Repeatability of Interlayer Shear Resistance determined with Two Test Procedures

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Synopsis

Interlayer bonding significantly influences the performance of multi-layered pavement systems. To correctly know how this bonding modifies the interlayer mechanical performance, theoretical and experimental projects are currently in progress in many countries. However, different equipments generally provide different results because these results are obtained under different test conditions in terms of applied stress and strain, rate of displacement, specimen size and specimen confinement. Since in European Standards there is a normative gap regarding interlayer resistance tests, in Italy a draft of a standard is currently under development based on a laboratory direct shear device called ASTRA (Ancona Shear Testing Research and Analysis). In the present paper, the repeatability of ASTRA test method is studied by analyzing the results obtained in two experimental investigations. In the first investigation, specimens prepared with the same material and the same compactor were tested with ASTRA test method and with another shear test method, the LPDS (Layer-Parallel Direct Shear), which is compatible with Swiss Standards (Schweizer Norm SN 671961, 2000). In the second investigation, the first series of ASTRA results were compared with repeatability results obtained by using different materials and different compaction methods for the double-layered specimens. The study shows that the two shear test equipments provide the same precision level in terms of scatter of the results. Moreover, the ASTRA investigation shows that the repeatability depends not only on the test method but also on the pavement material and compaction method. This study allows supporting Italian standardization of interlayer shear resistance testing and, at the same time, it shows that it is necessary to further investigate different materials and different compaction methods to improve the knowledge on repeatability.

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INTRODUCTION

The evaluation of interlayer shear resistance is important to better understand how multi-layered pavements behave under traffic conditions, in particular when an horizontal shear load is applied, as it is the case during breaking, in curves or in steep slopes. Recently, Rilem technical committee TC ATB *"Advanced Testing and Characterization of Bituminous Materials"* has started to initiate an international interlaboratory study on shear resistance test methods that underlines the general increasing importance of this subjects.
The Ancona Shear Testing Research and Analysis (ASTRA) apparatus, developed since 1992 in the Università Politecnica delle Marche (Ancona) [1, 2, 3], and the Layer-Parallel Direct Shear (LPDS) equipment, designed by EMPA (Swiss Federal Laboratories for Materials Testing and Research) in 1995 [4] based on the so-called Leutner shear test in Germany [5], are two different devices to experimentally estimate interlayer shear resistance of multi-layered specimens. In spite of the fact that both tests are based on different test conditions (rate of displacement, dimension of the specimen, way to confine the specimen, applied loads, etc…) their results seem to be comparable [6].
The standardization of ASTRA test method, currently in progress in Italy, needs a determination of accuracy in terms of preliminary assessment of precision. The same is true for the LPDS test method that is compatible with the Swiss Standards, where the Leutner shear test is required.
The precision is one of the characteristics needed to determine the accuracy of a test method. A complete statistical study of trueness and precision should be performed to obtain a correct determination of accuracy [7]. The trueness is the degree of agreement between the mean value of a high number of measurements and what is called 'true value' of the measurement. The precision is the degree of agreement between independent measurement results obtained in a defined condition. It can be expressed through repeatability and reproducibility. The accuracy experiment involves different laboratories to compare the results in performing the same tests in the same conditions.
Since ASTRA and LPDS equipments are still prototypes, in the present paper, only the results concerning the repeatability in a single laboratory both for ASTRA and for LPDS method can be presented.
Two different investigations were performed. In the first one, ASTRA and LPDS devices were used to study repeatability on specimens made with the same asphalt concrete material and the same compactor. In the second investigation, the ASTRA results were compared with repeatability results obtained by using different materials and different compaction methods for the double-layered specimens.

STATISTICAL ANALYSIS

When performing experimental investigations, the main problem is to obtain similar results in repeating the same test under the same conditions. Since it is impossible to keep every condition exactly the same, each type of measurement creates unavoidable casual errors that cause differences between the results of repeated tests.
In order to obtain a suitable assessment of a measured value with a particular test method, it is necessary to know this variability as a function of different factors: environmental conditions (temperature, humidity, etc..), device setup, time interval between repeated tests, test operator and laboratory in which the tests are performed. These factors describe the variability of a test method through repeatability (obtained by keeping fixed all the previous factors during the test) and reproducibility (obtained by keeping fixed the first three factors and making change operator and laboratory). Hence, repeatability conditions are defined as the conditions in which independent test results are obtained with the same protocol, the same material, the same laboratory, the same operator, the same equipment. On the other hand, reproducibility conditions are defined as the conditions in which test results are obtained with the same protocol, the same material, different laboratories, different operators and by using distinct test equipments.
With a repeatability test on a set of 'identical' specimens (at least 30), it is possible to obtain the repeatability limit r defined as the value, below which or in correspondence of which, the absolute difference among two test results, obtained under repeatability conditions, should fall within a 95% probability. On the other hand, it is possible to define the limit of reproducibility R as the value, below which or in correspondence of which, the absolute difference among two test results, obtained under reproducibility conditions, should fall within a 95% probability.
The repetition of the same test for a defined number of 'identical' specimens produces independent and identically distributed random variables that represent a sample of a population whose behaviour and properties can be described by a statistical model.

Usually, in engineering situations, the suitable statistical model to represent the measurement of a generic characteristic is the normal distribution. However, this assumption needs a verification.

Normal distribution

The usefulness of the normal distribution (or Gauss distribution) has a double reason. Primarily, theoretical themes and experimental results allow to assert that random measurement errors follow a normal distribution. Secondly, all the other distributions tend to the normal distribution. This property is defined by the central limit theorem [8] which states that the sum of many independent random variables tends, approximately, to a normal distribution. The number of samples to accept the approximation to a normal distribution depends on the initial distribution of the data obtained from the measurements. In particular, if the data are normally distributed the sum is normally distributed independently from the number of the sample. For other distributions it has been estimated that at least 30 specimens are necessary to make sure that the distribution of the sum of the variables is approximately normal.
The normal distribution is defined for the random variable x through the following expression:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \qquad (1)$$

$-\infty < x < +\infty$
$-\infty < \mu < +\infty$
$\sigma > 0$

where μ = mean value;
σ^2 = variance;
σ = standard deviation.

Function f(x) has the typical bell shape, it is symmetrical around the mean value μ and the maximum of the distribution is in correspondence of $x = \mu$. In the practice, equation *(1)* is too complicated to use. Therefore a normal standard distribution has been introduced with the purpose to make it independent from μ and σ. To obtain this result, it is necessary to introduce another variable z defined as follows:

$$z = \frac{x-\mu}{\sigma} \qquad (2)$$

The corresponding normal standard distribution has $\mu = 0$ and $\sigma^2 = 1$. It is defined as follows:

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} \qquad (3)$$

The normal standard distribution has been tabulated to provide the probability to find the random variable x to a distance $z \cdot \sigma$ from the mean μ . In this way, the probability to find the random variable x within a certain number of standard deviations depends neither on μ nor on σ.
If the 'true values' of the mean value μ and of the standard deviation σ are unknown, it is possible to give an estimation of them, denoted as $\bar{x}$ and s respectively, through the results of a measurement number of sample equal to n:

$$\bar{x} = \frac{\sum_i x_i}{n} \qquad s = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{n-1}} \qquad (4)$$

Normal Distribution Verification

The independent random variables derived from the repetition of the same test usually belong to a population that can be approximated by a normal distribution. However, it is necessary to verify this hypothesis by using graphic or analytic methods.
The analytic method is known as the W test or the Shapiro-Wilk test [9, 10, 11]. First of all it is necessary to evaluate the quantity c^2 as follows:

$$c^2 = \sum_i (x_i - \bar{x})^2 \; ; \qquad (5)$$

to rank the data from the smallest to the largest (x_1 to x_n) and to calculate the quantity

$$b = \sum_{i=1}^{k} a_{n-1+i} \left(x_{n-i+1} - x_i \right) \qquad (6)$$

where $k=n/2$ if n is even
$k=(n-1)/2$ if n is odd
a_{n-i+1} are tabulated in function of n.

Finally, the value W is computed:

$$W_{comp} = \frac{b^2}{c^2} \qquad (7)$$

and compared with a theoretical W_{tab} value, tabulated in function of n and of the probability to reject the hypothesis of normal distribution. Usually, this probability is equal to 5%. This means that if the W_{comp} value is smaller than the theoretical W_{tab} value, corresponding to the chosen probability and the chosen sample number n, the hypothesis of normal distribution has to be rejected at the chosen probability level.

Repeatability

A test performed under repeatability conditions, provides n independent random variables that are normally distributed with the same mean μ and the same standard deviation σ if the previous validation is verified.
A new random variable can be originated as difference among two generic values of the previous n test results. It is known that also this new variable is normally distributed with standard deviation $\sigma\sqrt{2}$.
To obtain the repeatability limit r, it is necessary to consider the z value (of the normal standard distribution) corresponding to a 95% probability to find the new random variable within a certain number of standard deviations and to multiply it for the standard deviation:

$$r = 1.96\sigma\sqrt{2} \qquad (8)$$

In absence of a complete study on accuracy, it is not possible to know the 'true value' of the mean and standard deviation. Hence, it is necessary to use an assessment of these values by using equation *(4)*. This leads to

$$r = 1.96 s\sqrt{2} \qquad (9)$$

MATERIALS AND EXPERIMENTAL PROGRAM

In the first part of the study, two series of 50 double-layered specimens were made in the laboratory and subjected to ASTRA and LPDS test respectively, by using the same material and the same compactor. The specimens were cored from slabs made with the MLS - Roller Compactor (Figure 1) at EMPA. This compactor was developed at University of Stellenbosch (South-Africa). The MLS-Roller Compactor is composed of: 1) a horizontal level surface where the loose asphalt concrete is placed; 2) a vibrating roller (diameter of about 35 cm and width of about 91 cm) that can rotate around a horizontal barycentric axle and can move in horizontal and vertical direction. The rotation and the horizontal displacement allow compacting the material in rectangular slabs 105x91 cm^2; the vertical movement allows obtaining different thicknesses for the layers.

Figure 1: MLS - Roller Compactor

Two different dense graded hot mixes were used: ACT 16 for the lower layer and AC 11 for the upper layer. The same aggregates type and the same bitumen were used to produce both mixes. Two different aggregate size distributions were used for the two layers. The materials and the slabs characteristics are shown in figure 2, table 1 and table 2. The upper layer of each slab was made one day after the preparation of the lower layer. The specimens were cored from the produced slabs, stored at room temperature for 10 days and conditioned about 8 hours at 20°C, before testing.

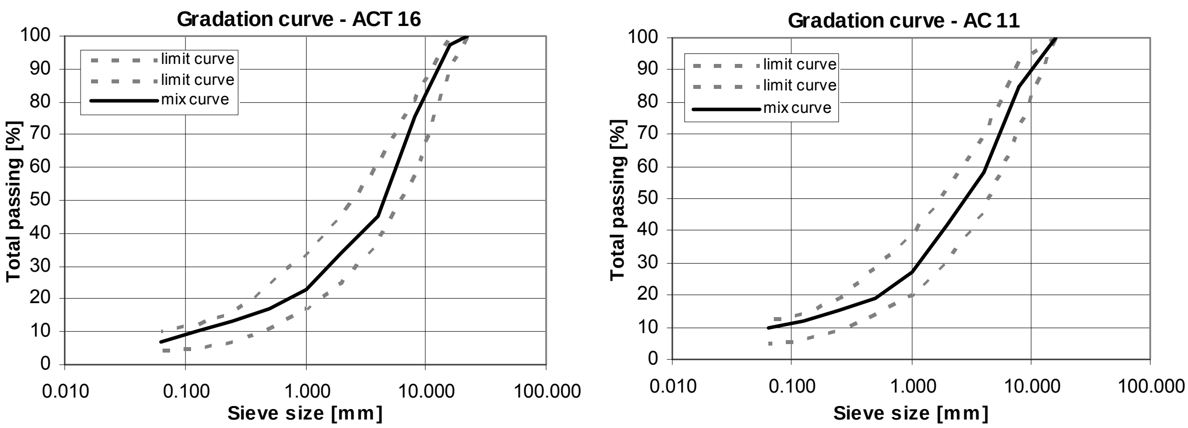

Figure 2: Aggregates size distributions – MLS Roller Compactor

Table 1: Bitumen characteristics –MLS Roller Compactor

Material	Type	Density $[t/m^3]$	Penetration [dmm]	T_{ReB} [°C]
bitumen	Normal	1.02	74	45.2

Table 2: Slabs characteristics –MLS Roller Compactor

Type	γ_{agg} $[t/m^3]$	γ_{asph} $[t/m^3]$	Filler type	bitumen content [%]	Air voids content [%]	Thickness [cm]
ACT 16	2.70	1.02	Netstal	5.0	4.41	6
AC 11	2.70	1.02	Netstal	5.6	6.40	4

In the second part of the study, a set of 40 double-layered specimens made with another compactor and another material were tested only with ASTRA device to compare the obtained *r* values. The double-layered specimens were made with the Superpave gyratory compactor by using the same material both for the upper and for the lower layer (figure 3, table 3 and table 4). The upper layer was made one day after the preparation of the lower layer. The specimens were stored at ambient temperature for 7 days and conditioned about 8 hours at 20°C, before testing.
The repeatability limits *r* were obtained considering a set of 40 or 50 specimens for each shear test method and performing the tests according to the standard conditions expected for each method as described below.

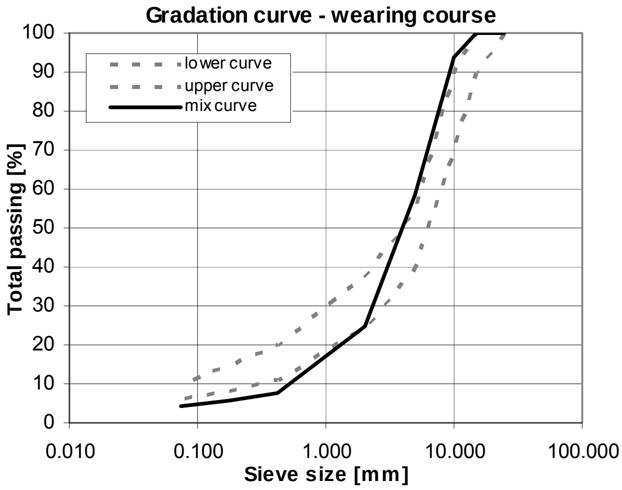

Figure 3: Aggregates size distributions – Gyratory Compactor

Table 3: Bitumen characteristics – Gyratory Compactor

Material	**Type**	**Density** [t/m^3]	**Penetration** [dmm]	**T_{ReB}** [°C]
bitumen	Normal	1.02	43	52

Table 4: Specimens characteristics – Gyratory Compactor

Type	γ_{agg} [t/m^3]	γ_{asph} [t/m^3]	**Filler type**	**bitumen content** [%]	**Air voids content** [%]	**Thickness** [cm]
wearing course	2.70	1.02	Limestone	5.3	4.53	4
wearing course	2.70	1.02	Limestone	5.3	5.74	4

EQUIPMENTS

ASTRA Device

ASTRA device is a direct shear box that allows applying a vertical normal load together with a horizontal shear load at the interface of a double-layered specimen (figure 4). During the test it is also possible to record vertical and horizontal displacements and to control temperature through a climatic chamber. Standard temperature condition is 20°C.
The cylindrical specimen (100 mm diameter) is placed in two independent half-boxes and mounted on a movable table. A constant vertical load (corresponding to a normal stress of 0.2 MPa in standard conditions) is applied up to the specimen. The lower movable table is moved at a constant displacement rate (2.5 mm/min in standard conditions) and transfers the shear force at the interface. During the test, the shear force, the vertical displacement and the horizontal displacement are continuously recorded allowing obtaining the maximum interlayer shear stress ($\tau_{peak\text{-}ASTRA}$). This value characterizes the interlayer shear resistance and is used as parameter for repeatability determination.

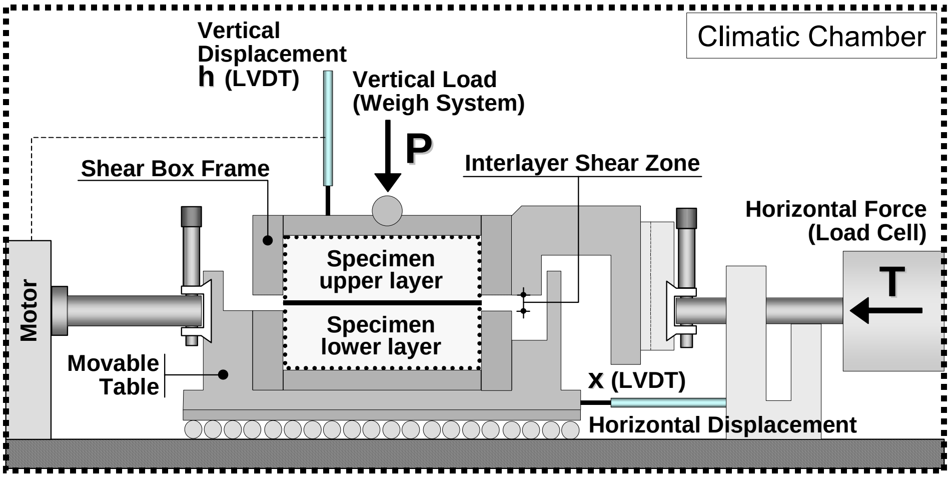

Figure 4: ASTRA device

LPDS Device

The LPDS is an EMPA modified version of the equipment developed in Germany by Leutner (1979). One part of the cylindrical specimen (150 mm diameter) is placed on a u-bearing support and the other part is suspended allowing to transfer the shear force in a defined shear plain (figure 5). A constant displacement rate (50.8 mm/min in standard conditions) is applied through a yoke. The shear force and this displacement are continuously recorded to obtain the maximum interlayer shear stress ($\tau_{peak\text{-}LPDS}$) that is used as parameter for repeatability investigation. The standard temperature for the test is 20°C.

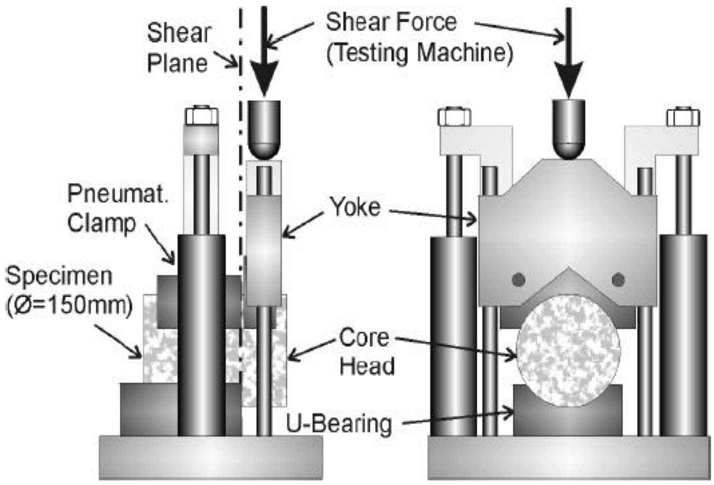

Figure 5: LPDS device

RESULTS AND DISCUSSION

For each test method, the independent random variables are the 50 (or 40) measurements of the interlayer shear resistance performed under the same conditions. The whole experimental investigation is shown in tables 5.a) and 5.b). The data analysis results are shown in table 6, where the assessment $\bar{x}$ for the mean value and s for the standard deviation are computed by means the formula *(4)*.
A comparison between the two test equipments (ASTRA and LPDS) can be made considering the variation coefficient ν defined as ratio between the standard deviation and the absolute value of the mean:

$$\nu = \frac{\sigma}{|\bar{x}|} \qquad (10)$$

The variation coefficient provides a measure of the scatter of the results, related to the mean value.

Table 5: Experimental investigation

5.a) MLS – Roller Compactor

Specimen	$\tau_{peak-ASTRA}$ [MPa]	$\tau_{peak-LPDS}$ [MPa]	a_{n-1+i}
1	0.436	1.129	0.3751
2	0.468	1.159	0.2574
3	0.474	1.210	0.2260
4	0.474	1.246	0.2032
5	0.476	1.272	0.1847
6	0.500	1.347	0.1691
7	0.500	1.349	0.1554
8	0.504	1.365	0.1430
9	0.504	1.393	0.1317
10	0.509	1.399	0.1212
11	0.510	1.414	0.1113
12	0.515	1.420	0.1020
13	0.520	1.435	0.0932
14	0.520	1.437	0.0846
15	0.521	1.439	0.0764
16	0.522	1.443	0.0685
17	0.522	1.449	0.0608
18	0.523	1.453	0.0532
19	0.525	1.453	0.0459
20	0.528	1.470	0.0386
21	0.528	1.473	0.0314
22	0.539	1.475	0.0244
23	0.549	1.486	0.0174
24	0.554	1.487	0.0104
25	0.557	1.498	0.0035
26	0.557	1.503	
27	0.562	1.503	
28	0.563	1.510	
29	0.563	1.514	
30	0.565	1.518	
31	0.567	1.520	
32	0.569	1.522	
33	0.571	1.528	
34	0.572	1.540	
35	0.578	1.542	
36	0.581	1.543	
37	0.582	1.553	
38	0.588	1.559	
39	0.590	1.563	
40	0.591	1.563	
41	0.592	1.566	
41	0.598	1.576	
43	0.599	1.582	
44	0.603	1.585	
45	0.603	1.603	
46	0.616	1.612	
47	0.616	1.643	
48	0.618	1.651	
48	0.624	1.706	
50	0.629	1.742	

5.b) Gyratory Compactor

Specimen	$\tau_{peak-ASTRA}$ [MPa]	a_{n-1+i}
1	0.514	0.3964
2	0.576	0.2737
3	0.610	0.2368
4	0.614	0.2098
5	0.634	0.1878
6	0.634	0.1691
7	0.642	0.1526
8	0.647	0.1376
9	0.665	0.1237
10	0.666	0.1108
11	0.669	0.0986
12	0.681	0.0870
13	0.689	0.0759
14	0.702	0.0651
15	0.714	0.0546
16	0.718	0.0444
17	0.721	0.0343
18	0.723	0.0244
19	0.723	0.0146
20	0.725	0.0049
21	0.725	
22	0.734	
23	0.735	
24	0.735	
25	0.747	
26	0.772	
27	0.774	
28	0.778	
29	0.781	
30	0.793	
31	0.807	
32	0.809	
33	0.832	
34	0.846	
35	0.848	
36	0.854	
37	0.862	
38	0.883	
39	0.911	
40	0.929	

Table 6: Data elaboration

	$\bar{x}$	s	ν	c^2	b^2	W_{comp}	W_{tab}	r
LPDS - MLS	1.4789	0.1254	0.0848	0.76993	0.72908	0.947	0.947	0.34746
ASTRA - MLS	0.5495	0.0461	0.0839	0.10416	0.10056	0.965	0.947	0.12780
ASTRA - gyratory	0.7355	0.0932	0.1267	0.33892	0.33411	0.986	0.940	0.25840

Table 6 shows that, for a given material and a given way to produce specimens, ASTRA and LPDS test methods provide approximately the same variation coefficient. This means that studying interlayer shear resistance by using ASTRA or LPDS, the obtained results have the same precision in terms of scatter around the mean value. This is true regardless of the fact that the devices produce a different mean value for maximum shear stress (τ_{peak}). In fact, as expected, considering the differences in boundary conditions for the two test equipments (rate of displacement, dimension of the specimen, contact between the frame and the specimen), $\bar{x}_{LPDS-MLS}$ is bigger that $\bar{x}_{ASTRA-MLS}$ and their ratio provide a factor equal to 2.7. However, a comparison between this value and the ratio (equal to 3) obtained in a previous study by Canestrari et al. [6] is not possible because the tests were performed under different conditions. In particular, in this case, a normal stress of 0.2 MPa was used for the ASTRA test (standard condition), whereas previously, the tests were carried out in absence of normal load. Further studies are necessary to investigate the possible relation between the results of the two test methods, considering standard conditions for both.

In the first investigation, the repeatability study has been performed verifying that the obtained τ_{peak} values are approximated by a normal distribution, through the Shapiro-Wilk test. The computed W_{comp} value was compared with W_{tab}, chosen considering the number of specimens equal to n and a 5% probability to reject the hypothesis of normal distribution. In the ASTRA test method, W_{comp} broadly overcomes W_{tab} hence confirming that the distribution is normal at the 95% level, both for MLS and for gyratory specimens. In the LPDS test method, the $W_{comp} \approx W_{tab}$ making less likely that the LPDS data distribution is normal at the 95% level. However, the assumption of a normal distribution is still acceptable for LPDS data, in this study.

According to the previous findings, the repeatability limit r has been determined for both test methods. The results are shown in table 6. This r value should be used for future measurements with each equipment. Since random errors occur during the measurements, a defined number of repetitions (depending on the equipment and on the test method) have to be performed in order to measure a parameter. The limit r, at 95% probability level represents the maximum acceptable absolute difference between two generic repetitions of the same test under the same conditions.

The second investigation has been performed to find out if the repeatability limit r can depend on the material and on the method to compact the specimens and not only on the test method.

Usually, the gyratory compactor provides specimens that show interlayer shear resistance that are too high (table 5) compared with the value obtained for a trial section [6]. For this reason, gyratory compactor seems not to be a good method to produce double-layered shear test specimens. In the present case, gyratory compactor has been used to study an extreme and common case to demonstrate possible differences in repeatability as a function of materials and compaction methods. Hence, only the ASTRA test method was used for this part of the study.

Table 6 shows that mean value and standard deviation and therefore the repeatability limit are different in the two cases (MLS and gyratory specimens). This suggests that r does not only depend on the test method but also on the material and method to compact the specimens. The comparison between the ν values shows that double-layered specimens produced with gyratory compactor suffer a bigger scatter than with MLS-Roller Compactor. This confirms the idea that one has to be careful in producing double-layered gyratory compactor specimens for shear tests.

CONCLUSIONS

This study on repeatability, to obtain the limit r, has been performed on specimens produced with the same material and compacted with the same method. Two different test methods (ASTRA and LPDS) for interlayer shear resistance evaluation were used. In the second investigation, specimens compacted with a different method and by using different asphalt concrete materials has been tested with ASTRA device to evaluate the possible differences in repeatability limit due to material and compaction type.

The conclusions are summarized below:

- LPDS test method provide a bigger value of interlayer shear resistance than ASTRA because of the difference in boundary conditions (e.g. speed, geometry, experimental setup) in performing tests;
- both test methods were found to provide results that are approximated by a normal distribution;
- the variation coefficient ν is the same for both test methods, which shows that in this study the precision level, in performing tests, is the same for both;

- it is not possible to determine an unique repeatability limit *r* for the specific test method because this value depends on different factors such as the used material or the way to prepare specimens and not only on the test method.

The present work is one step in the study of repeatability for the ASTRA and LPDS tests. Deeper studies are necessary to better investigate accuracy in terms of repeatability and also reproducibility before standardizing the test methods. An important step in this direction it is a international interlaboratory study, currently in preparation by the RILEM TC ATB committee, where the interlayer shear resistance is studied through different tests equipments and by using specimens made in different ways. It is expected that the research initiatives reported in this paper will also have a positive impact in this interlaboratory test.

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