View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Repositorio da Universidade da Coruña

Author's version

B. GÓMEZ-MEIJIDE and I. PÉREZ

-

Published in MATERIALS AND DESIGN as:

B. Gómez-Meijide, I. Pérez. A proposed methodology for the global study of the mechanical properties of cold asphalt mixtures. Materials and Design 57 (2014) 520–527

http://dx.doi.org/10.1016/j.matdes.2013.12.079

A proposed methodology for the global study of the mechanical properties of 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

Despite having been used for decades, the structural performance of emulsion-treated materials has still not been investigated as intensely as in the case of hot-mix asphalt (HMA). Proof of this is the lack of evolution of specific technical tests and standards. Due to this, many studies with cold asphalt mixtures (CAM) are carried out based on HMA specifications. Throughout the present paper, a new methodology is proposed in order to study different mechanical properties of CAM, such as unconfined compression strength (UCS), indirect tensile strength (ITS) and indirect tensile stiffness modulus (ITSM) not only in an independent way but also by giving a global approach. The consistency and applicability of the method is discussed and from its application to a practical case study with two very different CAM, new conclusions about their performance are laid down.

Keywords: *emulsion-treated material; cold asphalt mix; unconfined compression strength; indirect tensile strength; indirect tensile stiffness modulus*

1. Introduction

Cold asphalt mixes (CAM) have been considered inferior to hot-mix asphalt (HMA) over the last decades due to the high air-void content of the compacted mixtures, weak early life strength and long curing times required to achieve an optimal performance [1]. However, in general terms, CAM tend to be better in certain aspects, such as production and implementation costs, ecology and sustainability, safety and the health of workers and even regarding some mechanical properties (i.e. flexibility). Furthermore, day by day new improvements come to light, which have already allowed producers to obtain high quality CAM, which in many cases are more suitable for certain applications than HMA. It is no wonder then that over the last years the production of CAM has been increasing in many countries, reaching annual productions of 1.5 million tones in France or 2 million tones in Turkey [2].

However, the structural performance of emulsion-treated materials has not been investigated in detail although they have been used with great success for a number of years [3]. In fact, from the point of view of the laboratory tests, the specific tests for CAM have barely been developed in decades, so there is a problem that still has not been solved. On the one hand, there are tests which take into account the need of cold mixes to be subjected to a higher energy compaction than the hot mixes, in order to drain out the water and cause the setting of the emulsion while the residual bitumen flows through interstitial voids getting in this way a suitable coating of the aggregates. Examples include immersion-compression and simple compression tests governed by the Spanish Standards NLT-161 [4] and NLT-162 [4] (somehow heirs from the French *Duriez* test, NF P98-251 [5]), which explicitly required a static compaction.

On the other hand, there are numerous properties which do not have a specific test standard for CAM and that is why, for analysis, many authors resort to compaction methods more suitable for HMA (like the Marshall hammer) or granular materials (such as vibrating hammer) [6] which fail to achieve the desired effect, resulting in fragile, not very resistant and with consequent detachment of material specimens.

To some extent, even using a compaction method unsuitable for CAM, as long as it is kept the same for all tests, the results could be comparable, though probably far from reality. The problem, as mentioned, is that this does not happen from a normative point of view.

Therefore, in this research, the method that the authors have followed when analyzing the different properties of CAM, not only separately, but also analyzing the relationship between pairs of them in a faithful and true way is set out.

Finally, the results of application examples conducted on CAM made with two very different types of aggregates, in which the consistency and wide applicability of the proposed process is reflected, are presented.

2. Materials used

In order to show the wide applicability of the proposed method, two very different aggregates were used obtaining CAM whose properties can be compared. On the one hand, a hornfels, a metamorphic siliceous aggregate from a natural quarry (hereafter, natural aggregate or NA) and on the other hand, a 100% recycled aggregate from Construction and Demolition Waste (hereafter construction and demolition waste aggregate or CDWA) whose composition is given in Table 1 for the received coarse and medium fractions. Most of this aggregate was concrete and natural stone but impurities, such as asphalt materials, plaster, aerated concrete or limestone were found which, in some cases, needed the use of an X-Ray diffractogram to truly define their source. This aggregate has very different properties compared to a NA but it is suitable for use in both cold and hot asphalt mixes according to other investigations [7, 8].

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

Material	% in coarse aggregate	% in medium aggregate
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%
Plastics	0.015%	0.0%
Metal	0.002%	0.029%
Light materials (paper, plastics)	0.001%	0.002%
Asphalt materials	< 0.001%	< 0.001%
Glass	< 0.001%	< 0.001%
Other no identifiable	< 0.001%	0.008%

Table 2 shows the different properties of both natural and recycled aggregates such as a poor Los Angeles coefficient, Flakiness Index and Crushed Particles Percentage of CDWA. However, the most characteristic feature is its low specific gravity and the huge water absorption which will clearly affect the mechanical and rheological properties of the bituminous mixtures made from them.

Table 2. Characterization of recycled and natural aggregates

Property	Recycled aggregate	Natural aggregate
Flakiness Index (UNE EN 933-3 [9])	4.5%	19.8%
Crushed particles (UNE EN 933-5 [10])	89%	94%
Sand equivalent (UNE EN 933-8 [11])	77	78
Los Angeles coefficient (UNE EN 1097-2 [12])	38	14
Bulk specific gravity (UNE EN 1097-6 [13])	2.64 t/m^3	2.78 t/m^3
Dry specific gravity (UNE EN 1097-6 [13])	2.23 t/m^3	2.74 t/m^3
SSD specific gravity (UNE EN 1097-6 [13])	2.39 t/m^3	2.75 t/m^3
Absorption (UNE EN 1097-6 [13])	7.0%	0.5%

Table 3. Cumulative passing values of CDWA before and after compaction compared with ATEB recommendations

Sieve size (mm)	ATEB upper limit	ATEB lower limit	Selected gradation	Gradation after compaction
40	-	-	0	0
31.5	100	100	100	100
20	100	80	90	93.4
12.5	82	66	74	79.9
8	69	54	57	67.3
4	54	38	42	51.2
2	40	26	30	37.2
0.5	22	13	14	18.9
0.25	16	8	9	12.2
0.125	10	5	5.5	7.8
0.063	5	2	2.5	3.8

The adopted aggregate gradations were based on the recommendations given by the Spanish Technical Association of Bituminous Emulsions (ATEB) for GE1 grave-emulsions but slightly modified in order to keep it within the upper and lower limits after compaction since the gradation of recycled aggregate tended to get modified as observed and shown in Figure 1 and Table 3.

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

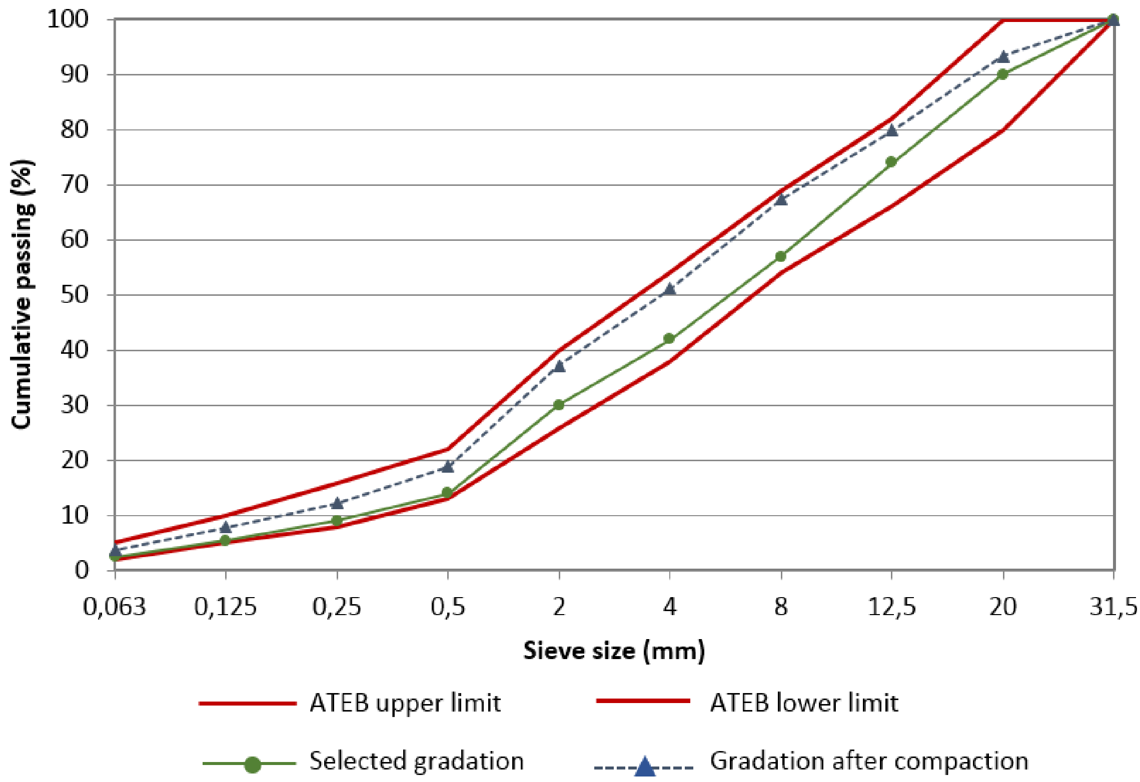

Figure 1. Aggregate gradation of CDWA before and after compaction compared with ATEB recommendations

3. Method

3.1 Specimen production

As explained, there is not a standardized production and compaction method generally adopted by diverse test standards. This way, for instance, the specimens made to be subjected to an Unconfined Compression Strength (UCS) test could have different properties than others made to be subjected to an Indirect Tensile Strength (ITS) test. As a consequence, both results could not be comparable to each other. Due to this, the aim of this research was to standardize a method which allows to get specimens of different sizes but with identical intrinsic properties, such as specific gravity, voids, moisture, aggregates degradation after compaction etc. in order to test them in different ways and to relate the results with a complete reliance. That is, if two series of results, such as UCS and ITS show no relationship to each other, at least the fact that this happens because the production of the specimens was performed with different methods can be rejected and therefore, the test samples might not be equal either.

The specific for CAM Immersion-Compression test (NLT-162 [4]) and Unconfined Compressive Strength test (NLT-161 [4]) contained a standard procedure by means of which 101.6 mm diameter by 101.6 mm height cylindrical specimens are obtained. The compaction process involves the application of the following steps (Figure 2 was collected by the monitoring equipment of the authors during the development of this research):

• 1-min loading ramp to reach a 1 MPa preload (8.11 kN for 101.6 mm diameter specimens)

• maintain the preload for 1 min

• 2-min loading ramp up to the 21 MPa peak load (170 kN for 101.6 mm diameter specimens)

• maintain the peak load for 2 min

• 1-min downloading ramp

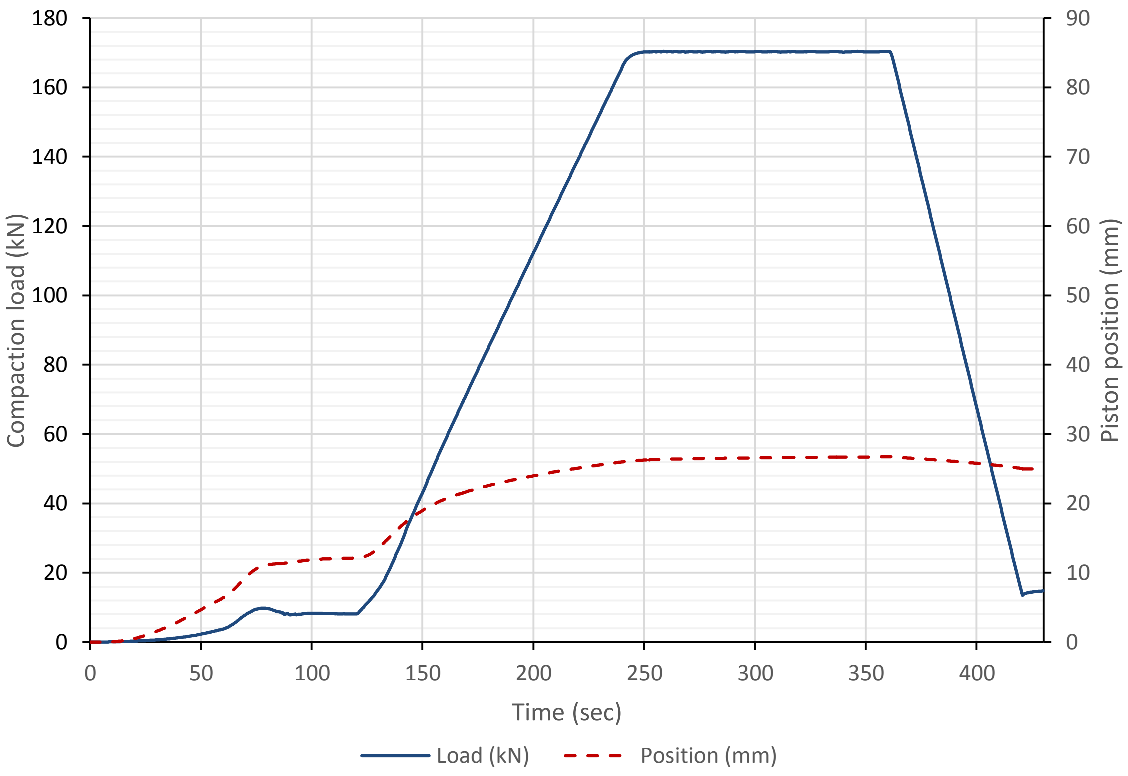

Figure 2. Recorded load and compactor position curves during static compaction process

However, ITS test (according to UNE-EN 12697-23 [14]) and ITSM test (UNE-EN 12697-26 [15]) require specimens whose height is between 35 mm and 75 mm and between 30 and 75 mm respectively. Hence, it was chosen to look for specimens between 35-75 mm height with different amounts of mixture and subjected to different peak loads (while keeping the original shape of the compaction curve shown in Figure 2) until they met the following criteria:

• The grain size of the test specimens should not be changed under the loads of compaction, so that it goes out of the limits. If this happens, it would be considered that the compaction energy is excessive for the amount of material compacted.

• Density and air voids content should be similar to the immersion-compression specimens. In this way, it is sure that the internal order of the specimens is similar, expecting similar behavior.

• The strain experienced by the material between the preload and peak load (Figure 2), should be similar to the immersion-compression specimens. Shortening too means that the peak compaction load was excessive while, if the deformation is lower than expected it would have to try with higher loads.

After diverse bitumen extractions, it was found that the deviation of the distribution curves after compaction was similar to that exhibited in the normal immersion-compression specimens. However, it failed to achieve a solution that fulfilled all criteria simultaneously. Three different compaction energies (21 MPa, 13 MPa and 10 MPa) were tested in 60 mm high specimens (Table 4) and it was found that the compaction load should be up to 21 MPa to match the density and voids content of the immersion-compression specimens. However, the strains appreciated for these stress levels were found to be too high and should not go from 13 MPa to achieve the same deformation observed in immersion-compression reference specimens (Table 5).

Table 4. Bulk density and air voids content of specimens subjected to different compaction energies (specimen 1 to 22) and compared to reference specimens (R1 to R4) made according to Spanish Standard NLT-161

Specimen	Compaction Energy (MPa)	Specimen Height (mm)	Bulk Density (t/m^3)	Air Voids (%)
1	21	58.9	1.964	20.69
2	21	59.2	1.977	20.19
3	21	58.7	1.972	20.37
4	21	62.0	1.982	19.97
5	21	62.1	1.974	20.31
6	21	62.1	1.958	20.94
Average			**1.971**	**20.41**
7	13	60.0	1.923	22.35
8	13	60.4	1.928	22.15
9	13	60.6	1.953	21.14
10	13	60.8	1.904	23.12
11	13	63.7	1.912	22.79
12	13	63.7	1.935	21.87
13	13	63.4	1.916	22.65
14	13	63.1	1.914	22.74
Average			**1.923**	**22.35**
15	10	61.1	1.899	23.33
16	10	61.9	1.892	23.64
17	10	61.7	1.911	22.85
18	10	62.0	1.904	23.12
19	10	64.8	1.902	23.22
20	10	65.4	1.898	23.36
21	10	64.9	1.898	23.36
22	10	64.7	1.907	23.01
Average			**1.901**	**23.24**
R1	21	100.8	1.974	20.32
R2	21	101.4	1.965	20.66
R3	21	101.9	1.979	20.13
R4	21	101.1	1.973	20.33
Average			**1.972**	**20.36**

Table 5. Strains observed in specimens subjected to different compaction energies (specimens 1 to 14) and compared to reference specimens (R1 to R10) made according to Spanish Standard NLT-161

Specimen	Compaction Energy (MPa)	Specimen Height (mm)	Strain
1	21	61.95	0.291
2	21	62.00	0.287
3	21	62.08	0.318
4	21	61.58	0.294
Average			**0.297**
5	13	63.70	0.233
6	13	63.80	0.224
7	13	63.30	0.225
8	13	63.20	0.230
9	13	63.20	0.215
Average			**0.225**
10	10	64.90	0.205
11	10	65.40	0.203
12	10	64.90	0.198
13	10	64.70	0.203
14	10	65.30	0.196
Average			**0.201**
R1	21	100.53	0.242
R2	21	100.20	0.216
R3	21	101.60	0.242
R4	21	100.60	0.224
R5	21	100.60	0.218
R6	21	99.30	0.212
R7	21	101.50	0.224
R8	21	100.40	0.217
R9	21	99.80	0.219
R10	21	99.00	0.215
Average			**0.223**

Because of this lack of conformity, the decision was to produce all of 101.6 mm height according to Standard NLT-161 [4] and then splitting them by cutting through the middle plane. Thus, each of these samples that could be named "mother specimens" became divided into two 50 mm high 'twin specimens' (Figure 3).

Figure 3. Schematic process to obtain two 50 mm height 'twin' specimens from the same 101.6 mm height 'mother specimen'. Three specimens have exactly the same intrinsic properties (specific gravity, voids content, moisture content, etc)

The cut was made with a radial saw blade suitable for concrete and stone materials and after having fixed the perimeters of the specimen with a couple of tapes on each side of the cut which prevented the release of material due to friction with the saw. In these operations, a steady stream of water usually cools the blade while it helps to produce less dust. However, in this case, it was critical to maintain a constant humidity of the samples so every cut was made dry and cooling the disk in the air between two successive sections. (Figure 4)

Figure 4. Cutting process of 'mother' specimens (101.6 mm high) to obtain two 'twin' specimens (50 mm high)

Each production day, a set of 15 101.6 mm high 'mother' specimens with a certain content of water and bitumen were made so as to be tested according to the aforementioned standard NLT-161 [4]. Of the 15 specimens, 10 would be sent to the immersion-compression test (5 specimens for wet group and 5 specimens for dry group) and 5 'mother' specimens would get split getting 5 pairs (10 specimens) of 'twin' specimens. From each pair, one specimen would go to the ITS test and the other to the ITSM test. In short, a total of 20 specimens (10 to 101.6 mm in height and 10 to 50 mm) with identical intrinsic properties (density, voids, humidity, degradation of aggregates during compaction, etc.) were tested in different ways and the correlation of the results was completely representative.

3.2 Tested properties

The properties studied were Unconfined Compressive Strength (UCS), Indirect Tensile Strength (ITS) and Indirect Tensile Stiffness Modulus (ITSM) at three temperatures: 2ºC, 10ºC and 20°C for different contents of water and bitumen.

The UCS was determined according to Spanish Standard NLT-161 [4]. Once made, a group of 5 test 'mother' specimens was subjected to a uniaxial load required for a constant strain rate of 0.05 mm/min per mm of height of the specimen. For specimens of 101.6 mm diameter, this value represents a strain rate of 5.08 mm/min. The resistance for each specimen was calculated as:

$$UCS=N_{max}/S \tag{1}$$

Where N_{max} is the peak value of axial load (kN) and S is the cross-sectional area (80.1 cm^2). The final result is calculated as the average value of 5 specimens.

The Indirect Tensile Strength (ITS) was carried out according to the Standard UNE-EN 12697-23 [14] at a room temperature of 25ºC. Five 50-mm 'twin' specimens from different 'mother' specimens per bitumen/water content were subjected to a diametral compression. The deformation rate was 50±2 mm/min and it was kept until fracture occurred. For each specimen the following equation was used:

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

In which P is the peak vertical load (kN), D is the diameter (mm) and H is the height of the cylindrical specimens (mm). Again, the ITS was considered as the average value of 5 tested specimens.

Finally, ITSM test was carried out following the Standard UNE-EN 12697-26, Annex C [15]. Thus, 5 semi-sinusoid impulses with a total duration of 3 s composed by a rise time of 124 ms and a visco-elastic deformations recovery, conducted in a regime of control of deformations (5 µm) was applied on every 50-mm 'twin' sample. The same test was conducted at three different temperatures: 2ºC (2ºC instead of 0ºC to avoid a possible freezing of internal mix water), 10ºC and 20ºC. Five specimens per bitumen/water content were tested under an assumed Poisson ratio condition of 0.35, being the final value the average value of them. For every pulse the Modulus was calculated as follows:

$$S_m = F(\nu + 0.27)/(z \cdot h) \quad (3)$$

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

3.3 Evaluation of the proposed method

Different points of the ITS-ITSM diagram were separated according to the half of the 'mother' specimen they corresponded to (upper or lower half) in order to determine whether this could influence the results. For example, in Figure 5, for a CAM with 100% of CDWA, all the pairs of values obtained from 'twin' specimens when the upper half of the 'mother' specimen was intended for ITSM test and the lower for ITS test are represented in squares (■), while diamonds (♦) belong to the opposite case.

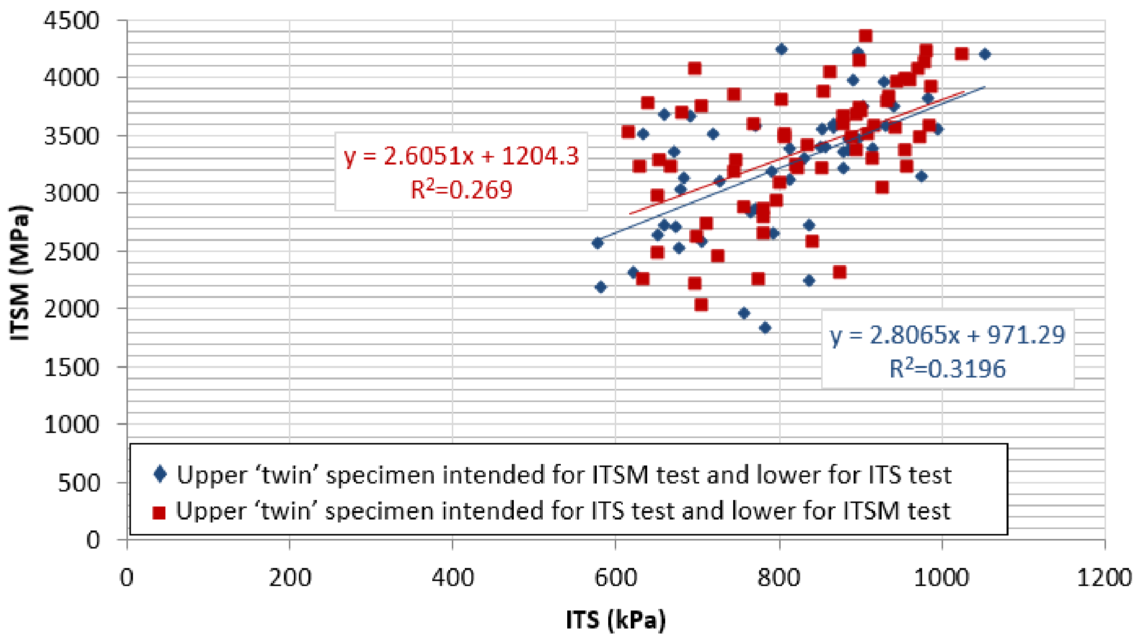

Figure 5. Relationship between ITS and ITSM of cold asphalt mixes with CDWA distinguishing the case when the upper half of the 'mother' specimen was intended for ITSM test and the lower for ITS test and the opposite case

As can be seen, both clusters of dots overlap and the trend lines turn out to be almost identical. Hence, both upper and lower 'twin' specimens which come from the same 'mother' specimen seem to be the same. This is really important, since it would mean that the proposed method does not alter the properties of the samples and that upper and lower ‘twin’ specimens are indeed identical.

In order to confirm this critical assumption, a statistical hypothesis testing was carried out. First, a new variable was defined as the product of the values ITS and ITSM obtained for each pair of ‘twin’ samples from the same ‘mother’ specimen. It must be noted that in the case of this influence existing, one half would be better than the other, so ITS would become higher than normal and the ITSM lower (downward-right shift of points) and the other way would be the ITS which would fall while the ITSM would get higher (upward-left shift of points). This means that in the graph of Figure 5, blue and red points would distance in the direction of a line perpendicular to the plotted trend lines.

Thus, a hypothesis testing was posed in which the null hypothesis (H_0) was that the variable *ITS*ITSM* (measured in MPa^2) does not depend on whether the upper twin specimen was taken for ITS test and the lower for ITSM test or vice versa. The average values of both groups were 2824.5 MPa^2 and 2636.5 MPa^2 that at first glance seem to be really similar. Assuming equal variances after the corresponding Levene test (F = 0.13 with a significance of 0.909> 0.05) a Student's t statistical of 1.373 with a significance of 0.172> 0.05 was obtained. Thus the null hypothesis H_0 must not be rejected and so it can be concluded with a 95% confidence level that the variable *ITS*ITSM* does not depend on whether the upper twin specimen was taken for ITS test and the lower for ITSM test or vice versa; or what is the same, that the upper and lower halves of the mother specimen are identical.

The same analysis was performed for CAM with 100% of NA (Figure 6). In this case, the average values were 1263.6 MPa^2 and 1.209.6 MPa^2 respectively. Again assuming equal variances ($F = 2.4\times10^{-4}$ with a significance of 0.988>0.05) a Student's t statistic of 0.404 with a significance of 0.688>0.05was found. Then again, with a confidence level of 95%, the conclusion is that the upper and lower half of the samples are identical. However, at first glance, we can appreciate how both trend lines tend to separate from each other with NA. It indicates that specimens made with NA show a slightly greater differentiation between the upper and lower halves of the 'mother' specimen, probably due to segregations between aggregates and bitumen before and during the compaction process (the aggregates would stay at the bottom while the water and the emulsion would form a distinct film on top). This way, high absorption aggregates such as CDWA were found to be beneficial in this regard to maintain the emulsion attached to them. This beneficial effect of the use of CDWA can be added to the growing list of benefits which other waste materials produce when they are introduced in asphalt mixes as well as other construction materials [16-20].

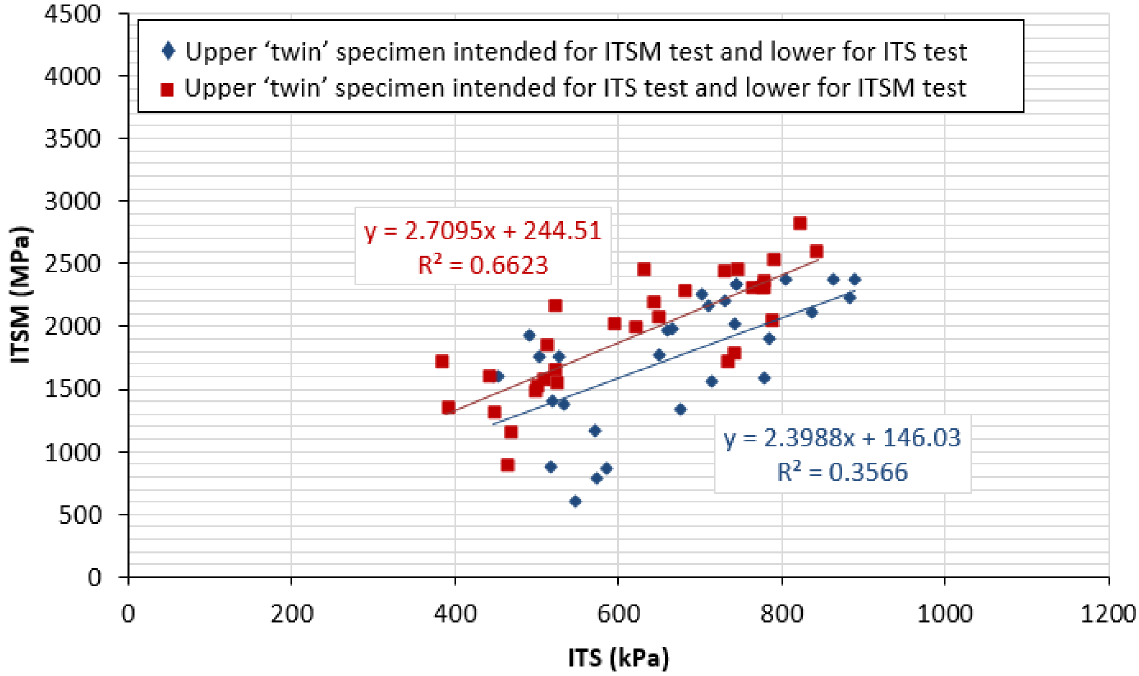

Figure 6. Relationship between ITS and ITSM of cold asphalt mixes with NA distinguishing the case when the upper half of the 'mother' specimen was intended for ITSM test and the lower for ITS test and the opposite case

To sum up, the method was assessed as valid and the adopted mixing process was carried out as follows: 1875 g of NA or 1550 g of CDWA (due to the different specific gravity) were dry mixed with the required pre-wetting water for 30 sec (to produce a homogeneous mixture and to avoid the loss of fine particles during the mechanical mixing) and then with the bitumen emulsion and remaining water for 90 sec (the necessary time to obtain a satisfactory coating).

After this a static axial compaction effort (Figure 2) and a 3-day curing time at 60ºC, as specified in NLT-162 [4] and ATEB recommendations, were applied. This way, 101.6 mm diameter x 101.6 mm height cylindrical specimens were produced. A set of 15 specimens was made for each kind of aggregate and each bitumen and water contents. 10 specimens were subjected to an immersion-compression test (5 for the wet group and 5 for the dry group) and the other 5 were split in order to obtain 5 pairs of twin halves from which one would be subjected to ITS test and the other to ITSM test.

4. Application example of relationship between properties

Peak values found for mixtures with CDWA and NA are summarized in Table 6. These values were obtained by combining a wide range of bitumen and water contents, both for CDWA and NA. It must be clarified that the water content refers to the total amount of water (water from the emulsion plus added water) incorporated in the mixture during the mixing process. After compaction and curing, it was found that the amount of remaining water in the specimens was considerably lower and barely varies from one to another.

Table 6. Peak values of different properties obtained in cold asphalt mixes with CDWA and NA. In parentheses are the mixture contents (% water*/% bitumen) with which each value has been achieved

	UCS_{dry}	UCS_{wet}	ITS	ITSM 2ºC	ITSM 10ºC	ITSM 20ºC
CDW aggregate	4411 kPa (15%/4%)	3197 kPa (15%/3%)	960 kPa (27%/6%)	8407 MPa (30%/7%)	6044 MPa (30%/7%)	4024 MPa (15%/5%)
Natural aggregate	2914 kPa (6%/3%)	2379 kPa (6%/3%)	851 kPa (3%/4%)	11096 MPa (3%/4%)	6230 MPa (3%/4%)	2537 MPa (3%/4%)

** % water content refers to the total amount of water (water from the emulsion plus added water) incorporated to the mixture during the mixing process*

In general terms, it can be seen that CDWA, due to its high water absorption, reached a better affinity with the bitumen film and a lower presence of water between aggregates and bitumen. As a consequence, the values obtained of UCS, ITS and ITSM at 20ºC were higher than those obtained with NA, although as it was shown before, CDWA is a weaker aggregate than NA.

It should be emphasized that the values just explained were obtained with different bitumen and water contents until a maximum was reached for each mechanical property. However, not every property is equally sensitive to bitumen and water contents. In cases like this, where it is interesting to establish a global comparison between the properties and not just to analyze them individually, the proposed methodology takes on great importance. It was precisely what was done and what is presented as a suitable application example.

4.1 Relationship between ITS and ITSM

In Figure 7, the relation between ITS and ITSM is shown graphically. At first glance, it could seem that the trend line which best approximates the points is a simple straight-line. However, when points are differentiated according to bitumen content (Figure 8) a new sense regarding the distribution of points and how the greater this content is, the greater the dispersion of points is too can be discovered (greater variation in ITS-ITSM relationship).

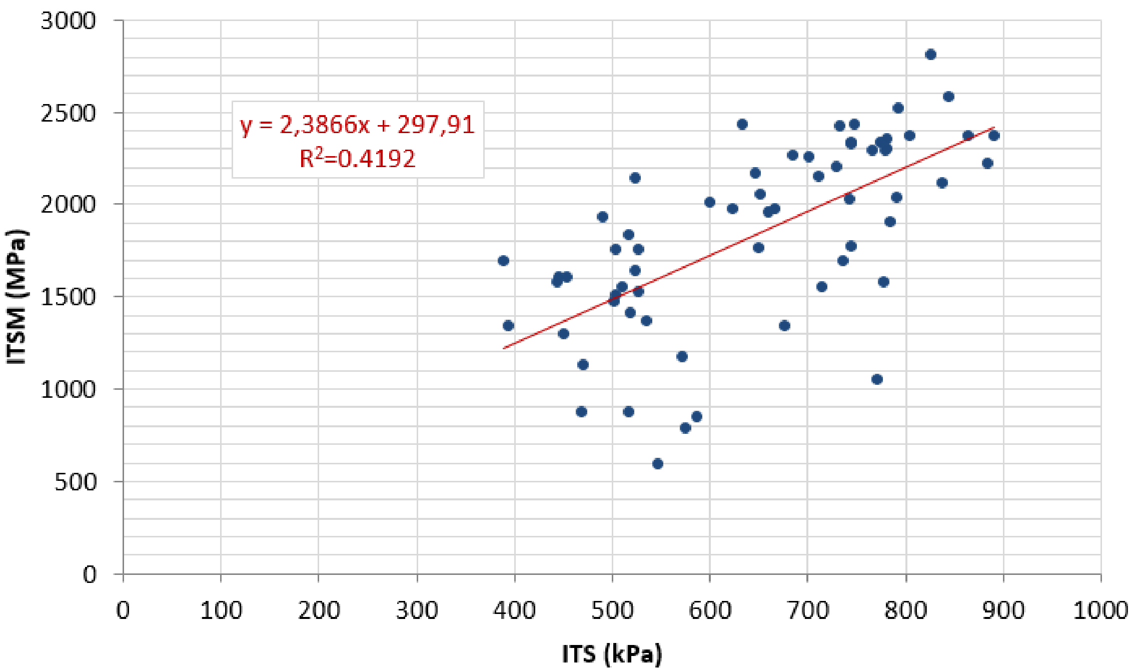

Figure 7. Relationship between ITS and ITSM of cold asphalt mixes with NA

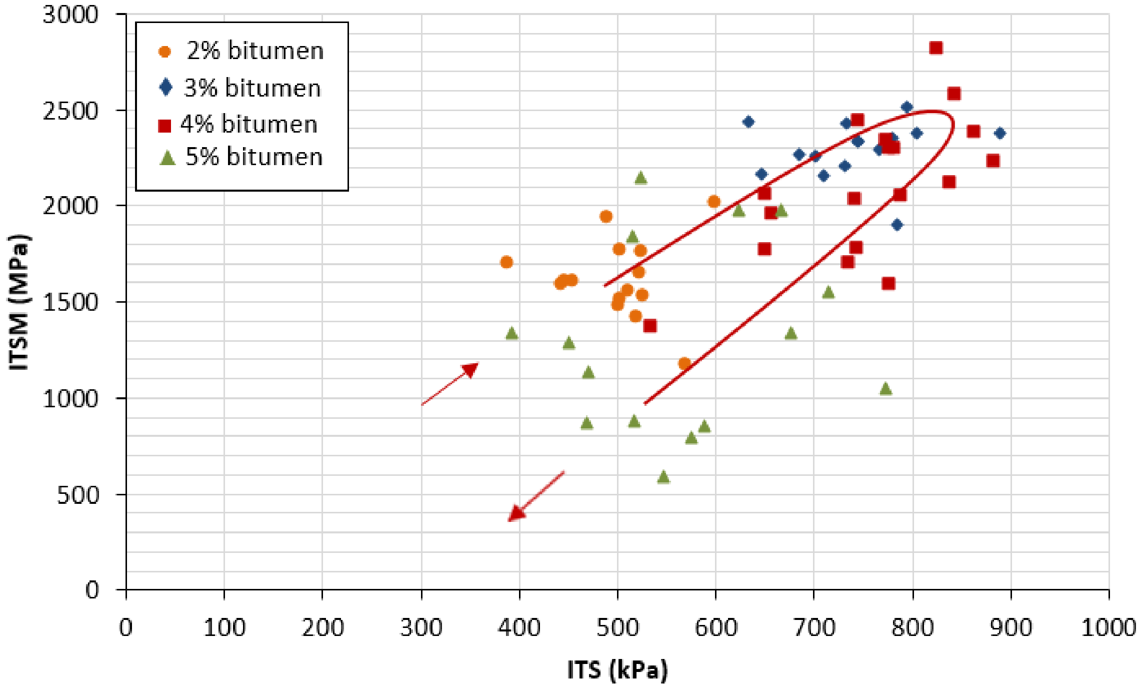

Figure 8. Relationship between ITS and ITSM of cold asphalt mixes with NA depending on the bitumen content. The red line indicates de trend with the increment of bitumen content

Furthermore, the graph shows a growth and subsequent decline in both properties with the increase of bitumen content in the mix. Therefore, at first, a growth in bitumen content improves the mix and gives it a higher stiffness and indirect tensile strength but once an optimal bitumen content was reached, (between 3% and 4% of dry aggregates weight) both properties fall again, being the stiffness the one which does it in a more noticeable way. For example, it can be observed how bitumen contents of 2% and 5% have similar ITS but different ITSM.

As an example, and to show that the explained is widely applicable, the relationship between ITS and ITSM for mixes with CDWA is shown in Figure 9. As can be seen, the shape of the trend curve is slightly different but similar conclusions can be deduced. Again, both ITS and ITSM were increased to achieve an optimal bitumen content about 5.5% after which, in this case, a pronounced loss of stiffness happened even when ITS kept growing. Therefore, like in the previous case, ITSM falls faster than ITS with the bitumen increase, which can be clearly observed by comparing 3.5% and 8.5% contents, which despite having similar ITS show noticeably different ITSM.

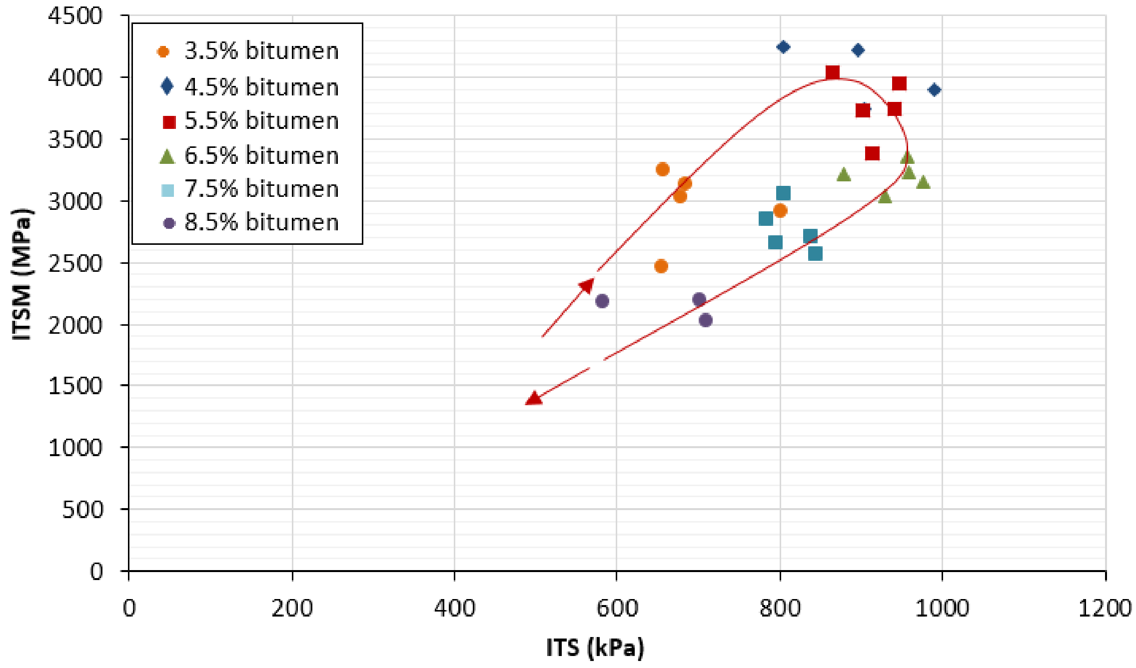

Figure 9. Relationship between ITS and ITSM of cold asphalt mixes with CDWA depending on the bitumen content. The red line indicates de trend with the increment of bitumen content

4.2 Relationship between UCS and ITS

The same thing as in ITS-ITSM relationship happens. Although the points seem to approximate a straight-line (Figure 10), when all the points get differentiated according with the bitumen content a new trend is found out (red line in Figure 11). Therefore, we can conclude anew that at first, both properties grow with the bitumen content but once an optimal percentage is reached, (again between 3% and 4% of dry aggregates weight) both fall. Parallel to the previous case, now the UCS is the property which falls faster than ITS.

This trend contrasts with the one observed in other stiffer materials such as limestone, where the relationship is practically linear [21]. Normally, asphalt mixes fail under unconfined compressive stress by a complex system of internal microcracking and microstructural breakdown with extensive cracking. This cracking can be largely tensile or shear/tensile in nature and as ultimate failure is approached, the cracking in the bituminous matrix itself predominates leading to final rupture. Here is why factors affecting tensile strength are similar to factors influencing compressive strength. So the observed behavior may be explained by the more important role of aggregates and mineral microstructure in the UCS test and regarding that CDWA is, by itself, a weak aggregate.

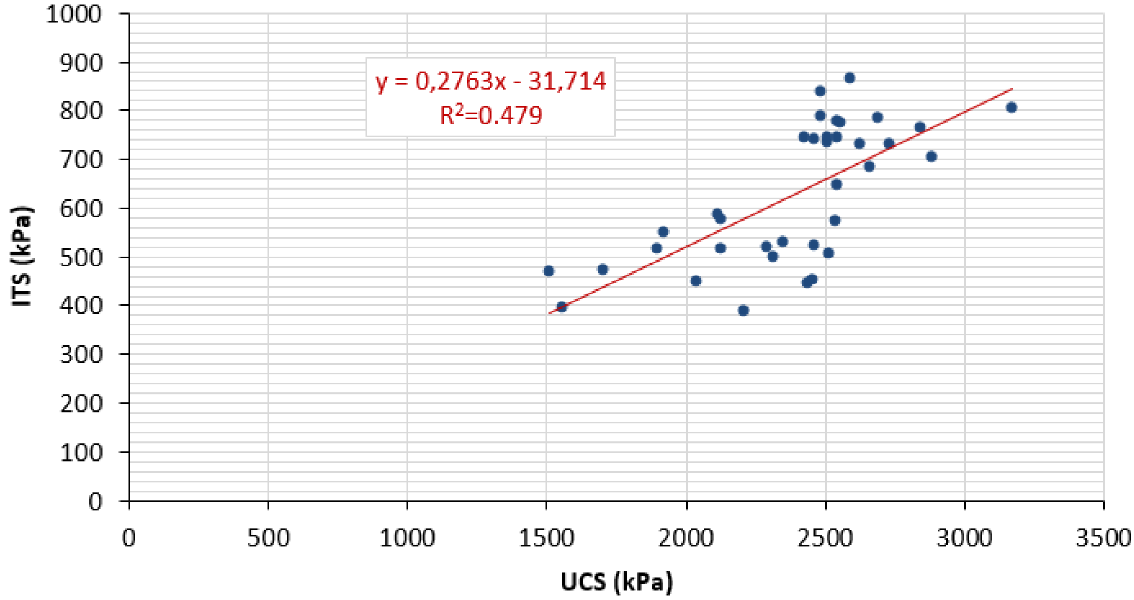

Figure 10. Relationship between UCS and ITS of cold asphalt mixes with NA

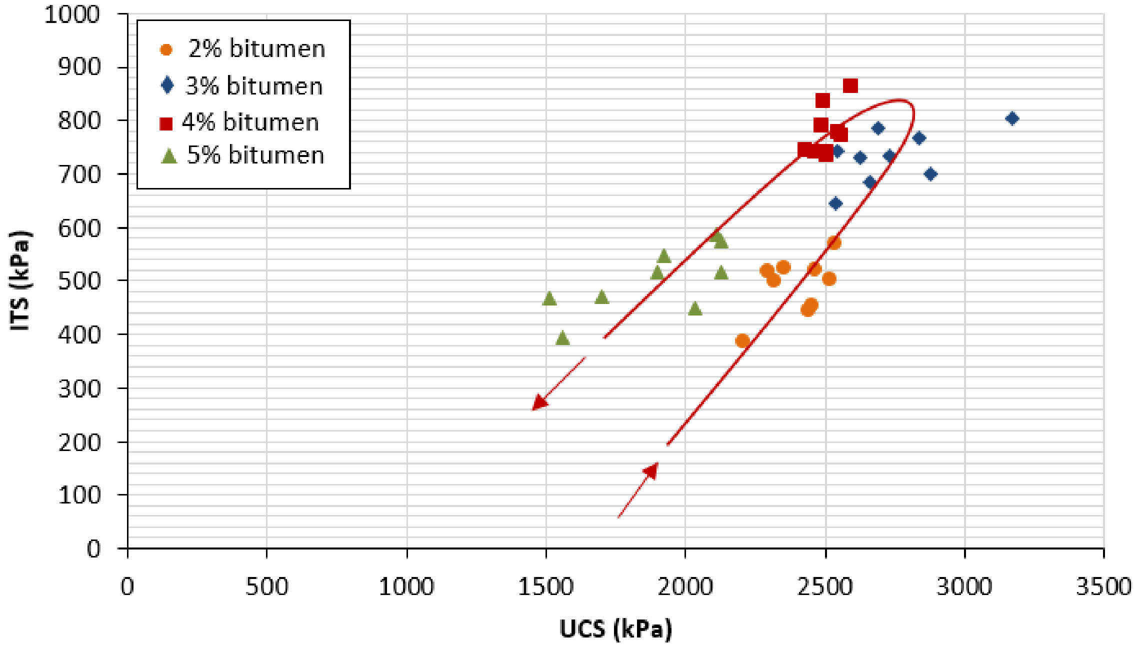

Figure 11. Relationship between UCS and ITS of cold asphalt mixes with NA depending on the bitumen content. The red line indicates de trend with the increment of bitumen content

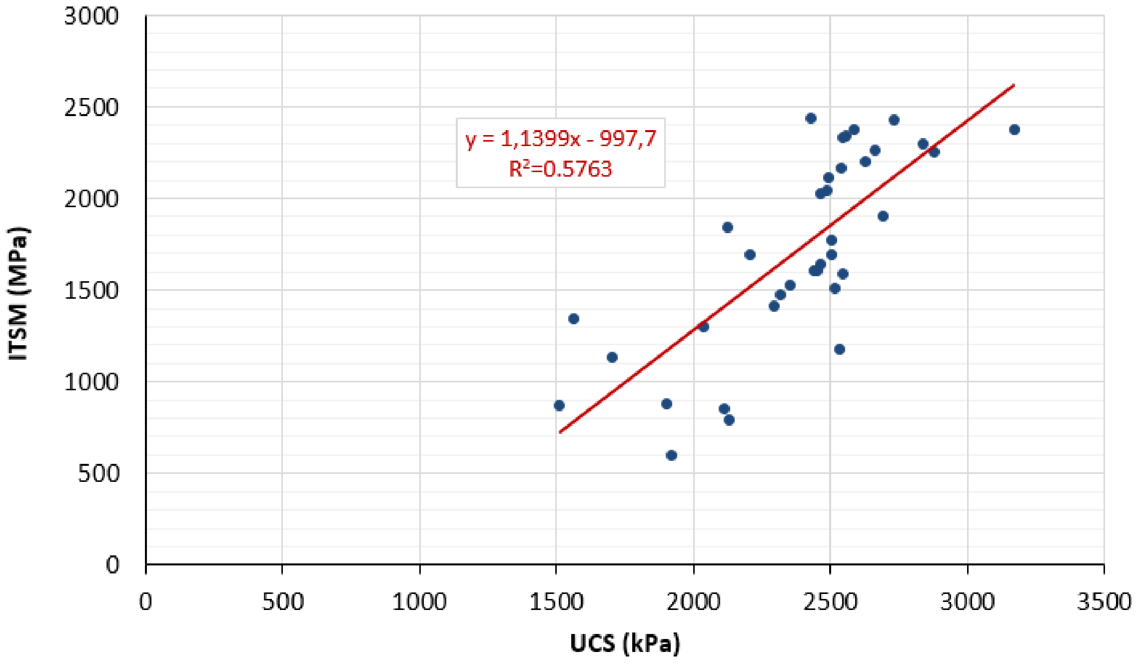

Figure 12. Relationship between UCS and ITSM of cold asphalt mixes with NA

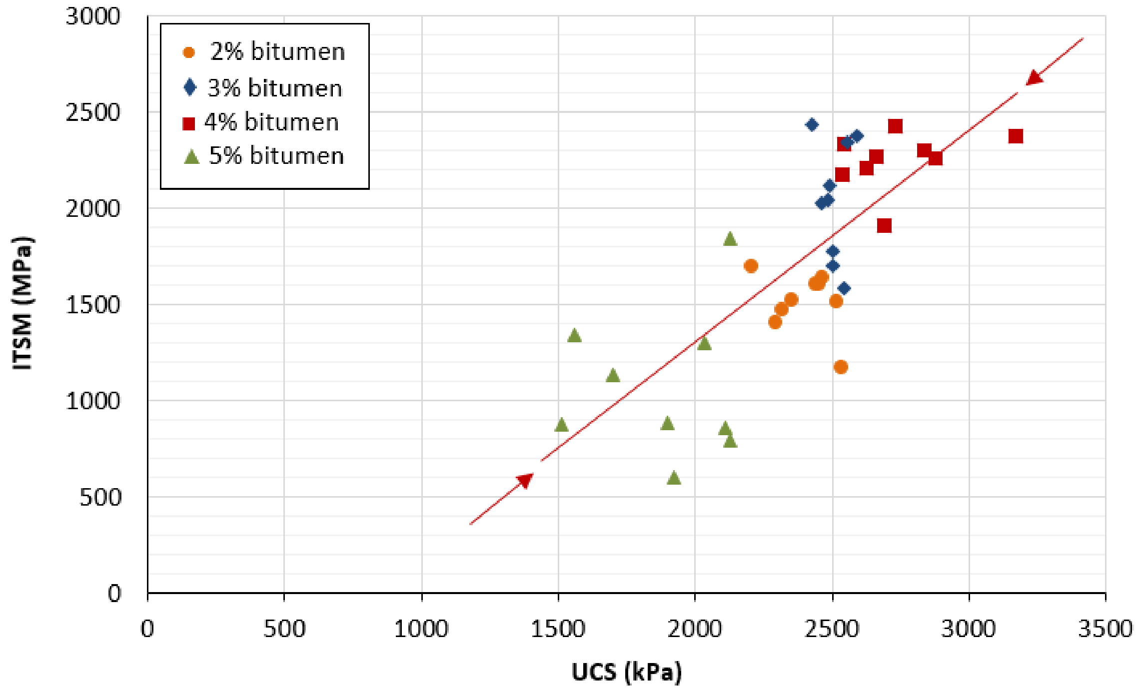

Figure 13. Relationship between UCS and ITSM of cold asphalt mixes with NA depending on the bitumen content. The red line indicates de trend with the increment of bitumen content

4.3 Relationship between UCS and ITSM

The relationship in this case is nearly linear (Figure 12 and Figure 13), which means that the higher the stiffness of a sample is, also the greater the compressive strength is. Figure 13 shows that although an optimum content of bitumen is again reached (in this case about 4%), both properties fall, in this case values slide up to the right and down to the left following the same trend line.

In previous sections, how ITS remained high while UCS and ITSM fell with increasing bitumen content above the optimum value was laid out. What it is remarkable in this case is that both properties follow this trend in a really similar way.

5. Conclusions

The research project was aimed at obtaining a method to get specimens of different sizes but with identical intrinsic properties, which allowed to compare the mechanical properties of a certain CAM in a truly reliable way. Based on the laboratory experiments, analyses and evaluations carried out, the following conclusions can be summarized:

1) A new protocol for the global study of the mechanical properties of CAM was proposed. The method involves making a set of 15 101.6 mm high 'mother' specimens with a certain content of water and bitumen. Of the 15 specimens, 10 are sent to the immersion-compression test (5 specimens for wet group and 5 specimens for dry group) and 5 'mother' specimens get split obtaining 5 pairs (10 specimens) of 50 mm high ‘twin’ specimens. From each pair, one specimen would go to the ITS test and the other to the ITSM test. In short, a total of 20 specimens (10 of 101.6 mm in height and 10 of 50 mm) with identical intrinsic properties (density, voids, humidity, degradation of aggregates during compaction, etc.) were tested in different ways and the correlation of the results was completely representative.

2) It was statistically demonstrated that the proposed method is consistent and applicable to different kinds of CAM, easily reproducible and does not affect the results. This way, the proposed method allows relating the results of different tests in a completely reliable way.

3) As an application example of the method, CAMs with different bitumen and water contents and made with two very different aggregates (NA and CDWA) were subjected to UCS, ITS and ITSM tests obtaining clusters of points which were reliably correlated to each other. Therefore, the following conclusions about the behavior of CAMs were obtained:

   3a) With increasing bitumen content UCS, ITS and ITSM tend to reach a peak value from which, the values fall again. This optimal bitumen content resulted between 3% and 4% for NA and 5.5% for CDWA.

   3b) UCS and ITSM tend to be linearly related. This means that the stiffer a CAM is, the higher UCS will perform. UCS is also related to ITS. Both grow with an increasing bitumen content until they reach an optimal percentage, from which on, both begin falling. However, in this case, it is clearly noticeable that UCS falls faster than ITS, appearing bitumen contents with the same ITS but different UCS. The same happened when comparing ITS and ITSM. In this case it is ITSM that fall faster than ITS with the increasing bitumen content after reaching the optimal point.

   3c) Therefore, it can be concluded that after reaching an optimal bitumen content not all properties perform in the same way. ITS is the mechanical property which less sensitivity shows to bitumen content while ITSM and UCS perform really alike and worse than ITS.

4) The method also allows checking possible differences between the upper and lower halves of the specimens or what is the same the homogeneity of a certain mix. In the case study, it was found that more absorbent aggregates (CDWA) tend to reduce these differences and segregations between aggregates and bitumen so that the asphalt mixture is, itself, more homogeneous.

Acknowledgements

The authors would like to acknowledge the founding of the project BIA2010-17751 as well as 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 GESTAN Group for the CDWA and to ECOASFALT for the bitumen emulsion kindly 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] European Asphalt Pavement Association (EAPA). Asphalt in figures. EAPA; 2012

[3] Liebenberg JJE, Visser AT. Towards a mechanistic structural design procedure for emulsion-treated base layers. Journal of the South African Institution of Civil Engineering. 2009;46(3):2-8

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

[5] Association Française de Normalisation. Norme Française NFP 98-251-1. Enrobés hydrocarbonés. Essais statiques sur mélanges hydrocarbonés, partie1: Essais Duriez sur mélanges hydrocarbonés à chaud. Paris;2004

[6] Pérez I, Medina L, Romana MG. Permanent deformation models for a granular material used in road pavements. Construction and Building Materials. 2006;20(9):790-800

[7] Gómez-Meijide B, Pérez I. Effects of the use of construction and demolition waste aggregates in cold asphalt mixtures. Construction and Building Materials. 2014;51:267-277

[8] Pérez I, Pasandín AR, Medina L. Hot mix asphalt using C&D waste as coarse aggregates. Materials and Design. 2012;36:840-846

[9] 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

[10] 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

[11] 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

[12] 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

[13] 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

[14] 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

[15] 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

[16] Al Nageim 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

[17] Ahmadinia E, Zargar M, Karim MR, Abdelaziz M, Shafigh P. Using waste plastic bottles as additive for stone mastic asphalt. Materials and Design. 2011;32:4844-4849

[18] Moreno F, Sol M, Martín J, Pérez M, Rubio MC. The effect of crumb rubber modifier on the resistance of asphalt mixes to plastic deformation. Materials and Design. 2013;47:274-280

[19] Silvestre R, Medel E, García A, Navas J. Utilizing recycled ceramic aggregates obtained from tile industry in the design of open graded wearing course on both laboratory and in situ basis. Materials and Design. 2013;50:471-478

[20] Iucolano F, Liguori B, Caputo D, Colangelo F, Cioffi R. Recycled plastic aggregate in mortars composition: Effect on physical and mechanical properties. Materials and Design. 2013;52:916-922

[21] Nazir R, Momeni E, Armaghni DJ, Amin MFM. Correlation between unconfined compressive strength and indirect tensile strength of limestone rock samples. Electronic Journal of Geotechnical Engineering. 2013;18:1737-1746