm0.03}$	$0.96_{\pm0.04}$
6%	$0.92_{\pm0.02}$	$0.80_{\pm0.03}$	$0.72_{\pm0.01}$	$0.76_{\pm0.02}$	$0.81_{\pm0.02}$	$0.90_{\pm0.04}$	$1.11_{\pm0.02}$	$1.16_{\pm0.02}$	$1.18_{\pm0.04}$	$1.15_{\pm0.06}$
7%	$0.95_{\pm0.03}$	$0.93_{\pm0.02}$	$0.90_{\pm0.03}$	$0.90_{\pm0.02}$	$0.94_{\pm0.02}$	$1.05_{\pm0.01}$	$1.22_{\pm0.05}$	$1.26_{\pm0.10}$	$1.30_{\pm0.03}$	$1.31_{\pm0.03}$
8%	$1.14_{\pm0.01}$	$1.07_{\pm0.01}$	$1.03_{\pm0.02}$	$1.00_{\pm0.04}$	$1.20_{\pm0.05}$	$1.36_{\pm0.08}$	$1.42_{\pm0.03}$	$1.45_{\pm0.05}$	$1.46_{\pm0.05}$	$1.43_{\pm0.03}$
After artificial curing time + 12 months at room temperature										
3%	$0.70_{\pm0.01}$	$0.71_{\pm0.02}$	$0.70_{\pm0.03}$	$0.69_{\pm0.02}$	$0.72_{\pm0.03}$	$0.74_{\pm0.04}$	$0.77_{\pm0.03}$	$0.79_{\pm0.03}$	$0.76_{\pm0.03}$	$0.73_{\pm0.03}$
4%	$0.76_{\pm0.02}$	$0.73_{\pm0.03}$	$0.74_{\pm0.02}$	$0.72_{\pm0.01}$	$0.74_{\pm0.03}$	$0.76_{\pm0.03}$	$0.79_{\pm0.02}$	$0.83_{\pm0.02}$	$0.80_{\pm0.02}$	$0.75_{\pm0.04}$
5%	$0.82_{\pm0.03}$	$0.77_{\pm0.03}$	$0.76_{\pm0.02}$	$0.77_{\pm0.02}$	$0.78_{\pm0.03}$	$0.80_{\pm0.02}$	$0.88_{\pm0.02}$	$0.96_{\pm0.02}$	$0.95_{\pm0.03}$	$0.88_{\pm0.03}$
6%	$0.93_{\pm0.02}$	$0.88_{\pm0.02}$	$0.81_{\pm0.03}$	$0.88_{\pm0.02}$	$0.84_{\pm0.02}$	$0.87_{\pm0.02}$	$0.99_{\pm0.03}$	$1.01_{\pm0.04}$	$1.03_{\pm0.03}$	$1.05_{\pm0.02}$
7%	$0.91_{\pm0.01}$	$0.90_{\pm0.01}$	$0.90_{\pm0.01}$	$0.87_{\pm0.02}$	$0.86_{\pm0.04}$	$0.94_{\pm0.01}$	$1.05_{\pm0.02}$	$1.10_{\pm0.03}$	$1.16_{\pm0.03}$	$1.22_{\pm0.03}$
8%	$1.00_{\pm0.02}$	$1.01_{\pm0.02}$	$0.98_{\pm0.01}$	$0.91_{\pm0.03}$	$0.96_{\pm0.03}$	$1.12_{\pm0.03}$	$1.13_{\pm0.02}$	$1.15_{\pm0.04}$	$1.24_{\pm0.02}$	$1.29_{\pm0.02}$
After artificial curing time + 18 months at room temperature										
3%	$0.83_{\pm0.01}$	$0.82_{\pm0.02}$	$0.81_{\pm0.02}$	$0.83_{\pm0.02}$	$0.84_{\pm0.03}$	$0.85_{\pm0.01}$	$0.88_{\pm0.02}$	$0.90_{\pm0.03}$	$0.89_{\pm0.02}$	$0.82_{\pm0.02}$
4%	$0.87_{\pm0.02}$	$0.84_{\pm0.01}$	$0.83_{\pm0.01}$	$0.84_{\pm0.02}$	$0.84_{\pm0.02}$	$0.87_{\pm0.02}$	$0.95_{\pm0.02}$	$0.97_{\pm0.02}$	$0.94_{\pm0.01}$	$0.91_{\pm0.02}$
5%	$0.92_{\pm0.01}$	$0.86_{\pm0.02}$	$0.82_{\pm0.01}$	$0.83_{\pm0.02}$	$0.85_{\pm0.01}$	$0.90_{\pm0.02}$	$1.03_{\pm0.02}$	$1.12_{\pm0.01}$	$1.06_{\pm0.02}$	$0.96_{\pm0.03}$
6%	$0.95_{\pm0.02}$	$0.92_{\pm0.02}$	$0.85_{\pm0.02}$	$0.89_{\pm0.02}$	$0.95_{\pm0.01}$	$0.97_{\pm0.01}$	$1.11_{\pm0.03}$	$1.12_{\pm0.02}$	$1.15_{\pm0.03}$	$1.17_{\pm0.02}$
7%	$0.98_{\pm0.02}$	$1.00_{\pm0.03}$	$0.98_{\pm0.02}$	$0.94_{\pm0.01}$	$0.96_{\pm0.02}$	$1.01_{\pm0.02}$	$1.12_{\pm0.02}$	$1.14_{\pm0.03}$	$1.24_{\pm0.02}$	$1.32_{\pm0.03}$
8%	$1.07_{\pm0.02}$	$1.12_{\pm0.02}$	$1.13_{\pm0.02}$	$1.04_{\pm0.01}$	$1.08_{\pm0.02}$	$1.16_{\pm0.03}$	$1.17_{\pm0.02}$	$1.18_{\pm0.03}$	$1.31_{\pm0.03}$	$1.33_{\pm0.03}$

Table 3. Water content at each curing time (% of the Dry Aggregate Weight) of the CAM with 100% of NA after Different Curing Times (Standard Deviations in subscript)

Bitumen content	**Initial water content in the mixing process**				
	3%	**6%**	**9%**	**12%**	**15%**
Immediately after artificial curing time					
2%	$0.23_{\pm0.03}$	$0.20_{\pm0.05}$	$0.15_{\pm0.02}$	$0.14_{\pm0.02}$	$0.14_{\pm0.04}$
3%	$0.09_{\pm0.03}$	$0.07_{\pm0.02}$	$0.12_{\pm0.02}$	$0.06_{\pm0.02}$	$0.08_{\pm0.02}$
4%	$0.15_{\pm0.02}$	$0.15_{\pm0.06}$	$0.34_{\pm0.10}$	$0.28_{\pm0.09}$	$0.27_{\pm0.06}$
5%	$0.27_{\pm0.10}$	$0.71_{\pm0.07}$	$0.79_{\pm0.08}$	$0.96_{\pm0.12}$	$0.54_{\pm0.18}$
After artificial curing time + 6 months at room temperature					
2%	$0.14_{\pm0.03}$	$0.17_{\pm0.01}$	$0.18_{\pm0.03}$	$0.18_{\pm0.004}$	$0.16_{\pm0.08}$
3%	$0.11_{\pm0.01}$	$0.10_{\pm0.004}$	$0.13_{\pm0.01}$	$0.12_{\pm0.01}$	$0.17_{\pm0.03}$
4%	$0.10_{\pm0.01}$	$0.13_{\pm0.01}$	$0.13_{\pm0.01}$	$0.11_{\pm0.01}$	$0.13_{\pm0.01}$
5%	$0.13_{\pm0.01}$	$0.14_{\pm0.01}$	$0.20_{\pm0.01}$	$0.30_{\pm0.09}$	$0.22_{\pm0.04}$
After artificial curing time + 12 months at room temperature					
2%	$0.13_{\pm0.014}$	$0.12_{\pm0.010}$	$0.12_{\pm0.022}$	$0.10_{\pm0.003}$	$0.15_{\pm0.07}$
3%	$0.11_{\pm0.006}$	$0.09_{\pm0.013}$	$0.10_{\pm0.006}$	$0.09_{\pm0.010}$	$0.11_{\pm0.014}$
4%	$0.10_{\pm0.007}$	$0.10_{\pm0.002}$	$0.11_{\pm0.001}$	$0.10_{\pm0.010}$	$0.11_{\pm0.004}$
5%	$0.10_{\pm0.007}$	$0.11_{\pm0.003}$	$0.12_{\pm0.007}$	$0.17_{\pm0.030}$	$0.16_{\pm0.012}$
After artificial curing time + 18 months at room temperature					
2%	$0.12_{\pm0.006}$	$0.10_{\pm0.002}$	$0.10_{\pm0.001}$	$0.10_{\pm0.003}$	$0.16_{\pm0.003}$
3%	$0.10_{\pm0.003}$	$0.08_{\pm0.020}$	$0.09_{\pm0.002}$	$0.08_{\pm0.005}$	$0.12_{\pm0.003}$
4%	$0.10_{\pm0.004}$	$0.11_{\pm0.002}$	$0.12_{\pm0.001}$	$0.10_{\pm0.004}$	$0.11_{\pm0.003}$
5%	$0.10_{\pm0.002}$	$0.12_{\pm0.003}$	$0.12_{\pm0.003}$	$0.12_{\pm0.001}$	$0.15_{\pm0.005}$

Table 4. Stiffness (in MPa) of the CAM with 100% of CDWA after Different Curing Times (Standard Deviations in subscript)

Bitumen content	**Initial water content in the mixing process**									
	9%	**12%**	**15%**	**18%**	**21%**	**24%**	**27%**	**30%**	**33%**	**36%**
Immediately after artificial curing time										
3%	$2379_{\pm294}$	$2622_{\pm282}$	$2490_{\pm302}$	$2710_{\pm287}$	$3043_{\pm330}$	$3312_{\pm219}$	$3596_{\pm259}$	$3566_{\pm298}$	$3558_{\pm214}$	$3570_{\pm111}$
4%	$2741_{\pm287}$	$3013_{\pm223}$	$3318_{\pm266}$	$3182_{\pm305}$	$3380_{\pm240}$	$3595_{\pm188}$	$3667_{\pm206}$	$3657_{\pm313}$	$3601_{\pm363}$	$3583_{\pm210}$
5%	$3024_{\pm316}$	$3723_{\pm266}$	$\mathbf{4024}_{\pm245}$	$3854_{\pm267}$	$3912_{\pm346}$	$4001_{\pm356}$	$3766_{\pm286}$	$3640_{\pm255}$	$3618_{\pm209}$	$3553_{\pm196}$
6%	$3515_{\pm270}$	$3642_{\pm254}$	$3418_{\pm198}$	$3866_{\pm223}$	$3896_{\pm207}$	$3786_{\pm116}$	$4006_{\pm154}$	$3799_{\pm289}$	$3586_{\pm186}$	$3451_{\pm175}$
7%	$3403_{\pm268}$	$3321_{\pm209}$	$2844_{\pm126}$	$2987_{\pm173}$	$3079_{\pm240}$	$2983_{\pm279}$	$3421_{\pm243}$	$3812_{\pm280}$	$3490_{\pm238}$	$3213_{\pm146}$
8%	$3288_{\pm164}$	$2837_{\pm191}$	$2668_{\pm193}$	$2394_{\pm211}$	$2311_{\pm363}$	$2269_{\pm391}$	$2565_{\pm112}$	$2707_{\pm178}$	$2724_{\pm103}$	$2526_{\pm95}$
After artificial curing time + 6 months at room temperature										
3%	$2571_{\pm391}$	$3021_{\pm369}$	$3328_{\pm399}$	$3215_{\pm281}$	$3354_{\pm175}$	$3727_{\pm277}$	$3921_{\pm268}$	$3994_{\pm427}$	$3912_{\pm360}$	$3913_{\pm142}$
4%	$3498_{\pm405}$	$4011_{\pm420}$	$4239_{\pm432}$	$4120_{\pm334}$	$4400_{\pm341}$	$4517_{\pm231}$	$4259_{\pm254}$	$4121_{\pm452}$	$4153_{\pm384}$	$4343_{\pm219}$
5%	$4489_{\pm437}$	$5017_{\pm411}$	$5368_{\pm456}$	$5478_{\pm446}$	$5412_{\pm487}$	$5529_{\pm434}$	$5007_{\pm297}$	$4770_{\pm520}$	$4772_{\pm309}$	$4889_{\pm629}$
6%	$5010_{\pm398}$	$5303_{\pm364}$	$5458_{\pm358}$	$6004_{\pm498}$	$6010_{\pm302}$	$5988_{\pm265}$	$5816_{\pm290}$	$5524_{\pm199}$	$5430_{\pm253}$	$5487_{\pm377}$
7%	$5512_{\pm506}$	$5576_{\pm307}$	$5497_{\pm267}$	$5491_{\pm387}$	$5499_{\pm317}$	$5666_{\pm310}$	$5844_{\pm388}$	$\mathbf{6169}_{\pm200}$	$6012_{\pm335}$	$5991_{\pm323}$
8%	$5374_{\pm407}$	$5461_{\pm522}$	$5274_{\pm458}$	$4772_{\pm504}$	$4759_{\pm546}$	$4934_{\pm567}$	$5339_{\pm335}$	$5524_{\pm270}$	$5607_{\pm234}$	$5584_{\pm212}$
After artificial curing time + 12 months at room temperature										
3%	$2883_{\pm409}$	$3229_{\pm312}$	$3490_{\pm600}$	$3324_{\pm341}$	$3409_{\pm222}$	$3924_{\pm368}$	$4220_{\pm354}$	$4189_{\pm440}$	$4212_{\pm287}$	$4163_{\pm112}$
4%	$3629_{\pm418}$	$4321_{\pm389}$	$4507_{\pm531}$	$4430_{\pm377}$	$4479_{\pm321}$	$4858_{\pm347}$	$4433_{\pm352}$	$4461_{\pm469}$	$4442_{\pm290}$	$4532_{\pm286}$
5%	$4761_{\pm351}$	$5274_{\pm379}$	$5511_{\pm484}$	$5642_{\pm430}$	$5754_{\pm457}$	$5827_{\pm406}$	$5251_{\pm379}$	$5123_{\pm808}$	$5223_{\pm271}$	$5379_{\pm569}$
6%	$5362_{\pm328}$	$5644_{\pm298}$	$5784_{\pm375}$	$6502_{\pm458}$	$6645_{\pm225}$	$6592_{\pm187}$	$6139_{\pm387}$	$5888_{\pm162}$	$5940_{\pm223}$	$6020_{\pm315}$
7%	$5738_{\pm673}$	$6012_{\pm268}$	$6230_{\pm367}$	$5993_{\pm452}$	$6089_{\pm287}$	$6177_{\pm290}$	$6603_{\pm307}$	$\mathbf{6811}_{\pm174}$	$6471_{\pm299}$	$6356_{\pm297}$
8%	$5543_{\pm385}$	$5987_{\pm422}$	$5787_{\pm700}$	$5370_{\pm497}$	$5751_{\pm613}$	$5614_{\pm270}$	$5964_{\pm258}$	$6240_{\pm234}$	$6236_{\pm205}$	$6147_{\pm235}$
After artificial curing time + 18 months at room temperature										
3%	$2890_{\pm418}$	$3294_{\pm396}$	$3442_{\pm482}$	$3389_{\pm424}$	$3583_{\pm332}$	$4080_{\pm290}$	$3844_{\pm314}$	$3912_{\pm406}$	$3915_{\pm254}$	$4051_{\pm156}$
4%	$3687_{\pm425}$	$4487_{\pm415}$	$4399_{\pm478}$	$4503_{\pm446}$	$4717_{\pm321}$	$4753_{\pm276}$	$4362_{\pm326}$	$4221_{\pm338}$	$4228_{\pm212}$	$4371_{\pm253}$
5%	$4993_{\pm395}$	$5554_{\pm401}$	$5681_{\pm492}$	$5767_{\pm487}$	$5808_{\pm422}$	$5770_{\pm462}$	$5019_{\pm352}$	$4900_{\pm861}$	$4893_{\pm222}$	$5124_{\pm524}$
6%	$5502_{\pm364}$	$5740_{\pm317}$	$6133_{\pm299}$	$6541_{\pm402}$	$6653_{\pm200}$	$6390_{\pm179}$	$6132_{\pm370}$	$5723_{\pm189}$	$5751_{\pm198}$	$5910_{\pm323}$
7%	$5934_{\pm755}$	$6170_{\pm290}$	$6221_{\pm298}$	$6189_{\pm410}$	$6031_{\pm218}$	$6304_{\pm256}$	$6917_{\pm307}$	$\mathbf{7007}_{\pm151}$	$6497_{\pm238}$	$6333_{\pm360}$
8%	$6061_{\pm377}$	$6001_{\pm389}$	$5720_{\pm603}$	$5423_{\pm443}$	$5439_{\pm580}$	$5669_{\pm264}$	$6161_{\pm305}$	$6459_{\pm179}$	$6376_{\pm188}$	$6181_{\pm462}$

Table 5. Stiffness (in MPa) of the CAM with 100% of NA after Different Curing Times (Standard Deviations in subscript)

Bitumen content	**Initial water content in the mixing process**				
	3%	**6%**	**9%**	**12%**	**15%**
Immediately after artificial curing time					
2%	$1844_{\pm147}$	$1619_{\pm21}$	$1387_{\pm185}$	$1469_{\pm83}$	$1691_{\pm212}$
3%	$2351_{\pm184}$	$2298_{\pm67}$	$2137_{\pm217}$	$2308_{\pm112}$	$2374_{\pm54}$
4%	**2537**$_{\pm296}$	$2197_{\pm210}$	$2137_{\pm381}$	$1795_{\pm222}$	$2184_{\pm198}$
5%	$1459_{\pm474}$	$963_{\pm149}$	$931_{\pm380}$	$1310_{\pm524}$	$1850_{\pm302}$
After artificial curing time + 6 months at room temperature					
2%	$1871_{\pm132}$	$1653_{\pm31}$	$1518_{\pm258}$	$1714_{\pm49}$	$1971_{\pm202}$
3%	$2532_{\pm92}$	$2610_{\pm34}$	$2432_{\pm273}$	$2476_{\pm154}$	$2716_{\pm161}$
4%	**3389**$_{\pm368}$	$2862_{\pm384}$	$2780_{\pm309}$	$2621_{\pm106}$	$3277_{\pm394}$
5%	$2326_{\pm397}$	$1872_{\pm116}$	$1923_{\pm416}$	$2299_{\pm365}$	$2949_{\pm171}$
After artificial curing time + 12 months at room temperature					
2%	$2208_{\pm186}$	$1858_{\pm59}$	$1663_{\pm266}$	$1848_{\pm101}$	$1887_{\pm297}$
3%	$2660_{\pm68}$	$2815_{\pm140}$	$2594_{\pm326}$	$2671_{\pm77}$	$2780_{\pm110}$
4%	**3580**$_{\pm410}$	$3365_{\pm363}$	$2953_{\pm422}$	$2856_{\pm214}$	$3156_{\pm128}$
5%	$2798_{\pm448}$	$2321_{\pm158}$	$2072_{\pm407}$	$2549_{\pm398}$	$3481_{\pm161}$
After artificial curing time + 18 months at room temperature					
2%	$2297_{\pm269}$	$1829_{\pm120}$	$1784_{\pm227}$	$1792_{\pm131}$	$1905_{\pm177}$
3%	$2806_{\pm117}$	$2795_{\pm61}$	$2630_{\pm174}$	$2813_{\pm101}$	$2810_{\pm231}$
4%	**3723**$_{\pm474}$	$3325_{\pm397}$	$3143_{\pm255}$	$2996_{\pm95}$	$3404_{\pm240}$
5%	$2933_{\pm423}$	$2372_{\pm210}$	$2128_{\pm371}$	$2594_{\pm305}$	$3408_{\pm117}$

Table 6. Cumulative increased stiffness (% of the stiffness after the artificial curing time) of the CAM with 100% of CDWA after different curing times at room temperature

Bitumen content	**Initial water content in the mixing process**									
	9%	**12%**	**15%**	**18%**	**21%**	**24%**	**27%**	**30%**	**33%**	**36%**
Increased stiffness after 6 months at room temperature										
3%	8.1	15.2	33.7	18.6	10.2	12.5	9.0	12.0	9.9	9.6
4%	27.6	33.1	27.8	29.5	30.2	25.6	16.1	12.7	15.3	21.2
5%	48.4	34.8	33.4	42.1	38.3	38.2	33.0	31.0	31.9	37.6
6%	42.5	45.6	59.7	55.3	54.3	58.2	45.2	45.4	51.4	59.0
7%	62.0	67.9	93.3	83.8	78.6	89.9	70.8	61.8	72.3	86.5
8%	63.4	92.5	97.7	99.3	105.9	117.5	108.1	104.1	105.8	**121.1**
Increased stiffness after 12 months at room temperature										
3%	21.2	23.2	40.2	22.7	12.0	18.5	17.4	17.5	18.4	16.6
4%	32.4	43.4	35.8	39.2	32.5	35.1	20.9	22.0	23.4	26.5
5%	57.4	41.7	37.0	46.4	47.1	45.6	39.4	40.7	44.4	51.4
6%	52.5	55.0	69.2	68.2	75.7	74.1	53.2	55.0	65.6	74.4
7%	68.6	81.0	119.1	100.6	97.8	107.1	93.0	78.7	85.4	97.8
8%	68.6	111.0	116.9	124.3	148.9	**147.4**	132.5	130.5	128.9	143.3
Increased stiffness after 18 months at room temperature										
3%	21.5	25.6	38.2	25.1	17.7	23.2	6.9	9.7	10.0	13.5
4%	34.5	48.9	32.6	41.5	39.6	32.2	19.0	15.4	17.4	22.0
5%	65.1	49.2	41.2	49.6	48.5	44.2	33.3	34.6	35.2	44.2
6%	56.5	57.6	79.4	69.2	70.8	68.8	53.1	50.6	60.4	71.3
7%	74.4	85.8	118.7	107.2	95.9	111.3	102.2	83.8	86.2	97.1
8%	84.3	111.5	114.4	126.5	135.4	**149.8**	140.2	138.6	134.1	144.7

Table 7. Cumulative increased stiffness (% of the stiffness after the artificial curing time) of the CAM with 100% of NA after different curing times at room temperature

Bitumen content	**Initial water content in the mixing process**				
	3%	**6%**	**9%**	**12%**	**15%**
Increased stiffness after 6 months at room temperature					
2%	1.5	2.1	9.5	16.7	16.6
3%	7.7	13.6	13.8	7.3	14.4
4%	33.6	30.3	30.1	46.0	50.0
5%	59.5	94.4	**106.5**	75.5	59.4
Increased stiffness after 12 months at room temperature					
2%	19.8	14.8	19.9	25.8	11.6
3%	13.2	22.5	21.4	15.7	17.1
4%	41.1	53.2	38.2	59.1	44.5
5%	91.8	**141.0**	122.4	94.6	88.2
Increased stiffness after 18 months at room temperature					
2%	24.6	13.0	28.6	22.0	12.7
3%	19.4	21.6	23.1	21.9	18.4
4%	46.8	51.3	47.1	66.9	55.8
5%	101.1	**146.3**	128.5	98.0	84.2