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APPLICATION OF VISCOELASTIC DAMAGE COMPUTER MODEL FOR ASPHALT CONCRETE ANALYSIS IN THE FENIX TEST

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Abstract. One of the most efficient experimental techniques used in the field of asphalt pavements subjected to intense traffic loads from vehicles is the Fenix test. It was designed to measure the dissipated energy during the cracking of the mixture under cyclic loads. This paper addresses the application of a computational-numerical tool for investigating the asphalt concrete under the conditions of the Fenix experimental test. In particular, a computer model was applied to characterize the mechanical properties of an asphalt mixture. This numerical model is based on the Finite Element Method and a viscoelastic-damage constitutive model. The new application of the tool complements the experimental side of the Fenix test, broadening the knowledge about the asphalt mixes. A calibration-validation procedure was performed, based on a set of experimental data obtained from the Fenix test. Energy dissipation and time-dependent properties of the mix were analysed and transformed in numerical parameters, for three different displacement rates. The numerical model showed a high capability to model the material's behaviour for several variables, leading to a fairly good approximation to the experimental reference.

1 INTRODUCTION

The need for infrastructure facilities in many underdeveloped countries makes pavement design a topic of central interest. Hundreds of kilometres of routes are built each year, linking remote villages. For the pavement design, the empirical WASHO (Western Association of State Highway Officials) and CBR (California Bearing Ratio) methods have been traditionally used since the 1950s. However, in general, the use of these codes has shown an inadequate behaviour of the many routes around the world. This occurs because the quality controls used are not the most adequate.

To prevent rutting on roads and routes, in general, the quality controls carried out only measure the reference density and the amount of bitumen in the mixture in the top layer of the structural package. However, it is documented that is not enough proof to guarantee the correct performance of the asphalt. In Spain, the Fenix test is used to determine the quality of a mixture, because it is the simplest and fastest one, among other reasons. In the year 2020, the Fenix test was standardized in Spain and the formula was updated (NLT-383/20, 2020).

The relevance of this experimental test demands a methodology for numerical simulation in order to extend its range of uses. However, the numerical analysis of the asphalt mixes presents an obstacle to overcome. The experimental treatment of the asphalt mixes and the properties measured are not directly related to the constitutive parameters commonly used in the mechanical formulations. In concrete asphalt, simple compression tests are not common, therefore we have to determine the modulus of elasticity and the yield strength. The prediction of the viscosity coefficient is commonly approached as a relaxation time from specific tests. All these properties are typically requested by commercial softwares for structural calculus. The relationship among these parameters and their counterparts coming from the Fenix test, were determined in this paper.

The objective of this paper is to contribute to improving the experimental-numerical link with a calibration-validation procedure for an experimental reference like the Fenix test. The conception of the test and the experimental part of this work is provided by Department of Transportation and Territory of the Universitat Politècnica of Catalunya (UPC), while the numerical modelling part is assumed by the Centre of Numerical and Computational Methods in Engineering (CEMNCI) of Tucuman, in collaboration with the International Centre for numerical Methods in Engineering (CIMNE), hosting the research.

2 STATE OF THE ART

The state of the bibliography on the numerical-computational and experimental modeling of asphalt concrete applied to the Fenix test, is briefly described below.

The first steps in numerical-computational modeling of rheological materials came probably around the 90s. Models were defined for frictional cohesive materials by (Etse and Willam, 1994) and (Luccioni and Rougier, 2005), based on Plasticity and Plasticity coupled with Damage respectively.

As regards asphalt concrete, the first evidence of the numerical computational aspect can be found in (Miró et al., 2008) and (González et al., 2007). The authors developed a deformation rate dependent constitutive model based in Perzyna viscoplastic therory. On the other hand, the viscoelastic model coupled with damage used in this paper, had been designed to calibrate the structure analysis of the Cathedral of Mallorca; built of brick masonry and described in (Roca et al., 2012).

Finally, regarding the experimental experience, the first evidence of the Fenix test applied in bituminous mixtures may be the one described in (Pérez-Jiménez et al., 2010). This test was used to evaluate the influence of variables such as binder type, content and temperature in specimens. The complete experimental development of the Fenix test in the bituminous mixture AC16 50/70, used in this paper, can be seen in (Valdés Vidal, 2012).

3 EXPERIMENTAL DATA

In this section, the experimental data used to perform the adjustment with numerical results are described, in addition to the importance of the Fenix test in control quality assessment.

3.1 Description of the Fenix test

The Fenix test was originally designed to calculate the dissipated energy during the cracking process. Its results were later related with those of fatigue tests, making the Fenix more useful for pavement design. Fatigue tests are very effective to perform an optimal design of the mixtures, given the energy released for a high number of cycles. However, sophisticated and expensive equipment is required for fatigue test and the test is time consuming because some may last one or two days. The Fenix test comes to replace fatigue test, offering equally reliable results at a lower cost, using the corresponding correlations with those tests.

The specimens in the Fenix test are obtained by sawing across their diametric plane, a compacted material cylinder by Marshall or gyratory procedure. Both halves are glued with an adhesive mortar to two steel plates which are joined to the machine by their extremes (Fig. 1a). The prescribed displacement is applied to half of the diametric plane while the other half is fixed. The specimen is 101.6 mm in diameter by 63.5 mm high and a notch with a 6 mm deep is cut in the middle of the flat plane to lead the damage and cracking process (Fig. 1b).

The Fenix test is a direct simple-tensile test, where a monotonic displacement is applied at a constant rate over the specimen described in the previous paragraph. The output data from the test is a force-displacement curve (F-D), as the structural response of the material. The evolution during the test is sketched in Fig. 1c, where some elements can be easily identified. The first part of the curve is a loading branch showing a linear-like behavior, similar to a proportional force-displacement relation, that could be characterized by an initial slope (sl_0). Close to the peak, the curve shows a small hardening interval where the slope is not constant, until the peak force (F_p) is reached. After the peak, the curve shows an exponentially decreasing trend to an asymptotic residual value, characterized by a final slope (sl_f) and the residual force value (F_r). The whole response curve defines another relevant value related to the energy dissipation in the test: the area below the curve (A_C).

It is important to mention that asphalt concrete is a highly non-linear and temperature dependent material. The non-linearity may be manifested even for very low loads or temperatures over a certain threshold. When the test temperature is higher than 15°C, the limits among the linear-like interval, the peak and softening zone become diffuse.

3.2 Properties of the mixture

A semi-dense mixture was taken into account for the experimental test, the AC16 S mixture, as already mentioned in section 2. This denomination is according to the Spanish standard, which is generally used in wearing courses. The gradation of aggregates is summarized in Table 1, with a maximum aggregate size of 16 mm, called AC16 S centered on the spindle. The composition of specimens was: Porphyry coarse aggregate, limestone fine aggregate, calcium carbonate filler. Bitumen: penetration 50/70, 5% bitumen content over mix. Manufacturing: 75

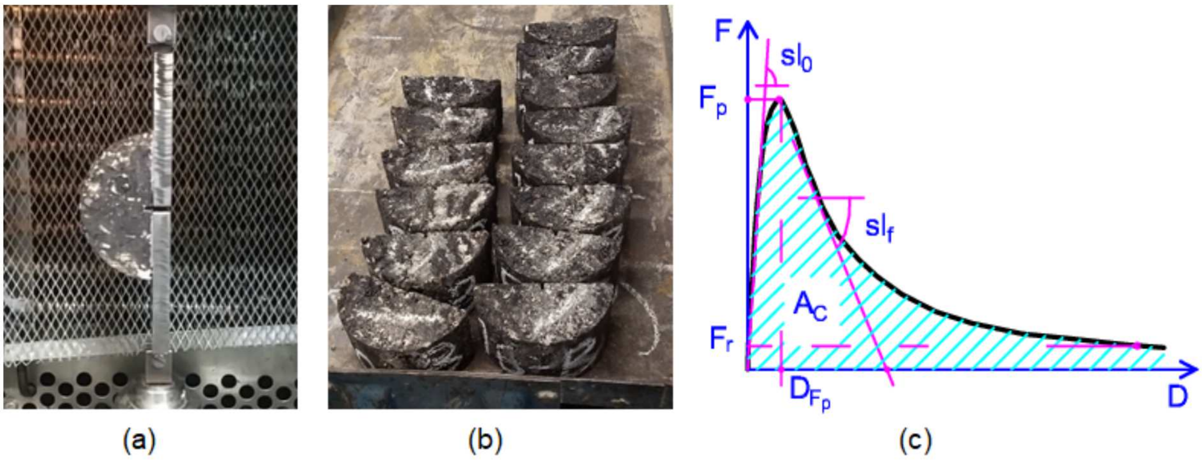

Figure 1: (a) Configuration of FENIX test (b) Asphalt mixes specimens (c) Scheme of the structural response of the asphalt mix for Fenix test

blows per face compaction. Air content: 4.3%.

SIEVE SIZE (mm) UNE-EN 933-2 – Percent passing								
Mixture	22	16	8	4	2	0.500	0.250	0.063
AC16S	100	90-100	60-75	35-50	24-38	11-21	7-15	3-7

Table 1: Data of aggregates, according to Spanish standards.

The experiments described were developed in the UPC. Some of the available test results over AC16 B50/70 S mixture, are described in the following section.

3.3 Curves $F - \Delta$ of Fenix test

The tests were conducted for three constant displacement velocities: 0.1, 1.0 and 10.0 mm/min and a temperature of 20°C. The forces applied were recorded throughout the tests, as a function of the prescribed displacement.

The curves Force-Displacements for three sets of three specimens for each displacement rate, are shown in Fig. 2. Some dispersion can be seen for each rate displacement, attributable to the dispersion of the mixtures. In each case, one representative curve is chosen: Specimen 10A, 15A and 18A for 10.0, 1.0 and 0.1 mm/min respectively.

Experimental results show a significant increase in the loading slope, the area under the curve and in the softening slope, with the increase in displacement rate. The aim of this research is to build a numerical model able to reproduce this behavior. This task involves selecting a constitutive formulation for the asphalt from the bibliography, identifying of the mechanical parameters of the model and calibrating of these parameters. The determination of the parameters from the curves is performed as follows:

In the Fenix test, the slope of the initial branch of the curve $F - D$ is defined as the tension stiffness index (IRT). This is adopted like a measurement of the modulus of elasticity, and it is determined with Eq 1.

Fracture energy is the necessary work to produce a unitary displacement. In the case of the Fenix test specimen, fracture mode 1 is predominant. In this paper, it is calculated as the area

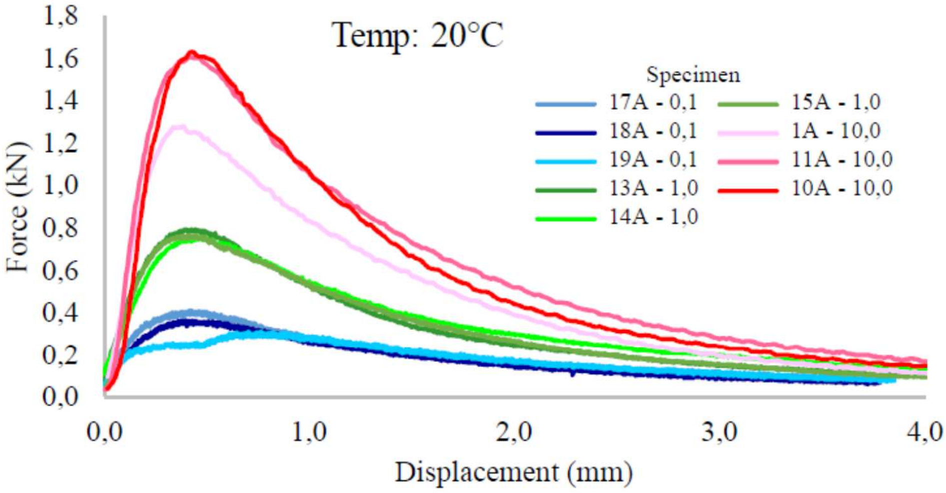

Figure 2: Experimental results from Fenix test. Displacement rates: 0.1, 1.0 and 10.0 mm/min

under the force-displacement curve, using Eq 2.

$$IRT = \frac{F_{50} - F_{25}}{1000S(d_{50} - d_{25})} x L_0 \tag{1}$$

$$G_D = \frac{\int_0^{d_f} F(x)dx}{S} \tag{2}$$

where, IRT: tensile stiffness index, F_{50} and F_{25}: 50% and 25% of the peak load, d_{50} and d_{25}: displacement values at 50% and 25% of the peak load, G_D: fracture energy during cracking, F: load, x: displacement, S: surface fracture, d_f: displacement at the end of the test and L_0: height of the flat side of the specimen.

Fenix peak strength (R_{pF}) is the maximum force reached in a Fenix test. This value may be related to the tensile strength of the material.

Finally, the parameters obtained from the experimental curves are summarized in Table 2.

Displ. rate mm/min	G_d $[J/m^2]$	IRT $[MPa]$	R_{pf} $[kN]$
V1=0.1	175.50	28.45	0.360
V2=1.0	362.20	93.47	0.770
V3=10.0	793.20	191.01	1.610

Table 2: Parameters obtained using the Fenix test experimental results.

4 NUMERICAL MODEL

4.1 Geometry, mesh and boundary conditions

This section describes the numerical model developed for the FENIX test, using the Finite Element Method and assuming a plane stress problem. Fig. 3a shows a scheme of the geometry and the boundary conditions in the numerical model. The constraints and imposed displacement simulate the planes of contact between the steel plates and the specimen. As already mentioned in Section 3.1, the specimen is fixed to the testing machine by means of steel plates. As the plates are much more rigid than the specimen, it can be considered that all the points of the specimens in the contact plane move together.

Fig. 3b shows a scheme of the prescribed boundary conditions. Three lines can be easily identified in the figure. In the lower part of the diametric plane, along line 3, the specimen is fixed only in the vertical direction, and the lower point of that line is also constrained in the horizontal direction. In the upper part of the diametric plane, along line 1, vertical displacements are imposed with controlled velocity, and the upper point of that line is constrained only in the horizontal direction.

This Figure also shows an outline of failure mode. The failure observed in the experiment guides these modelling techniques. A crack is expected in the midplane (line 2) due to the effect of the prescribed displacement. Line L2 is where the fissure propagates and separates the upper from the lower sector. Due to the eccentricity of load in respect of shear centre and of Poisson's effect, deformations occur in the X and Y directions in all the specimens. Both sectors twist around the pole, line 1 and line 3 twist around their vertices.

The geometry of the specimen was discretized with linear triangular elements and represented in a finite element meshes, as shown in Fig. 3c. Stable results were obtained with this mesh, i.e. the same responses were obtained even when the size of the finite elements was reduced. Mesh has 7200 triangular elements of 1 mm of longitude and 3702 nodes. The size of the time step is related to calculation time and the precision of results. Several tests were done until an appropriate value of time step of 0.01 sec. arose.

4.2 Constitutive model

For modeling the material behavior, a viscoelastic constitutive model coupled with a damage model was chosen, because the material has brittle behavior. The plastic deformation produced is low compared with that of cracking and elastic deformation. The energy released by the specimen during the whole test is obtained as the sum of the energy of elastic and plastic deformation and the fracture energy originated during the cracking. This constitutive model was previously used by (Roca et al., 2012) and is presented as customarily used in FE bibliography and in codes. The rate dependent structural behavior of the asphalt is represented by a well-known constitutive model. The one-dimensional representation of this model is made up by an elastic spring and a dashpot placed in series. This is a simple viscoelastic model defined by two material parameters: the modulus of elasticity (E) and the delay time (τ). This time, which characterizes the time dependent behaviour, is related to the viscosity parameter (η) through the relation (Eq. 3):

$$\eta = E\tau \tag{3}$$

The constitutive model assumes two additive components for the strain. These two strain components have a defined constitutive relation according to Eq. 4:

$$\sigma^e = E\varepsilon^e; \sigma^v = \eta\dot{\varepsilon^v} \tag{4}$$

The model assumes that the stress applied to the material (σ) is the same for both strain components, i.e. $\sigma^e = \sigma^v = \sigma$, and so considering Eq. (4), the constitutive relation for the model is Eq. 5:

$$\varepsilon(t) = \varepsilon^e(t) + \varepsilon^v(t) = \frac{\sigma}{E} + \int \frac{\sigma(s)}{\eta} ds \tag{5}$$

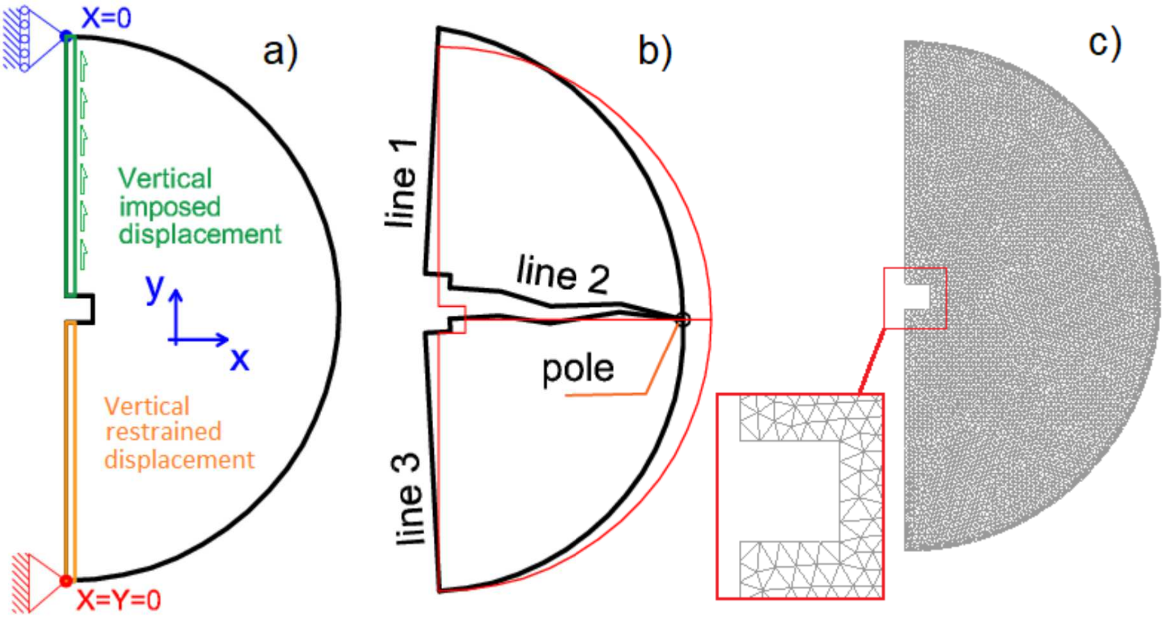

Figure 3: Sketch of numerical model. a) Prescribed displacement and boundary conditions, (b) Failure mode. (c) Numerical model of the Fenix specimen.

DAMAGE CRITERION

The stress tensor $\boldsymbol{\sigma}$ and the strain tensor $\boldsymbol{\varepsilon}$ are linked by the constitutive equation (Eq. 6)

$$\boldsymbol{\sigma} = \boldsymbol{C_d} : \boldsymbol{\varepsilon} \tag{6}$$

In a damage model, $\boldsymbol{C_d}$ is a function of a set of internal variables $\boldsymbol{d}$ that describe the degradation of the material, such that $\boldsymbol{C_d} = \boldsymbol{(1-d)C_0}$. Rankine criterion (Eq. 7) is used here and it requires the specification of the tensile stress strength f'_t.

$$\Phi(R, r) = R - r \leq 0; R = \sqrt{\sigma : \Lambda : \sigma} \tag{7}$$

where Φ is damage function, R is a scalar positive quantity and Λ is the shape of each damage criterion.

At the end, the evolution of the damage index is defined by the following function (Eq. 8):

$$d(r) = 1 - \frac{r_0^2}{r} e^{2H_{dis}(\frac{r_0 - r}{r_0})} \tag{8}$$

where H_{dis} is related with the positive softening parameter, which controls the rate of material degradation. In FE simulations of quasi-brittle failure, the softening parameter is linked to the material fracture energy G_f. More details about the constitutive model used here are in (Cervera et al., 2017) and (Cervera et al., 2010).

The solution of the problem under study involves a time-dependent constitutive model, as can be seen in the Eq. 5, even though it is not a dynamic problem. It includes a time derivative of the viscous strain, obtained by means of integration in the time domain. Similarly, stresses are time-dependent functions. However, the inertial forces are not taken into account since the speeds used in tests are relatively low.

Lastly, the tridimensional extension of this constitutive model is escential and can be found in the aforementioned paper (Roca et al., 2012). This representation also shows a physical interpretation of the delay time in the relaxation curve.

CONSTITUTIVE PARAMETERS

For analyzing the capacities of the numerical model, a calibration procedure was developed. The procedure had to find the constitutive model parameters to reproduce the experimental curves from the FENIX test, and for the three loading rates considered. It started from values coming from a numerical research which bears some similarities to the one presented here. Then, the input data was modified until both, the experimental and numerical curves, match.

The data coming from (González et al., 2007), was used for reference in viscous and mechanic properties. There, a simple tensile test was applied in a prismatic specimen with the following characteristics: height 140 mm, square base 50x50 mm, indent (depth) 5.0 mm, temperature 20.0°C. Bitumen properties: Content of bitumen 80/100 and Air content 4.3%.

5 NUMERICAL SIMULATION OF THE FENIX TEST

The following describes the outputs of FE software for three levels of displacements: low (around 5.0% of peak load), medium (around peak load), and high (around displacement of 4.0mm). The results are expressed in terms of curve displacement-force ($F - D$).

5.1 Structural response of the mixture

The software used in our nonlinear solid mechanics problem, was performed using an enhanced version of the software COMET (Cervera et al., 2002). Data visualization and the mesh files were generated using the GID software (GID, 2021), both were developed in the CIMNE.

We shall focus on the results of the numerical test, in terms of the total force (reactions) vs. displacement. Let us remember, the tests consist of applying prescribed displacements on point 1 (belonging to the upper plate, Fig. 4a). The total reaction is the sum of force in each restrained point (point 2). The numerical and experimental results are shown in Fig. 4b.

The evolution of the force with respect to the displacements for the numerical and experimental models show a quite similar behavior. An excellent match can be seen between numerical and experimental results, which proves the capabilities of the numerical model. The fracture energy, the slope of the initial branch, and that of the exponential decay branch are quite similar. The maximum forces are 0.36 kN, 0.76 kN and 1.62 kN for displacement loads of 0.1, 1.0 and 10.0 mm/min, respectively. However, a small displacement around 0.05 mm is observed in the maximum force peaks for the three cases.

The parameters obtained with the numerical simulation are summarized in Table 3. The inputs of FE software are: Tensile Strength f'_t, Modulus of Elasticity E, Fracture Energy G_f, Viscosity Coefficient η, and delay time τ. It is important to mention that the data that can be measured directly from the Fenix test, are not entered as input in the FE software. Furthermore, in some cases there may be a different physical phenomenon. But, they keep some proportionality and we can only relate the numerical values through correction factors. Next, f'_t, E and G_f, inputs of FE software, were related with R_{pF}, IRT and G_d, determined from the Fenix experimental test. Analysing the case of 1mm/min for the fracture energy, from FE software is 468.44 [J/m^2], and from the experimental is 362.20 [J/m^2]. The relationship between them is 468.44/362.20= 1.29. For the other displacement rates, similar approximations were obtained. The average ratios obtained for the Fracture Energy, Modulus of Elasticity and Tensile Strength,

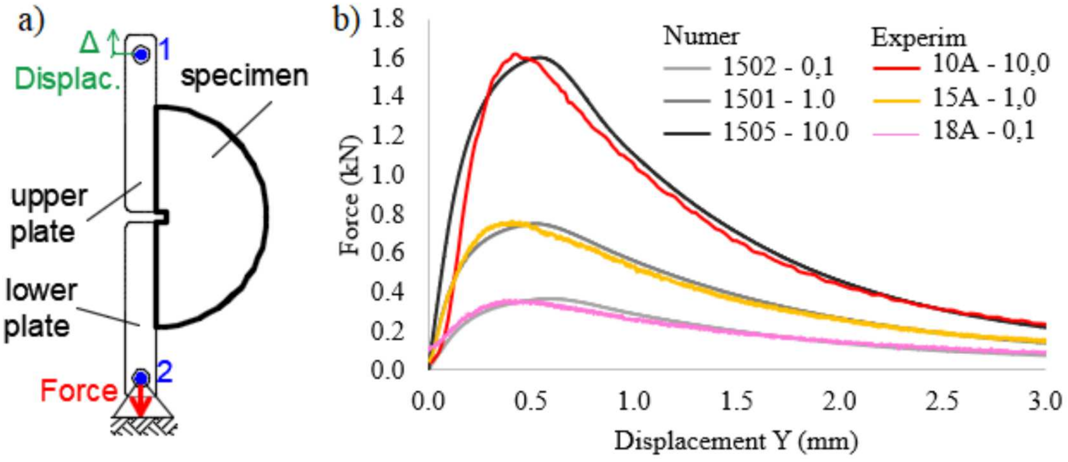

Figure 4: a) Test configuration, b) Experimental vs numerical results

were 1.32, 0.26, and 0.88, respectively.

Displ. rate mm/min	G_f $[J/m^2]$	E [MPa]	η [MPa.s]	f'_t [MPa]	τ [s]
V1=0.1	277.46	114.70	833.00	0.41	7.26
V2=1.0	468.44	407.76	251.55	0.84	0.62
V3=10.0	850.00	660.00	55.70	1.89	0.08

Table 3: Input data of FE software.

6 CONCLUSIONS

This paper presented a numerical modeling of a reference experimental test, to improve the research capabilities for characterizing asphalt mixes. This numerical model is a complementary piece of the characterization methodology for the FENIX test.

A viscoelastic-damage model was used to reproduce the time-dependent behaviour characteristic of the asphalt mixes under traffic loads. In addition, a calibration procedure was developed to find the constitutive parameters for a given mix.

The paper focuses especially on showing the capability of the constitutive model to capture the response of an experimental test under the FENIX specifications. It also centers on defining the numerical parameters involved, analyzing their influence in the response, and proposing a way to obtain correction factors. The numerical procedure results showed an excellent match to the experimental curves for the three displacement rates.

According to the proposed procedure, the material parameters such as elasticity modulus, fracture energy, and tensile strength, depend on the displacement rate of the test. This can be considered as a limitation for the procedure, and requires investigations that go beyond the scope of this work.

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COMPETING INTERESTS' STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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