Binder performance and testing

Comparative analysis of the BBS and Mortar Pullout tests in the evaluation of adhesive properties and moisture damage in asphalt binders

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Abstract

Facing the evolution of the problems caused by the deleterious effect of water on pavements, in recent years some researchers have been developing new tests for the experimental and analytical evaluation of this damage. The present work aims to compare the BBS (Binder Bond Strength) tests and an adaptation of the Mortar Adhesion test for the evaluation of the moisture damage in the adhesive properties of the bitumen/aggregate system. For this purpose, a PG 64-22 binder was modified with an SBS polymer, an adhesion agent (D.08 Dope) and the sap of Euphorbia Tirucalli (petroleum plant), in various contents. The adhesive properties and the moisture damage between the modified binders and a granite substrate were evaluated by the BBS tests, with the Positest AT-A equipment, and the Mortar Adhesion test, with the mortar pull-out equipment. The main difference between both tests is that the BBS equipment has hydraulic operation while de mortar pull out test is mechanically actuated. The tests were performed on dry and saturated conditioning of the samples, to quantify the damage caused by moisture. The results of the statistical treatment of the data showed that both tests, considering equal conditioning, were able to maintain the same trend of results. However, the magnitude of the values is higher in the BBS, once the rate of load application, being automated, is larger and more accurate. In the mortar pull out test the rate and accuracy are subject to the ability of the operator. It was observed that both tests showed similar repeatability. It can be concluded that the test performed by the mortar pull out equipment can be used as an alternative method to the BBS test, for the evaluation of adhesiveness and the moisture damage of asphalt binders.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

The deleterious effect of moisture on pavements is still a complex problem, as it is dependent on the physical, mechanical and especially chemical properties of its components. The harmful action of water has become a serious worldwide problem [1]. Loss of adhesion between bitumen film and aggregate surface due to water action may account for about 30 to 50% of the asphalt pavement defects observed in some US states, as indicated in [2]. Given this, the evaluation of the damage caused by moisture has great importance, since it directly affects the pavements performance and life cycle.

As an alternative to control the moisture damage on the adhesive properties of the bitumen/aggregate system [1], additives known as Adhesion Agents are being incorporated into asphalt mixtures. Such additives may either have natural or industrial origin, being dopes, hydrated lime and polymer modified binders the most widely used agents [3].

Tests for evaluating the moisture damage resistance in asphalt mixtures can be classified into two main categories: qualitative and quantitative [4; 1]. Visual analysis tests are qualitative and verify some detachment of the bitumen film covering the aggregate. These methods are subjective and empirical. However, the biggest criticisms about them are their low correlations with actual pavement performance and the lack of information they can provide concerning the adhesion phenomenon itself [5; 6].

Regarding the quantitative or mechanical tests, they have an advantage over the visual ones, once they can simulate the field circumstances through conditioning and/or mechanical efforts to which the samples can be submitted [7]. Quantitative responses of mechanical tests are achieved by correlating parameters such as resilient modulus ratio, tensile strength and permanent deformation in test specimens, with or without saturation conditioning. These results are obtained by indirect means, what represents a limitation of these methods.

However, when it comes to tests that evaluate the moisture damage in the bond between the bitumen and the aggregate, the importance of obtaining both qualitative and quantitative results is noticeable. In the last years, it was developed a test that can evaluate qualitatively the adhesive characteristics of the bitumen/aggregate contact while it measures the tensile strength that is necessary to break this interaction [8]. This test was named the Binder Bond Strength (BBS) and it was standardized by the American Association of State Highway and Transportation Officials (AASHTO) [9].

According to [10], the test is important in assessing moisture damage for both bitumen and asphalt emulsions. As happens in mechanical tests, BBS can also simulate the field conditions to which the pavement is subjected by submitting the samples to well-controlled temperature and humidity conditions during test procedures.

A new adaptation for the BBS test was proposed in [11], by replacing the pneumatic load application equipment with the equipment usually employed in mortar adherence testing. The author obtained inicial satisfactory results, once the alternative method showed the same trend of results than the standardized one. This adaptation has as main advantages the low cost of the device. It should also be mentioned that many civil engineering materials laboratories already use this device currently.

Therefore, the present work aims to perform a comparative analysis between the Binder Bond Strength (BBS) test and the Mortar Adherence adaptation used in the evaluation of the moisture damage in the adhesive properties between bitumen and aggregates.

2. MATERIALS AND METHODS

2.1 Materials

The materials used in this research were a PG 64-22 bitumen (50/70, by penetration), a granite aggregate, and some asphalt modifiers: a commercial dope D.08, an industrial polymer SBS and the sap of the *Euphorbia Tirucalli* plant (petroleum plant).

The bitumen, referred on this paper as LA, was modified with 0.2% and 0.4% of the D.08 dope, 4.5% and 5% of the SBS, and with 10% and 20% of the sap. These samples were nominated as DOPE 0.2%, DOPE 0.4%, SBS 4,5%, SBS 5%, Sap 10% and Sap 20%, in this order.

2.3 Binder Bond Strength Test (BBS)

The BBS test was performed with the Positest AT-A equipment, shown on Figure 1. This device works hydraulically, and it is possible to control the pullout rate (the rate of the applied stress). There is no regulatory standard to this Positest AT-A equipment test. Hence, the tests were performed according to AASHTO TP 91-11 standard and all test conditions (pullout rate, conditioning temperatures, stub surface condition and others) were strictly followed.

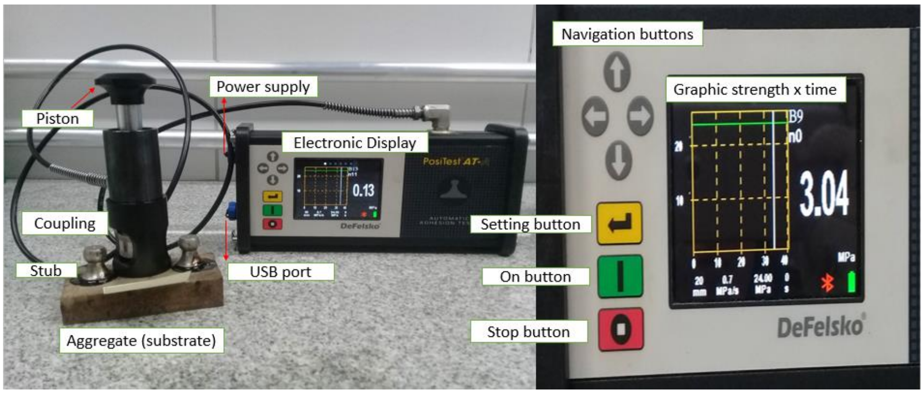

Figure 1: Positest AT-A equipment.

The materials preparation, prior to testing, is divided into two parts: mineral substrate preparation and bitumen/substrate system preparation. The mineral substrate must be cut, resulting in a block with parallel faces, and then sanded in order to present standard surface roughness. The procedures for preparing the bitumen/substrate system are described below.

a) The substrates are washed on ultrasonic bath at 60°C, for 1 hour, to vanish any residue from the sanding process and to neutralize the aggregate surface to its original condition.
b) The stub and substrate set are oven heated at 150°C, for at least 30 minutes, to evaporate the residual humidity. In the sequence, the oven is set into the mixing temperature, previously determined for each sample.
c) The bitumen sample is poured in a silicone mold, with controlled weight (0,4g ± 0,05 g), and let to cool for 15 minutes at room temperature.
d) The bitumen samples are unmolded and applied to the hot bottom surface of the stubs, where the bitumen is spread.
e) The stubs with the bitumen samples are layered on the hot surface of the substrate. The standard recommends applying the stubs under a 50g weight, however in this test the stub was handmade pressed for 10s. It is also necessary to press the stub in an angle of 90° in order to avoid twisting it and forming air bubbles inside the sample.
f) Half of the samples are cured at room temperature for 24 hours (dry condition), and the other half is cured over water immersion for 24 hours (saturated condition) in order to quantify the moisture damage. It is important to emphasize that immersed samples must be cooled at room temperature for 1 hour before submersion. After the conditioning process, samples must be stabilized for 1 hour at room temperature, prior to testing.

To perform the test, first the load application is set, and the piston is clamped to the stub. The stress rate applied to all samples was 0.70 MPa. Then the Positest AT-A test is started. In the end of the test, the maximum stress applied to the sample is obtained, called the *Pull-Off Tension Strength* (POTS).

It is also possible to evaluate qualitatively through visual analysis the type of failure on the bitumen/aggregate system. If it happens between the binder and substrate interface it is said that it is an adherence failure; if the failure happens into the bitumen sample, it is said cohesion failure. It is also possible calculate the POTS relation (RPOTS), determined by the equation 1. The RPOTS must be higher than 70%, as recommended for many authors [12].

$$RPOTS = \frac{humid\ POTS}{dry\ POTS} \quad (1)$$

Where:
Dry $POTS$: air-conditioned samples $POTS$ (MPa);
Humid $POTS$: saturate conditioned samples $POTS$ (MPa).

2.4. Mortar Adherence Test

The adhesion tests using the mortar adherence equipment was performed with the device presented at Figure 2.

Figure 2: Mortar adherence device

This test is an adaptation proposed by [11], hence there is no specific standard to follow. Once again most of the recommendations of AASHTO TP 91-11 were followed. Nevertheless, the stubs applied on the methods had slightly different dimensions, as shown on Figure 3. The stubs dimensions of the mortar adhesion test are larger than the ones used in the BBS test, resulting in thinner bitumen layers.

Figure 3: a) BBS Stubs and b) mortar adhesion stubs

When performing the first mortar adhesion test, it was observed that the mineral substrate, being smaller than the support area of the device, was pulled together with the stub and the failure did not happen. Thereby, it was concepted a feature to fasten the substrate under the device support, so the pullout process would happen. This feature is shown on Figure 4.

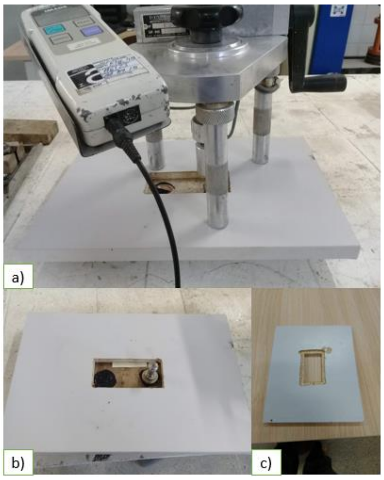

Figure 4: Fixing device for the Mortar Adherence test a) test system; b) up view; c) bottom view

To start the test with the mortar adherence equipment, the load meter is reseted in the digital controller. Then, the load is applied by the turn of the hand winch. The test finishes when the stub is separated from the substrate and the controller exhibits the maximum load (F), expressed in kgf. The *Pull-Off Tension Strength* (POTS) is then calculated by the Equation 2.

$$POTS = \frac{F}{A} \text{ x } 0{,}098 \qquad (2)$$

Where:
POTS: Pull Off Tension Strength (MPa);
F: rupture strength (Kgf);
A: stub area (mm²).

3. RESULTS

3.1 Qualitative Evaluation

The qualitative evaluation consists on identifying the failure mechanism. The failure can occur in two different ways: by adhesion, when it happens between the binder and substrate interface, and by cohesion, when it happens completely inside the binder sample. All tests were replicated 3 times for each sample, resulting in four observation for each one. The results are shown in Table 1, for both dry and saturated conditioning, presenting the predominance of failing mode, for BBS and Mortar Adherence method as well.

Table 1: Failure Mechanism

Sample	Conditioning Type			
	DRY		SATURATED	
	BBS	Mortar Adherence	BBS	Mortar Adherence
LA	cohesion	cohesion	cohesion/adhesion	cohesion/adhesion
DOPE 0.2%	cohesion	cohesion	cohesion/adhesion	cohesion/adhesion
DOPE 0.4%	cohesion	cohesion	cohesion/adhesion	cohesion/adhesion
SBS 4,5%	cohesion/adhesion	cohesion/adhesion	cohesion/adhesion	cohesion/adhesion
SBS 5%	cohesion	cohesion	cohesion/adhesion	cohesion/adhesion
Sap 10%	cohesion	cohesion	cohesion	cohesion
Sap 20%	cohesion	cohesion	cohesion	cohesion

When only flaw spots were observed, instead of detaching most of the area, the failure mechanism was considered as being cohesion/adhesion. Figure 5 shows both kinds of failure observed in this research.

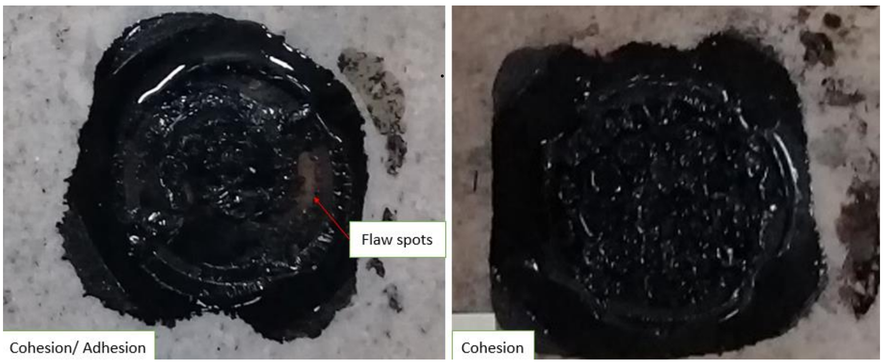

Figure 5: Failure mechanism

In both test methods, considering the dry condition, most of the samples undergone failure by cohesion mechanism (unless for the SBS 4.5%). However, the water immersion has changed the kind of failure, and dislocated bitumen film spots were observed for almost all samples (but the Sap modified ones), as shown on Figure 5.

These flaw-kind changes driven by water immersion were also observed in [11] and [8]. In [11], the reference binder, LA, has failed by cohesion under dry conditions and in saturated conditions has undergone rupture by cohesion/adhesion. In [8], PG 64-22 binders, applied over granite substrate, showed cohesion failure when in dry conditions and adhesion failure in saturated conditions (24 hours of water immersion).

It is worth noting that the mechanism of failure did not change between testing methods. For all the samples tested and all the conditioning types, BBS and mortar testing agreed about the failure mechanism.

3.2 Quantitative Evaluation for Dry Conditioned Samples

The quantitative evaluation was performed through statistic analysis of the POTS values from BBS and mortar adherence tests, over two conditioning types (dry and saturated). The statistic parameters were mean, standard deviation and coefficient of variation (CV). It was also applied a simple linear regression method to try to find if both tests were related.

The mean POTS were obtained from four repeated tests. Table 2 and Figure 6 show the results obtained from the BBS and Mortar Adherence tests, both in dry conditions.

Table 2: POTS values for BBS and Adherence tests in dry condition

	BBS			Mortar Adherence		
Sample	**Mean**	**StandDev**	**CV (%)**	**Mean**	**StandDev**	**CV (%)**
LA	1,990	0,087	4,381	0,561	0,056	10,024
SBS 4,5%	3,353	0,125	3,729	1,744	0,110	6,284
SBS 5%	2,493	0,275	11,045	0,767	0,045	5,889
Dope 0,2%	3,065	0,202	6,593	1,069	0,050	4,686
Dope 0,4%	2,217	0,162	7,293	0,628	0,029	4,615
Sap 10%	1,640	0,086	5,245	0,524	0,039	7,435
Sap 20%	1,247	0,108	8,652	0,354	0,046	13,083

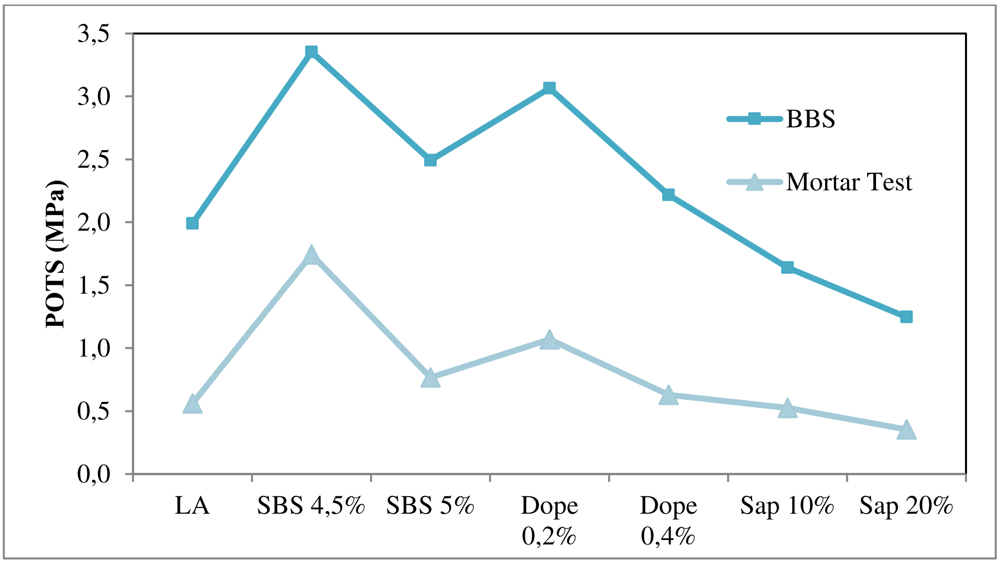

Figure 6: POTS values for BBS and Mortar Adherence tests in dry conditions

The magnitude of the results from both tests are different because the loading application rate is higher on th BBS than in the mortar test. BBS device works hydraulically and consequently the loading rate is faster and automated, not being influenced by the operator. In the mortar adherence test the loading is handmade applied, slower and quite influenced by the operator. This loading application speed is important due to the binder viscoelastic character. So, as seen on table 1, the BBS POTS scores are higher than the adherence ones. The same conclusions were also driven by [11], as well.

However, despite this difference between the POTS mean magnitude it is noticeable that both tests point the same tendency in results. This tendency can also be seen on Figure 6.

The standard deviation achieved can be considered low, as in [11] they scored between 0,080 to 0,226, and [8] found them ranging from 0,010 to 0,120. The closer to zero they are, the closer the data spots are to the mean value, showing good repeatability. Thus, the results found can be considered adequate. It must be pointed that the Mortar test results tends to lower standard deviation than the BBS, and it can be explained by either the lower mean values, or to the thickness of the bitumen layer, that is thinner on the mortar method.

The coefficient of variation indicates the dispersion of the results, and it is a more acured parameter of repeatability, once once it considers the mean value, being a more efficient parameter to compare the repeatability of the two methods. In [13] a reference binder PG 64-28, in dry condition, showed 5,58% as CV on BBS Test. This score is close to the one found in this report to LA binder, which was 4,38% on BBS Dry condition test. For this set of samples, the mortar test showed higher CV than the BBS test, which indicates that the alternative method has lower repeatability than the original one.

The same LA and Sap 10% samples were evaluated by [11], using other kind of equipment (PATTI) and the mean POTS for these samples were 3,21 and 2,73 MPa, respectively. On the present research, BBS test to same samples resulted in 1,99 MPa and 1,64 MPa of POTS, in this order. It is believed that the difference between these results can be explained by two reasons: first, the fact the stub dimensions used in [11] are larger than the used here; second, differently from PATTI, the Positest device gets the tensile stresses values automatically, considering a general stub dimensions, not taking into account that stubs had to be changed in order to guarantee adhesion and film thickness. It is known that is possible to determine the proportion relation between the two stub dimensions, finding the actual tensile stress. However, for practical reasons it was chosen to use the scores gotten directly from Positest, since the motivation for this application was the method simplicity.

3.3 Quantitative Evaluation for Saturated Conditioned Samples

Table 3 and Figure 7 show the results from BBS and Mortar Adherence tests, both in saturated condition.

Table 3: POTS values for BBS and Mortar Adherence test in saturated condition

Sample	BBS			MORTAR ADHERENCE		
	Mean	StandDev	CV (%)	Mean	StandDev	CV (%)
LA	1,713	0,063	3,705	0,472	0,005	1,009
SBS 4,5%	2,340	0,095	4,077	0,743	0,071	9,609
SBS 5%	2,560	0,294	11,495	0,845	0,060	7,148
Dope 0,2%	2,563	0,365	14,229	0,950	0,150	15,749
Dope 0,4%	2,573	0,258	10,016	0,826	0,036	4,357
Sap 10%	1,177	0,103	8,722	0,394	0,039	9,960
Sap 20%	1,120	0,101	9,017	0,290	0,039	13,473

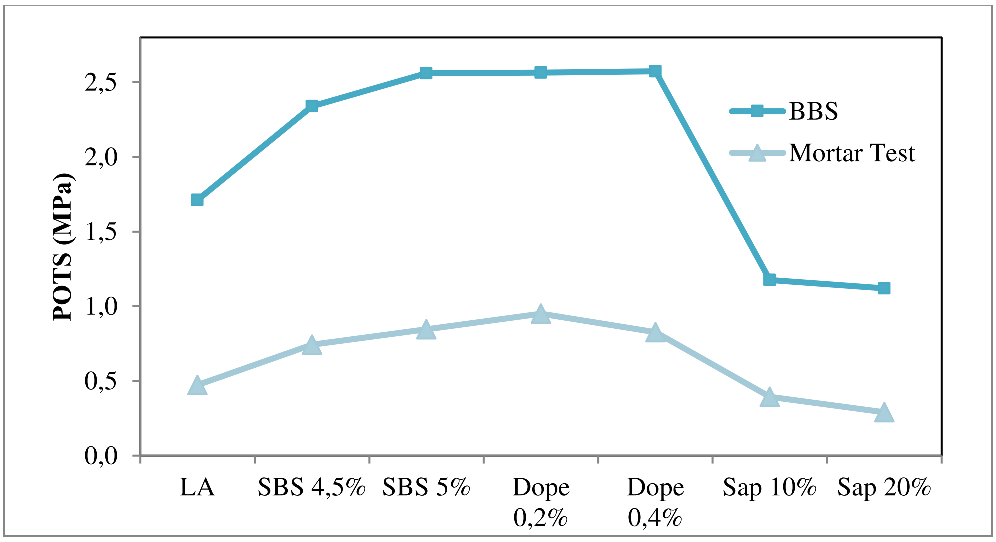

Figure 7: POTS values for BBS and Mortar Adherence tests for saturated conditioning

As in dry condition, the POTS magnitude is different for both tests. As can be seen on table 3, the BBS ones are higher than the mortar adherence ones. This difference happens, just like in dry conditions, due to the different loading application rate to each test, once the devices work distinctly. As the mortar test goes slowly, the viscoelastic properties of the bitumen are more prone to be observed than in BBS one.

The results on Table 3 and Figure 7 show, one more time, they have the same results tendency, what is clear, mainly on Figure 7.

The standard deviation scores are low and match with the results found in [11], which showed scores between 0,048 and 0,479, and [9], between 0,050 and 0,260. Generally, the CV scores found in saturated condition are also adequate once there were not observed high scores. On the other hand, for saturated samples, the CV values of the mortar test were smaller than the BBS ones, showing better repeatability of the alternative method for this set of samples.

In [11], the LA and Sap 10% BBS test mean POTS found was 2,339 MPa and 1,743 MPa, while in this research it was found to be 1,713 MPa and 1,177 MPa, respectively. This difference also happened in dry conditions test, thus emphasizing the previous conclusions.

3.4. Dry and Saturated Conditions Tests Comparison

The POTS relation, or RPOTS, was used to compare both conditioning states, dry and saturated, in which the samples undergone during the tests. Table 4 and Figure 8 show the RPOTS results to samples on BBS and Mortar Adherence tests.

Table 4: POTS relation for BBS and Mortar Adherence tests

RPOTS (%)		
Sample	**BBS**	**Mortar Adherence**
SBS 4,5%	70	43
Seiva 10%	72	75
Dope 0,2%	84	89
LA	86	84
Seiva 20%	90	82
SBS 5%	103	110
DOPE 0,4%	116	131

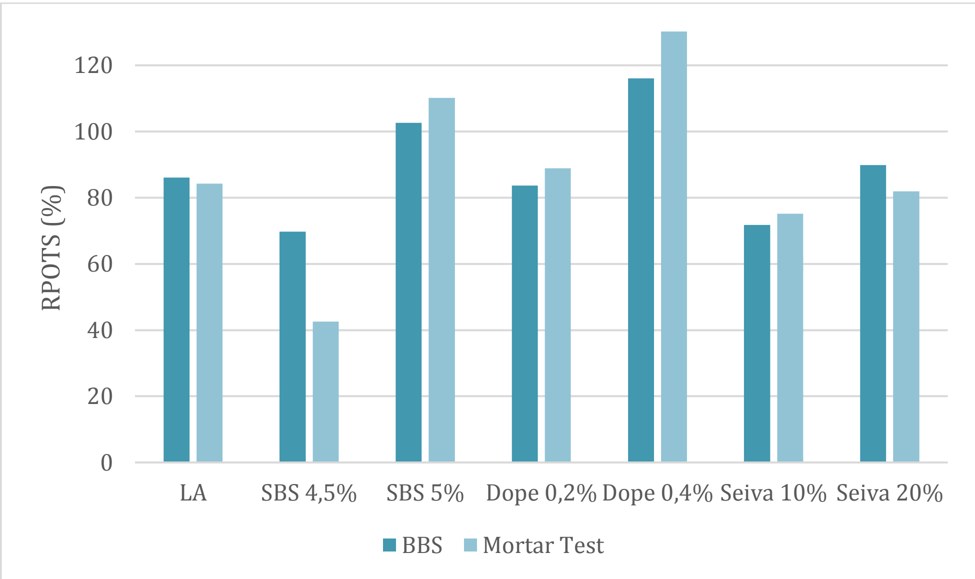

Figure 8: POTS relation (RPOTS) between dry and saturated conditioning

The results on table 4 are disposed on crescent order which shows that the BBS and mortar adherence test scores follow the same tendency. This fact can also be noticed on Figure 8. The DOPE 0.4% sample got the best result, 116% on BBS test and 131% on Mortar Adherence test. The sample of the SBS 4,5% in the Mortar Test was the only one that did not reach the minimum limit of 70% for RPOTS, recommended by [12].

Two dispersion graphics charts correlating the BBS and the Mortar adherence tests were plotted in order to separate the effects of the different conditioning types, dry and saturated conditions, shown in Figures 9 and 10, in this order.

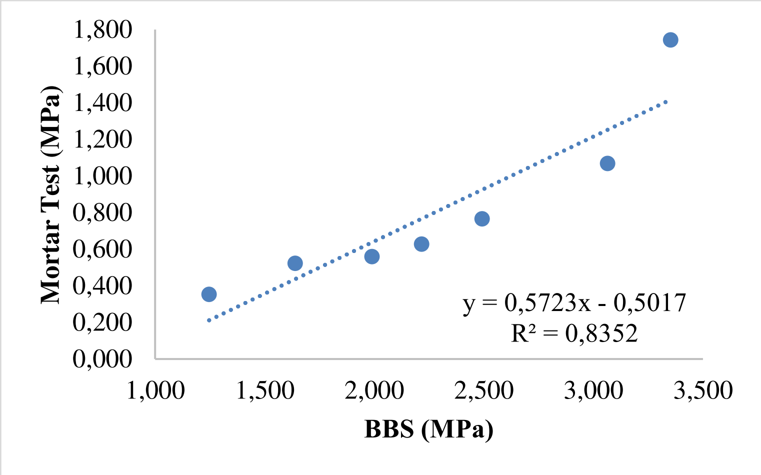

Figura 9: BBS and Mortar Adherence tests correlation for dry conditioning

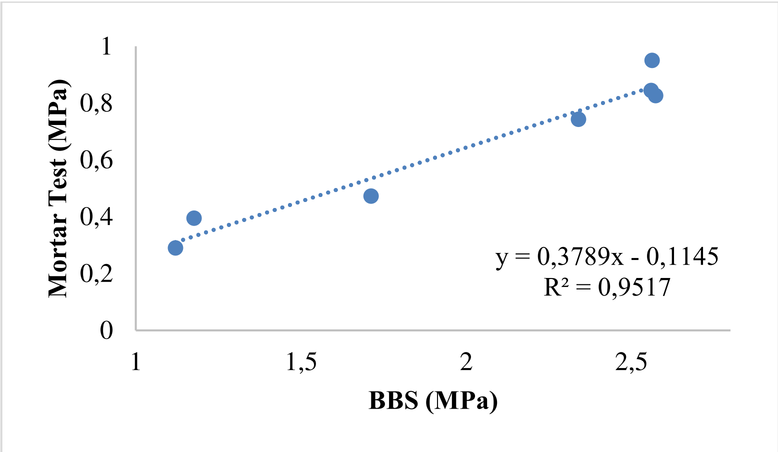

Figura 10: BBS and Mortar Adherence tests correlation for saturated conditioning

The tendency line in Figure 9, for dry condition, presented R^2 of 0,84, and the one in Figure 10, for saturated condition, presented R^2 of 0,95. Both results are near 1, indicating both models are adequate. These results are expected once mean POTS of both tests showed the same results tendency and because the standard deviation and CV were low, matching with other scores from literature.

Finally, trying to find a correlation between BBS and Mortar Adherence tests, now considering the two conditioning types together, Figure 11 was plotted. Each graphic point refers to a sample and a conditioning kind. The function that relates the tests is determined by linear regression, presented on Figure 11.

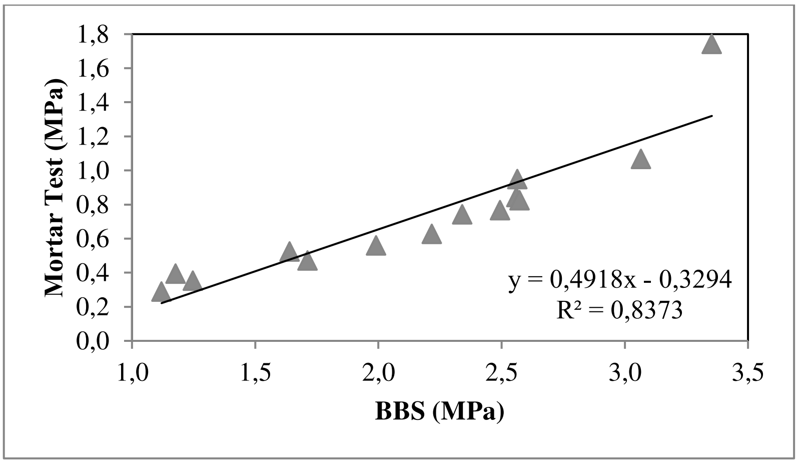

Figure 11: BBS and Mortar Adherence tests correlation

In this general case, R^2 found was 0,84 which is larger than the one found by [11], that was 0,73. Thus, this score is satisfactory once there is a variability found in both tests. It is believed this variability happened due to the following reasons: Stubs dimensions were different in the tests, and due to the difficulty to reach a standard to substrate dimensions and inclinations.

4. CONCLUSION

According to the results shown, it can be concluded that this research contributed to show that adhesiveness and moisture damage evaluation can be done by means of a method that uses a non-standardized equipment, but which has low cost, easy access and simple handling.

By the light of the qualitative results, it can be stated that in both tests performed, BBS and Mortar Adherence, samples failure mechanism happened equally. Thus, showing that the Mortar Adherence method can be used for qualitative evaluation of adhesion and moisture damage, once there was no divergence in their results when compared with BBS method.

Regarding the quantitative results found for both conditioning types analysed separately, it can be concluded that they were satisfactory, since they presented in the BBS and Mortar Adherence tests the same tendency of results, a small variability in the values (observed through the small standard deviation and CV values) and appropriate coefficient of determination (R^2).

The comparative analysis between the two tests, BBS and Mortar Adherence, considering both conditioning types together, dry and saturated, also showed satisfactory results. The coefficient of determination, R^2, overall was 0.84, meaning that there is a positive correlation of 84% reliability between the two trials.

Therefore, it can be concluded that the test performed by the mortar adherence equipment can be used as an alternative method to the BBS test, since it was found that the method has potential to be used for both qualitative and quantitative evaluations of the adhesion and moisture damage of bitumens.

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