Asphalt mixture performance and testing

Evaluation of test methods for measuring adhesion between asphalt pavement layers according to NLT-382 (EN 12697-48)

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Abstract

Within the context of Spanish and European specifications, the need to perform the adhesion test between asphalt pavement layers according to NLT-382 standard is established, to verify that the shear strength exceeds the minimum values of said specifications. It is therefore of great importance to deepen the knowledge of this test, which allows the use of two different devices (A and B). In addition, the European standard EN 12697-48 is being revised to evaluate the adhesion between layers, in which different alternative methods are proposed to evaluate this parameter, among which are the equivalent to NLT-382 with device A, and the inclusion of device B is being evaluated. The objectives of this work are, evaluate the differences between the results obtained with the devices included in the NLT-382 standard, estimate the accuracy of the test and analyze, with cores extracted from recently constructed pavements, how the different tack coat dosages and mixture types used influence the adhesion values. In this paper, it is showed the results (on 2000 testing specimens) of the intercomparing exercise with the device B to obtain accurate data for this test. The results obtained with both devices have been compared on laboratory manufactured specimens and cores extracted from constructed pavements, obtaining higher results when tested with the device A. An evaluation of the accuracy of both methods has been made, obtaining smaller dispersions with the device B than the device A. The precision in the determination of other parameters of the test, deformation at maximum load and energy of deformation, presents worse values (greater dispersions) than the resistance to permanent deformation shear stress, with both devices. Likewise, with all the results obtained, we intend to model, by means of the finite elements method, the adhesion values between different layers of asphalt pavements.

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1. INTRODUCTION

1.1. Background

Over the past ten years, adhesion testing of pavement layers has gained more and more importance throughout Europe and in many other countries. Several tests are currently available to evaluate the bonding performance between layers based on different loading modes (shear, torque and tensile). They vary in regard of test devices, test temperature, loading mode as well as sample geometry and preparation and hence they lead to different results. Due to these dissimilarities in experimental conditions, the comparison of the test results obtained from these test methods is often not possible.

In this context, the European standardisation committee CEN/TC227/WG1/TG2 "Test methods for bituminous mixtures" is working on a pre-standard prEN 12697-48 [1] for the determination of interlayer bond strength where three main normative test methods are considered: tensile adhesion test (TAT), shear bond test (SBT), torque bond test (TBT).

In the case of Spain, with the modification of the article 531 of PG-3, document of the Spanish Ministry of Development for road works [2], in December 2014, it is established, as mandatory, the determination of interlayer bond strength according to the NLT-382 standard [3]. Spanish requirements state minimum levels of shear strength for specimens drilled out from pavement, 0.60 MPa when one of the layers is a surface course, or 0.40 MPa in the rest of the cases. Different penalties are also established when 90% of this value is not reached, or when it is between 90 and 100%. It is therefore of great importance to deepen the knowledge of this test.

According to the NLT-382 standard, the interlayer bonding test can be carried out with two different devices (Figure 1):

- In device A, load is applied by means of a jaw with two bodies, contained in a plane perpendicular to the test-specimen, on which an effort is applied at the interface of the two layers (pure shear force).
- The device B consists of a removable cylindrical jaw into which the test-specimen is inserted. Load is applied in a point which is equidistant from the two support points of the assembly, which acts, as well as a beam mounted on two supports, where the test section is subjected to a shear stress.

At the beginning of this project, there was not sufficiently available contrasted data to ensure the equivalence of the results obtained by both devices.

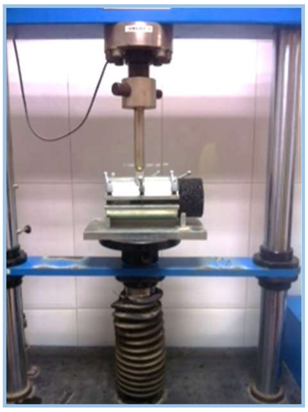


Figure 1. Devices A (left) and B (right) of NLT 382/08

1.2. Objectives

The objectives of this study are:

- Evaluate if there is a significant difference between the results obtained with the devices included in the NLT-382 standard and estimate the accuracy of the test.
- Analyse, by testing field specimens (drilling cores), how different emulsion rates and asphalt mixture types can affect the bonding shear bond strength.
- Establish, for different types of mixtures, the relationship between the residual bitumen rate and the test parameters (shear bond strength and energy).
- Develop a finite element model (FEM) to obtain the share stress that can reach the joint between different layers of an asphalt mix pavement.

2. EXPERIMENTAL PLAN

2.1. Interlaboratory comparison

Two interlaboratory exercises have been carried out: The first one, with the device B and the second one, with the device A, for two consecutive years. Previously, a specific protocol to curry out the interlaboratory exercise was established among the participants, as well as the necessary materials were distributed: AC16 asphalt mixture, and two commercial thermoadherent emulsions (a C60B3 emulsion, manufactured with a conventional bitumen, and a second emulsion which was a modified C60BP3 emulsion).

Test specimens were prepared as follows:

- The support layer specimens, diameter 100 mm, were manufactured with an asphalt concrete type AC16 mixture, by a gyratory compactor, according to the standard UNE-EN 12697-31[4]. (Pressure: 600 kPa; Angle: 0.82º; Number of gyrations: 288; Compaction Tª: 170ºC; Preheating: 2 hours).
- Standardised manufactured specimens (130 mm height) were cut in half to a final height of 65 mm. On the cut smooth surface, the emulsion was applied at a 200 g/m^2 rate of residual bitumen.
- Asphalt concrete type AC16 was also used for the top layer with a minimum thickness of 50 mm. Compaction was carried out at 170 °C, following the procedure described in the standard NLT-161 [5], by means of a double piston press applying a maximum pressure of 21 MPa for 2 minutes.
- Specimen testing were carried out at 20 °C with a loading speed of 2.5 mm/min. From the load-strain graph of each test specimen, the following parameters are determined:
  - ✓ Maximum shear force, $F_{\max}$ (N).
  - ✓ Shear bond strength, Tc, calculated from the maximum shear force at failure by the expression:

    - *$Tc = F_{max} / S$; for the device A,*
    - *$Tc = (F_{max} / 2*S)$; for the device B,*

  Where S is the surface of the specimen cross section, in mm^2 and, Tc is the shear bond strength in N/mm^2 (MPa). Deformation energy until force at failure is also determined (Ed), corresponding to the limited area under the test curve until maximum load value is reached.

2.2. Drilling cores on pilot sections

Cores were taken from two different pilot sections:

1. In the first pilot section, a surface course of 30 mm of a BBTM11 (2016) on an existing AC22 (2000). The applied residual bitumen rate was, in one half of the section, 0.5 kg/m^2, and in the other half 1.0 kg/m^2. In both cases the type of emulsion was C60BP3TER. These are the sections identified as MS in table 3 and in figure 5.
2. The second pilot section, in the same location than the first one, a 30 mm of a BBTM11 surface layer was laid (2016) on an existing BBTM11 (2016). The applied residual bitumen rate was, in one half of the section 0.5 kg/m^2, and in the other half 1.0 kg/m^2. In both cases the type of emulsion was C60BP3TER. They are the sections identified as MM in table 3 and figure 5.

The cores were drilled in 2018 and tested in six (6) different laboratories, a total number of eight (8) cores from each pilot section per laboratory, four (4) to be tested with the device A and four (4) with the device B, under the conditions stated in NLT-382 standard.

2.3. Determination of optimal emulsion (residual bitumen) rate

It was proposed, four different macrotextures in the support layer and two in the surface layer, with different theoretical residual bitumen rates of 0 g/m^2, 200 g/m^2 (minimum stated in Spanish specifications), 500 g/m^2 and 800 g/m^2.

The work plan was as follows:

- Selection of the AC22 and BBTM11 pilot section, which will be used as support layers
- Measure of the macrotexture in these sections, with laser profilometer and sand circle test
- Core drilling (a minimum of 288 for AC22 and 144 for BBTM11)
- Manufacturing of mixtures for surface layer (420 kg AC22 and 840 kg BBTM11)
- Manufacturing of support specimens with a gyratory machine (same number and type as drilled cores)
- Determine the macrotexture of these specimens. For this, slab specimens were prepared, and the macrotexture was measured by the sand circle test
- Testing of all prepared specimens

For every of the 6 participating laboratories, the works were established in 6 sets, as outlined in the following figure:

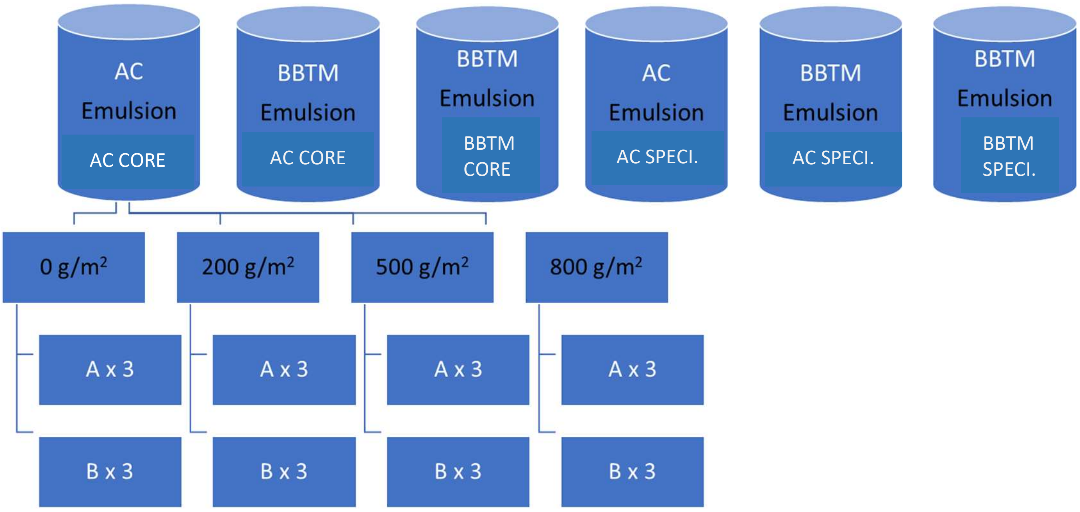


Figure 2. Experimental plan to determine the optimal residual bitumen in different types of mixtures

So, there is 6 sets of samples, in two sets the support layer is an AC type drilled core (AC CORE) on which the AC or BBTM mixture is compacted and in the third one, the support layer is a BBTM drilled core (BBTM CORE) on which the BBTM mixture is compacted. In the following three sets, the combination of mixtures is the same, but the support layer was a manufactured specimen in the gyratory machine (AC SPECI. and BBTM SPECI.). For every set, 24 specimens were prepared, 6 for each residual bitumen rate (0 g/m^2, 200 g/m^2, 500 g/m^2 and 800 g/m^2), three of them were tested with the device A (A x 3) and three with the device B (B x 3).

In this case, unlike those performed in section 2.1, the support layer specimens were not cut. The exact amount of residual binder is determined by weighing, after 24 hours have elapsed since the extension of the emulsion.

Figure 3. Details of the experimental plan

3. RESULTS

3.1. Interlaboratory comparation

In the interlaboratory exercise, 14 laboratories participated, each one has performed 6 replicas of the test for each emulsion. To perform the statistical treatment of the results, the extreme values were removed, so that n = 4. The parameters analysed are shear bond strength and deformation energy. The energy has been calculated as the area under the load-strain curve to maximum load, as indicated in the following figure:

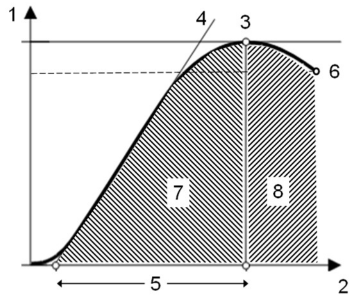


Figure 4. Calculation of energy and post-deformation energy

The statistical treatment of the data begins with the detection of anomalous data, by means of graphical techniques of consistency (h and k of Mandel) and Cochran and Grubbs test. Once the anomalous data has been eliminated, the general average and the variances are calculated. The repeatability variance, the interlaboratory variance and the reproducibility variance are calculated, according to UNE 82009-2 [6], and the average and robust standard deviation according to ISO 13528 [7].

Results for shear bond strength: Table 1 summarizes the results obtained with the C60B3 and C60BP3 emulsions for each device (A and B, NLT-382):

Table 1. Results for shear bond strength

	Emulsion C60B3				Emulsion C60BP3			
	Device A		Device B		Device A		Device B	
	UNE 82009	ISO 13528	UNE 82009-2	ISO 13528	UNE 82009	ISO 13528	UNE 82009-2	ISO 13528
Average, MPa	1.84	1.85	1.34	1.34	1.94	1.99	1.37	1.38
S_r	0.17		0.13		0.13		0.12	
S_R	0.25	0.20	0.20	0.19	0.30	0.19	0.21	0.12
% CV_r	9.0		9.4		6.9		9.1	
% CV_R	13.5	10.9	15.2	14.0	15.3	9.5	15.6	8.3

With this data, we can establish that the precision obtained with both devices is comparable, with repeatability variation coefficients between 5-10% and reproducibility variation coefficients between 10-15%. In addition, the average values obtained with device A are greater than those obtained with B (from 27 to 30%). There is not significant difference between the results obtained with each emulsion at the test temperature of 20 °C.

Results for deformation energy: Table 2 summarizes the results obtained with the C60B3 and C60BP3 emulsion in each of the devices.

Table 2. Results for deformation energy

	Emulsion C60B3				Emulsion C60BP3			
	Device A		Device B		Device A		Device B	
	UNE 82009	ISO 13528	UNE 82009-2	ISO 13528	UNE 82009	ISO 13528	UNE 82009-2	ISO 13528
Average, J	8.7	8.9	11.4	9.3	9.4	9.3	9.8	8.6
S_r	1.0		1.3		1.3		1,2	
S_R	1.6	1.3	8.2	3.2	1.5	1.1	6.1	2.5
% CV_r	12		11		13		12	
% CV_R	19	15	72	35	16	12	62	30

The homogeneity of the results has been considerably improved with the device A, with both emulsions, and reproducibility coefficients of variation below 20% have been achieved. Although the accuracies obtained were very different and may affect the comparison of the mean values, no significant differences were observed in the mean deformation energy values obtained with both devices.

3.2. Drilling cores on pilot sections

Statistical treatment is performed for each test section and device. For the treatment of the data the same scheme is followed as in section 3.1.

The average values obtained for the shear bond strength are shown in Table 3. Higher values are obtained with device A (Fig. 5). The increase in the emulsion rate, from 0.5 to 1.0 kg/m^2, reduces the shear bond strength value. Regarding compliance with the specifications, only the results obtained with the device A and a residual bitumen of 0.5 kg/m^2 ensure compliance with the Spanish specifications for surface layers.

Table 3. Results for shear bond strength on drilled cores

	MM 0.5 kg/m^2		MM 1 kg/m^2		MS 0.5 kg/m^2		MS 1 kg/m^2	
	Device A	Device B	Device A	Device B	Device A	Device B	Device A	Device B
Average, MPa	0.713	0.512	0.521	0.420	0.696	0.389	0.584	0.389
S_r	0.141	0.054	0.113	0.050	0.223	0.049	0.141	0.070
S_R	0.178	0.089	0.173	0.072	0.264	0.062	0.145	0.106
CV_r	20	11	22	12	32	13	24	18
CV_R	25	17	33	17	38	16	25	27

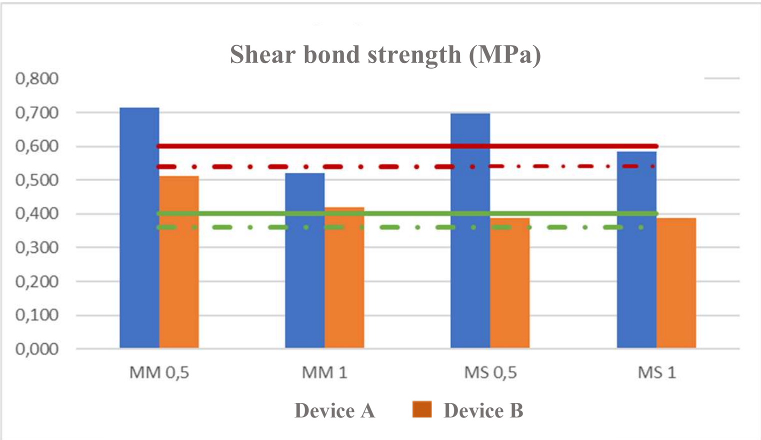


Figure 5. Average values of shear bond strength on cores and specifications (red and green continuous line, minimum specification value and, red and green discontinuous line, 90% of the minimum value).

For deformation at maximum load and deformation energy, the high dispersions found, both in terms of repeatability (CV_r, about 30%) and reproducibility (CV_R greater than 50%) with both devices, do not allow comparisons between the results.

3.3. Determination of optimal emulsion (residual bitumen) rate

The average results obtained for AC-AC mixtures are shown in Figure 6. In terms of shear bond strength, device A led to higher values than device B. In terms of energy (deformation energy, ESBT, and sum of deformation and post-deformation energy, E) the values were also higher when the support layer is a laboratory manufactured specimen, but the differences were not significant when the support layer was a core.

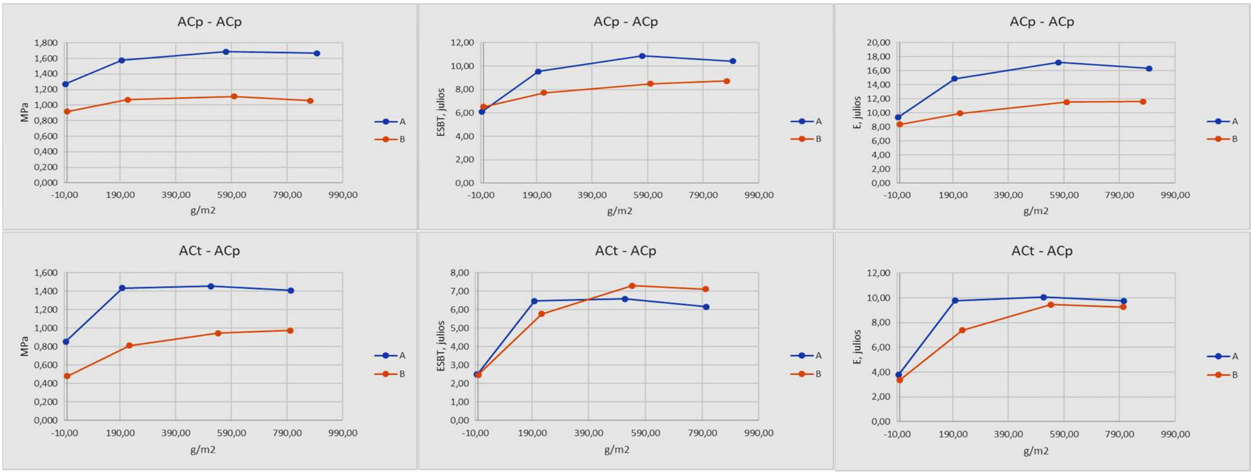


Figure 6. Shear bond strength and energy vs. residual bitumen for AC-AC specimens (ACt: AC drilling core; ACp: AC laboratory manufactured specimen)

If the values obtained when the support layer is a drilled core (ACt-ACp graphs) and the support layer is a specimen (ACp-ACp graphs) are compared, we observe higher values of all the parameters when the support layer is a laboratory manufactured specimen. These supports have different macrotextures, lower in laboratory-manufactured specimens than in cores drilled from the pavement of the pilot sections, that is, the values are higher for lower macrotextures. The optimal residual bitumen rates were found about 400-600 g/m^2, both in terms of resistance to shear bond strength and energy.

The same conclusions are reached when AC-BBTM samples are tested, as shown in Figure 7, higher values in all parameters for device A, and lower values when the support layer is a drilled core, that is, higher macrotextures.

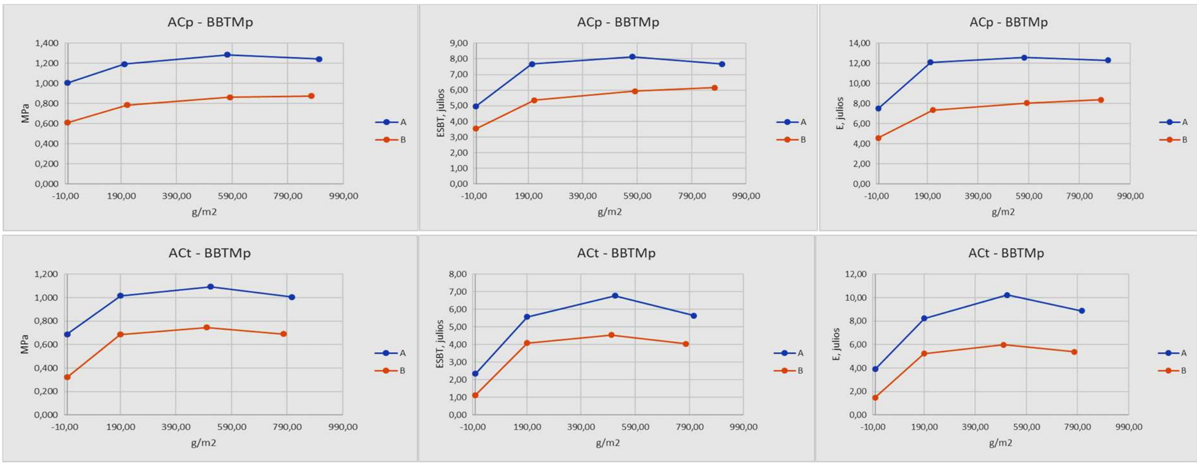


Figure 7. Shear bond strength and energy vs. residual bitumen for AC-BBTM specimens (ACt: AC drilling core; ACp and BBTMp: AC and BBTM laboratory manufactured specimen)

As the macrotexture increases, the difference between the two devices is better observed, both in terms of shear bond strength and energy.

Finally, in the case of BBTM-BBTM, the results are similar, in terms of influence of the type of device and macro texture.

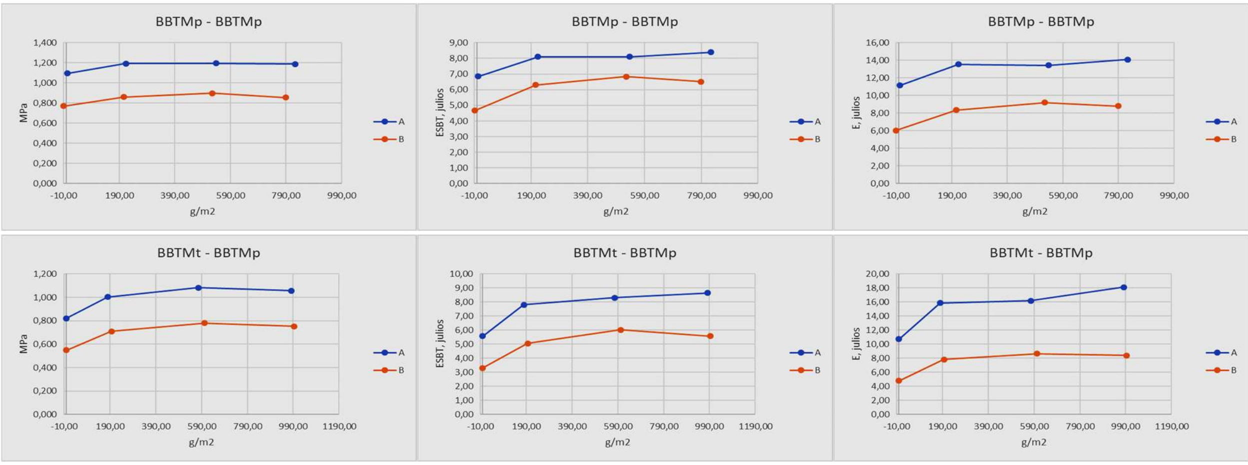


Figure 8. Shear bond strength and energy vs. residual bitumen for BBTM-BBTM specimens (BBTMt: BBTM drilling core; BBTMp: BBTM laboratory manufactured specimen)

The average global values per device and mixtures are shown in Figure 9. The significant difference between the results provided by each device is confirmed, and the results we observed previuosly are confirmed.

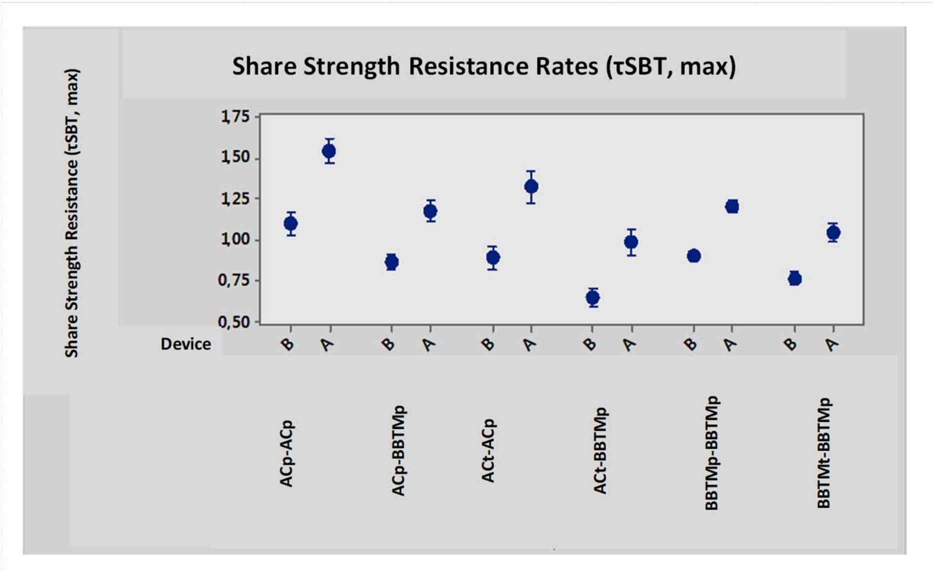


Figure 9. Overall average values per device for each combination of mixtures

In general, the highest values are obtained for AC-AC combinations, and among these are higher when the macrotexture of the support layer is lower. The following best results are obtained for samples with support specimens (ACp-BBTM and BBTBp-BBTM), and the worst results were found for drilled core support layers and BBTM top layer.

- The ACp-ACp combination (macrotextures of 0.70-0.70, respectively) reproduces the type of adhesion that occurs between two AC mixtures just extended to each other. It presents the highest results in share bond strength and energy. It is the one with the lowest macrotexture, 0.70, which helps retain a greater amount of emulsion on its surface.
- The ACt-ACp combination (macrotextures of 0.82-0.70, respectively) reproduces the type of adhesion that occurs between an exhausted AC type layer and the extension of a new AC surface layer on it. It is one of the combinations that is most frequently used in pavement reinforcements. They are the ones that get the second best results of all the combinations, only below the ACp-ACp combination.
- The ACp-BBTMp combination (macrotextures of 0.70-1.90) reproduces the type of adhesion that occurs when a surface layer of BBTM type mixture is laid on a new AC layer. If we compare it with the ACp-ACp, its results are lower, which indicates that the macrotexture of the upper layer also influences the bonding performance, but if we compare it with the ACt-BBTM, the values are higher.

- The ACt-BBTM combination (macrotextures of 0.82-1.90) reproduces the type of adhesion that occurs between an exhausted AC type layer and BBTM surface layer laid on it. It is the combination that gives the worst result. If we compare it with the ACt-ACp combination, it is confirmed that the increase in the macrotexture of the upper layer negatively affects the shear bond strength.
- The BBTMp-BBTMp combination (macrotexture of 1.90-1.90) reproduces the type of adhesion that occurs between a two new BBTM layers. In practice, it is a combination that is not used. It is a combination that is found in the middle zone of all those tested due, on the one hand, to its high shear value with zero residual bitumen and, as observed in the laboratory, to the interaction and anchoring of the particles between the two mixtures with high macrotexture. Likewise, the residual bitumen of the mixture favours this increase at zero rate, which in the next combination tested, BBTMt-BBTMp, disappears.
- Finally, the BBTMt-BBTMp combination (macrotexture of 2.65-1.90) reproduces the type of adhesion that occurs between an exhausted BBTM layer and a new BBTM surface layer on it. In practice, it is a combination that is not used due to doubts regarding its behavior related to the adhesion between these layers; however, according to the obtained tests result, the behaviour is practically the same as the most used ACt-BBTMp.

The next step, in order to determine the optimal residual bitumen, the shear bond strength / residual bitumen curves were adjusted for the different combinations of asphalt mixtures and the maximum value were determined. The results are shown in Figure 10. In global values, the shear resistance improves when the rate increases, until reaching a maximum shear resistance in the rate of about 400-600 g/m^2 of residual bitumen, then decrease or practically maintain, depending on the type of mixture, at a rate of 800 g/m^2.

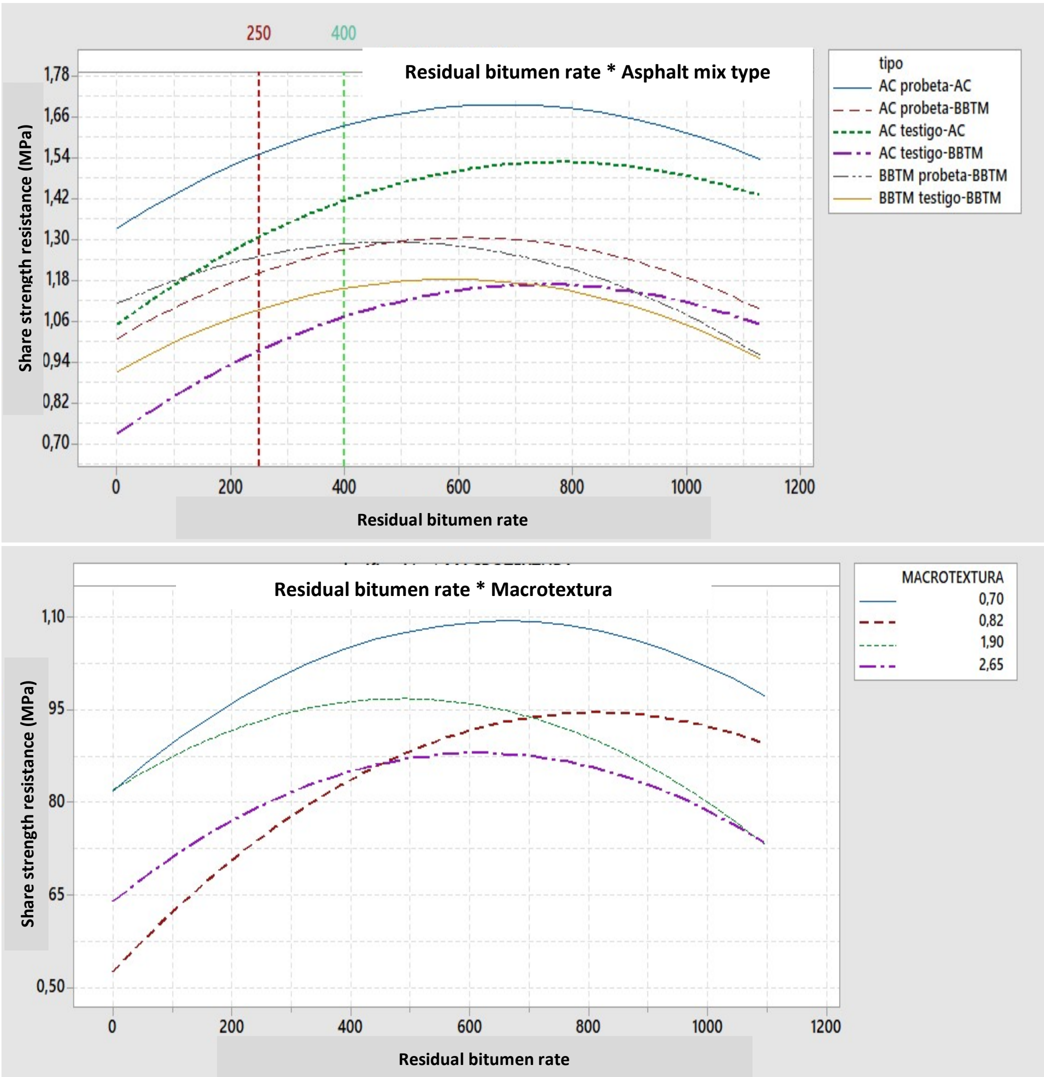


Figure 10. Optimal residual bitumen rate estimates for each combination of mixtures

Finally, the results of shear bond strength obtained for each residual bitumen rate were related to the maximum theoretical values, understanding these as those that would produce a continuous specimen of each type of mixture. The results are shown in table 4.

In this regard, it was found that:

- Average values of 66% (between 58 and 74% depending on the type of mixture) related to the optimal residual bitumen rate are obtained.
- The greatest variations occur between 0 and 200 g/m^2.
- Only a 5% is improved when it goes from 200 to 500 g/m^2,
- A minimal decrease is observed when it goes to 800 g /m^2.

Therefore, an increase in emulsion rate, does not substantially improve share strength resistance.

Table 4. Percentage of shear bond strength with respect to the maximum theorical value

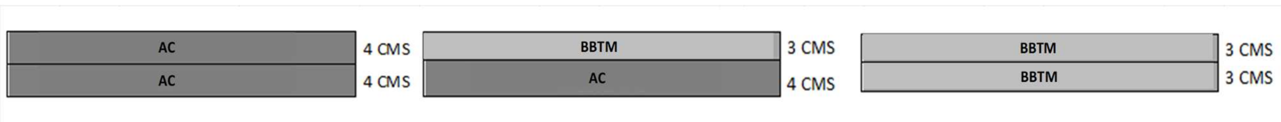
Support Layer Macrotexture	Maximum Share strength resistance (MPa) (100%)	Combination of Asphalt mixtures	Average of share bond strength (MPa), for each target residual bitumen rate (g/cm^2) 0	200	500	800	Share bond strength related to the maximum theorical value (%) 0	200	500	800
0.70	1.65	ACp- ACp	0.94	1.14	1.22	1.21	57%	69%	74%	73%
0.70	1.39	ACp- BBTMp	0.77	0.87	0.92	0.94	55%	63%	66%	68%
0.82	1.65	ACt- ACp	0.58	0.95	1.06	1.09	35%	58%	64%	66%
0.82	1.39	ACt- BBTMp	0.36	0.77	0.81	0.79	26%	55%	58%	57%
1.90	1.39	BBTMp- BBTMp	0.82	0.92	0.98	0.90	59%	66%	71%	65%
2.65	1.39	BBTMt- BBTMp	0.64	0.79	0.85	0.83	46%	57%	61%	60%

4. INTRODUCTION TO A FINITE ELEMENTS MODEL (FEM) OF TANGENTIAL STRESS IN JOINTS OF ASPHALT MIX PAVEMENT LAYERS

On the other hand, a Finite Elements modelling was carried out for double layer asphalt mix systems, in order to verify and compare the calculated maximum theorical shear stress values, with the minimum share bond strength requested by the Spanish technical specifications. To analyse the flexible pavement under loads, it was used the finite element software ANSYS. The loads introduced in the model have been those indicated in the Spanish Instruction on the Actions to be considered in the Road of Bridges Projects (IAP-11) [8], since they are loads greater than those indicated in the pavement sizing regulations for roads, higher shear stress will be obtained from the model.

4.1. Geometric definition

Three models have been performed for the different possibilities of joining between an AC asphalt mix layer and a BBTM asphalt mix layer. As for the thicknesses of each of them, and to stay on the side of security, 4 cm was chosen for the AC mixture and 3 cm for the BBTM one. As for the joint between layers, and to achieve maximum shear stress, it has been considered compatibility of deformations, so there can be no movement between both layers.



4.2. Definition of materials

The two types of bituminous mixtures have been characterized by their modulus of elasticity and their Poisson coefficient and to obtain the results indicated in the last section, the following values have been considered:

- AC asphalt mixture: Modulus of elasticity: 6,000 MPa and Poisson coefficient: 0.33
- BBTM asphalt mixture: Modulus of elasticity: 4,000 MPa and Poisson coefficient: 0.35

4.3. Definition of applied loads and results

As it was said, loads introduced in the model have been those indicated in the Spanish Instruction on the Actions to be considered in the Road of Bridges Projects (IAP-11) [8], it has to take into account since they are loads greater than those indicated in the pavement sizing regulations, higher tangential stress will be obtained from the model.

Vertical loads due to vehicle traffic have been considered, both the distributed load (each heavy vehicle will consist of two axles, with Q_{ik} being the load of each axle) and the punctual overload (q_{ik}) of the heavy vehicle,

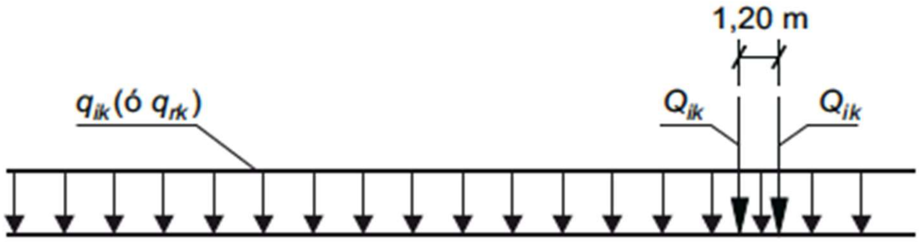


Table 5. Characteristic Loads

SITUATION	VALUE OF CHARACTERISTIC LOADS	
	HEAVY VEHICLE $2{*}Q_{ik}$ (kN)	PUNCTUAL OVERLOAD (qik) (kN/m2)
Virtual Lane 1	2 * 300	9.0

the horizontal loads due to braking and starting of vehicles (Q_{lk}),

$$\boxed{Q_{lk} = 0.60 * 2 * Q_{1k} + 0.1 * q_{1k} * w_1 * L}$$

where, loads due to braking and starting of vehicles (Q_{lk}), are equal to a fraction of the value of the vertical characteristic load that is considered acting on virtual lane number 1; w_1 is the width of virtual lane number 1; and L is the distance between adjacent joints of the bridge, or bridge length if they do not exist.

and those due to skidding due to braking (Q_{trk}), are equal to a fraction of the value of the loads due to braking and starting of vehicles (Q_{lk}):

$$\boxed{Q_{trk} = 0.25 * Q_{lk}}$$

The results of the maximum shear stress obtained between the layers in the three models defined in the section 4.1 are shown below:

Table 6. Maximum Shear Stress

Section	**Maximum Shear Stress (MPa)**
4 cm AC – 4 cm AC	0.151
4 cm AC – 3 cm BBTM	0.169
3 cm BBTM – 3 cm BBTM	0.162

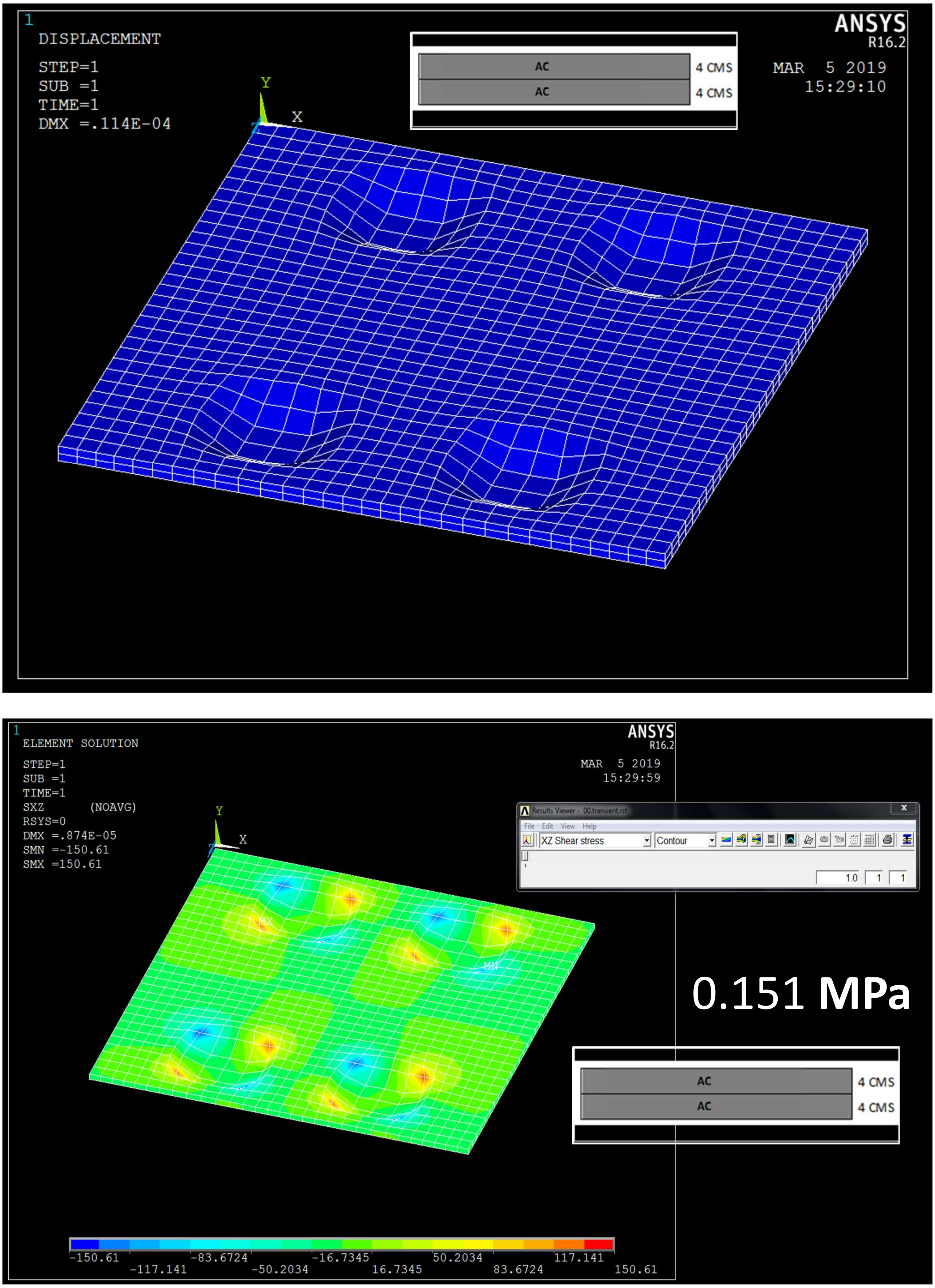


Figure 10. Example: Detail of calculated shear stress between different pavement layers AC-AC (ANSYS)

5. CONCLUSIONS

According to laboratory comparation exercises results, regarding the effect of device type (A and B, NLT-382)., significant differences between devices A and B have been found. Higher results with device A, for any residual bitumen rate and macrotexture. They vary with the type of mixture (15-35% lower with device B).

Regarding the effect of macrotexture:

- Tendency to higher values at low macrotextures, both in shear bond strength and in terms of energy.
- The macrotexture of the top layer affects also shear bond strength.
- It is not possible to establish a residual bitumen rate-macrotexture correlation.

Considering, test curried out with different residual bitumen rates:

- Optimal residual bitumen rates were found at 500-700 g/m^2.
- From a residual bitumen rate of 200 g/m^2, values close to the optimum are already reached.
- Shear bond strength at the optimum residual bitumen rate is about 55-75% of the maximum theorical value.

The finite elements model leads to maximum shear stress values below 0.2 MPa, these values are lower than the minimum share bond strength requested by the Spanish technical specifications (0.6 MPa).

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