A NEW STEP TOWARDS PERFORMANCE BASED SPECIFICATIONS FOR ASPHALT PAVEMENTS

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ABSTRACT

Technical specifications of many Agencies are quickly moving from prescriptive to performance based, that requires field compliance tests of the constructed pavement, such as in situ pavement stiffness measurements by the Falling-Weight Deflectometer (FWD). This creates a number of issues for material suppliers, constructors, consultants, designers and end users who are now required to rely on data produced from such devices for design and compliance checks in the field. Whilst there is wide experience on the use of such devices, issues remain such as optimisation of test methodology, data interpretation and use, comparison between laboratory and in situ measured moduli.

The aim of this work is to define a data interpretation procedure and a framework for the analysis of results obtained by using such device to ensure high quality data and decision making, particularly for their role in performance based specifications. In a previous work, a particular testing and data interpretation procedure have been proposed in order to evaluate strains in pavement layers directly from FWD deflections and pavement layer thickness; here the values of elastic modulus back-calculated in the previous work are compared with those of resilient modulus M_R evaluated by laboratory tests carried out on cores taken from pavement.

Stiffness Master Curves (SMC) have been developed by using the resilient modulus data determined at various test temperatures and loading frequencies, and they have been used for shifting data to the in-situ asphalt pavement conditions. The frequency spectrum of FWD load has been calculated in order to assume a representative loading frequency for this device. For this loading frequency, the back-calculated asphalt modulus has shown excellent correlation with the corresponding values of the SMC. This illustrates that reasonable estimates of the in situ asphalt modulus can be provided by using the Indirect Tensile Test for Cylindrical Specimens (IT-CY) protocol to determine resilient modulus on cores or specimens compacted in laboratory; values obtained by this test must be shifted to in situ test conditions in order to be related to in situ asphalt modulus values, and to be used with elastic theory in pavement design.
Keywords: resilient modulus, pavement stiffness, FWD, master curve, pavement design

1. INTRODUCTION

The mechanistic-empirical design method is widely used in new pavement design or in evaluation of existing ones.

Because material structural properties affect pavement response and performance, their specification is a fundamental of pavement design process. One of the key parameters for analytical methods is the evaluation of layer elastic modulus to be used in the elastic theory for pavement design. The resilient modulus, which is based on recoverable strains measured in laboratory under repeated load, is widely considered a good estimator of the elastic modulus to be used with the elastic theory.

In order to fulfill design requirements, the resilient modulus becomes a goal during mix design phase and his evaluation is necessary in quality controls during pavement construction. In the design phase, resilient modulus can be determined using laboratory testing methods, while in quality control phase non-destructive field trials such as FWD tests are recommended to evaluate elastic modulus of layers trough back-calculation.

Since asphalt concrete is a viscoelastic material, loading duration heavily affects resilient modulus. Because vehicle speed is strictly correlated to loading frequency, design values of resilient modulus should be selected commensurate with the design speed to be representative of in situ loading characteristics and layer stiffness.

While loading frequencies of FWD tests are comparable to ones due to traffic, laboratory test methods involve using loading durations that vary from vehicle ones; different testing conditions and methods, in terms of temperature control and stress application, make laboratory resilient moduli not comparable directly to design values or to values determined by FWD.

The knowledge of a relationship between values of elastic modulus calculated by FWD tests and of resilient modulus determined by laboratory IT-CY can be an helpful tool in mix design phase to develop asphalt mixtures matching project requirements.

Comparisons between modulus values calculated by FWD and those of resilient modulus by IT-CY cannot be found in literature. Some studies about this topic were conducted comparing FWD moduli with laboratory values determined using different testing procedures (Newcomb, 1986; Thom, 1997; Shalaby, 2004; Maher, 2005), but not ever satisfactorily results have been obtained. Bonaquist (1986) related measured deflections to predicted ones calculated using laboratory moduli as input in n-layer linear elastic software, but no clear relationship was found.

The aim of this work is to define a procedure for the analysis of results obtained by IT-CY *and FWD tests in order to obtain high quality data required for both pavement design and compliance checks in the field, which have a primary role in performance based specifications for asphalt pavement layers. The result of this procedure is to find the mean for relating in a reliable way laboratory resilient modulus values determined by IT-CY to in situ stiffness modulus values back-calculated from FWD deflection measurements. By this way, resilient modulus values shifted to in situ conditions can be used with the elastic theory in pavement design, providing reasonable estimates of the in situ asphalt modulus*

2. THEORETICAL BACKGROUND

Mechanical properties of visco-elastic materials such as asphalt concrete are strongly influenced by temperature and loading time. For an asphalt mix in linear visco-elastic phase, stiffness variations obtained by modifying temperature at fixed loading frequency, can be replicated by changing loading duration at the same test temperature; this behaviour is defined termo-rehological simple and it allows the application of time-temperature superposition principle. Experimental data collected at various test temperatures, in a stiffness versus frequency graph, lie on different isothermal curves. Ferry (1980) has shown that the influence of temperature can be described by a shift factor α_T; if the stiffness is known as a function of frequency at one temperature, it may be obtained at a different temperature by multiplying the frequency *f* by the appropriate shift factor. In this way material behaviour can be described in a wide load frequency and temperature range by a unique parameter: the reduced frequency f_{fict} that at the same time takes into account of each factor:

$$\log f_{fict} = \log f + \log \alpha_T \qquad \text{(Eq. 1)}$$

Shift factor α_T can be determined through William, Landel and Ferry equation (Eq. 2), or by Arrhenius form (Eq. 3):

$$\log \alpha_T = -\frac{C_1 \cdot (T - T_{ref})}{C_2 + T - T_{ref}} \qquad \text{(Eq. 2)}$$

$$\log \alpha_T = \log e \cdot \frac{\Delta H}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \qquad \text{(Eq. 3)}$$

Where:

C_1, C_2	empirical constants
T_{ref}	reference temperature (K)
T	experimental temperature (K)
ΔH	activation energy (J/mol)
R	ideal gas constant (J/mol·K)

In this work, the shift factor α_T has been determined by an optimization procedure carried out by using the resilient modulus values determined in laboratory at different temperatures and loading frequencies.

In order to describe asphalt mix time dependent behaviour at low and medium temperature, it is common to use the generalized power law. In this study, it has been used the sigmoidal model (Fig. 1) proposed by Medani and Molenaar in 2004, modifying the one introduced previously by Pellinen and Witczak.

The mixture stiffness S_{mix} (MPa) at a temperature *T* and at a loading frequency *f* is evaluated by the following model:

$$\log S_{mix} = \log S_{min} + (\log S_{max} - \log S_{min}) \cdot \left(1 - e^{-\left(\frac{10 + \log f_{fict}}{\beta}\right)^{\gamma}} \right) \qquad \text{(Eq. 4)}$$

Where the four parameters to be determined are:

S_{min} minimum mixture stiffness (MPa)
S_{max} maximum mixture stiffness (MPa)
f_{fict} reduced frequency
β, γ shape factors

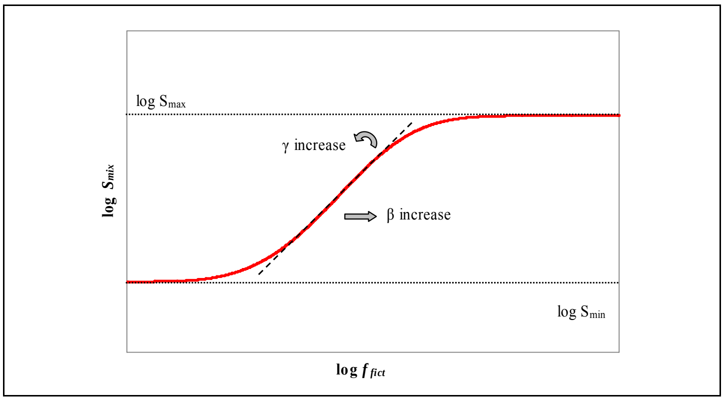

Figure 1 Stiffness Master Curve sigmoidal model

3. METHODOLOGICAL APPROACH

In order to calculate the four parameters of the SMC, IT-CY have been carried out to determine the resilient modulus at different temperatures and rise times; the parameters of the SMC have been evaluated by fitting the experimental data of resilient modulus to the sigmoidal model described in the previous paragraph.

3.1 Fitting process

Fitting experimental data to the sigmoidal model is a non linear optimization problem; in order to solve this problem, the Generalized Reduced Gradient (GRG) algorithm (Landson, 1978) has been used, which is a nonlinear extension of the simplex method for linear programming. The GRG algorithm reduces the original nonlinear problem to simpler reduced problems which are solved by a gradient method.

In the fitting process, the reduced frequency f_{fict} has been introduced in the sigmoidal model by using the Arrhenius form (Eq. 3), where the parameter to be evaluated by the fitting model is the activation energy ΔH, while the load frequency is determined for each test condition by considering the spectral components of the load recording.

3.2 Evaluation of the representative loading frequency

Time histories recorded by the load cells of both the FWD and the testing machine for IT-CY are multifrequency transient signals. The analysis of signals in the frequency domain allows to evaluate wave amplitude for each spectrum frequency component.

In this study, a data reduction method has been proposed to extract from the original load time-history the parameters that are useful in specifying an appropriate loading single frequency. For the evaluation of the single frequency which can be considered representative of the whole spectrum, an energetic approach has been followed; by this way, the center of the frequency band which contains the most part of the energy has been considered to be the representative frequency.

By using the Fast Fourier Transform (FFT) algorithm, the Power Spectral Density (PSD) of the signal in third octave bands has been calculated and expressed in energy levels by the following relationship:

$$L_\lambda = 10 \cdot \log \frac{PSD_\lambda \cdot \Delta f_\lambda}{a^2_{ref}} \qquad \text{(Eq. 5)}$$

Where:
- L_λ energy level (dB)
- PSD_λ power spectral density (kN^2s)
- Δf_λ ⅓ octave band width (Hz)
- a^2_{ref} reference RMS, assumed equal to10^{-6} kN

By defining *-3dB band* the frequency band which contains the maximum energy level and within which the signal energy reduces of 3 dB with respect to the maximum level, the representative frequency f_R is calculated as the *-3dB band* center frequency by the following relationship:

$$f_R = \sqrt{f_{LL} \cdot f_{UL}} \qquad \text{(Eq. 6)}$$

where f_{LL} and f_{UL} are respectively the frequency of lower and upper limits (Hz).

The representative loading frequency for the FWD device (Fig. 2) has been evaluated equal to 16 Hz, while for IT-CY (Fig. 3) with rise time equal to 0.125” and 0.200” they have been evaluated respectively equal to 1.8 e 1.1 Hz.

4. EXPERIMENTAL PROGRAM

In the framework of the National Road Safety Plan, the Ministry of Infrastructures and Transport, the Region and the 10 Provinces of Tuscany funded the “Leopoldo” research project, in memory of the construction works undertaken by the Grand-Duke of Tuscany.

The project is targeted towards the definition of guidelines for the design, construction and maintenance of regional road pavements, with the aim of improving road safety and environmental compatibility.

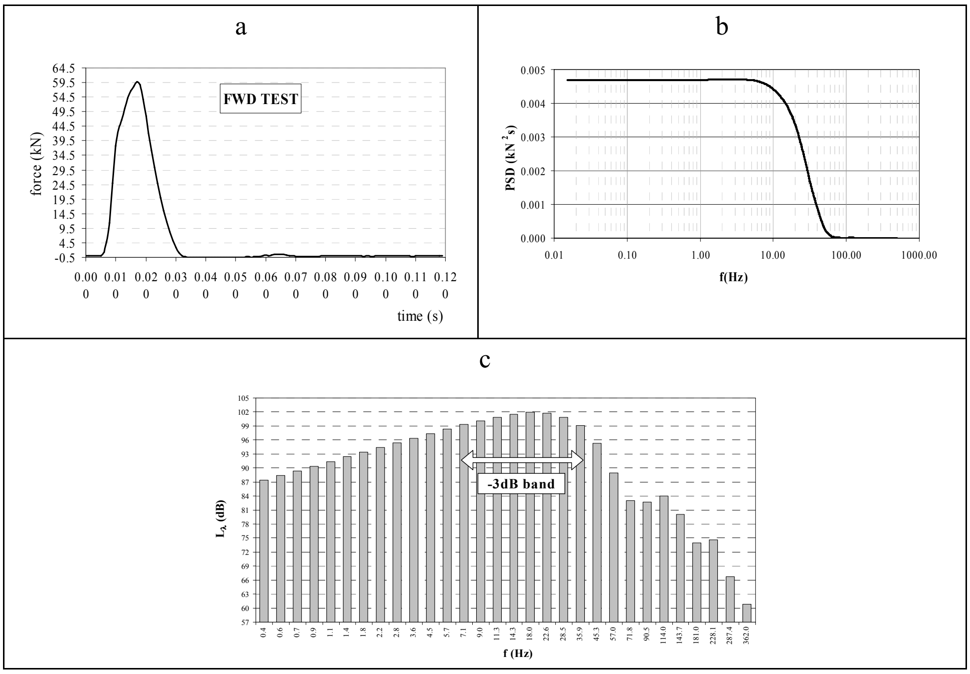

Figure 2 FWD test: (a) time history - (b) PSD - (c) energy levels and -3dB band

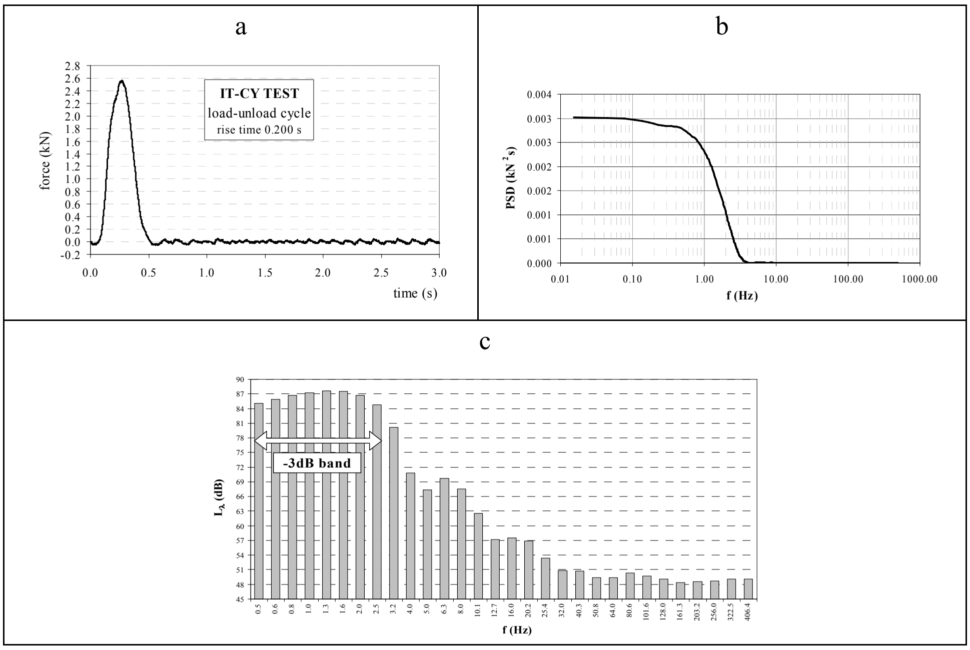

Figure 3 IT-CY test: (a) time history - (b) PSD - (c) energy levels and -3dB band

In order to determine functional and structural characteristics of existing pavements, six road sections have been selected within the highway network of the Region of Tuscany; among other field trials, deflectometric tests have been performed by using FWD equipment and stratigraphical surveys by GPR (Ground Penetrating Radar) equipment; from some FWD test point, located on the right wheel path, cores of asphalt layers have been extracted for laboratory characterization of materials.

4.1 Elastic modulus evaluation by FWD tests

Deflectometric tests performed by FWD are non-destructive tests for structural evaluation of multi-layered pavements. A dropping mass applies a dynamic impulse on the surface, emulating the effect of moving traffic; peak pavement deflections under applied load are measured by some geophones in predefined locations. During backcalculation process, knowing layer thicknesses and predicted elastic modulus values, an algorithm assign to each layer a modulus value, which theoretically allows matching the produced pavement deflection.

Deflectometric tests have been performed by using the Dynatest FWD 8000 system. Three drops have been made at three contact pressure levels (600-800-1000 kPa), with a 300 mm ∅ segmented plate, and deflections have been collected by nine geophones placed at 0, 200, 300, 450, 600, 900, 1200, 1500 and 1800 mm away from the centre of loading plate. Layer elastic moduli from FWD trials have been evaluated by using Linear Elastic Theory (LET) method implemented in the ELMOD 5.1 software (Losa et alii, 2007).

4.2 Resilient modulus evaluation by IT-CY

Laboratory resilient modulus has been determined by IT-CY procedure on the basis of recoverable strains which occur during unloading phase of the load-unload cycle. As it is well known, in this test a haversine loading wave is applied along the vertical diameter of a cylindrical specimen to generate a transient horizontal strain of 50 μm/m. Cycle duration is 3 ± 0.1 s and the rise time to achieve maximum load is fixed by standards (EN 12697-26 Annex C) equal to 124±4 ms, but other loading times are allowed. Measuring recovered horizontal strains, resilient modulus is determined by the following equation:

$$S = \frac{F \cdot (\nu + 0.27)}{z \cdot h} \quad \text{(Eq. 7)}$$

Where:
- F peak load (kN)
- ν Poisson coefficient
- h specimen height (mm)
- z horizontal recovered displacement amplitude (mm)

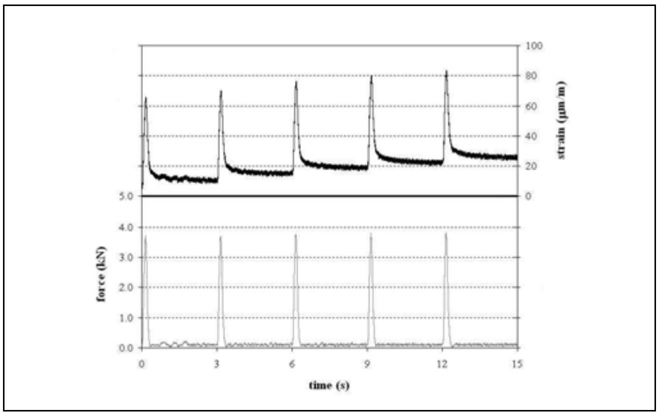

Figure 4 IT-CY test output

Laboratory IT-CY have been performed with a 50 kN electro-hydraulic Universal Testing Machine (UTM) designed by M. Losa and manufactured in Italy (Fig. 5). Tests have been carried out using two pulse duration (125, 200 ms) and at four temperatures (2, 10, 20 and 30°C); samples have been conditioned at test temperature at least 12 hours in a climatic chamber.

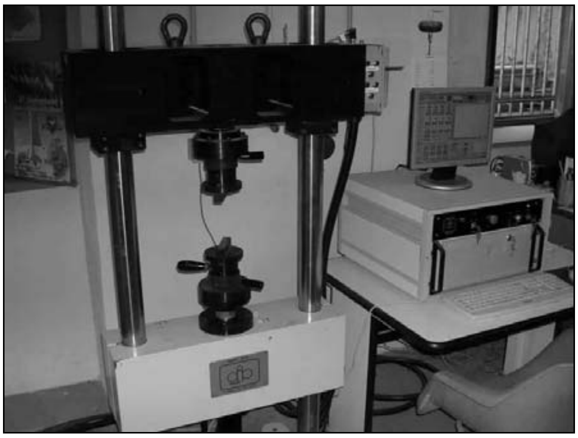

Figure 5 Universal testing machine (UTM)

Ten cores have been used for experimental tests and they have been decomposed obtaining specimens for different pavement layers which have thicknesses according to standard specification.

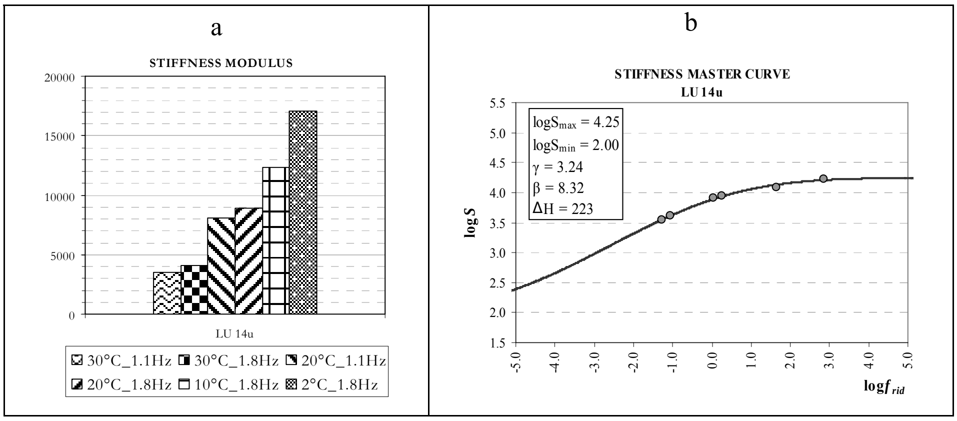

Figure 6 Results of tests performed on a core from the LU site: (a) Modulus at different temperatures and loading frequencies; (b)stiffness master curve

In order to evaluate the resilient modulus of the asphalt layer system, the Odemark's method has been used by considering the bending stiffness of each layer is related to:

$$\frac{E_i \cdot h_i^{\,3}}{1-\nu_i^{\,2}} \qquad \text{(Eq. 8)}$$

where E_i is the elastic modulus, h_i is the thickness, and υ_i is the Poisson ratio of the *i-th* layer.

By assuming that the stiffness of the equivalent system, which has thickness $h_{tot}=\sum h_i$ and the equivalent resilient modulus E_{eq}, is the same of the real asphalt layer system, the transformation shown in Fig. 7 can be used and the equivalent resilient modulus can be evaluated by using the following relationship:

$$E_{eq} = \frac{\left(\sum_{i=1}^{n} h_i \cdot \sqrt[3]{E_i}\right)^3}{h_{tot}^3} \qquad \text{(Eq. 9)}$$

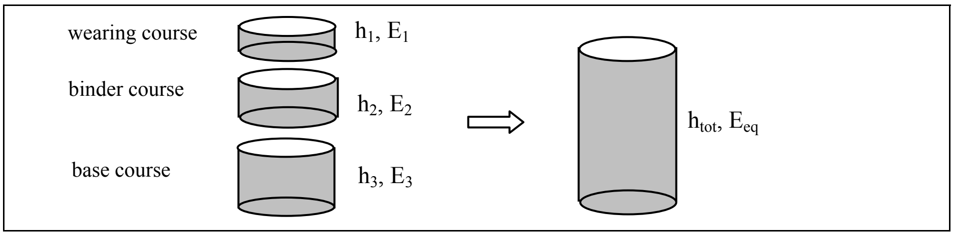

Figure 7 Odemark's transformation of a layered system

5. ANALYSIS OF RESULTS

The results obtained by the analysis of experimental data appear to be not comparable directly.

Three factors affecting results have been identified:

a) Loading frequency: laboratory resilient modulus is evaluated for a representative loading frequency close to 1.8 Hz while in situ stiffness modulus is evaluated at a frequency close to 16 Hz;
b) Test temperature: laboratory tests are carried out in controlled temperature conditions while in situ FWD tests are carried out at temperatures varying with layer depth and governed by meteorological conditions.
c) Stress state: elastic modulus evaluated by FWD tests is based on deformation of pavement layer system and it is similar to the dynamic stiffness modulus *S*, which is based on the resilient deformation of a beam; Witczak and Root (1974) indicated that a plot of Log*S* versus the extreme fiber stress σ results in a straight line showing that the stiffness modulus decreases with the increase of strains in bending tests. On the contrary, laboratory tests are carried out at a fixed level of horizontal strain, which is the same for all the layers.

Table 1 In situ and laboratory resilient modulus values

SITE	layer	$\log(S_{min})$ (MPa)	$\log(S_{max})$ (MPa)	β	γ	ΔH (kJ/mol)	$\log(f_{fict})$ (Hz)	E_{FWD} (MPa)	M_R (MPa)
AR 2	wearing	4.31	2.00	8.14	3.58	201	3.240	12559	21521
	binder	4.37	2.00	8.32	3.45	198	3.239		
AR 5	wearing	4.26	2.41	8.84	4.63	202	3.252	10273	21007
	binder	4.51	2.00	8.30	2.23	206	3.299		
AR 10	wearing	4.27	2.00	8.06	3.42	200	3.240	11038	20516
	binder	4.36	2.00	8.47	3.66	200	3.239		
PI 2	wearing	4.37	2.74	9.06	4.62	201	1.082	8496	15665
	binder	4.48	2.00	8.99	3.23	202	1.081		
	base	4.43	2.63	8.81	3.25	247	1.054		
PI 14	wearing	4.43	2.00	8.09	3.52	200	1.083	6545	14404
	binder	4.44	2.00	8.74	2.60	263	1.045		
	base	4.38	2.60	8.89	3.71	217	1.072		
PT 2	wearing+binder	4.08	2.55	9.50	4.61	201	2.895	5457	11631
	base	4.11	2.00	8.34	3.04	228	3.123		
PT 10	wearing+binder	4.07	2.28	9.40	3.93	200	2.889	5368	11055
	base	4.07	3.09	10.42	7.40	202	2.885		
PT 18	wearing+binder	4.07	2.28	9.40	3.93	200	2.889	6367	13504
	base	4.35	2.00	8.67	2.48	207	2.888		
LU 8	wearing	4.18	2.00	8.63	3.32	209	0.890	3115	5728
	binder +base	4.05	2.18	9.82	4.70	161	0.961		
LU 14	wearing	4.25	2.00	8.32	3.24	223	0.868	5743	10694
	binder +base	4.31	2.00	8.29	2.71	212	0.884		

In order to identify a relationship between modulus values evaluated by the two methods, they must be shifted to the same conditions with regard to the previous three factors. For this purpose, SMCs at the reference temperature of 20°C have been determined for each material tested; by using the parameters obtained by the fitting process (Table 1), values of resilient modulus have been evaluated at the reduced frequency of respective field tests taking into account of different loading frequency and test temperature. By using the transformation equation (Eq. 9), resilient modulus of the layer system has been calculated on the basis of resilient modulus of each layer.

In order to take into account the effect of different strain state for the evaluation of in situ elastic modulus, it has been referred to FWD tests carried out at the same stress level equal to 800 kPa; values of maximum strains at bottom of asphalt layers vary in the range between 60 and 200 με.

In Table 1 there are reported modulus values evaluated by FWD tests and those obtained from SMCs at the same reduced frequency of FWD tests.

By using these data, the following relationship has been determined (Figure 6):

$$M_R = 1.7 \cdot E_{FWD} + 1900 \text{ (MPa)} \qquad \text{(Eq. 10)}$$

Where M_R is the resilient modulus shifted to the FWD test reduced frequency and E_{FWD} is the elastic modulus calculated by using FWD data without temperature corrections; this relationship is valid for $2500 \leq E_{FWD} \leq 12500$ (MPa)

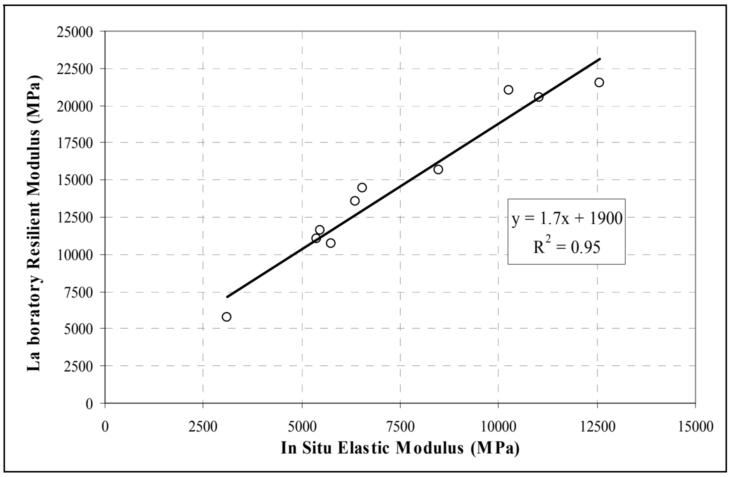

Figure 6 - Relationship between laboratory and in situ values

6. CONCLUSION

In this work it has been proposed a rigorous procedure for data interpretation and analysis of results obtained by FWD tests and IT-CY; this aspect is of particular interest for the role that results of these tests have in performance based specifications. The procedure proposed takes into account factors affecting the results obtained by using the two test methods, and it has allowed to relate values of elastic modulus estimated by FWD tests with those of resilient modulus M_R evaluated by laboratory tests.

This illustrates that specimens compacted in laboratory for pavement design or cores taken from pavements for compliance checks in the field can be tested using the IT-CY protocol to determine resilient modulus values which must be shifted to in situ test conditions in order to be used with the elastic theory in pavement design; shifted data are strongly related to elastic modulus values calculated by FWD tests carried out on pavements for a particular stress-strain state.

The obtained relationship is an helpful tool in mix design phase to develop asphalt mixtures matching project requirements, but it is valid only in the range of analysed data; it needs to be checked for modulus values out of the range used in this work, and with regard to the effect of different stress-strain states in filed tests.

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