Effects of the use of construction and demolition waste aggregates in cold asphalt mixtures

B. GÓMEZ-MEIJIDE and I. PÉREZ

-

Published in CONSTRUCTION AND BUILDING MATERIALS as:
B. Gómez-Meijide, I. Pérez. Effects of the use of construction and demolition waste aggregates in cold asphalt mixtures. Construction and Building Materials 51 (2014) 267–277
http://dx.doi.org/10.1016/j.conbuildmat.2013.10.096

Effects of the use of construction and demolition waste aggregates in cold asphalt mixtures

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

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

Abstract:

Cold asphalt mixtures (CAM) with 100% recycled aggregates from construction and demolition waste (CDW) were researched to ecologically and economically improve cold asphalt mixtures. The present study indicates that the UCS, ITS, ITSM and moisture susceptibility were very satisfactory not only compared with a control mix with 100% natural aggregates (NA) but also with values given by different standards and recommendations. A new global approach to design these aggregates has also been explored because conventional methods are inaccurate in this case.

Keywords: *Construction and Demolition Waste; cold asphalt mixture; sustainable pavement engineering; Indirect Tensile Strength; Indirect Tensile Stiffness Modulus*

1. Introduction

Cold asphalt mixes (CAM) have been considered inferior to hot-mix asphalt (HMA) in the last several decades, mainly due the high air-void content of the compacted mixtures, their weak early life strength and the long curing times required to achieve an optimal performance [1].

After lay-down, these mixtures need to pass through a number of stages in which the binder and mastic cohesion, binder-aggregate adhesion and mixture shear strength develop. During these stages, cold asphalt does not lend itself to studies of the influence of material and/or process variables, e.g., moisture condition, on its mechanical properties [2]. This drawback is due to the associated peculiarities of cold asphalt, which include the presence of water, emulsion-aggregate reactivity, evolving characteristics with time and an undeveloped internal structure [3].

Many studies have been conducted to minimise these considerations and approximate hot asphalt mixtures, such as incorporating a certain amount of cement, as well as modified asphalt emulsions in the mixture [4-6]. In addition, cold mixes have features that make them preferable to hot mixes, such as a lower energy consumption, ecological impact, economic costs or occupational hazards for operators. Moreover, cold mixes are storable at room temperature until lay-down, non-polluting and show a lower tendency for cracking, due to their flexibility when the subgrade is not of great quality. Thus, cold mixes are especially suitable for low/medium traffic local roads, which are normally placed far away from the manufacturing plants.

Cold asphalt mixtures are currently regaining their importance within the asphalt world market, reaching annual production levels of 1.5 million tonnes in France or 2 million tonnes in Turkey in recent years [7]. Nevertheless, researchers and producers continue to improve these mixtures in an attempt to increase their competitiveness.

As such, and to improve the ecological and economic properties of CAM, CAM containing 100% recycled aggregates from construction and demolition waste (CDW) were studied. An extensive, growing and successful body of research on hot asphalt mixes with recycled aggregates from waste materials [8-16] reinforces this new approach in pavement engineering.

This research was focused on the mechanical properties of CAMcontaining 100% construction and demolition waste aggregates (CDWA) once they have already reached a high curing degree. The results obtained were satisfactory not only compared with a control mix containing 100% natural aggregates (NA) but also with values given by different standards and recommendations.

An ANOVA statistical analysis was performed to test and support the experimental results. Because the interaction between water and bitumen is unclear, one 2-way ANOVA and two 1-

way ANOVA (one for each fixed variable water/bitumen) were performed for each studied property. As explained, both analyses served to confirm the results because the conclusions drawn from both follow the same direction and did not contradict in any of the cases.

2. Materials Used

Two different aggregates were used: a hornfels, a metamorphic siliceous aggregate from a natural quarry used to produce the control mixes (hereafter, natural aggregate or NA) and a 100% recycled aggregate from construction and demolition waste (hereafter CDWA), whose composition is given in Table 1 for the received coarse and medium fractions. This composition was used to analyse the potential behaviour of this material in CAM. Most of this aggregate was concrete and natural stone but also contained other materials (Figure 1) that required the use of an X-Ray diffractogram to truly define their source in some cases. In this way, materials such as asphalt materials, plaster, aerated concrete or limestone with quartzite particles were identified.

The different properties of both natural and recycled aggregates are shown in Table 2. CDWA materials are weaker because they have a lower Los Angeles coefficient, Flakiness Index and Crushed Particles after the crushing process. However, the most characteristic feature is the low specific gravity and the extensive water absorption, which clearly affect the mechanical and rheological properties of the bituminous mixtures they comprise.

Table 1. Components of recycled aggregate (% of total dry weight)

Material	**% in coarse aggregate (12/24 mm)**	**% in medium aggregate (6/12 mm)**
Concrete and mortar	70%	55%
Natural aggregates	25%	40%
Ceramics and masonry materials	3.7%	4.1%
Concrete with metal pieces	1.121%	< 0.001%
Concrete with textile fibers	0.146%	0.042%
Plaster/gypsum	0.103%	0.012%
Other materials (metal, paper, plastics, glass)	<0.1%	<0.1%

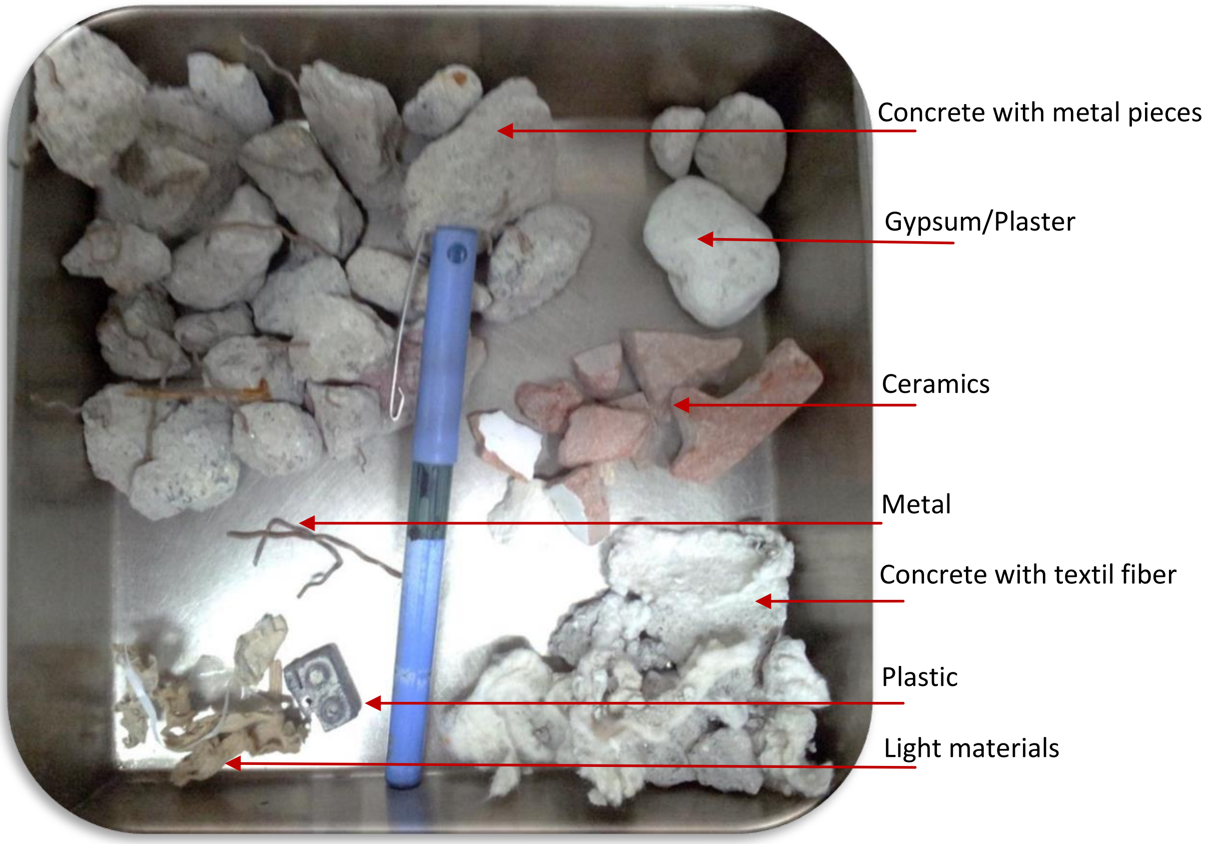


Figure 1. Some of the materials found in the recycled aggregate

Table 2. Characterization of recycled and natural aggregates

Property	**Recycled aggregate**	**Natural aggregate**
Flakiness Index (UNE EN 933-3 [17])	4.5%	19.8%
Crushed particles (UNE EN 933-5 [18])	89%	94%
Sand equivalent (UNE EN 933-8 [19])	77	78
Los Angeles coefficient (UNE EN 1097-2 [20])	38	14
Bulk specific gravity (UNE EN 1097-6 [21])	2.64 t/m^3	2.78 t/m^3
Dry specific gravity (UNE EN 1097-6 [21])	2.23 t/m^3	2.74 t/m^3
SSD specific gravity (UNE EN 1097-6 [21])	2.39 t/m^3	2.75 t/m^3
Absorption (UNE EN 1097-6 [21])	7.0%	0.5%

The binder used was a cationic bitumen emulsion (60% bitumen content) with 100 pen. grade base bitumen. The other relevant properties are shown in Table 3. The aggregate gradations of all the design mixtures used in this investigation were based on the technical recommendations given by the Spanish Technical Association of Bituminous Emulsions [22] for grave-emulsions. The initial gradation, which corresponds to a grave-emulsion GE1, required modification to be maintained within the upper and lower limits after compaction because the recycled aggregate tended to break, as shown in Figure 2.

Table 3. Properties of the asphalt emulsion used during the present investigation

PROPERTIES	UNIT	STANDARD	VALUE	CLASS
Original Emulsion				
Perceptible properties	--	1425	OK	--
Temperature	ºC	N.A.	15-35	--
Bitumen content	%	1428	58-62	CLASS 5
Flow time (40 ºC, 2mm)	s	12846-1	15-45	CLASS 3
Residue (sieve), (Sieve 0.5 mm)	%	1429	≤ 0.1	CLASS 2
pH	--	12850	≤ 7	--
Storage stability	%	12847	≤ 10	CLASS 3
Setting index	g	13075-1	120-180	CLASS 5
Adhesiveness	%	13614	≥ 90	CLASS 3
Bitumen recovered by evaporation (UNE EN 13074-1)				
Penetration 25 ºC	0.1 mm	1426	≤ 100	CLASS 3
Softening point	ºC	1427	≥ 43	CLASS 4
Stabilized binders (UNE EN 13074-1 + UNE EN 13074-2)				
Penetration 25 ºC	0.1 mm	1426	≤ 100	CLASS 1
Softening point	ºC	1427	≥ 43	CLASS 1
Aged bitumen (UNE EN 13074-1 + 13074-2 + UNE EN 14769)				
Penetration 25 ºC	0.1 mm	1426	≤ 100	CLASS 2
Softening point	ºC	1427	≥ 43	CLASS 2

3. Laboratory Testing Program

3.1 Mixture production and mechanical properties tested

Many emulsified mix-design methods are currently being used, such as Modified Hveem Method for emulsified asphalt-aggregate cold mixture design or the Marshall Method for emulsified asphalt-aggregate cold mixture design, as well as different empirical formulas [23]. In some countries (i.e., Spain), first obtaining an optimal total water content from the Modified Proctor test (UNE 103-501-94) [24] and then testing the mixes with different bitumen/emulsion contents is common; here, the total water content is the sum of the water from the bitumen emulsion plus the added water. Nevertheless, all tests were carried out with a wide combination of both contents to exactly determine the optimal bitumen and water contents. As such, the variations of a certain property due to either the water or bitumen content are clarified and easily understood, and the optimal values were real and not simple approximations.

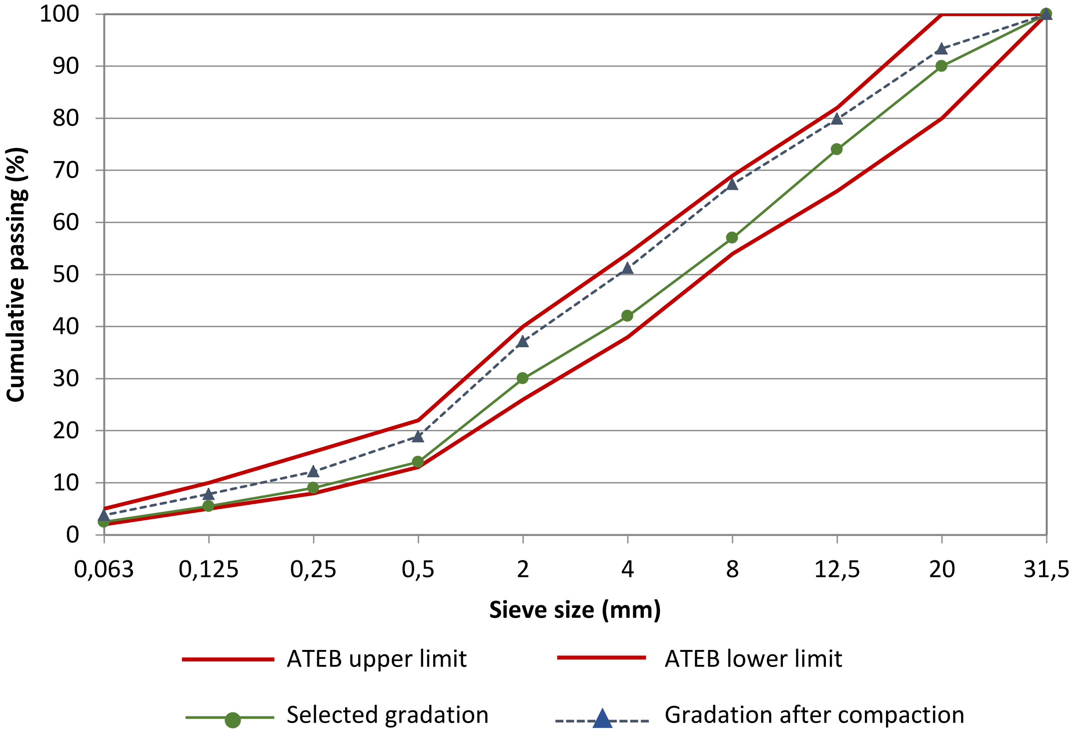


Figure 2. Aggregate gradation of CDWA before and after compaction compared with ATEB recommendations

The water content discussed hereafter refers to the total water in the mixing process, which consists of water from the asphalt emulsion plus the added water. After compaction, the amount of water remaining inside the specimens was found to be lower and depending on the bitumen content as well as the type of aggregate (Table 4). The NA facilitates the water outlet, while the CDWA tends to retain it due to its high absorption. Similarly, larger amounts of bitumen waterproof the aggregate, and the water losses tend to increase again. The precise amount of water in the mixing process remarkably minimally influences this remaining water. However, the added water influenced the mechanical properties, as discussed below. Thus, it was necessary to test different water amounts.

Table 4. Water contents (% of dry aggregate weight) remaining in the specimens after compaction process

CDWA mix						**NA mix**			
% bitumen	**% of water in mixing process**					**% bitumen**	**% of water in mixing process**		
	9%	**12%**	**15%**	**18%**	**21%**		**6%**	**9%**	**12%**
2%	9.6%	9.6%	9.7%	9.3%	9.1%	**2%**	3.35%	3.5%	3.6%
3%	9.5%	9.5%	9.5%	9.3%	8.8%	**3%**	2.2%	2.5%	2.5%
4%	9.0%	9.0%	9.0%	8.7%	8.6%	**4%**	1.5%	1.8%	1.8%
5%	8.6%	8.4%	8.3%	8.1%	8.35	**5%**	1.3%	1.5%	1.6%
6%	8.2%	8.0%	7.9%	7.8%	7.9%				

All specimens of the current study consisted of 100% CDWA or 100% NA. A CDWA content of 100% is higher than the top contents published by other authors for hot asphalt mixtures [25]. However, in cold asphalt mixtures, this material potentiated the mixes even when the aggregate content consisted entirely of CDWA.

In summary, the mixing process was carried out as follows: 1550 g of CDWA or 1875 g of NA (this adjustment was necessary due to the different specific gravities) were dry mixed with the required pre-wetting water for 30 sec (to produce a homogeneous mixture and avoid the loss of fine particles during mechanical mixing). The bitumen emulsion and remaining water were then added and mixed for 90 sec (the necessary time to obtain a satisfactory coating). A static axial compaction effort of 21 MPa was subsequently applied for 2 min, and the resultant material was cured for 3 days 60ºC, as specified in the Spanish Standard NLT-162 [26] and ATEB recommendations. This method was used to produce 101.6 mm diameter x 101.6 mm height cylindrical specimens. These samples were suitable for the unconfined compression test but not for the indirect tensile test or stiffness test. To produce specimens with the same intrinsic properties (specific gravity, voids content, moisture content, etc.) irrespective of the test and thus correlate all results in the most reliable way possible, the authors developed a novel method by which two 101.6 mm diameter x 50 mm height were obtained from the split of the same 101.6 mm height "mother specimen".

The height of the specimen tended to slightly increase by increasing the bitumen content. This effect was not observed for the water content. As such, specimens containing 100% or CDWA showed heights ranging from -2 mm to +2 mm from the target height for bitumen contents of 3% to 8%. Conversely, specimens that consisted of 100% NA showed variations near 1 mm for bitumen contents of 2% to 5%. These variations were not observed with respect to the diametrical dimensions, even though this dimension was found to be closer to 101.8 mm than to the target 101.6 mm. The bitumen or water content did not affect the standard deviation. Thus, an almost random range of values was obtained from values close to 0 to those greater than 1; the standard deviation in the height was close to 0.85, and the standard deviation in the diameter was close to 0.07.

A volumetric analysis was carried out to determine the void content present in the studied asphalt mixes. The parameters studied were VMA (voids in mineral aggregate, which includes all voids filled with air, bitumen and water), V_{aw} (voids filled with air and water) and V_a (air voids, just filled with air), as well as the bulk specific gravity, which was obtained by using the following expressions proposed by the Asphalt Institute [23]:

$$G=D/(F-E) \tag{1}$$

$$VMA\ (\%)=[((100+A+K)/G-100/C)\div((100+A+K)/G)]\times 100 \tag{2}$$

$$V_{aw}\ (\%)=[((100+A+K)/G-100/C-A/B)\div((100+A+K)/G)]\times 100 \tag{3}$$

$$V_a\ (\%)=V-[((K\times 100)/L)\div((100+A+K)/G)] \tag{4}$$

where *G* is the bulk specific gravity; *D* is the mass of specimen in air (g); *E* is the mass of specimen in water (g); *F* is the mass of specimen in saturated surface-dry (SSD) condition (g); *A* is the asphalt residue as percent of dry aggregate mass; *B* is the specific gravity of asphalt; *L* is the specific gravity of water and *K* is the water content at testing (%), which can be calculated as follows:

K (%)=(mass of water (g))/(mass of dry mixture (g))×(100+A) (5)

A static press was used for the static tests to analyse the following mechanical properties:

- Unconfined Axial compression test (Spanish NLT-161 [26])
- Moisture susceptibility: Immersion-Compression test (Spanish NLT-162 [26])
- Indirect Tensile Strength (ITS) at 20ºC (UNE EN 12697-23 [27])

Furthermore, a Cooper NU 14 (Figure 3) dynamic testing machine was used to evaluate the stiffness by means of ITSM at 2ºC, 10ºC and 20ºC (UNE-EN 12697-26 [28]).

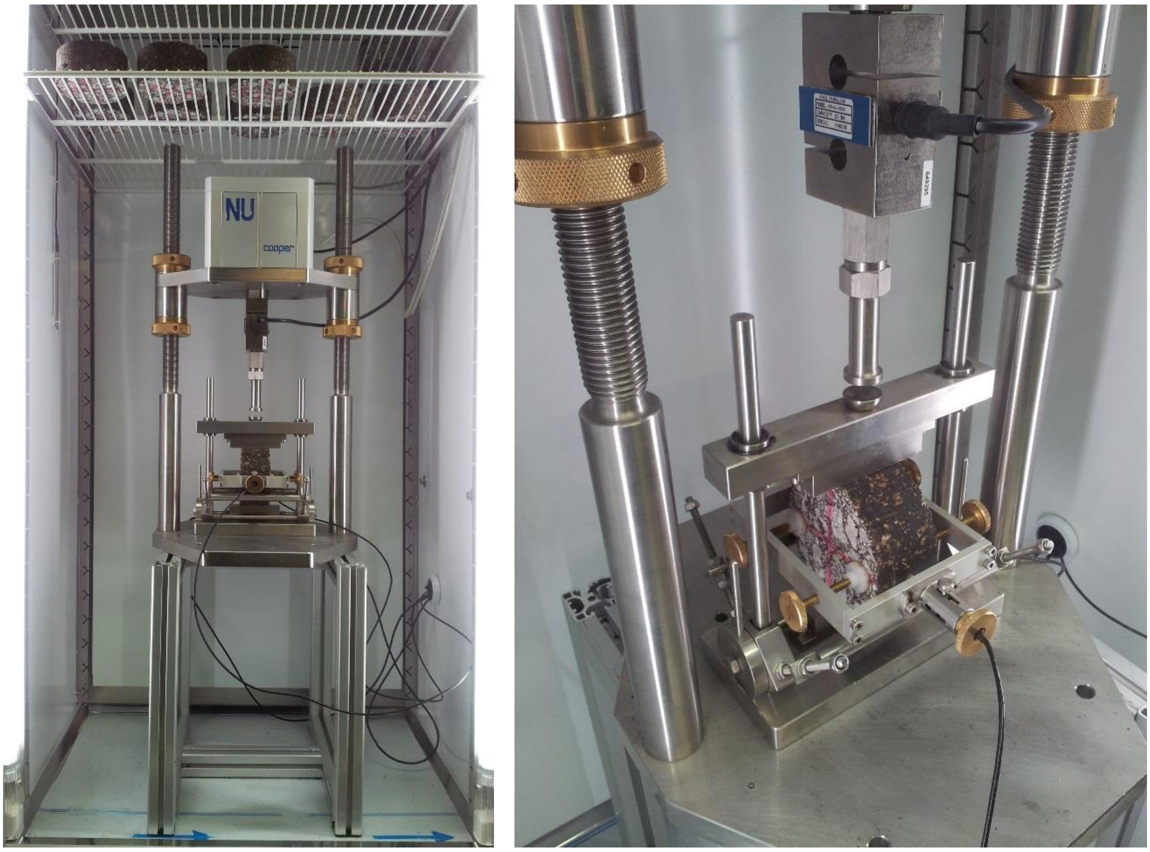


Figure 3. ITSM dynamic tests according to Standard UNE-EN 12697-26

3.2 Immersion-Compression

This test was performed according to the Spanish NLT-162 standard [26] (a test method for assessing the effect of water on the Unconfined Compression Strength (UCS) of compacted bituminous mixtures). Ten 101.6 mm diameter x 101.6 mm height cylindrical specimens were produced. Five specimens were immersed in water at a temperature of 49ºC for 96 h, and the other five were maintained at room temperature without being submerged in water. They were later subjected to unconfined compression (Axial Compression test, NLT-161 [26]), and the average value of the strength in each group was determined. The retained strength ratio (RSR) was calculated as follows:

$$RSR=UCS_{wet}/UCS_{dry} \tag{6}$$

where UCS_{wet} is the unconfined compression strength of the group immersed in water at 49ºC (MPa) and UCS_{dry} the unconfined compression strength of the group that was not submerged. According to Spanish legislation (PG-3) [29], this index must be higher than 50% in grave-emulsions and higher than 60% according to ATEB. Furthermore, ATEB defines the lowest UCS at 1.2 MPa for the non-immersed group and 1.0 MPa for the immersed group for medium and low traffic roads.

3.3 Indirect Tensile Strength

The indirect tensile strength (ITS) was tested according to the Standard UNE-EN 12697-23 [27] at room temperature of 25ºC to evaluate the stress cracking resistance. Five cylindrical specimens per bitumen/water content were subjected to diametral compression with a constant deformation rate of (50±2) mm/min until fracture occurred. The ITS was obtained for each specimen with the following equation:

$$ITS=(2\cdot P)/(\pi\cdot D\cdot H) \tag{7}$$

where P is the peak vertical load (kN), D is the diameter (mm) and H is the height of the cylindrical specimens (mm). Finally, the ITS was considered to be the average value of five tested specimens.

3.4 Stiffness Modulus

The stiffness of bituminous mixes can be considered a synthetic indicator of the structural properties of the mixtures because it is related to the capacity of the material to distribute traffic loads. The test was carried out following the Standard EN 12697-26, Annex C. The test is characterised by 5 semi-sinusoid impulses with a total duration of 3 s that consists of a rise time of 124 ms and a visco-elastic deformation recovery, conducted in a regime of deformation control (5 µm). To evaluate the thermal sensitivity of the mixtures, indirect tensile stiffness modulus (ITSM) tests were conducted at three different temperatures: 2ºC, 10ºC and 20ºC. A temperature of 2ºC instead of 0ºC was selected to avoid the possible freezing of internal mixing water. Five specimens per bitumen/water content were tested under an assumed Poisson ratio condition of 0.35, which represents the final value the average value of these specimens. For each pulse, the modulus was calculated as follows:

$$S_m=F(\nu+0.27)/(z\cdot h) \tag{8}$$

where S_m is the stiffness modulus (MPa), F represents the peak value of the applied vertical load (N), z is the amplitude of the horizontal deformation obtained during the load cycle (mm), h is the mean height of the cylindrical specimen (mm) and ν is Poisson's ratio.

4. Test Results

4.1 Volumetric properties

The parameters VMA, V_{aw}, V_a and the bulk specific gravity are shown in Table 5 for both NA and CDWA asphalt mixes. As expected, the obtained values for VMA, V_{aw}, and V_a are much higher in the CDWA than in the NA mixtures due to the high porosity of CDWA. Overall, the VMA tended to slightly increase by increasing the bitumen content and be almost independent of the water content. However, V_{aw} and V_a tended to markedly decrease by increasing bitumen content and slightly decrease by increasing water content. Nevertheless, the void content of the CDWA mixes never dropped below 10% and was sometimes higher than

20%, which is a typical value in granular materials or open-graded asphalt mixes. Moreover, mixes prepared with CDWA showed a lower bulk specific gravity (around a 18% lower) due to the lightness of CDWA. The specific gravity of the NA mixes was maximised at 4% bitumen content, while the specific gravity of the CDWA materials continued to increase due to the persistent high void content that was neither filled with bitumen nor with water and could continually be filled. As explained below, this feature not only strongly affects the properties of CDWA but also results in the inaccuracy of classical design methods for this case.

Table 5. Voids contents and density of CDWA and NA mixtures made with different bitumen and water contents

CDWA mix						**NA mix**			
% bitumen	**Total water in mixing process (% weight of dry aggregate)**					**% bitumen**	**Total water in mixing process (% weight of dry aggregate)**		
	9%	**12%**	**15%**	**18%**	**21%**		**6%**	**9%**	**12%**
VMA (Voids in Mineral Aggregate)									
2%	28.7%	28.6%	28.5%	28.1%	28.3%	**2%**	17.4%	17.5%	17.5%
3%	29.0%	28.6%	28.3%	28.3%	28.7%	**3%**	18.2%	17.6%	17.3%
4%	29.4%	28.6%	28.5%	28.7%	28.8%	**4%**	17.1%	17.5%	17.1%
5%	29.7%	29.4%	29.0%	28.9%	29.0%	**5%**	18.0%	18.6%	18.0%
6%	29.9%	29.9%	30.0%	29.8%	29.8%	-	-	-	-
V_{aw} (voids filled with air and water)									
2%	24.6%	25.0%	24.5%	24.2%	23.2%	**2%**	12.9%	13.1%	13.0%
3%	23.3%	23.3%	22.8%	22.9%	22.8%	**3%**	11.5%	10.9%	10.6%
4%	22.4%	21.5%	21.4%	21.5%	21.8%	**4%**	8.2%	8.5%	8.2%
5%	21.2%	20.3%	20.1%	19.9%	19.9%	**5%**	7.0%	7.6%	6.9%
6%	19.4%	19.2%	19.2%	19.2%	19.2%	-	-	-	-
V_a (voids filled with air)									
2%	21.1%	20.7%	19.8%	18.1%	17.5%	**2%**	12.5%	12.8%	12.6%
3%	18.8%	18.4%	17.7%	17.1%	16.7%	**3%**	11.3%	10.6%	10.3%
4%	16.9%	16.1%	16.0%	16.2%	16.3%	**4%**	7.7%	8.0%	7.5%
5%	14.9%	14.3%	14.2%	14.6%	14.9%	**5%**	5.6%	6.3%	6.2%
6%	12.2%	12.9%	13.2%	12.5%	12.1%	-	-	-	-
Bulk specific gravity									
2%	1.925	1.920	1.922	1.932	1.937	**2%**	2.344	2.346	2.345
3%	1.941	1.938	1.938	1.940	1.944	**3%**	2.361	2.359	2.366
4%	1.947	1.951	1.957	1.958	1.954	**4%**	2.401	2.390	2.400
5%	1.952	1.959	1.968	1.970	1.967	**5%**	2.391	2.378	2.391
6%	1.958	1.965	1.967	1.972	1.973	-	-	-	-

4.2 Immersion-compression

The results of the retained strength index can be found in Table 6. The strongest CDWA mixture showed an SI of 81.5%, while the strongest NA mixture had an SI of 92.5%. These values are much higher than the specification threshold of 60%. Although the mixtures that consist of CDWA seemed to be weaker than the NA mixtures, we must consider that both dry and wet UCS were noticeably higher for mixes with CDWA in general. In fact, the peak values shifted from 2914 kPa and 2379 kPa (with NA) to 4411 kPa and 3197 kPa (with CDWA), which constitute increases of 51.4% and 34.4%, respectively.

Table 6. Unconfined Compression Strength (dry and wet) and retained strength ratio of specimens with 100% of recycled aggregate and 100% of natural aggregate

Bitumen content (%)	**CDWA mixture**			**Bitumen content (%)**	**NA mixture**		
	Water content (%)				**Water content (%)**		
	12 %	**15 %**	**18 %**		**6%**	**9%**	**12%**
UCS_{dry} (kPa) non submerged in water specimens							
2%	3412	3776	3508	**2%**	2520	2514	2384
3%	3907	4214	3920	**3%**	**2914**	2570	2761
4%	3883	**4411**	4209	**4%**	2431	2483	2467
5%	3439	4001	3973	**5%**	1579	1624	2074
6%	3052	2777	3345	**-**	-	-	-
UCS_{wet} (kPa) submerged in water specimens							
2%	2704	2892	2860	**2%**	1991	1920	1822
3%	2735	**3197**	2888	**3%**	**2379**	2256	2232
4%	2675	3030	2791	**4%**	2075	2179	2100
5%	2321	2566	2448	**5%**	1396	1286	1918
6%	2049	1884	2009	**-**	-	-	-
RSR (%)							
2%	79.2%	76.6%	**81.5%**	**2%**	79.0%	76.4%	76.5%
3%	70.0%	75.9%	73.7%	**3%**	81.6%	87.8%	80.8%
4%	68.9%	68.7%	66.3%	**4%**	85.4%	87.8%	85.1%
5%	67.5%	64.1%	61.6%	**5%**	88.4%	79.2%	**92.5%**
6%	67.1%	67.8%	60.1%	**-**	-	-	**-**

Thus, mixes with NA have a higher retained strength, not because they are better, but because the improvements obtained by changing NA to CDWA are more marked in the dry strength than the wet strength. In fact, the wet strength for CDWA is even higher than the dry strength of NA. Hence, the mixtures containing 100% CDWA were less likely to be damaged by moisture with respect to the UCS value than mixtures containing 100% NA.

Furthermore, the results show that the optimal bitumen content is almost the same for both mixtures (3% for NA and between 3% and 4% for CDWA). However, the optimal amount of total water in the mix is much higher for mixes containing CDWA (15% against 6%), which is to be expected due to the large absorption capacity of this aggregate.

Finally, Figures 4 and 5 show that the curves for CDWA are more pronounced than for NA. This effect could indicate that small deviations from the optimal binder and water content significantly affect the CDWA. Therefore, the mix and the production must be carefully and accurately designed.

A two-way analysis of variance (ANOVA) was conducted to determine the effect of the water (12%, 15% and 18%) and bitumen (2%, 3%, 4%, 5% and 6%) content on the UCS for CAM with CDWA. The results showed that statistically speaking, only the bitumen content is significant at the 99% confidence level both for the UCS_{dry} ($p_{bitumen}=0.002<0.01$) and UCS_{wet} ($p_{bitumen}<0.001$). The p-values obtained for the water content were not significant even for a 95% confidence level ($p_{water}=0.126>0.05$ and $p_{water}=0.069>0.05$). Similar results were observed for the NA. The content of bitumen (2%, 3%, 4% and 5%) and water (6%, 9% and 12%) was studied, but only the bitumen content was statistically significant for UCS_{dry} ($p_{bitumen}<0.001$) and UCS_{wet} ($p_{bitumen}<0.001$). The p-values obtained for the water content were not significant even at a 95% confidence level ($p_{water}=0.094>0.05$ and $p_{water}=0.389>0.05$). Thus, while the optimal bitumen contents are clear (3% for NA and between 3% and 4% for CDWA), the obtained optimal water contents must be approximated.

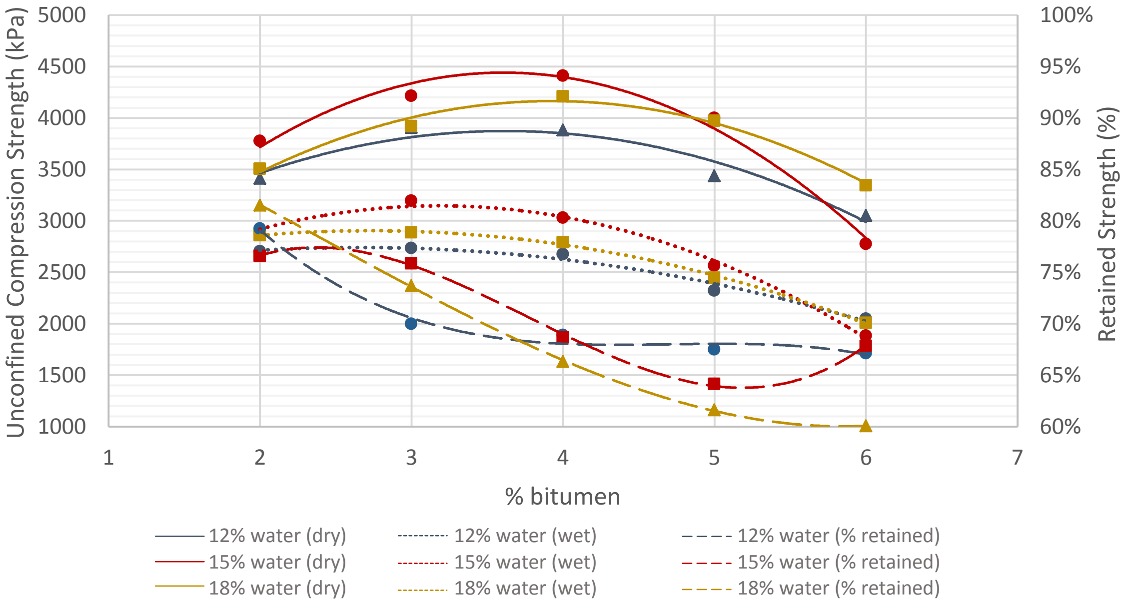


Figure 4. UCS_{dry} (kPa), UCS_{wet} (kPa) and retained strength (%) of dry and wet specimens of cold asphalt mixtures with different water and bitumen contents and a 100% of recycled aggregate

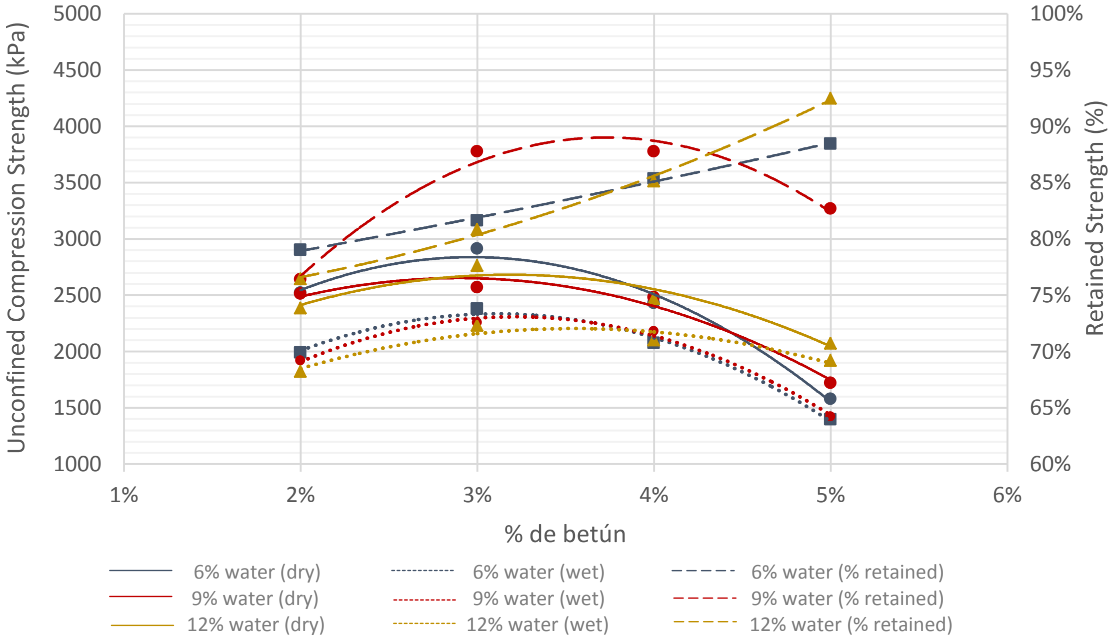
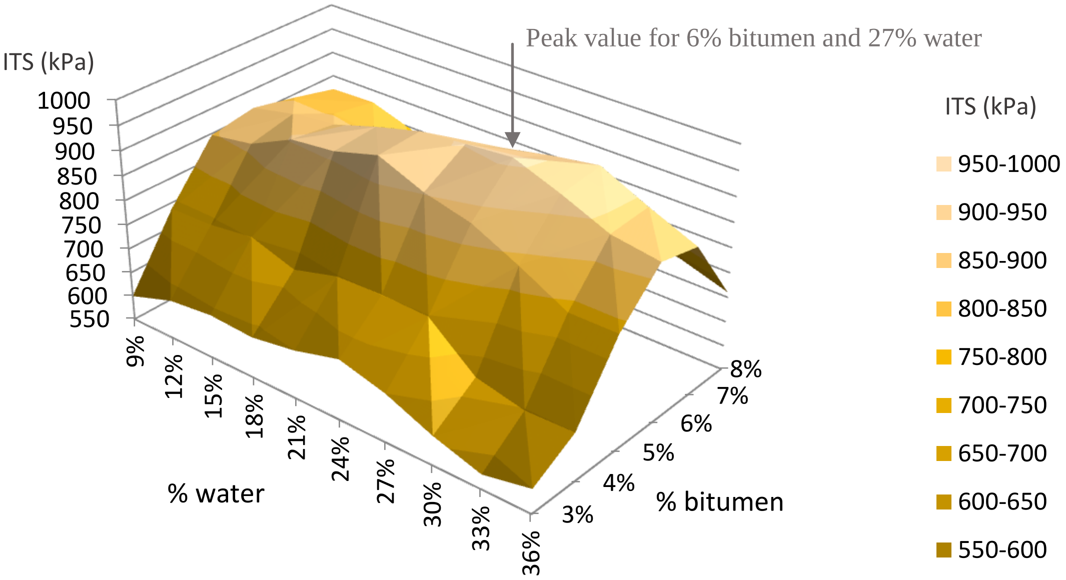


Figure 5. UCS_{dry} (kPa), UCS_{wet} (kPa) and retained strength (%) of dry and wet specimens of cold asphalt mixtures with different water and bitumen contents and a 100% of natural aggregate

4.3 Indirect Tensile Strength

First, the results show that the ITS values more strongly depend on the bitumen content than the water content (Figure 6 and Table 7). Therefore, the curves in Figure 6 tend to be parallel lines from left to right. Thus, the water content of the mixture does not significantly influence the ITS value, but it does influence the bitumen content. In fact, large amounts of water (up to 36%) needed to be tested to obtain a clear ITS peak value, unlike with mixes containing NA. As mentioned above, the amount of water that remained within the specimens after the compaction process does not vary significantly depending on the amount of water added to the mix. Thus, this behaviour is explained by the higher water absorption of CDWA, which forces the premature setting of the emulsion and produces clots and a deficient coating of aggregates during the mixing and compaction processes. Thus, large amounts of water are necessary to maintain the emulsion in a liquid state until the curing process, although most of this water is lost during the compaction process.



Peak value for 6% bitumen and 27% water

Figure 6. Indirect Tensile Strength (kPa) of cold asphalt mixes with 100% of recycled aggregate and different contents of bitumen and water

Table 7. Indirect Tensile Strength (kPa) of cold asphalt mixes with 100% of recycled aggregate and different contents of bitumen and water

	% water (by dry aggregate weight)									
% bitumen	**9%**	**12%**	**15%**	**18%**	**21%**	**24%**	**27%**	**30%**	**33%**	**36%**
3%	602	634	646	635	652	671	652	619	587	606
4%	738	740	752	723	748	751	748	670	648	655
5%	847	862	904	914	940	903	880	835	785	784
6%	862	881	892	920	944	952	**960**	925	885	868
7%	843	841	829	825	860	901	920	935	890	858
8%	821	824	795	747	745	767	777	753	745	713

Compared to NA (Figure 7 and Table 8), CDWA mixtures require considerably more water because NA mixtures do not set the emulsions. Therefore, the water acts as a harmful element, and the peak ITS values are achieved at the lowest studied water percentage. A lower amount would not be possible because a 3% water content is approximately equal to the water provided by the emulsion.

Conversely, the bitumen content of 100% CDWA and NA mixtures was optimised at 6 and 4%, respectively. This extra amount of bitumen is consistent with the publications of other authors that studied different types of CDWA in hot mixes.

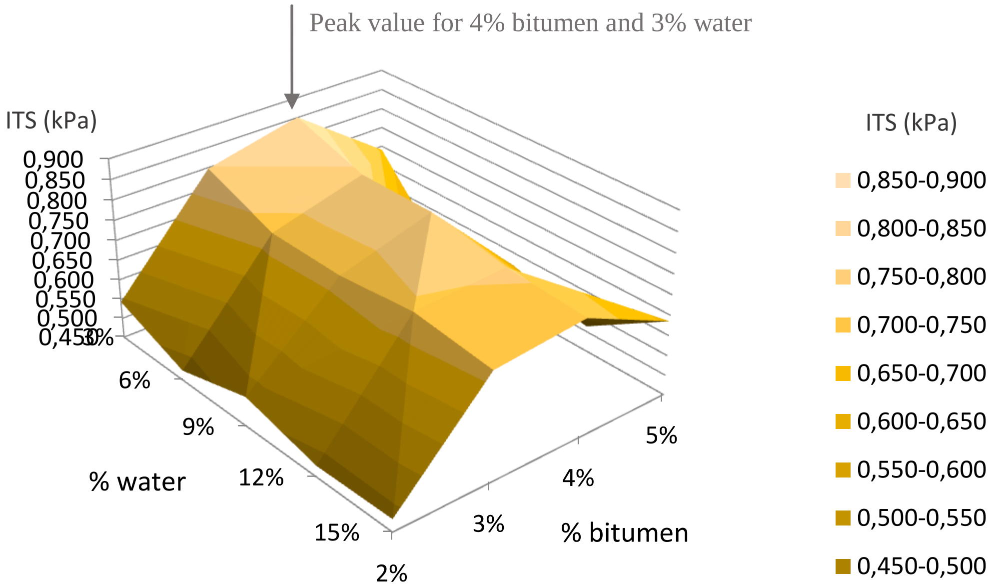

Peak value for 4% bitumen and 3% water

Figure 7. Indirect Tensile Strength (kPa) of cold asphalt mixes with 100% of natural aggregate and different contents of bitumen and water

Table 8. Indirect Tensile Strength (kPa) of cold asphalt mixes with 100% of natural aggregate and different contents of bitumen and water

% bitumen	% water (by dry aggregate weight)				
	3%	**6%**	**9%**	**12%**	**15%**
2%	543	475	525	478	482
3%	798	729	724	743	719
4%	**851**	792	791	755	739
5%	690	485	567	513	635

Finally, the peak ITS value for mixes containing CDWA is 12.8% higher than for those containing NA. Thus, CDWA is again beneficial for asphalt cold mixes.

A two-way ANOVA was again conducted to determine the effect of the water (9%, 12%, 15%, 18%, 21%, 24%, 27%, 30%, 33%, 36%) and bitumen (3%, 4%, 5%, 6%, 7%, 8%) content on the ITS. The results confirm the above explanation and indicate that both the water and bitumen contents are statistically significant at the 99% confidence level (p_{water}=0.002<0.01 and $p_{bitumen}$<0.001). For NA, the ANOVA showed that the studied percentages of water (3%, 6%, 9%, 12% and 15%) and bitumen (2%, 3%, 4% and 5%) are significant at the 99% confidence level (p_{water}<0.001 and $p_{bitumen}$<0.001).

4.4 Stiffness modulus

The resilient modulus test results are shown in Figure 8 and Table 9 for CDWA mixes and in Figure 9 and Table 10 for NA mixes. Like the ITS results, the ITSM results more strongly depend on the bitumen content than the water content, and the curves tended to be lines that are parallel to the axis of water content. The ITSM is higher in mixes containing CDWA, but at 20ºC, it is higher in mixes containing NA, which indicates that the mechanical behaviour of mixes containing CDWA is less susceptible to changes in temperature. For example, heating NA from 2ºC to 20ºC results in a loss of stiffness near 80% in many cases, which does not occur for CDWA (the loss is near 50%). Thus, mixes containing CDWA are less susceptible to temperature changes and therefore less prone to cracking at lower temperatures and rutting at high temperatures.

Table 9. Resilient Modulus (MPa) of cold asphalt mixes with 100% of CDWA and different contents of bitumen and water at 2ºC. 10ºC and 20ºC

% bitumen	**% water**									
	9%	**12%**	**15%**	**18%**	**21%**	**24%**	**27%**	**30%**	**33%**	**36%**
ITSM at T=2ºC										
3%	3256	4567	4551	4114	4944	6009	5993	5911	5839	5820
4%	4990	6010	6493	5900	6228	6592	6493	6433	6352	6434
5%	6486	7586	7606	7738	7740	7485	7058	6976	6822	6957
6%	7512	7461	7374	7731	7859	7959	8010	7560	7531	7545
7%	7532	7325	7140	7023	6851	7412	8019	**8407**	7611	7518
8%	7251	7140	6723	6359	6082	6234	7385	7480	7105	6689
ITSM at T=10ºC										
3%	3132	4022	4201	3496	3887	4811	5064	4808	4679	4552
4%	3805	4654	4912	4659	4895	5284	5102	5094	5063	4989
5%	4610	5670	5889	5890	5831	5880	5530	5392	5402	5410
6%	4254	5813	5448	5950	6007	5980	6010	5941	5693	5607
7%	5778	5468	5153	5199	5105	5170	5492	**6044**	5741	5599
8%	5632	5254	4790	4506	4220	4400	4717	5015	4913	4720
ITSM at T=20ºC										
3%	2379	2622	2490	2710	3043	3312	3596	3566	3558	3570
4%	2741	3013	3318	3182	3380	3595	3667	3657	3601	3583
5%	3024	3723	**4024**	3854	3912	4001	3766	3640	3618	3553
6%	3515	3642	3418	3866	3896	3786	4006	3799	3586	3451
7%	3403	3321	2844	2987	3079	2983	3421	3812	3490	3213
8%	3288	2837	2668	2394	2311	2269	2565	2707	2724	2526

The results are comparable and even higher than the ones published by different authors about CAM containing NA, even with additions (i.e., cement) or a much longer curing time [4, 5, 30, 31]. Conversely, the resilient modulus did not reach the 5000 MPa at 20ºC, a value more typical of hot asphalt mixes. Thus, the obtained mixes retain a certain stiffness that is very useful in low and medium traffic roads, where the subgrades are usually not of good quality.

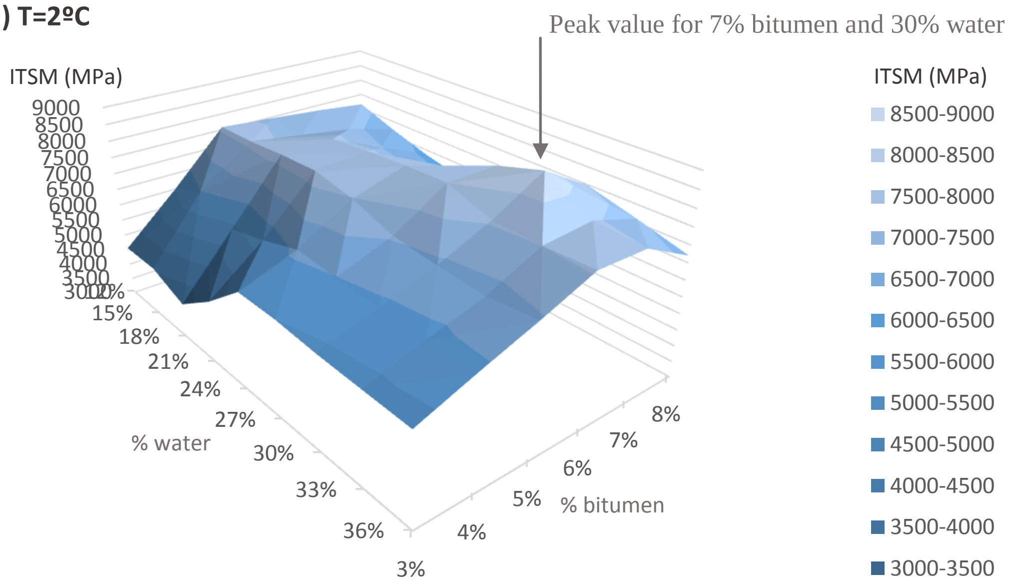
Finally, the optimal water/bitumen contents (understood as the contents that result in the highest resilient modulus) depend on the test temperature. For CDWA, the optimal contents range from 7% bitumen and 30% water at 2ºC to 5% bitumen and 15% water at 20ºC. The latter bitumen/water contents could be defined as better because they result in the highest stiffness at high temperatures (favourable to prevent permanent deformations), but not the highest stiffness at low temperatures (favourable to avoid fatigue cracking). Conversely, the NA materials showed a peak value at 20ºC for 4% bitumen and 3% water (the minimum allowed by the inherent water of the emulsion). Thus, the water is noxious to mixes with NA but necessary for mixes with CDWA.

Again, a three-way ANOVA was carried out to statistically evaluate the results of ITSM. For CDWA, both the water (9%, 12%, 15%, 18%, 21%, 24%, 27%, 30%, 33%, 36%) and bitumen content (3%, 4%, 5%, 6%, 7%, 8%) as well as the temperature (2ºC, 10ºC and 20ºC) showed statistically significant effects at a 99% confidence level (p_{water}=0.001, $p_{bitumen}$<0.001 and $p_{bitumen}$<0.001). For the NA, all contents also resulted in significant effects (p_{water}<0.001 and $p_{bitumen}$<0.001 and $p_{bitumen}$<0.001).

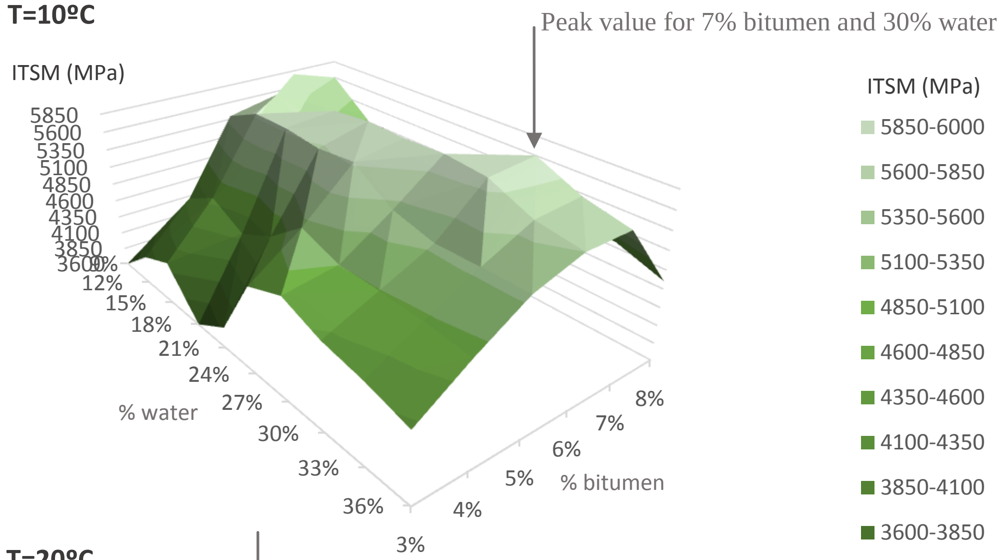
Table 10. Resilient Modulus (MPa) of cold asphalt mixes with 100% of NA and different contents of bitumen and water at 2ºC. 10ºC and 20ºC

% bitumen	% water				
	3%	**6%**	**9%**	**12%**	**15%**
			ITSM at T=2ºC		
2%	6892	5980	5938	6528	6471
3%	9821	10431	9375	9560	9852
4%	**11096**	10184	9521	8810	10004
5%	8303	6189	5777	6905	8939
			ITSM at T=10ºC		
2%	4203	3608	3478	3784	3944
3%	5457	5882	5529	5684	5602
4%	**6230**	5678	5495	4918	5699
5%	4404	3167	2954	3751	5059
			ITSM at T=20ºC		
2%	1844	1619	1387	1469	1691
3%	2351	2298	2137	2308	2374
4%	**2537**	2197	2137	1795	2184
5%	1459	963	931	1310	1850

a) T=2ºC



b) T=10ºC



c) T=20ºC

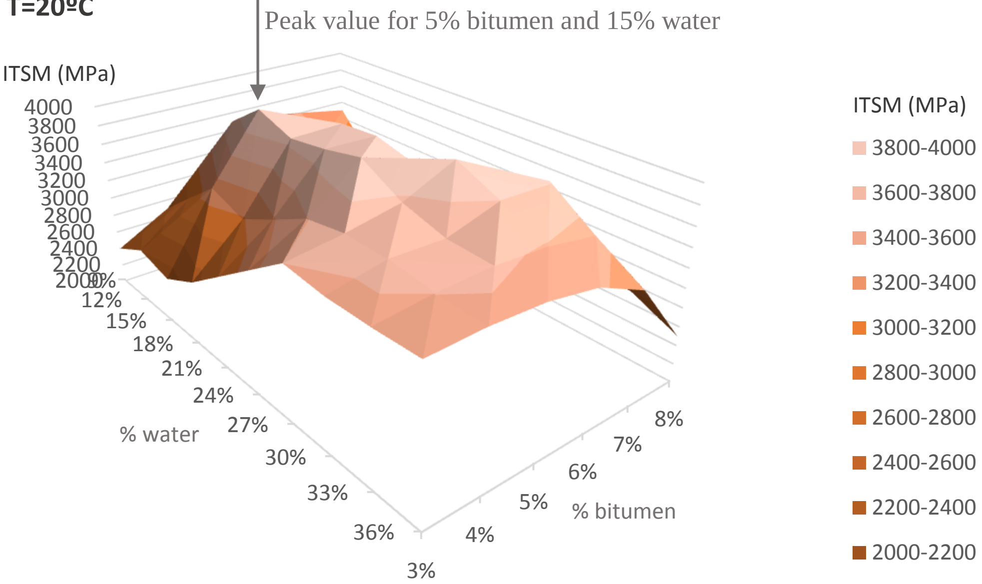


Figure 8. Resilient Modulus (MPa) of cold asphalt mixes with 100% of CDWA and different contents of bitumen and water at a) 2ºC, b) 10ºC and c) 20ºC

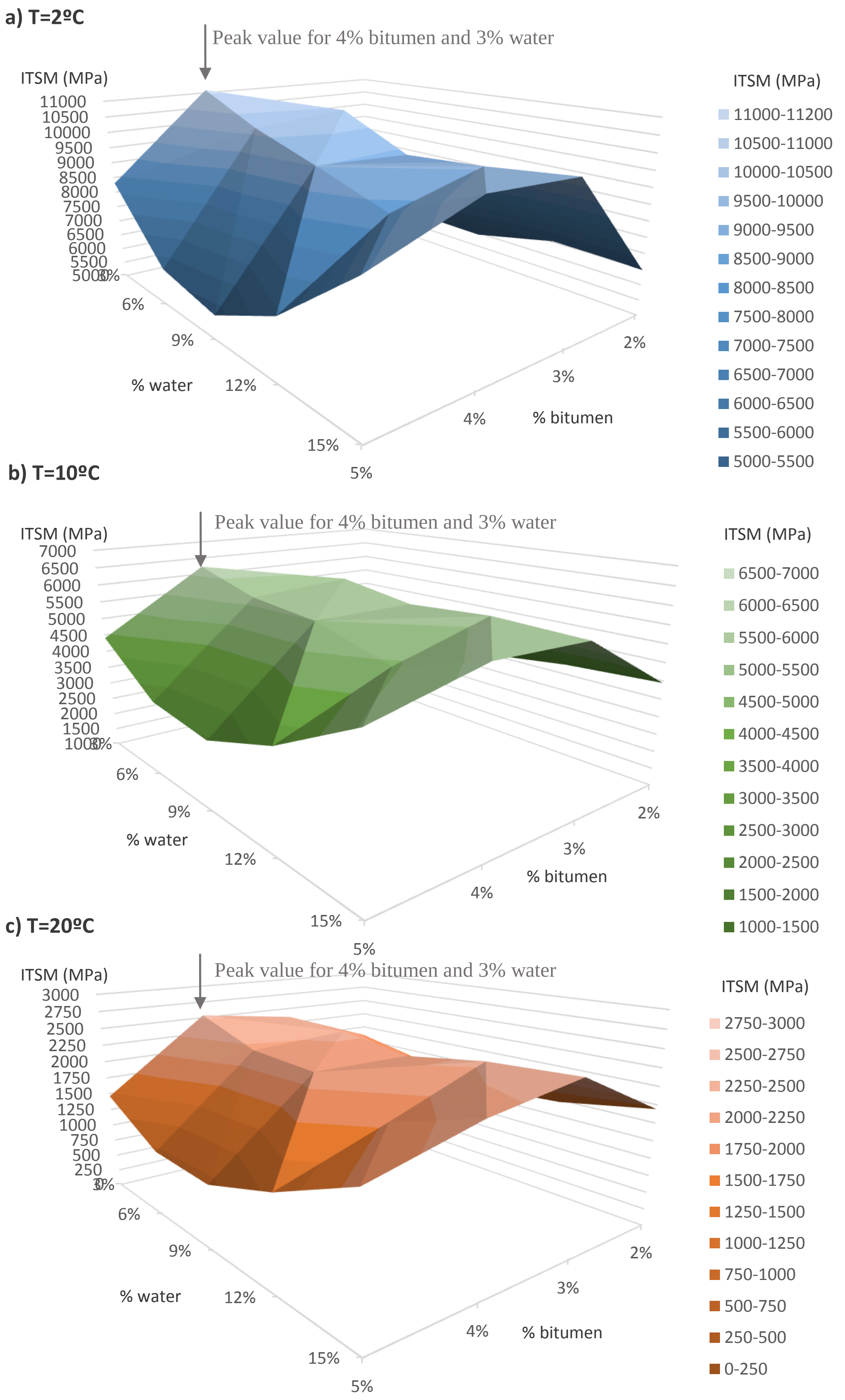


Figure 9. Resilient Modulus (MPa) of cold asphalt mixes with 100% of NA and different contents of bitumen and water at a) 2ºC, b) 10ºC and c) 20ºC

5. Discussion

When studied as an aggregate, CDWA exhibited poor properties that make these materials less favourable than NA in principle. For instance, they were weaker, more prone to breaking, had a higher Los Angeles coefficient and absorbed large amounts of water. Moreover, they result in the premature setting of bituminous emulsions to produce clots and an incomplete coating of aggregates. However, carefully and accurately designing the mixing process and production, which usually involved slightly greater amounts of bitumen and noticeably greater amounts of water, cold asphalt mixes containing 100% CDWA showed properties that were preferred to those of the NA.

Both the wet and dry UCS were improved and met all of the considered standards and recommendations, such as the RSR, by substituting NA with CDWA. The peak values of UCS_{dry} and UCS_{wet} shifted from 2914 kPa and 2379 kPa in mixes with NA to 4411 kPa and 3197 kPa in mixes with 100% CDWA, which constitutes increases of 51.4% and 34.4%, respectively. Because the wet strength grew less than the dry strength, higher retained strength indices were obtained. However, this pattern does not indicate that mixes containing CDWA are more susceptible to moisture damage because the UCS_{wet} of CDWA mixes continued to exceed the UCS_{dry} of NA mixes.

CDWA also favourably contributes to CAM with respect to the ITS (and therefore stress cracking resistance), reaching ITS values of 12.8% or higher.

As expected, the ITSM negatively correlated with the temperature, but this effect was less pronounced in cold asphalt mixes that contained 100% CDWA. Hence, CDWA mixes retain a higher stiffness at higher temperatures (favourable for protecting against permanent deformations) and a lower stiffness at low temperatures (favourable for avoiding fatigue cracking). Furthermore, the ITSM values of CDWA mixes were found to fall between the values of NA cold mixes and hot asphalt mixes, which indicates that they should perform well in practice.

The water and bitumen optimal content (meaning the optimum water content and the total amount of water present during the mixing process) depends on the type of aggregate and the tested property (Table 11). Conversely, the bitumen percentages that produced peak values tended to be slightly greater for CDWA (up to 3% difference). Nevertheless, the amounts of water that are required for CDWA are very large when compared with the ones needed for NA. However, the curves are more susceptible to bitumen than water variations. Hence, lower water contents could be used for a mix design without significant losses in the ITS or ITSM.

Once all of these considerations have been taken into account, the authors propose a compromise mix design that consists of 15% water and 5% bitumen. In this situation, the UCS_{dry} (4001 kPa), UCS_{we}t (2566 kPa) and RSR (64.1%) remain above the specification limits of 1200 kPa, 1000 kPa and 60%, respectively. The ITS would fall from 960 kPa to 904 kPa (an acceptable reduction), and the ITSM at 2ºC and 10ºC would fall from 8407 MPa and 6044 MPa to 7606 MPa and 5889 MPa, respectively (which helps to prevent fatigue cracking at low temperatures). Nevertheless, the ITSM would be maximised at 20ºC (optimal ITSM value to avoid rutting at high temperatures).

Table 11. Water and bitumen contents which produce the peak values of tested properties

Property	CDWA Aggregate		Natural Aggregate	
	% water	% bitumen	% water	% bitumen
UCS_{dry}	15%	4%	6%	3%
UCS_{wet}	15%	3%	6%	3%
ITS	27%	6%	3%	4%
ITSM – 2ºC	30%	7%	3%	4%
ITSM – 10ºC	30%	7%	3%	4%
ITSM – 20ºC	15%	5%	3%	4%

Notably, other water and bitumen percentages could be used if the conditions of service so require. For example, the results indicate that lower water and bitumen contents would be desirable (12% and 3%) if the average rainfall in the area is high but the average temperature is near 20ºC because the UCS_{wet} is optimal without losing much stiffness. This versatility makes cold asphalt mixes with recycled aggregates more suitable to a wider range of uses.

6. Conclusions

The research project aimed to evaluate the potential of using CDWA as an aggregate for CAM for low traffic asphalt roads. Based on the laboratory experiments and analyses, the following conclusions can be summarised:

1. The traditional mix design methods for cold asphalt mixtures are not suitable when incorporating CDWA into the mix. A global study of different properties must be conducted to reach a compromise depending on the use of the cold asphalt mix. Moreover, the design and production requires precision and care.

2. Cold asphalt mixes containing CDWA are more versatile than NA mixes. These mixes can be suitable for a wide range of environmental features (e.g., temperature, rainfall) and service conditions (traffic loads) by simply varying the water and bitumen contents.

3. Mechanical properties, such as the UCS, ITS and ITSM, show important improvements shortly after production when the NA are replaced by CDWA.

4. Cold asphalt mixes containing CDWA perform better under conditions of abundant moisture and/or temperature variations.

5. In general terms, aggregate CDWA materials have poor properties, which make them worse than NA. However, CDWA can potentiate CAM to improve their performance. Therefore, CDWA has a great market potential when being transformed to a raw material for road engineering from waste.

6. The amount of water present within the specimens after the compaction process does not strongly depend on the total amount of water incorporated during the mixing process. However, the water is important to maintain the bitumen emulsion in a liquid state while mixing it with an extremely absorbent aggregate, such as CDWA. Hence, low amounts of water result in the premature setting of the emulsion, which can be noticed by examining at the results obtained for the mechanical properties.

Acknowledgements

The authors would like to acknowledge the funding of 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 sincere gratitude to the GESTAN Group for the CDWA and to ECOASFALT for the bitumen emulsion that were generously donated for the present research.

References

[1] Thanaya INA, Zoorob SE, Forth JP. A laboratory study on cold-mix, cold lay emulsion mixtures. Proceedings of the Institution of Civil Engineers. February 2009; Transport 162:47-55.

[2] Khalid HA, Monney OK. Moisture damage potential of cold asphalt. International Journal of Pavement Engineering. October 2008;10(5):311-318

[3] Serfass JP. Advantages peculiarities and mysteries of emulsion cold mixes. Revue General des Routes et Autoroutes 2002;802: 60-68

[4] Oruc S, Celik F, Akpinar MV. Effect of Cement on Emulsified Asphalt Mixtures. Journal of Materials Engineering and Performance. October 2007;16(5):578-583

[5] Thanaya INA. Evaluating and improving the performance of cold asphalt emulsion mixes. Civil Engineering Dimension. September 2007;9(2); 64-69

[6] Chávez-Valencia LE, Alonso E, Manzano A, Pérez J, Contreras ME, Signoret C. Improving the compressive strengths of cold-mix asphalt using asphalt emulsion modified by polyvinyl acetate. Construction and Building Materials 2007;21:583-589

[7] European Asphalt Pavement Association (EAPA). Asphalt in figures. EAPA; 2012

[8] Mills-Beale J, You Z. The mechanical properties of asphalt mixtures with Recycled Concrete Aggregates. Construction and Building Materials 2010;24:230-235

[9] Pérez I, Gallego J, Toledano M, Taibo J. Asphalt mixtures with construction and demolition debris. Proceedings of the Institution of Civil Engineers. Transport November 2010;163:165-174

[10] Shen DH, Du JC. Application of gray relational analysis to evaluate HMA with reclaimed building materials. Journal of Materials in Civil Engineering. July/August 2005:400-406.

[11] Paranavithana S, Mohajerani A. Effects of recycled concrete aggregates on properties of asphalt concrete. Resources Conservation & Recycling 2006;48:1-12

[12] Wong YD, Sun DD, Lai D. Value-added utilization of recycled concrete in hot-mix asphalt. Waste Management 2007;27:294-301

[13] Chen MZ, Lin JT, Wu SP. Potential of recycled fine aggregates powder as filler in asphalt mixture. Construction and Building Materials 2011;25:3909-3914

[14] Pasetto M, Baldo N. Mix design and performance analysis of asphalt concretes with electric arc furnace slag. Construction and Building Materials 2011;25:3458-3468

[15] Wu S, Zhu J, Zhong J, Wang D. Experimental investigation on related properties of asphalt mastic containing recycled red brick powder. Construction and Building Materials 2011;25:2883-2887

[16] Akbulut H, Gürer C. Use of aggregates produced from marble quarry waste in asphalt pavements. Building and Environment 2007;42:1921-1939

[17] AENOR. Asociación Española de Normalización y Certificación. UNE EN 933-3. Ensayos para determinar las propiedades geométricas de los áridos. Parte 3: Determinación de la forma de las partículas. Índice de lajas. Madrid, Spain; 2012

[18] AENOR. Asociación Española de Normalización y Certificación. UNE EN 933-5. Ensayos para determinar las propiedades geométricas de los áridos. Parte 5: Determinación del porcentaje de caras de fractura de las partículas de árido grueso. Madrid, Spain; 1999

[19] AENOR. Asociación Española de Normalización y Certificación. UNE EN 933-8. Ensayos para determinar las propiedades geométricas de los áridos. Parte 8: Evaluación de los finos. Ensayo del equivalente de arena. Madrid, Spain; 2000

[20] AENOR. Asociación Española de Normalización y Certificación. UNE EN 1097-2. Ensayos para determinar las propiedades mecánicas y físicas de los áridos. Parte 2: Métodos para la determinación de la resistencia a la fragmentación. Madrid, Spain; 2010

[21] AENOR. Asociación Española de Normalización y Certificación. UNE EN 1097-6. Ensayos para determinar las propiedades mecánicas y físicas de los áridos. Parte 6: Determinación de la densidad de partículas y la absorción de agua. Madrid, Spain; 2006

[22] Technical Association of Bituminous Emulsions (ATEB). Gravel-emulsion specifications. ATEB (consulted on-line in http://www.ateb.es/pdf/PLI_GRAVA.pdf last time on 08/08/2013)

[23] Asphalt Institute. Asphalt Cold Mix Manual. Manual Series No. 14 (MS.14).Third edition. Asphalt Institute; 1997

[24] AENOR. Asociación Española de Normalización y Certificación. UNE 103-501-94. Geotecnia. Ensayos de compactación. Proctor modificado. Madrid, Spain; 1994

[25] Pasandín AR, Pérez I. Laboratory evaluation of hot-mix asphalt containing construction and demolition waste. Construction and Building Materials 2013;43:497-505

[26] Ministerio de Obras Públicas y Transportes. Normas NLT. Ensayos de carreteras. Dirección General de Carreteras, 2nd ed. Madrid, Spain; 2002.

[27] AENOR. Asociación Española de Normalización y Certificación. UNE EN 12697-23. Métodos de ensayo para mezclas bituminosas en caliente. Parte 23: Determinación de la resistencia a la tracción indirecta de probetas bituminosas. Madrid, Spain; 2004

[28] AENOR. Asociación Española de Normalización y Certificación. UNE-EN 12697-26. Métodos de ensayo para mezclas bituminosas en caliente. Parte 26: Rigidez. Madrid, Spain; 2006

[29] Ministerio de Fomento. O.C. 24/08 sobre el Pliego de Prescripciones Técnicas Generales para obras de carreteras y puentes (PG-3); 2002

[30] Ozsahin TS, Oruc S. Neural network model for resilient modulus of emulsified asphalt mixtures. Construction and Building Materials. 2008;22:1436-1445

[31] Nageim Al H, Al-Busaltan SF, Atherton W, Sharples G. A comparative study for improving the mechanical properties of cold bituminous emulsion mixtures with cement and waste materials. Construction and Building Materials 2012;36:743-748