ASSESSMENT OF MECHANICAL TESTS FOR STIFFNESS MODULUS DETERMINATION OF BITUMINOUS MIXTURES

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ABSTRACT

During the last decades the laboratory mechanical characterization of asphalt concretes has evolved thanks to the development of innovative testing methodologies and equipments like those for the assessment of stiffness modulus.

Those pieces of equipments enable the user to obtain the mechanical parameters of asphalts needed for the road pavement structures rational and mechanistic design.

The European Standard EN12697 part 26 'Stiffness' has been recently harmonized in Italy by UNI. This standard describes some of the available methods for the laboratory assessment of asphalt stiffness, defining each test procedure as well as the calculations needed to obtain the mentioned parameters.

In this paper two different methodologies have been adopted and compared performing tests on a single bituminous mix; indirect tensile tests (IT-CY) and four point flexural tests (4PB-PR) are the most common configurations for stiffness assessment, even though several set-up variables are possible.

After the stiffness appraisal and the comparison of the tests by means of the EN13108 specifications, the method and timing of production of specimens as well as those needed to set up and to perform the test have been considered.

Keywords: bituminous mixture, bending test, indirect tensile test, Stiffness modulus, European standard.

1. INTRODUCTION

The need of characterising the pavement bituminous layers response when subjected to traffic loads has led to the development of several laboratory testing procedures used to define the materials'stiffness modulus. This mechanical parameter is considered one of the most important performance-based ones when a bituminous layer design has to be achieved. Many laboratory methods have been introduced to predict the structural behaviour of pavement's materials such as tension-compression test, shear test, bending test and indirect tension test; each of them enables the user to obtain some mechanical parameters of asphalts in dynamic-cyclic conditions, for the rational and mechanistic design of road pavement structures. A standardisation of these procedures was required.

The EN12697- 26 was issued in 2004 from CEN to unify the theoretical definitions and the testing procedures needed to measure the stiffness modulus of bituminous mixtures. This standard collects different testing methods from different European (and non EU) countries experiences.

In the study described in this paper, indirect tension test on cylindrical specimens (IT-CY) and four point bending tests on prismatic specimens (4PB-PR) have been analysed and compared; these configurations for the stiffness assessment, have been applied in accordance with EN12697-26 with some considerations regarding the Poisson's ratio assumption and the 4PB clamping device and stiffness basic relationships. Finally, some considerations have been drawn relating to the EN13108-20 requirements that specify the type testing procedures to be used for asphalt concretes CE marking.

2. EXPERIMENTAL AGENDA

2.1 Materials and sample production

The experimental investigation was carried out on a continuously graded binder course asphalt mixture with a maximum nominal aggregate size of 20 mm. This mixture was produced with a 4.7% (in weight on total mix mass) of standard 50/70 pen bitumen and a gradation of Italian limestone aggregates, dust and fillers. Figure 1 shows the continuous aggregate gradation.

The investigation was conducted on two different types of specimens: cylindrical specimens for the IT tests and prismatic specimens for the 4PB test. All the samples were obtained from slabs manufactured in the laboratory by means of a hand driven steel roller specifically built for this purpose as to reproduce the in situ compaction.

The compacted slabs of asphalt mixture were allowed to cool down, stripped from the moulds and cored or sawed to produce the specimens for testing. From each slab it was possible to obtain 3 prismatic beams (length of 400 mm, width of 60 mm and height of 50 mm) and 6 cores (100 mm diameter and height of 40 mm). The edges of the slabs were trimmed to eliminate side effects on samples. The slab target air voids content was fixed at 4%.

The bulk densities of the specimens were determined as detailed in (EN12697-6) using the dry procedure.

Sieve size [mm]	passing (%)
31	100
20	98.4
14	79.6
10	60.8
6.3	50.2
4.75	45.3
2.36	33.7
0.3	13.7
0.075	8.1

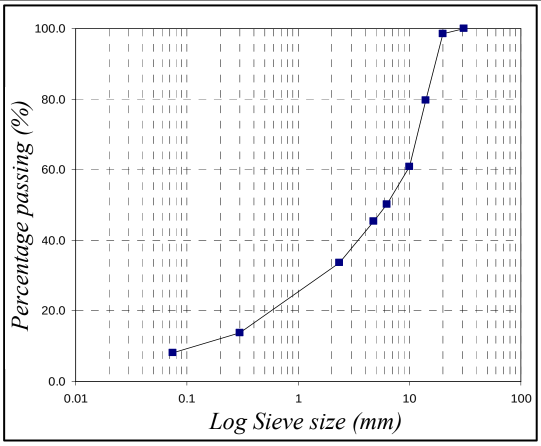

Figure 1 Bituminous mixture gradation

The bulk densities were used together with the maximum theoretical density, determined on loose mix samples by the volumetric procedure (EN12697-5), to calculate the percentage of air voids of each test specimen. Only the prismatic and cylindrical specimens that met the target air voids content were marked and stored. Specimens were conditioned at test temperature for at least 4 hours prior to testing at the controlled test temperature.

2.2 Stiffness modulus and testing procedures

The stiffness modulus of bituminous mixtures, is defined as the norm of complex modulus E^* which describes the relationship between stress and strain for a visco-elastic material subjected to repeated monoaxial loads variable with a sinusoidal law. The complex modulus is a complex number where, the real component summarises part of the elastic properties of the material and gives a measure of the reversible work under load applications, while the imaginary component summarises the viscous properties responsible of the irreversible work (visco-elastic character of the material).

The formulae used to calculate the complex modulus are the following:

$$E^* = E_1 + iE_2 \quad \text{(Eq. 1)}$$

where the real component and the imaginary component are:

$$E_1 = \gamma \, (F/z \cos\varphi + \mu\omega^2) \quad \text{(Eq. 2)}$$
$$E_2 = \gamma \, (F/z \sin\varphi) \quad \text{(Eq. 3)}$$

where: γ: form factor related to the geometry of the specimen;
μ: mass factor for inertial effects related to the mass of the specimen and the mass of the moving parts;
φ: phase angle representing the lag between stress and strain;

ω: test pulsation;
F: loading force;
z: displacement.

The stiffness modulus is therefore calculated as follows:

$$|E^*| = (E_1^2+E_2^2)^{0,5} \quad \text{(Eq. 4)}$$

In order to avoid the material non-linear behaviour effects, the tests were performed in strain-control mode with a target maximum strain of 50με. In these conditions, all the modulus tests can be considered as non-destructive and, in theory, could be repeated on the same sample. However, as reported in previous studies (H.DiBenedetto et al., 2001), heating effects may occur and mislead the stiffness measurements, therefore further research on this topic should be conducted.

2.2.1 Indirect tensile test

The indirect tensile test is considered as the most convenient, simple and cost effective laboratory test method for measuring the stiffness modulus of bituminous mixtures. This method was introduced in 1993 in the BS as Draft for Development n°213 and now is described in the Annex C of the EN12697-26 standard. Here, the IT-CY test consists of applying a certain number of load pulses along the vertical plane of a specimen to achieve a peak transient horizontal strain of 50με. The specimen is turned through 90° and a second loading is assigned. The final stiffness modulus is the mean value from the two performed tests. The relationship used to calculate the stiffness modulus (S_m or ITSM) from the recorded signals is the following:

$$S_m = \frac{F}{z \cdot h} \cdot (\nu + 0.27) \quad \text{(Eq. 5)}$$

where: S_m: calculated stiffness modulus [MPa];
F: peak value of the applied vertical load [N];
z: amplitude of peak horizontal measured deformation [mm];
h: mean thickness of the specimen [mm];
ν: Poisson's ratio for the bituminous mixture.

A load area factor, based upon the shape of the load pulse, is used to correct the calculated stiffness modulus using the formula:

$$S'_m = S_m\,(1 - 0.322\,(\log(S_m) - 1.82)\cdot(0.6- k)\,) \quad \text{(Eq. 6)}$$

where: S'_m: stiffness modulus adjusted on the load area factor [MPa];
k: measured load area factor;
S_m: measured stiffness modulus [MPa].

The stiffness modulus is therefore obtained directly from the measured quantities. However, no phase angle and dissipated energy per cycle can be evaluated. See figure 2.

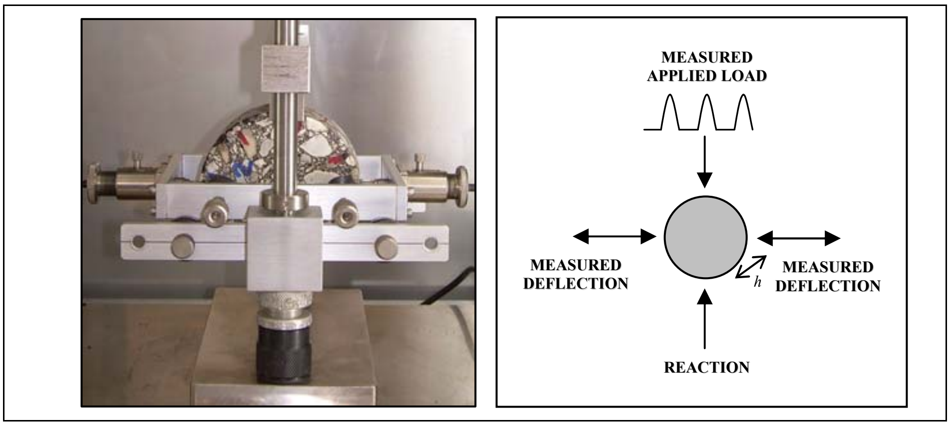

Figure 2 Indirect tensile test equipment and configuration (IT-CY)

2.2.2 Four point bending test

The four point bending test is conducted on prismatic specimens which are held horizontally and sinusoidally loaded by a suitable clamping device. This test can be performed both for stiffness and for fatigue characterisation of asphalt mixture samples.

All tests were carried out under controlled strain conditions (ε_{max}= 50με). Under loading, the prismatic specimen is subjected to a sinusoidal zero-mean bending stress at a constant frequency. The applied load is measured by a load cell situated between the specimen and the actuator, while the deflection at the centre of the specimen is measured by a displacement transducer (LVDT) (see scheme in Figure 3).

The analysis of the simply supported prismatic beam carrying the two point loads was conducted using the conventional bending theory. Since the deflection of the beam occurs due to both bending and shear stresses, the analysis results in the following expression for the stiffness modulus S_m [MPa] of the asphalt mixture sample:

$$S_m = \frac{F \cdot A}{z \cdot b \cdot h} \cdot \left(\chi(1+\nu) + \frac{3L^2 - 4A^2}{4h^2} \right) \quad \text{(Eq. 7)}$$

where: *F*: vertically applied load [kN];
L: distance between the outer clamps [m];
A: distance between the outer and the inner clamps ($A = L/3$) [m];
z: displacement at beam centre (due to bending and shear stresses) [mm];
h: mean thickness of the specimen [m];
b: mean width of the specimen [m];
ν: assumed Poisson's ratio;
χ: assumed shear factor.

The EN12697-26 suggests to derive the norm of the complex modulus ($|E^*|$) from the proposed equations (Eq. 2, 3 & 4) for calculating both the real and the imaginary components. In this case, in addition to the form factor *γ* related to the specimen geometry, also the mass factor μ, which is a function of the mass of the specimen and the mass of the moving parts, should be taken into account in the stiffness calculation.

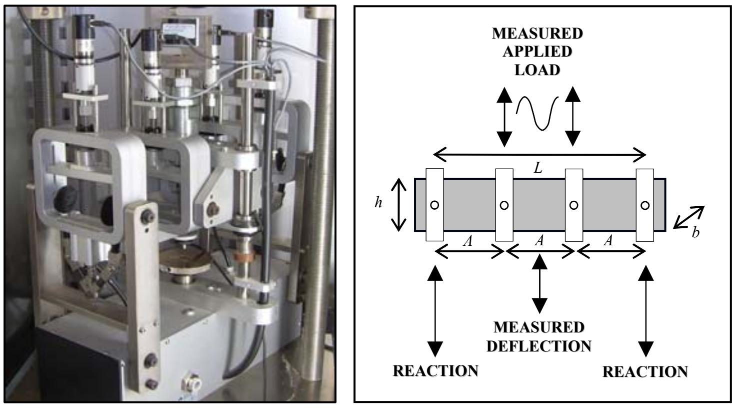

Figure 3 Four point bending test equipment and configuration (4PB-PR)

However, as reported in previous stiffness studies (H.Di Benedetto et al., 2001), for frequencies less than 30 Hz, the mass factor could be negligible and the stiffness calculation could be therefore simplified and Eq. 7 would result in the following expression:

$$S_m = \frac{F \cdot A}{z \cdot b \cdot h} \cdot \left(\frac{3L^2 - 4A^2}{4h^2} \right) \qquad \text{(Eq. 8)}$$

This relationship, already used in previous research, can be obtained also from Eq. 7 by neglecting the shear effect on the displacement [$\chi(1+v) << (3L^2\text{-}4A^2)/4h^2$]. In fact, as reported in previous studies (C.L.Monismith, 1994), the specimen geometry selected for that investigation resulted in approximately a 5% shear deformation and was neglected. Similarly, in this research, assuming $\nu = 0.35$ and $\chi = 1.5$, it was found that the shear deflection equals 5.9% of the total deflection for the chosen beam geometry.

2.3 Testing programme

The testing programme consisted of 2 main parts: specimen testing and results' analysis. The programme involved the stiffness modulus and phase angle assessment of the asphalt mixture using both IT-CY and 4PB-PR configurations.

Five cylindrical specimens were tested in IT-CY under the following test conditions:

- mode of loading: controlled strain with haversine waveform;
- temperatures: 10, 20 and 30 °C;
- loading rise-time: 124 milliseconds;
- pulse repetition period: 3000 milliseconds;
- υ = 0.25&0.35@10°C, 0.35@20°C, 0.45&0.35@30°C;
- target peak horizontal deformation: 5 μm (ε = 50μstrain);
- stiffness modulus as the mean of 5 load pulses applied on 2 orthogonal diameters.

Three prismatic specimens were tested in 4PB-PR under the following conditions:
- mode of loading: controlled strain with sinusoidal waveform;
- temperatures: 10, 20 and 30 °C;
- frequencies: 0.1, 0.2, 0.5, 1, 2, 5, 8, 10, 20, 50 Hz;
- υ = 0.25@10°C, 0.35@20°C, 0.45@30°C;
- maximum strain amplitude at the centre of the beam: 50 μstrain;
- stiffness modulus determined at the 100th cycle.

3. RESULTS AND ANALYSIS

The results from the IT-CY test are shown in the following table:

Table 1 Indirect tensile test stiffness results (IT-CY)

Specimen	**S_m@10°C** [MPa]		**S_m@20°C** [MPa]	**S_m@30°C** [MPa]	
	ν =0.25	***ν= 0.35***	***ν =0.35***	***ν =0.45***	***ν= 0.35***
S3-IT1	12179	10202	4477	1011	1160
S3-IT3	11993	9680	4035	1002	1176
S3-IT4	12538	10523	4943	1057	1227
S3-IT5	12049	10120	4154	916	1065
S3-IT6	12671	10481	4704	1186	1379

For the IT-CY test, it was possible to calculate the mean value of the stiffness for all the samples, since the stiffness determined on the second diameter was within +10% or -20% of the value recorded loading the first diameter. Test results are adherent to the common finding that stiffness is higher at lower temperatures; if a Poisson's ratio of 0.35 is considered, the stiffness variation rate within the 20°C investigated range is of about 10 times, confirming the significant thermal dependency of asphalt. In the same table, the stiffness moduli have been calculated assuming two Poisson's ratio conditions: the first one considers different values for Poisson's ratio depending on different temperatures, as suggested in the BS DD213:1993; the second one considers a constant value (0.35) for all temperatures, conforming to the EN12697-26 Annex C. For the IT-CY test, the DD213:1993 suggestions leads to a variation in the stiffness results of about 20% at 10°C and 16% at 30°C with respect to those calculated according to the EN12697-26. This finding recommends a clear account for the adopted value and suggests further investigations concerning the issue of the Poisson's ratio choice.

The 4PB results are shown in the following tables (2, 3 & 4) where the symbols are:

Sfl: flexural stiffness modulus;

Sfl+shr: flexural stiffness modulus with shear stress contribute;

φ: phase angle.

For the 4PB-PR test, the Poisson's ratio has influence only if the stiffness is calculated also considering the shear stress: i.e. the (Sfl+shr) column uses ν; however, since the EN12697-26 Annex B defines the stiffness modulus with no shear contribute, the Poisson's ratio evaluation is not necessary and (Sfl) could be determined also with Eq. 8.

Table 2 4PB results @ 10°C

Poisson's ratio = 0.25									
specimen	*S3-4PB1*			*S3-4PB2*			*S3-4PB3*		
f [Hz]	Sfl [MPa]	Sfl+shr [MPa]	φ [°]	Sfl [MPa]	Sfl+shr [MPa]	φ [°]	Sfl [MPa]	Sfl+shr [MPa]	φ [°]
0,1	5767,2	6109,1	23,5	5762,3	6106,3	22,8	5896,0	6259,6	23,9
0,2	6504,5	6890,1	21,5	6778,4	7183,0	20,9	6960,8	7390,1	22,1
0,5	8186,7	8671,9	16,5	8325,1	8822,0	17,3	8044,1	8540,1	18,0
1	8927,4	9456,5	18,5	9469,2	10034,5	15,6	9045,3	9603,1	9,3
2	10205,5	10810,3	14,4	10493,1	11119,4	14,7	10397,3	11038,4	16,2
5	11580,7	12267,0	13,3	11986,5	12702,0	11,8	11051,9	11733,4	8,2
8	12249,1	12975,0	12,6	12543,3	13292,1	9,7	12833,7	13625,1	9,8
10	12977,8	13746,9	10,8	12969,3	13743,5	10,2	13736,0	14583,1	9,9
20	14060,1	14893,3	10,8	14558,1	15427,1	9,3	13294,5	14114,4	3,5
50	13647,8	14456,6	7,0	14269,0	15120,7	7,4	13702,8	14547,9	6,3
0,1	5825,1	6170,3	24,3	5732,1	6074,2	23,8	5980,5	6287,5	21,9

Table 3 4PB results @ 20°C

Poisson's ratio = 0.35									
specimen	*S3-4PB1*			*S3-4PB2*			*S3-4PB3*		
f [Hz]	Sfl [MPa]	Sfl+shr [MPa]	φ [°]	Sfl [MPa]	Sfl+shr [MPa]	φ [°]	Sfl [MPa]	Sfl+shr [MPa]	φ [°]
0,1	1707,3	1816,6	43,3	1550,5	1650,4	40,5	1568,6	1673,1	40,0
0,2	2257,0	2401,4	39,0	2048,6	2180,7	35,7	2148,8	2292,0	34,4
0,5	3193,2	3397,6	38,4	2885,5	3071,5	33,3	3041,5	3244,0	33,4
1	3693,9	3930,3	25,7	3867,9	4117,2	29,8	3775,4	4026,8	30,5
2	4483,7	4770,7	29,1	4626,1	4924,3	28,4	4645,3	4954,7	27,4
5	5985,8	6368,9	21,3	5949,9	6333,5	24,9	5957,0	6353,7	22,5
8	6587,5	7009,2	21,5	6589,9	7014,7	18,6	6651,8	7094,8	22,3
10	6934,7	7378,5	18,3	6915,3	7361,1	29,8	6788,2	7240,3	27,2
20	8119,9	8639,6	17,8	8324,0	8860,6	18,5	8076,9	8614,8	17,3
50	8941,2	9513,5	20,9	8803,5	9371,0	15,6	9570,0	10207,4	22,3
0,1	2021,8	2151,2	31,2	1673,4	1781,2	26,2	1673,4	1781,2	26,2

Table 4 4PB results @ 30°C

Poisson's ratio = 0.45									
specimen	*S3-4PB1*			*S3-4PB2*			*S3-4PB3*		
f [Hz]	Sfl [MPa]	Sfl+shr [MPa]	φ [°]	Sfl [MPa]	Sfl+shr [MPa]	φ [°]	Sfl [MPa]	Sfl+shr [MPa]	φ [°]
0,1	476,3	509,1	38,6	506,1	541,2	41,9	441,9	473,5	38,3
0,2	670,2	716,2	46,6	640,4	684,8	35,8	550,1	589,4	43,8
0,5	905,9	968,2	42,8	947,3	1012,9	39,4	823,1	882,0	41,1
1	1249,3	1335,2	41,2	1151,4	1231,2	38,3	1192,2	1277,4	42,1
2	1648,1	1761,4	39,3	1555,1	1662,8	37,0	1594,2	1708,3	37,4
5	2355,8	2517,8	36,7	2352,6	2515,5	35,7	2205,6	2363,4	33,6
8	2813,8	3007,2	36,3	2780,3	2972,8	36,0	2785,6	2984,9	33,9
10	3034,9	3243,5	36,5	3027,0	3236,6	35,1	2952,7	3164,0	34,4
20	3768,9	4028,0	31,4	3727,1	3985,2	34,9	3823,6	4097,1	34,3
50	4830,3	5162,4	38,5	5091,1	5443,6	55,2	4502,8	4824,9	35,4
0,1	489,8	523,5	46,3	453,2	484,6	40,9	427,1	457,6	38,3

From the overall 4PB results it was determined that the shear contribute increases the flexural stiffness modulus of about 6%. This corroborates the theoretical evaluation proposed earlier and confirms the findings of other researchers (C.L.Monismith, 1994).

The EN12697-26 doesn't impose any specific testing temperature or frequency and advise to carry out the 4PB tests in various conditions for the same specimen in order to obtain data that allow the determination of the isothermal curves. Nevertheless, the norm refers also to the product Standards (EN13108) which define the test conditions to be used for all the test methods when CE marking is pertained. The 4PB tests were therefore conducted for the 3 chosen temperatures, at a set of frequencies ranging from 0.1 Hz to 50 Hz and finally at the starting frequency of 0.1 Hz to assess whether the specimen had undergone some fatigue. The stiffness calculated in the second test carried out at 0.1 Hz has, in some cases, increased from the first value, although after quite a few tests, it was expected to decrease due to damages likely to be occurred in the specimen. Hence, further investigations should be conducted to define the actual feasibility of retesting the same specimen considering the time lag between tests and the consequent healing.

The results of stiffness modulus for the 4PB tests confirmed again that the material stiffness is widely affected by temperature and load frequency. Furthermore, at 30°C the material is also more susceptible to load frequency as the stiffness modulus curve plotted in figure 4 has a higher slope than the curves fitting the test points at 10 or 20°C.

The phase angle graph in figure 5 shows that the measurements suffered of some scatter if compared with the stiffness ones; the overall trend exhibits a decrease of phase angle with increasing frequency and decreasing temperature. At 30°C the unmodified bitumen and its relatively high percentage, tend to act on the bituminous material consistency as the phase angle seems to be independent from the applied frequency.

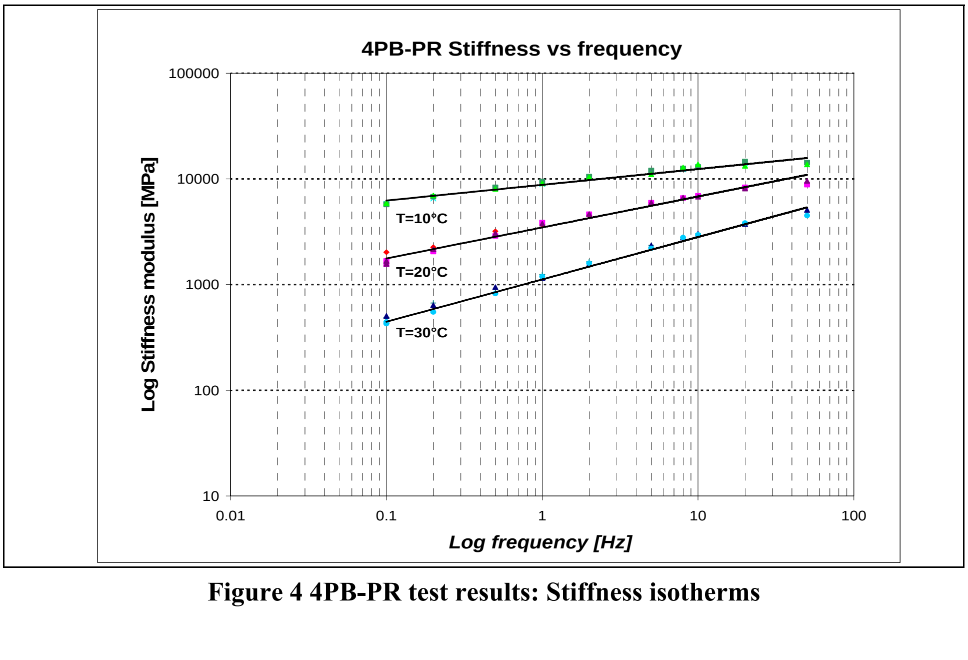

Figure 4 4PB-PR test results: Stiffness isotherms

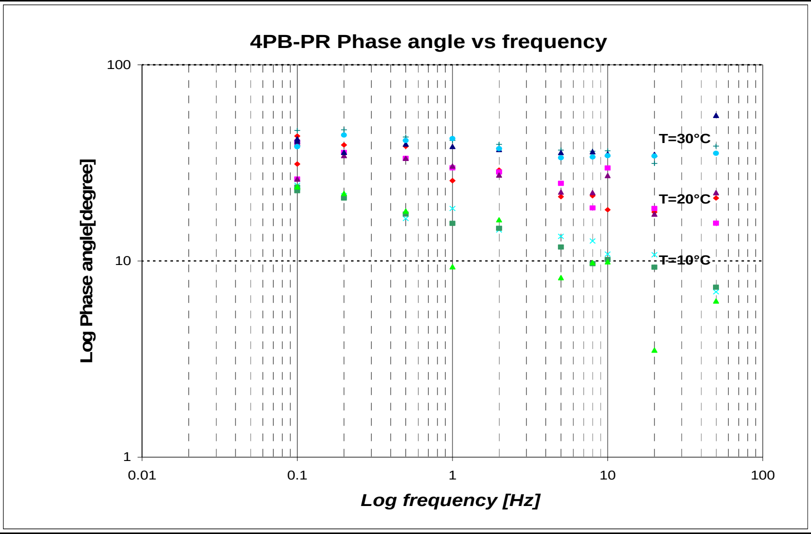

Figure 5 4PB-PR test results: Phase angle isotherms

A comparison between the two presented methodologies for the stiffness assessment of bituminous materials may be conducted by means of the already quoted European standard on asphalt concretes specifications and CE marking. In fact, only applying the EN13108-20 norm, that defines the testing procedures to be used in the bituminous mixtures classification, it is possible to compare the two tests, since they are considered as equivalent (norm table D.8) and a single stiffness value should be given. The selected results from this comparison are summarised in the following table 5.

The stiffness values for the tested bituminous material, indicate that stiffness moduli determined with the 4PB-PR test are grater than those calculated with the IT-CY test; this suggests, if the ongoing research will not deny these very first findings, to clearly state the method adopted for the stiffness modulus' evaluation into the product CE label, as misleading conclusions may be taken in the a.c. and hot rolled asphalt choice.

Table 5 Application of EN13108-20 prescriptions for determining the Stiffness modulus with IT-CY and 4PB-PR testing procedures

Specimen	Stiffness modulus [MPa]	Test conditions	
		Frequency or loading time	Temperature
S3-IT1	4477 MPa	124ms	T=20°C
S3-IT3	4035 MPa	124ms	T=20°C
S3-IT4	4943 MPa	124ms	T=20°C
S3-IT5	4154 MPa	124ms	T=20°C
S3-IT6	4704 MPa	124ms	T=20°C
S3-4PB1	6587 MPa	8Hz	T=20°C
S3-4PB2	6589 MPa	8Hz	T=20°C
S3-4PB3	6651 MPa	8Hz	T=20°C

With reference to tables 1, 2, 3 and 4, the expected equivalency between IT-CY and 4PB-PR stiffnesses at the prescribed frequency and loading time may be achieved, for the tested bituminous mixture, only if a temperature of 10°C and a ν=0.25 are considered for both the methodologies. Similarly, the equivalency with IT-CY data may be obtained by adopting the 4PB-PR values measured at a 2 Hz and 20°C.

4. CONCLUSIONS

In this investigation indirect tensile and flexural stiffness tests have been performed to evaluate the stiffness modulus of a single standard bituminous mixture. The EN12697-26 requirements were followed with some considerations regarding the Poisson's ratio assumption and the 4PB clamping device and stiffness basic relationships. The results have been analysed and compared also on the stream of the recent Italian harmonisation of the EN13108-20 standard for asphalt product specifications and CE marking. Furthermore, after the stiffness appraisal and the comparison of the tests by means of the EN13108 specifications, the method and timing of production of specimens as well as those needed to set up and to perform the test have been considered.

The following general remarks can be drawn from this study.

For IT-CY test:

- the specimens are very easy to produce with low likelihood of geometric imperfections even if taken from a real pavement;
- the test is relatively simple to carry out and not time consuming;
- temperatures play a fundamental role in the stiffness evaluation; hence, a specific set of dummy specimens should be always produced and instrumented for the conditioning and testing temperatures' measurements;
- it is not possible to determine the phase angle and the dissipated energy per cycle during the test;
- the test doesn't permit stress reversal and the stiffness is evaluated applying haversine impulses;
- the adoption of a single Poisson's ratio (if not measured) for all the testing temperatures requires further judgement, as substantial differences in stiffnesses have been observed using BS DD213 indications;
- the evaluated stiffness modulus acceptance criteria adopted within the EN12697-26 Annex C (C.4.3.4.2) is questionable with regard to the order of the two tests reckoning.

For the 4PB test:

- the specimen production is quite difficult if no roller compactors are available and geometric imperfections are likely to happen as the slenderness of the specimen is high and sides' parallelism may be lost during sawing;
- frequency and temperature sweep tests may lead to long testing times;
- the test permits stress and strain reversal;
- phase angle and dissipated energy for the material are calculated;

- the likelihood of loosing the linearity between stress and strain on the specimen (especially for elevated temperatures) requires strain sweep tests at constant frequency;
- the retesting of a single specimen to the next temperature step should be seriously addressed with particular reference to high testing temperatures and short resting periods;
- according to EN12697-26 the Poisson's ratio is not needed for acceptably accurate determinations of stiffness;
- the influence of the mass factor on the stiffness modulus evaluation is under current investigation;
- since no free translations were allowed in correspondence to the specimen supports of the testing equipment, further research is needed to investigate any influences on the stiffness assessment this may cause. This also concerns the EN standard assumptions.

An important conclusion refers to the opportunity of clearly reporting the methodology adopted for the stiffness assessment in the CE marking label (EN13108-1 and 4) as a significant difference in the measured values from the ITT and the 4PBT has been observed. The testing conditions of the two adopted tests are quite different and not easily comparable. The evaluated mixture stiffnesses are therefore affected by these differences and the user should be distinctly warn.

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