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RILEM TC 182-PEB PERFORMANCE TESTING AND EVALUATION OF BITUMINOUS MATERIALS

Stiffness testing for bituminous mixtures

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Recommendations

The text presented hereafter is a draft for general consideration. Comments should be sent to the TC Chairman: Dr. Manfred N. Partl, EMPA Swiss Federal Laboratories for Materials Testing and Research, CH-8600 Dübendorf, Switzerland. Fax +41 1 821 62 44; e-mail: manfred.partl@empa.ch by September 2001.

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1. SCOPE

Interlaboratory tests on bituminous materials were organised by the RILEM technical committees TC 101-BAT "Bitumen and Asphalt Testing" and TC 152-PBM "Performance of Bituminous Mixes". Among these tests a program on complex modulus and fatigue has been performed [10, 14-16, 22]. The aim was to compare different test methods to study or test the cyclic behaviour in the small strain domain (of about 10^{-6} m/m to 10^{-4} m/m) of a compacted bituminous mix. Only the properties related to stiffness (complex modulus) are treated in this recommendation paper. These properties can be introduced only if the behaviour of the material can be considered as linear. An evaluation of the linear viscoelastic domain of bituminous mixtures is given in Fig. 1 [7] when considering the axes Logarithm (base 10) of the strain amplitude – Logarithm (base 10) of the number of applied cycles.

From the interlaboratory test results by 15 laboratories conclusions on test facilities, specimen preparation, testing and calibration procedures for stiffness properties testing of bituminous mixtures under cyclic (and not dynamic, as explained further) loading were drawn to improve repeatability and reproducibility of this type of tests. In addition, theoretical input from some members of the Rilem TC helped to improve rational analysis. This experimental and theoretical work led to the guidelines for stiffness testing of bituminous mixtures, which are summarised in this paper. More details on the intelaboratory tests results and analyses can be obtained from the Rilem report 17 [15].

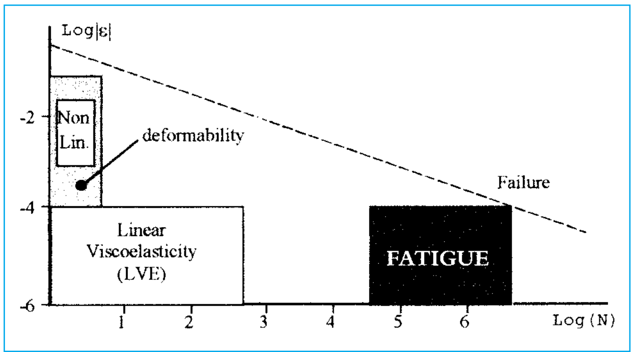


Fig. 1 – "Typical" domains of behaviour observed on bituminous mixtures (ε) strain - (N) number of loading [7].

2. DEFINITION OF THE COMPLEX MODULUS

Let us assume that the material is subjected to sinusoidal loading at varied frequencies. If the hypothesis of linear viscoelastic material is valid, the response to a sinusoidal loading is also sinusoidal.

It should be emphasised that this type of test is not a dynamic test due to i) the normally applied frequencies (less than about 10 Hz), ii) the size of the specimen and, iii) the stiffness of the mix, which prevent to consider the stress and strain fields propagation in the sample (no wave propagation effects). Hence, the terminology "cyclic test" (and not "dynamic tests") should be used.

The complex modulus E^* is a complex number defined as the ratio between the complex amplitude of the sinusoidal stress of pulsation ω applied to the material $\sigma = \sigma_0 \sin(\omega t)$ and the complex amplitude of the sinusoidal strain that results in a steady state.

Due to the viscoelastic character of the material, the strain lags behind the stress (Fig. 2), which is reflected by a phase angle φ between the two signals, *i.e.* $\varepsilon = \varepsilon_0 \sin(\omega t - \varphi)$. Given this definition, the complex modulus is not a function of time but depends on the pulsation ω (or on the Frequency $f_r = \omega/(2\pi)$) for a fixed temperature.

Hence:

$$\sigma(t) = \mathrm{Im}\left[\sigma^*(t)\right] \quad with \quad \sigma^*(t) = \sigma_0 e^{i\omega t}$$
$$\varepsilon(t) = \mathrm{Im}\left[\varepsilon^*(t)\right] \quad with \quad \varepsilon^*(t) = \varepsilon_0 e^{i(\omega t - \varphi)} \qquad (1)$$
$$E^*(\omega) = \frac{\sigma_0}{\varepsilon_0 e^{-i\varphi}} = \left|E^*\right| e^{i\varphi}$$

where i is the imaginary number; $|E^*|$ is the norm of the complex modulus or stiffness modulus and φ is the phase angle of the material (for example used to estimate the energy dissipated in the material).

It is also possible to use the following notations:

$E^* = E_1 + iE_2$

with the storage modulus E_1 and the loss modulus E_2.

In addition, the complex bulk modulus $K^*(\omega)$ and shear modulus $G^*(\omega)$ are also defined.

Assuming a linear viscoelastic and isotropic behaviour, the relations between these rheological parameters are the following:

$$K^* = \frac{E^*}{3\left(1 - 2\nu^*\right)} \qquad (2)$$

$$G^* = \frac{E^*}{2\left(1 + \nu^*\right)} \qquad (3)$$

where ν^* is the Poisson's ratio.

In these relations, ν^* is a priori a complex number. However, direct measurements of ν^*, based on radial strain measurements in tension-compression complex modulus tests with [3] or without [12] a confining pressure, tend to show that its imaginary part is very small. ν can therefore be treated as real; its value varies between 0.2 and 0.5 depending on temperature and frequency.

More details on stiffness modulus and the relation between the viscoelastic functions in the time and frequency domains are given in [11].

3. RECOMMENDATION FOR STIFFNESS TESTING

Stiffness testing of bituminous mixtures should take into account the following recommendations:

3.1 Reproducibility (inter-laboratory variations)

Whenever stiffness properties are determined it is highly recommended to determine not only the norm of the complex modulus, but also the phase angle. The reproducibility of the phase angle regardless of the testing modes and testing conditions, is better than for the norm.

Experimental reasons for systematic deviations are:

– Lack of accuracy on force measurement in the high temperature range and lack of accuracy of the displacement in the low temperature range. The accuracy of the test equipment must be in accordance with the range of values to be measured.

– Bad specimen fitting,

– Too low stiffness of the apparatus when high specimen stiffnesses are to be measured.

All these aspects should be carefully checked.

3.2 Repeatability (intra-laboratory variations)

A careful selection of representative specimens using statistical procedures on the basis of bulk densities and dimensions should be made to minimise the intra-laboratory variations of the complex modulus. With a careful process, the standard deviation could reach 5%, which appears a limiting lower value. The complex modulus can be used as a good indicator of consistency and quality of the material composition.

3.3 Type of tests and specimen geometry

For bituminous mixtures, and more generally geomaterials, two main categories of tests can be distinguished: homogeneous tests and non-homogeneous tests.

Homogeneous tests give direct access to the stresses and strains, and therefore to the constitutive law (whether viscoelastic or not). Non-homogeneous tests call for postulating a constitutive law first (linear viscoelasticity, for example) and taking into account the geometry of the specimen calculations to obtain the parameters of the constitutive law (linear viscoelastic modulus, for example).

Non-homogeneous tests can be used for complex modulus determination only if the behaviour is linear viscoelastic. If the behaviour of the tested material deviates from the linear behaviour, a large error may be introduced.

An overview on various existing homogeneous and non-homogeneous test methods for complex modulus measurements [14] are given in Table 1. Generally, for all of the tests, from the values of force F and displacement D applied to the boundaries of the specimen and from the phase angle φ between these two signals (the monitored signals should be corrected from electronic time lag during the calibration procedure), the complex modulus of bituminous mixtures can be determined using two factors:

– a shape factor γ that depends on the dimensions of the specimen;

– a mass factor μ that takes into account (if necessary) the effects of inertia related to the mass M of the moving specimen and the mass m of moving parts (attachment helmets, specimen-loading frame coupling, etc.). For classical test conditions (less than 30 Hz) this factor is negligible.

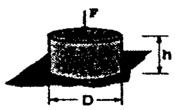
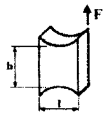
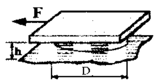
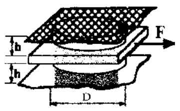
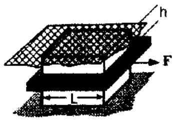
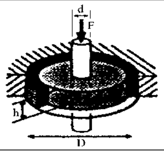
The real and imaginary parts of the complex modulus are then given by:

$$E_1 = \gamma\left(\frac{Fo}{Do}\cos\varphi + \mu\omega^2\right) \qquad (4)$$

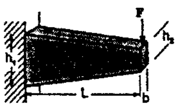
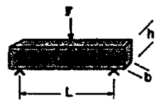
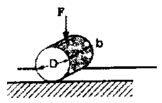
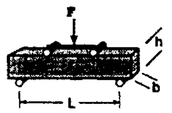
$$E_2 = \gamma\left(\frac{Fo}{Do}\sin\varphi\right) \qquad (5)$$

where ω is the pulsation.

Table 1 – Existing test methods for complex modulus measurements [10]: a) Homogeneous tests, b) Non-homogeneous tests

(a)	Principle	Shape factor* γ [L^{-1}]	Literature
Tension compression (with or without confining pressure)		$\frac{h}{\pi D^2}$	Charif [3] Doubbaneh [12] Witczak *et al.* [27]
Shearing test		$\frac{l}{h e}$	Assi [1] de La Roche [5]
Constant height shearing test		$\frac{h}{\pi D^2}$	Sousa [24]
Shearing test machine		$\frac{h}{\pi D^2}$	Lempe *et al.* [20]
		$\frac{h}{2Lb}$	
Co-axial shearing test**		$\frac{\ln\left(\frac{D}{d}\right)}{2\pi h}$	Gubler [17]

* In the case of shearing tests, the shape factor is given for the calculation of G
** The validity of the homogeneity hypothesis depends on the ratio D/d

(b)	Principle	Shape factor* γ [L-1]	Literature
2-point bending		$\frac{4L^3}{bh^3}$	Francken *et al.* [13]
		$\frac{12L^3}{b(h_1-h_2)^3}\left[\left(2-\frac{h_2}{2h_1}\right)\cdot\frac{h_2}{h_1}-\frac{3}{2}-\ln\frac{h_2}{h_1}\right]$	Huet [18] Chauvin [4]
3-point bending		$\frac{24L^3}{\pi^4 bh^3}$	Myre [21]
Indirect tensile test		$\frac{1}{b}(\nu+0.27)$	Brown [2] Kennedy *et al.* [19] Tayebali *et al.* [25]
4-point bending		$\frac{2L^3-3Ll^2+l^3}{8bh^3}$	Pronk [23]

The shape (or form) and mass factors are indicated in Table 1. The sinusoidal signals of load, displacement, stress and strain are schematically shown in Fig. 2. The stress and strains amplitude varies from one point of the sample to another for the non-homogeneous tests.

However, non-homogeneous tests give good results if the behaviour of the mixture tested is linear viscoelastic.

3.4 Material non-linearity

The complex modulus remains independent of the strain amplitude for linear viscoelastic materials. As this is not the case for bituminous mixtures [3, 9, 10, 12], linearity tests should be performed to define the maximum acceptable stress and strain levels for complex modulus measurement. To avoid errors due to material non-linearity, testing strains should be lower than $100 \cdot 10^{-6}$ m/m. Most of the laboratories involved in the RILEM interlaboratory campaign proved able to test at strains in the order of $40 \cdot 10^{-6}$ m/m to $50 \cdot 10^{-6}$ m/m (one even succeeded to use $7.5 \cdot 10^{-6}$ m/m). For such a range of strain, the hypothesis of a linear viscoelastic behaviour can be considered with good accuracy (see Fig. 1).

For bending tests (Table 1b) trapezoidal and prismatic specimens are suitable and lead to similar results in the RILEM interlaboratory test. The measurement of moduli in bending tests by 10 laboratories, using different size of samples and type of tests (2, 3 and 4-point bending), are in agreement within a range of 10 to 20% around the average master curve. The reason for some laboratory systematic errors could be explained by the reasons listed in paragraph 3.1.

3.5 Comparison for different types of tests

Other experimental works show that all the tests providing the complex Young's modulus (*i.e.* all the tests of Table 1a and 1b except the four shear tests of Table 1a) give complex modulus values in a good agreement, if the

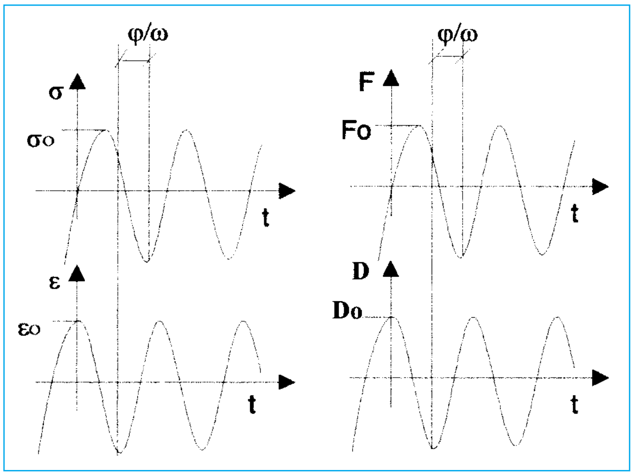


Fig. 2 – Sinusoidal load (F) and displacement (D) applied and resulting sinusoidal stress and strain response at a given point of the sample.

conditions and recommendations given in this paper are taken into account. For example, De La Roche *et al.* [6] carried out a comparison between two-point bending tests on trapezoidal samples and tension compression tests for samples with different maximum aggregate sizes. The results show an agreement within some percent for the master curves. It was demonstrated that the temperature calibration is an important element. More recent comparisons, made among the task group members TG3 of the RILEM technical committee TC 182-PEB (Performance testing and Evaluation of Bituminous Materials), show that even the non-homogeneous indirect tensile test may give correct results, when considering a sinusoidal loading and test conditions that are carefully chosen and controlled.

The four shear tests (cf. Table 1) do not give direct access to the complex Young's modulus (E^*) but allow to determine the shear modulus (G^*). The relation between E^*, G^* and Poisson's ratio (ν^*) (Equation (3)) holds only if the material is isotropic. At present no clear conclusion can be derived concerning the ability for obtaining E^* from shear tests. Some results reveal a great difference while others give closer results. In any case, it appears that bituminous mixes are anisotropic [12] and more studies are needed to deal with the influence of this aspect.

3.6 Size of the sample

From the dimensions of the bending specimens used by the different laboratories it follows that the minimum height of the specimen should not be smaller than about a factor of 2.5 of the maximum aggregate size of the mix. Otherwise the specimen becomes too heterogeneous and the scatter of the results can increase significantly. This means that the determination of the moduli of mixtures for layers with a thickness significantly smaller than 2 times the maximum aggregate size cannot be considered as realistic. In these cases the hypothesis of continuous medium, which is postulated to calculate the stress and strain fields, is not an appropriate design assumption.

For the homogeneous test samples the ratio of 2.5 between the minimum dimension of the sample and the maximum aggregate size, seems too low. A value of 5 appears safer.

3.7 Measuring devices

Accuracy of the measuring devices for force measurements at high temperatures and displacement measurements at low temperatures must be in accordance with the range of values to be measured. Specimen installation and stiffness of the apparatus must have negligible effect even on high specimen stiffness measurements. More generally calibration procedures for mechanical measurement and thermal chamber regulation should be carefully checked and respected.

3.8 Heating due to repeated loading

Amplitudes and the number of load cycles should be small to avoid thermodynamic effects on modulus measurement. The dissipated energy created during each cycle heats the sample at the beginning of the test and the modulus decreases. This decrease is proportional to the frequency and to the square of the strain amplitude. Due to local heating effect, the modulus variation can rapidly reach some percent. For example, 2% were obtained in some hundred cycles at 10Hz, $100 \cdot 10^{-6}$ m/m and 10°C. Therefore it is recommended to apply less than 100 cycles for a modulus determination and to consider the frequency and temperature sweep procedure under that respect.

3.9 Testing conditions

To evaluate the temperature-frequency dependency of the stiffness properties, testing conditions should be chosen in a reasonably broad range. Taking into account the possibilities of most of the laboratory equipments, a minimum temperature and frequency range of -10°C to 40°C and 0.5 Hz to 30 Hz could be considered.

3.10 Master curve

The validity of the temperature-time (or frequency) superposition principle is generally verified with good accuracy for mixes with pure bitumen. An Arrhenius type of equation, which has only one parameter, is easy to use. It reveals to adjust correctly, at least for temperature range higher than 10°C. The WLF [26] formula is another alternative. It needs 3 constants and seems to be accurate on a larger temperature range.

3.11 Elastic modulus

To determine the purely elastic component E_{el} (E^* for very high frequency and/or very low temperature) of the complex modulus the plot of Black diagrams (|E*| versus phase angle φ) is recommended.

4. CONCLUSION

It can be concluded that the determination of the one-dimensional linear viscoelastic properties of bituminous mixtures is possible with good accuracy for a wide range of test methods and sample sizes, when sinusoidal cyclic tests are considered. Nevertheless, it is a delicate measurement and some conditions should be respected. The most important sources of errors are pointed out in this paper. They are not listed again, but have the following very different origins:
– quality of the measurement devices,
– calibration procedure,
– specimen preparation, preconditioning and fitting,
– rheological properties of the material (linearity, dissipation,…).

In addition it appears that the temperature-time (or frequency) superposition principle holds with good accuracy for pure bitumen asphalt mixes. The master curve can be determined with Arrhenius or WLF equations.

Some aspects remain rather unknown and need further investigations, such as:
– multiaxial stress and strain distribution in the samples,
– theoretical modelling (non linearity,…),
– anisotropy, (Young's and shear moduli [E* and G*] relationship,…).

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