Evaluation of the stiffness modulus of bituminous mixtures using laboratory tests (NAT) validate by field back-analysis

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ABSTRACT: This paper concerns the evaluation of the stiffness modulus of bituminous mixtures by using the Nottingham Asphalt Tester (NAT). On the basis of indirect tensile laboratory test results, a practical model for stiffness modulus prediction in pavement bearing capacity analysis was established and calibrated for some typical bituminous mixtures used in Portuguese asphalt pavements. Validation of this model was based on two experimental full-scale pavements instrumented during construction. To study the bearing capacity of the pavement structure, wheel load tests were carried out with simultaneous instruments measurements. Experimental pavements response modelling during load tests was performed using the finite elements method. The reasonably agreements between the calculated and measured strains indicate that the stiffness modulus prediction method is greatly reliable for the bituminous mixtures tested and could be very useful for further bearing capacity design of asphalt pavements.

KEY WORDS: Road pavement, performance, bituminous mixture, indirect stiffness modulus, laboratory test.

1 INTRODUCTION

A research program was developed at the “Instituto Superior Técnico” (IST) in Technical University of Lisbon related to the development of performance tests which can be used in practice to determine mechanical properties of Portuguese pavement materials. The main purpose is to contribute to the easy evaluation of the mechanical properties of pavement materials in laboratory tests, validated by field back-analysis, for the purpose of bearing capacity analysis using rational methods.

In the case of bituminous mixtures, mechanical properties determined with sinusoidal loading tests can be modelled using the complex modulus which is described by the stiffness modulus and the phase angle. For many years research activities have focused on the derivation of predictive models for the mechanical properties, based on the composition and components characteristics of the bituminous mixtures. This paper presents part of the results of an evaluation of the indirect tensile stiffness modulus evaluation using the Nottingham Asphalt Tester (NAT) and covers three typical bituminous mixtures currently used in Portuguese roads.

Indirect tensile tests are often used in laboratory characterization of bituminous mixtures. The NAT is well-known test equipment and can be used to carry out various performance tests on bituminous materials, such as the indirect tensile tests to evaluate the stiffness modulus of test specimens prepared in laboratory, by compacting materials into suitable cylindrical moulds, or cored from compacted bituminous layers of pavements.

The paper presents a general description of NAT equipment and the procedure adopted in laboratory tests, which were performed on three typical bituminous mixtures used in Portuguese pavement roads. The main properties of these materials are presented in order to better understand their mechanical behaviour. Temperature, porosity, rise-time and peak load factors influencing indirect tensile stiffness modulus were investigated. The results obtained in repeatability conditions have allowed the validation and calibration of a practical model, which indicate the influence of temperature conditions and material porosity.

In order to validate this predictive model, two full-scale asphalt pavements, which include in their structures the bituminous mixtures tested in laboratory, were instrumented and observed during in situ load tests. The instrumentation plan and characteristics of the testing tests are described. Experimental pavement behaviour has been modelled by using the finite element method and considers the model developed in this research to predict the stiffness modulus of bituminous materials. A comparison of the measured and calculated strains reveals a good agreement of the results, which indicates an appropriately adjusted model.

2 DESCRIPTION OF THE BITUMINOUS MIXTURES TESTED

Three types of bituminous mixtures currently used in Portuguese road construction were studied: bituminous concrete applied in the wearing course with crushed basaltic aggregates (maximum aggregate size 19 mm), sand and filler with a bitumen binder (BD); dense bituminous concrete applied as a binder layer with crushed limestone aggregates (maximum aggregate size 19 mm), sand and filler with a bitumen binder (MBD); bituminous macadam applied in the base layer and composed of crushed limestone aggregates (maximum aggregate particle size is 25 mm), sand and filler with a bitumen binder (MB).

Table 1 presents the main properties of the bituminous mixtures. The properties indicated are the mean values determined from the test specimens, cored from the pavement test sections. The diameters of the bituminous cores were approximately 140 mm (bituminous macadam) and 100 mm (bituminous concrete and dense bituminous concrete). The curves in the Figure 1 represent the grain size distribution for the aggregates of the tested bituminous mixtures. Two samples for each material have been tested. Materials properties are conform to Portuguese standards.

All bituminous mixtures were composed of a 60/70 grade bitumen binder, characterized by a penetration of 68 (0.1 mm) and softening point of 48°C.

Table 1: Bituminous mixture properties.

Bituminous mixture	ρ_{mix} (g/cm^3)	P_b (%)	V_V (%)	V_b (%)
BD	2.28	5.3	8.6	10.4
MBD	2.39	4.1	4.4	8.6
MB	2.28	4.9	8.6	10.4

Symbols: ρ_{mix} – density; P_b – binder weight content; V_V – void volume content; V_b – binder volume content

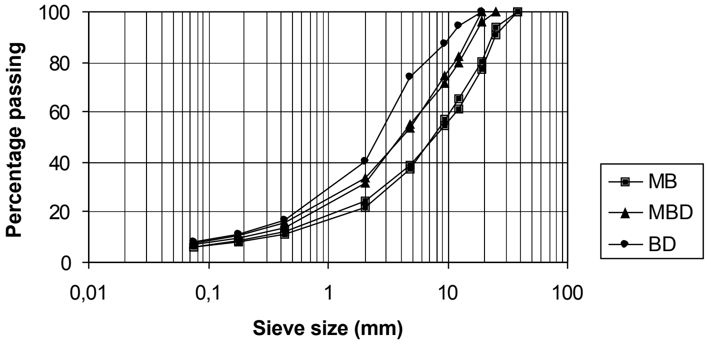


Figure 1: Aggregate grain size distribution of the tested bituminous mixtures.

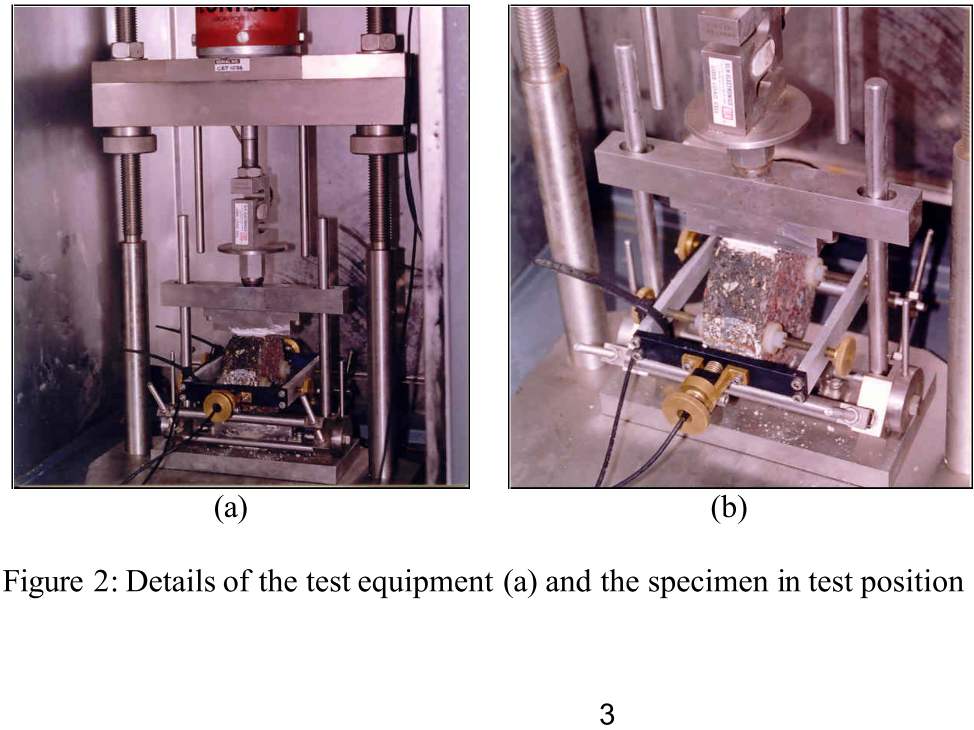
3 LABORATORY TEST EQUIPMENT AND PROCEDURE

3.1 Laboratory test equipment

Indirect tensile tests were performed in using NAT apparatus installed at the Geotechnical Laboratory of the Department of Civil Engineering and Architecture (IST).

The test equipment comprises: the loading system, incorporating a pneumatic load actuator, a steel load frame, a load cell and two loading platens; the deformation measurement system, including two linear variable differential transducers (LVDTs) mounted on a rigid frame clamping the test specimen; and the recording equipment, comprising an interface unit connected to a personal computer which monitors and records the electrical signals from the load actuator and LVDTs.

The tests are performed inside a refrigerated incubator, suitable for storing the loading and deformation measurement systems, and the test specimens, in a dry atmosphere at a constant temperature of between -10ºC and +50ºC. Figure 2 shows details of the test equipment placed inside the refrigerator incubator and of the test specimen mounted on the loading platens and the deformation measurement system.



(a) (b)

Figure 2: Details of the test equipment (a) and the specimen in test position (b).

3.2 Laboratory test procedure

The laboratory test procedure adopted in this research is in accordance with British Standard DD 213 (1993). Tests were carried out in 1999 and 2000. Test cylinder specimens were obtained from core samples extracted from the bituminous layers of full-scale experimental pavements. Before testing, test specimens were stored overnight inside the refrigerator incubator at the specified test temperatures. All specimens were tested at six different test temperatures: 5, 10, 15, 20, 25 and 30ºC.

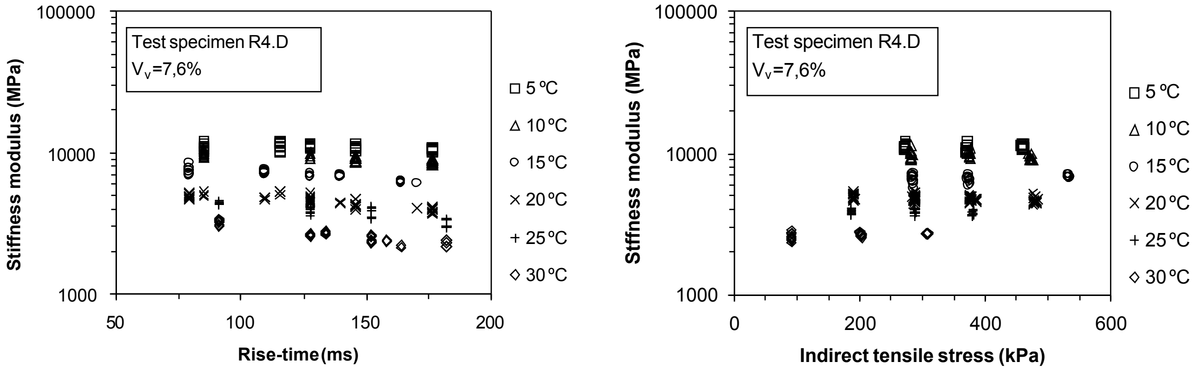
Special procedures were adopted to provide the proper adjustment and to centre the specimen in the loading platens and in the deformation measuring device. A preliminary conditioning of five load pulses was applied to bed the test specimen on the loading platens and to enable the equipment to adjust the vertically applied load in order to give the specified horizontal diametral deformation.

The loading test consists of sinusoidal load pulses characterized by the rise-time and peak value. Series of tests were performed for different values of rise-time and peak load pulse. For each load pulse, the peak load, peak horizontal diametral deformation and rise-time were recorded and the indirect tensile stiffness modulus was calculated according to the expression presented in BS DD 213 (1993). For each test performed in specified conditions of temperature, load peak and rise-time, a minimum of ten load pulses was applied in two or four diameters, depending on the degree of anisotropy of the material as indicated in British Standard test procedure.

4 STIFFNESS MODULUS PREDICTION

The laboratory tests have pointed out the influence of temperature, porosity, rise-time and load factors in the indirect tensile stiffness modulus of bituminous materials. All results presented in this study are the mean of the series of indirect tensile stiffness moduli obtained in each test performed in repeatability conditions.

Figures 3a and 3b show the influence of rise-time and indirect tensile stress, respectively, on the indirect tensile stiffness modulus of BD material. In general, the conclusion could be drawn that the stiffness modulus is not dependent on applied indirect tensile stress for all test temperatures. Instead, the stiffness modulus depends on rise-time, mainly in the case of high temperatures. Similar conclusions were obtained for MBD and MB materials (Neves, 2001).



(a) (b)

Figure 3: Influence of rise-time (a) and indirect tensile stress (b) on the indirect tensile stiffness modulus of BD material.

Figure 4 provides reliable evidence of the influence of test temperature and material porosity on the stiffness modulus of all tested materials. Suggested by following these tests results, a practical model was developed to be used for stiffness modulus prediction in pavement bearing capacity analysis. This model is function of temperature and porosity. The general expression for the predictive model is:

$$S_m = (A_1 + A_2\ V_v)\, e^{\left[\frac{T\,(A_3 + T)}{A_4}\right]} \tag{1}$$

where S_m is the indirect tensile stiffness modulus (MPa), V_v is the void volume content (%) and T is the test temperature (ºC). The parameters of the expression are A_1, A_2, A_3 and A_4.

Calibration of the above expression for the three bituminous mixtures BD, MBD and MB provides the model parameters and correlation coefficient (R^2) values presented in Table 2. Figure 4 shows the predicted values of stiffness modulus versus experimental values. The coefficient of correlation indicates that the predictive expression is appropriate to indirect tensile stiffness modulus modeling. The best adjustment of the model is achieved for the case of BD material.

Table 2: Values of the predictive model parameters.

Bituminous mixture	A_1	A_2	A_3	A_4	R^2
BD	21527.4	-311.937	27.4371	-1175.09	0.91
MBD	28469.3	-1391.58	283.637	-5494.51	0.94
MB	19729.5	-961.788	33.8706	-1243.78	0.97

5 FIELD BACK-ANALYSIS

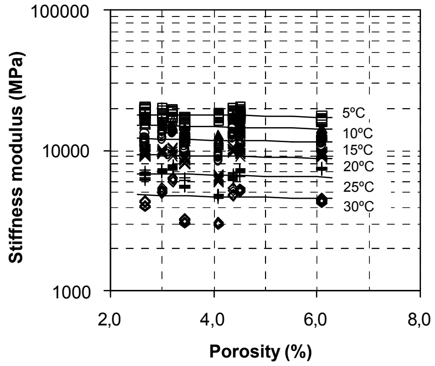
5.1 Description of experimental pavements

Two experimental pavement sections – CRIL1 and CRIL2 – of the IC17, a road located in Lisbon, were selected during the construction phase for instrumentation with the general purpose of field validation of analytical models and calibration of model response variables (Neves, 2001). In the particular case of this study, a field validation of the predictive stiffness modulus model was intended.

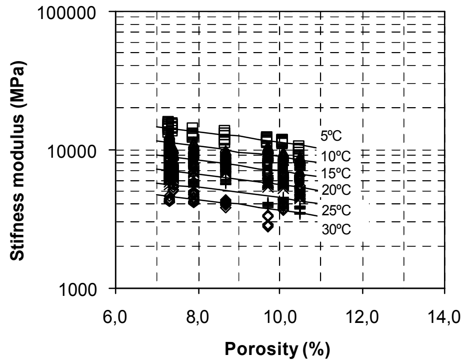
The structures of the experimental pavements are composed of the bituminous mixtures, the same tested in laboratory tests (NAT), and unbound granular materials (0/25 crushed limestone material with a fines content passing Nº200 ASTM sieve (75µm) of 9.8%), applied in the base and sub-base layers. The subgrade soil of the both experimental pavement foundations is classified as SM – silty sand (ASTM D 2487) and A-7-5 (5) (AASHTO M145). Tables 3 and 4 indicate the general characteristics of the pavement materials and geometry.

5.2 Instrumentation and experimentation

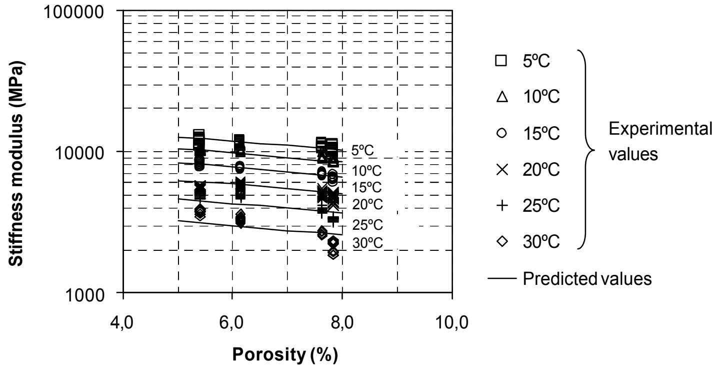
The Instrumentation of the experimental pavements was defined and implemented by the "Laboratoire Centrale des Ponts et Chaussées" (LCPC), in Nantes (France), and was composed of strain gauges and thermocouple probes.



(a) MB bituminous mixture



(b) MBD bituminous mixture



(c) BD bituminous mixture

Figure 4: Prediction of the indirect tensile stiffness modulus.

Table 3: General characteristics of the experimental bituminous layers.

Test section	Layer	Thickness (cm)	ρ_{mix} (kg/m^3)	P_b (%)	V_v (%)	V_b (%)	P_{200} (%)
CRIL1	BD	4.3	2460	5.3	6.7	12.7	8.1
	MBD	5.1	2270	5.0	9.4	11.0	7.9
	MB	12.5	2390	4.2	4.5	9.8	6.4
CRIL2	MBD	5.7	2280	4.9	8.6	10.4	7.3
	MB	20.8	2390	4.1	4.4	8.6	6.4

Symbols: ρ_{mix} – density; P_b – binder weight content; V_V – void volume content; V_b – binder volume content; P_{200} - percent aggregate passing a No. 200 ASTM sieve

Table 4: General characteristics of experimental unbound granular layers and subgrade soil.

Test section	Layer	Thickness (cm)	Compaction characteristics (*)	
			ρ_d (g/cm^3)	w (%)
CRIL1	Base	22.0	2.35	3.4
	Sub-base	48.0	2.36	2.9
	Soil	-	1.82	12.4
CRIL2	Base	19.0	2.35	3.5
	Sub-base	28.0	2.37	2.7
	Soil	-	1.84	12.6

(*) Mean values of in-situ control.
Symbols: ρ_d - dry density; w - moisture content

The instruments installed in the pavements were:

- bituminous strain gauges, placed in a horizontal position at the bottom of the bituminous base layer to measure horizontal strains in a longitudinal and transversal direction;
- unbound granular material and soil strain gauges, placed in a vertical position at the top of the subbase layer and subgrade soil to measure vertical strains;
- thermocouple probes, placed in three different vertical positions to monitor the temperature in the bituminous macadam base layer, and one added to measure ambient air temperature.

All the strain gauges were the Kyowa model, type KFL-30-350-C1-11 (Ódeon et al. 1996) and were positioned with a similar configuration in the two test sections. A total of eighteen horizontal strain gauges and nine vertical strain gauges were placed in each section. Some of them were already broken during the construction of the upper pavement layers. The instrumentation plan is described in detail by Neves (2001) and Neves and Gomes-Correia (2002).

The experimentation in the instrumented test sections was based on wheel load tests that were conducted in 1996 and 1997. Vehicle speed during the tests varied from 1 to 4 km/h. Tests characteristics indicated in Table 5 are referred to the front axle of single wheels. Loads were applied at the center of the gauges installed in the pavement structures. The aacquisition system used for collecting data from the strain gauges was from the LCPC (Ódeon et al. 1996). Temperature measurements for the thermocouple probes were made using a HANNA Instruments digital thermometer.

Tests I.A (Section CRIL1), II.A1, II.A2 and II.A3 (Section CRIL2) were carried out during the construction of the pavement when only the base layer of macadam was constructed. Tests I.B (Section CRIL1) and II.B2 (Section CRIL2) were carried out on final pavement structure.

Table 5: Characteristics of the in situ load tests.

Test	I.A	I.B	II.A1	II.A2	II.A3	II.B2
Volvo vehicle model	FL7	N720	NL10			N720
Axle load (kN)	34.3	34.1	36.0	34.0	32.2	34.1
Tyre type	Toyo 10.00R19.5	Baurun 10.00R20	Continental 315/80R22.5			Baurun 10.00R20
Tyre pressure (kPa)	689.0	564.0	826.8			564.0

Measured temperatures of the air (T_a) and of the wear, binder and base bituminous layers (T_w, T_b and T_{bm}), during the load tests, have the following values:

- Test I.A: $T_a = 22°C$; $T_{bm} = 25°C$.
- Test I.B: $T_a = 7\text{-}8°C$; $T_{bm} = 11°C$; $T_b = 10°C$; $T_w = 10°C$.
- Tests II.A1, II.A2 and II.A3: $T_a = 21°C$; $T_{bm} = 20°C$.
- Test II.B2: $T_a = 9.5\text{-}15.2°C$; $T_{bm} = 15°C$; $T_b = 10°C$.

5.3 Numerical analysis

Numerical analysis of experimental pavements during field load tests was accomplished using FENLAP2. This program was originally created at Nottingham University and was modified in 2001 by Neves (2001). In this program, the pavement structure is modeled as an axi-symmetric system and non-linear elastic analysis of pavement layers can be performed.

In the case of bituminous mixtures modelling, the elastic stiffness modulus was evaluated by laboratory tests performed on the Nottingham Asphalt Tester (NAT), in accord with temperatures measured by thermocouple probes during field tests. It was considered that Poisson coefficient value is a function of temperature as describe in BS DD 213 (1993).

The most recent generalization of the non-linear elastic Boyce model to the case of cross-anisotropic granular material (anisotropy between both vertical and horizontal directions) was adopted for unbound granular material, from base and sub-base layers (Hornych et al. 1998). In fact, Neves (2001) concluded that the most appropriate modelling was achieved by considering anisotropic non-linear elastic behaviour for granular materials. Parameters of this model were inferred from repeated load triaxial tests (Neves, 2001). The Drücker-Prager equation considered is $q=1.75p+165$.

Linear elastic behaviour was assumed for subgrade soil. Elastic parameters – Young's moduli (E) and the Poisson coefficient (ν) – were obtained by back-analysis of Benkelman beam tests performed with automatic acquisition of the deflection basins.

Table 6 presents the parameters of soil and unbound granular material models used in the numerical analysis. Boyce model parameters of n and β are 0.316 and 0.753, respectively.

Table 6: Parameters of soil and unbound granular material models.

Test	Soil		Unbound granular material			
			Sub-base layer		Base layer	
	E (MPa)	ν	K_a(MPa)	G_a(MPa)	K_a(MPa)	G_a(MPa)
I.A	81	0.40	150.6	177.0	111.9	133.7
I.B			111.9	133.7	111.9	133.7
II.A1, II.A2, II.A3	140	0.40	166.1	194.3	104.1	125.1
II.B2			111.9	133.7	111.9	133.7

5.4 Comparison of field and numerical results

The main purposes of numerical analysis of pavement test sections behaviour during load tests was to validate the predictive model of the stiffness modulus of bituminous mixtures, by comparing results from test section pavements monitored during load tests with the predicted performance obtained by numerical analysis.

Tests IIA.1, IIA.2 and IIA.3 may to investigate the influence of load level on pavement response. Figure 5 represents this influence on the strains at the bottom of the bituminous layer of macadam. The numerical predictions were found to be close to the values measured experimentally. It could be concluded that bituminous materials exhibit a quasi-linear behaviour, and so, the linear elastic modelling adopted for the bituminous materials was appropriate (Neves and Gomes-Correia 2002).

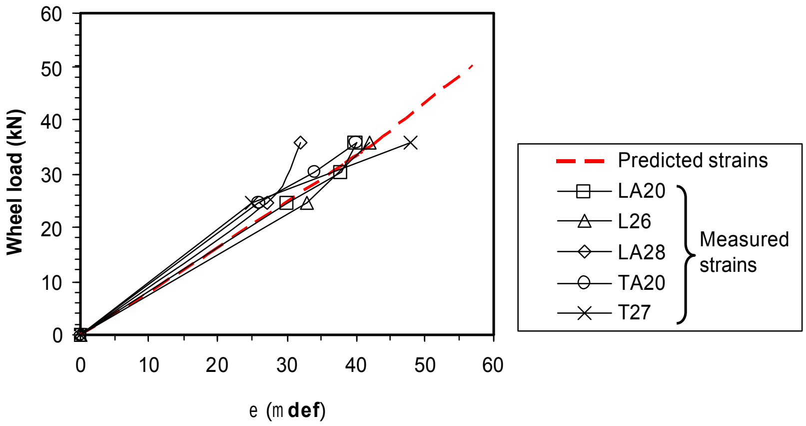


Figure 5: Influence of load level on the strains at the bottom of the bituminous layer.

Figure 6 shows the influence lines of measured and predicted strains at the bottom of the base layer MB in the case of tests IB and IIB. Besides experimental data scattering, the comparison of results allows us to conclude that the adjustment of values is very reasonable. Identical conclusions were obtained for the other numerical analyses.

In general, the comparison of field results with numerical simulations indicates that the stiffness modulus predictive model was appropriate for numerical bearing capacity analysis of the experimental pavements, composed of the bituminous materials tested in indirect tensile tests performed on NAT equipment.

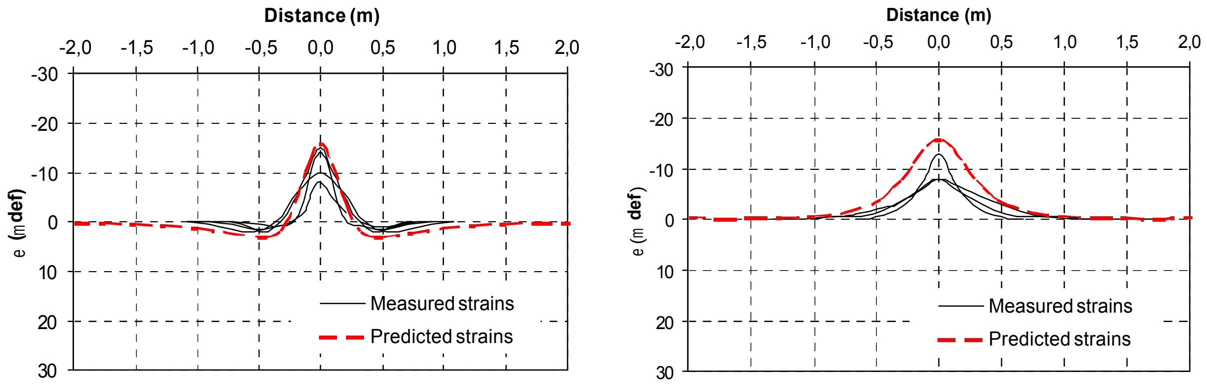
6 CONCLUSIONS AND RECOMMENDATIONS

This paper presents some of the results of a research program performed at IST. The purpose was to evaluate the indirect tensile stiffness modulus of bituminous mixtures, using NAT equipment, in order to provide design parameters useful for the structural analysis of asphalt pavements.

Several laboratory tests were performed on three typical bituminous mixtures currently used in Portuguese road construction, under different temperatures. It can be concluded that the NAT equipment is highly appropriate for characterizing these materials and easy to operate. The testing program allowed us to investigate the influence of temperature, porosity, rise-time and peak load factors on the indirect tensile behaviour of materials. The results obtained shows the influence of the rise-time and peak load factors in the behaviour of all materials. Otherwise, mechanical behaviour is strongly dependent on porosity and temperature.

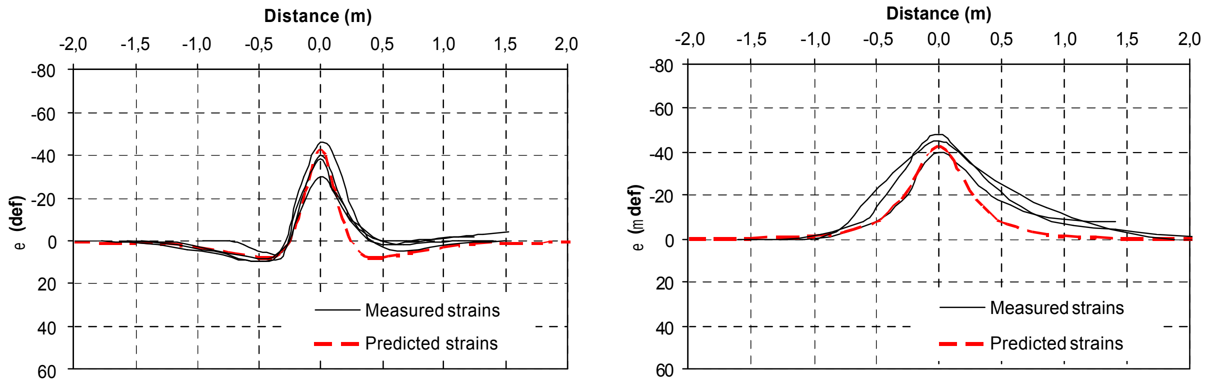
Consequently, a practical model for stiffness modulus prediction was validated and calibrated for the testing materials and a good quality of adjustment was achieved.

The results obtained from the numerical back-analysis of field tests performed on full-scale instrumented asphalt pavements, using the proposed model, were compared with strain measured during in situ tests. It can be conclude that the predictive model is appropriate for the materials tested. However, further research is needed in order to validate and calibrate the predictive model for other types of bituminous mixtures.



Horizontal strains in longitudinal direction　Horizontal strains in transversal direction

Test I.B



Horizontal strains in longitudinal direction　Horizontal strains in transversal direction

Test II.B2

Figure 6: Influence lines of measured and predicted strains at the bottom of the base layer.

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