Cyclic triaxial apparatus for the study of permanent deformations of bituminous mixes

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ABSTRACT: Rutting is one of the main modes of degradation of bituminous pavements. In order to study the rutting behaviour under realistic stress states, the "Laboratoire Central des Ponts et Chaussées" (LCPC) has acquired a new cyclic triaxial apparatus for bituminous materials. This apparatus allows to perform cyclic tests in compression and tension, on 80 mm or 100 mm diameter specimens, at controlled temperatures between 0 and 60 °C. Axial and radial strains are measured on the sample.
This paper describes the experimental work that is going on at LCPC using this new device and the conclusions of these first tests. The first part of the paper presents the experimental device. The choice of appropriate test conditions, for the study of permanent deformations is also discussed, on the basis of the modelling of stress states in pavement layers under traffic loading. The second part of the paper presents first experimental results of creep tests at constant stress and at constant strain rate performed with the triaxial apparatus. Based on these results and complex modulus tests, parameters of the DBN visco-elasto-plastic model have been determined. A first assessment of the capacity of this model to simulate creep tests at constant stress and at constant strain rate is presented.

KEY WORDS: Permanent deformations, rutting, triaxial tests, bituminous mixes.

1 INTRODUCTION

One of the main distress mechanisms that may affect bitumen-paved roads are permanent deformations, the presence of which is revealed by longitudinal profile irregularities and especially by transverse profile deformation in the wheel paths (ruts) (Verstraeten, 1995).

Deficiencies on the comfort and safety of road users results from these adverse effects. For these reasons, LCPC has undertaken an extensive research program on the permanent deformations of road materials. One of the main objectives is the development of a suitable laboratory test for the study of permanent deformations of bituminous materials.

None of the existing laboratory tests is able to exactly reproduce stress path existing in the road. Nevertheless, different authors underline the importance of considering triaxial behavior including confining pressure (De Vissher et al., 2006, Ebels and Jenkins, 2006, Clec'h et al., 2009, Taherkani et al., 2007).

Therefore, it was decided to develop a triaxial apparatus for bituminous mixes, able to perform different kinds of tests: monotonic creep tests, cyclic permanent deformation tests, at large strain levels (up to 5 %), complex modulus tests, at low strain levels (around 50 μdef), at different temperatures (from 5 to 60°C), at different frequencies (up to 10 Hz) and at different levels of confining pressure.

2 TESTS CONDITIONS FOR THE STUDY OF PERMANENT DEFORMATIONS

2.1 Laboratory tests for the study of rutting

Rutting develops under conditions of large tire-pavement contact pressure, slow traffic of heavy vehicles and high temperature. Various hot mix design parameters like binder properties, angularity of aggregate, particle size distribution and compaction have an influence on rutting.

The standard laboratory test used in France, to verify the resistance to rutting of bituminous surface layers is the wheel tracking test. This test consists in submitting a slab of material to the loading of a moving wheel, with a pneumatic rubber tire. The test is performed at 60°C, with load and pressure conditions similar to those of heavy vehicles. This test simulates the effect of moving wheel load, but it has several shortcomings:

- The stress state in the specimen is not homogeneous, and so it is difficult to use this test to determine the rheological properties of tested materials.
- The test conditions (load, temperature, frequency) cannot be changed.

Thus, in spite of not reproducing the stress rotation due to moving loads, the triaxial test appears as a much more appropriate test for studying the permanent deformation behaviour of bituminous mixes under homogeneous stress states. It can be used to study the monotonic or cyclic behaviour, under a large range of conditions of stress and frequency.

In this work, pavement structure calculations have been performed to assess the stress states produced by wheel loads in bituminous pavement layers, in order to define the most appropriate stress states (axial stress and confining pressure) to apply during triaxial tests. The results of these calculations are presented below.

2.2 Calculation of stress states in pavement layers and determination of triaxial test conditions

The pavement structure calculations have been performed with the pavement design software Alize LCPC. Computation is based on a linear elastic model. The pavement layers are supposed isotropic, and infinite in the horizontal plane.

Stress path calculations have also been performed using a viscoelastic model, by means of the software Viscoroute (Duhamel et al., 2005, Chabot et al., 2009). However, differences between results are not significant in terms of stress paths induced in the pavement. For brevity, only results of elastic simulations will be presented.

Simulations have been performed for a pavement made of 6 cm of dense-graded asphalt mix (DGAM) and 16 cm of road base asphalt (RBA) at 35°C. The tire load is simulated by a circular surface, with a diameter of 25 cm and a contact pressure of 0.662 MPa (see figure 1).

Results are presented on figures 1 and 2. Figure 1 shows the values and signs of the vertical stress σ_V and horizontal (or radial) stress σ_H under the center of the wheel:

- On the top of the pavement (A1), σ_V and σ_H are both in compression.
- In the middle of the pavement (A2), σ_V and σ_H are both in compression
- At the bottom of the pavement (A3 and A4), there is compression in the vertical direction and tension in the horizontal direction

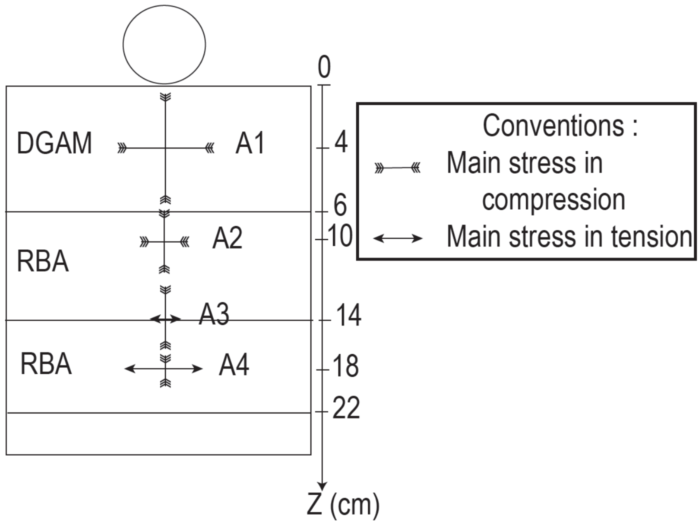

Figure 1: Stress states in a pavement layer under wheel loading

Figure 2 shows the stress paths produced, at different depths, by the moving load, in terms of mean stress $p = \frac{2\sigma_H + \sigma_V}{3}$ and deviatoric stress $q = |\sigma_V - \sigma_H|$. The stress paths induced in the structure have a complex shape, and range from compression at the top of the layer to tension, at the bottom, with a large range of q/ p slopes (for this example from -2 to 3).

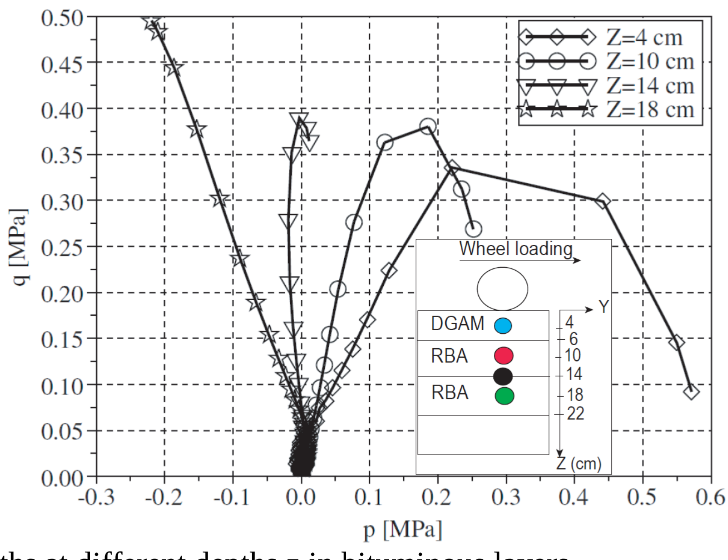

Figure 2: Stress paths at different depths z in bituminous layers

To simulate this range of stress paths during a cyclic triaxial test, it is necessary to cycle both the axial load and the cell pressure. However, this requires a complex loading system, and for the LCPC apparatus, it was decided to work, first, with a constant confining pressure, and to add this possibility in a second phase.

2.3 Choice of temperatures and frequencies for the future tests

According to Verstraeten (1995), Heck, (2001) and Di Benedetto and Corte, (2005) rutting appears only for high temperatures. Furthermore, experimental observations on the LCPC (Laboratoire Central des Ponts et Chaussées) test track confirm these results : rutting appears at 40 or 45°C (Corte et al., 1997). At 60°C the depth of rut is multiplied by 2. So, high temperatures (above 40°C) are required for the study of rutting. According to Aussedat, (1977), normal truck velocity (about 60 km/h) can be represented by a loading frequency of 10 Hz.

3 PRESENTATION OF THE TRIAXIAL APPARATUS WITH TEMPERATURE CONTROL

3.1 Experimental device

The triaxial apparatus has been developed using an existing servo-hydraulic loading frame. The pressure cell, the temperature control system, and the instrumentation have been developed specifically for the triaxial tests on bituminous mixtures (see figure 3).

The apparatus is designed for specimens with a diameter of 80 mm and a height of 160 mm. The maximum axial load is 25 kN, the maximum confining pressure is 700 kPa, and the temperature range is from 5°C to 60°C. The maximum loading frequency is 10 Hz.

3.2 Triaxial cell and loading frame

The loading frame used to apply the axial load is a SCHENCK frame, with a servo-hydraulic actuator with a load capacity of ±100 kN and a ± 100 mm axial stroke. The loading frame is equipped with a numerical control system, which allows to perform a large range of loading tests (monotonic or cyclic) with load or displacement control.

The triaxial cell for bituminous materials has been developed by GDS Instruments. It is all made of aluminum, has a diameter of 300 mm, and can accept 80 mm or 100 mm diameter specimens. The confining fluid can be water or air. Water allows a better homogeneity of the temperature. The cell is equipped with an internal load cell of 25 kN capacity, and a 1000 kPa pressure transducer, placed outside the cell, on the confining fluid supply circuit (see figure 3).

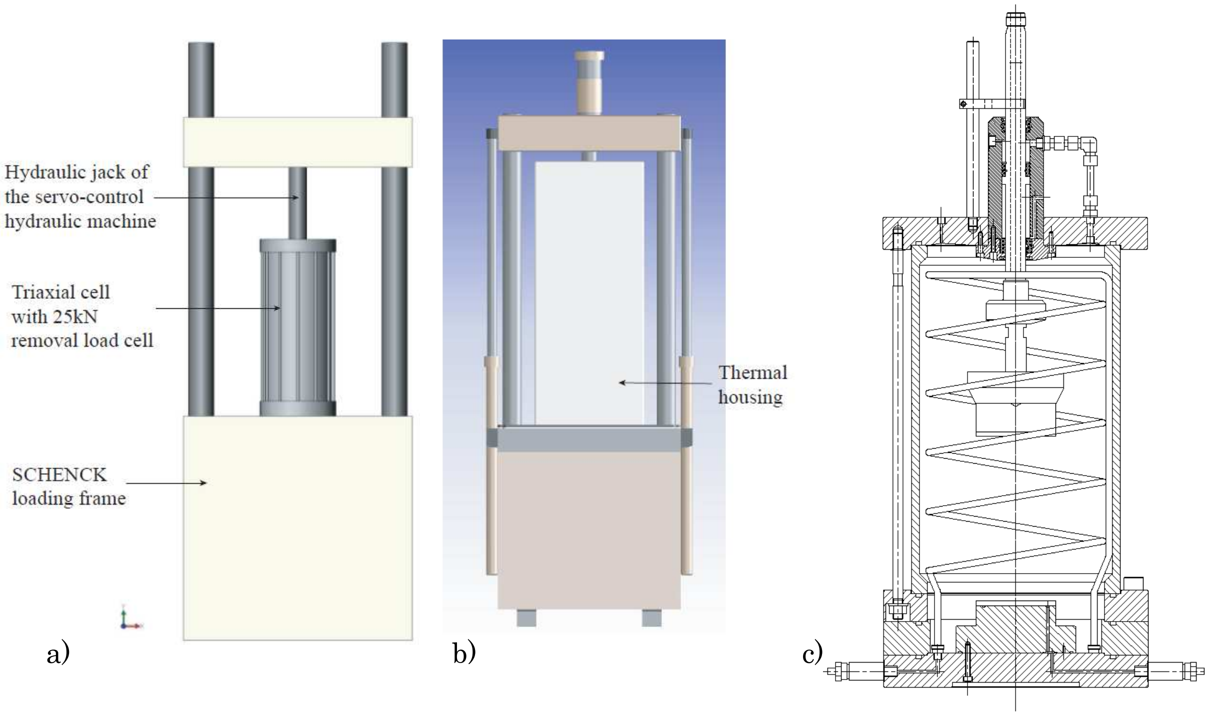

Figure 3: Schematic view of the triaxial testing equipment without (a) and with (b) the thermal chamber and schematic view of the triaxial cell (c)

3.3 Temperature control system

The temperature in the triaxial cell is regulated thanks to a double heating and cooling system (figure3c). The first system consists of a coil, situated inside the triaxial cell, in which circulates the heating and cooling fluid (water with anti-freeze). This coil is connected with an external, removable heating and cooling system. In order to ensure a good homogeneity of the temperature in the cell, a thermal housing is added around the triaxial cell (figure 3b). A thermocouple placed inside the cell, at mid-height of the specimen is used to control the temperature. A second thermocouple measures the temperature inside the thermal housing.

To ensure uniformity of temperature, the specimens are stored in the triaxial cell with thermal housing at the testing temperature for at least 4 hours prior to testing.

3.4 Axial and radial displacement transducers

The axial and radial strains of the specimen are measured using a specific system of LVDT sensors. The axial strains are measured on the central part of the specimen using two LVDTs, placed vertically, on opposite sides of the specimen (see figure 4). The average of the signals of the two sensors is used to calculate the axial strain. The homogeneity of the strain fields is also checked by comparing the values given by each sensor.

The radial strains are measured using an articulated ring, equipped with an LVDT, placed at mid-height of the specimen. The LVDT measures the opening of the ring, and thus the variations of the specimen diameter (see figure 4). The axial LVDTs and the articulated ring are attached to the specimen using metallic clamps, glued on the specimen. The LVDTs have a measurement range of 5 mm and a resolution of 1 μm.

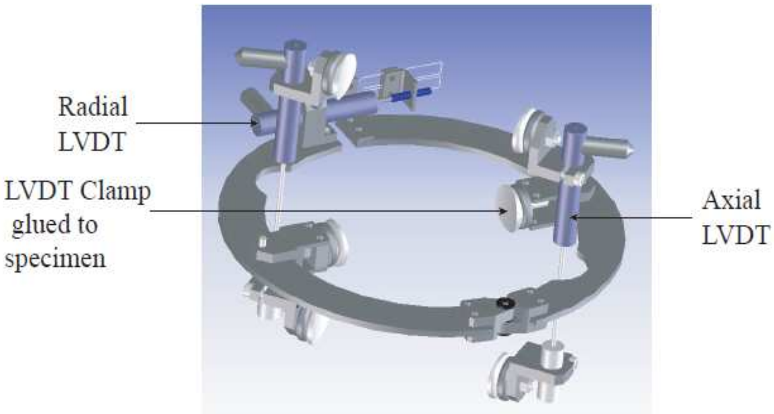

Figure 4 : Schematic view of the axial and radial LVDT sensors

4 EXPERIMENTAL PROCEDURES

4.1 Material and Sample preparation

The first tests with the triaxial apparatus have been performed on a standard French dense-graded bituminous mix, used for wearing courses (BBSG or Béton Bitumineux Semi Grenu). The characteristics of this mix are given in table 1. Mechanical properties of this material had been determined in previous studies.

Table 1 : Characteristics of the tested bituminous mix

Size of aggregates (mm)	Percentage (by mass)
0/2	27%
2/4	10%
4/6	25%
6/10	35.5%
Limestone filler	2.5%
Penetration grade bitumen	50/70

The specimens were obtained from plates compacted using a slab compactor with Rubber-Tired wheels (NF EN 12697-33 + A1). The dimensions of the plates are 600 mm by 400 mm by 120 mm thick. After a minimum of two weeks of storage, 6 cylindrical cores (80 mm in diameter and 160 mm high) were taken from the central part of each slab. The specimens were stored in a room at a controlled temperature of 18°C before testing.

4.2 Tests procedures

To perform tests in compression and tension, a metallic platen is glued at each end of the specimen, which allows then to attach the sample to the cell base and to the piston. To ensure homogeneity of the stress states in the specimen, a good alignment of the specimen and end platens is required. A specific stand, for gluing the specimens, has therefore been developed.

Then, the LVDT clamps are glued to the specimen. A latex membrane is placed around the specimen, above the clamps and finally, the LVDT sensors are fixed on the clamps.

Two types of tests procedures have been selected, to study the permanent deformation behaviour of bituminous mixes :

- Monotonic creep tests, with two different loading modes: constant stress or constant strain rate.
- Cyclic, stress controlled permanent deformation tests, which consist in applying a cyclic sinusoidal axial stress varying between σ_{min} and σ_{max}, (in compression or in tension) and a constant confining pressure.

5 FIRST EXPERIMENTAL RESULTS – CREEP TESTS

A first experimental study has been carried out, with the triaxial apparatus, to study the creep behaviour of the BBSG bituminous mix, and to evaluate and calibrate the visco-elasto-plastic DBN model (presented in the next part) which can be used for the modelling of rutting. For this purpose, two series of tests have been performed:

- Three creep tests at constant axial displacement rate (0.1mm/s, 0.01mm/s and 0.001mm/s) at 20°C, in order to calibrate the DBN model.
- Three creep tests at constant axial stress level (0.2MPa, 0.4MPa and 0.6MPa) at 10°C in order to verify the prediction obtained with the DBN model.

Experimental results of the tests at constant displacement rate are presented in figure 7, with the axial stress as a function of the axial strain. These results highlight the influence of the strain rate on the response of bituminous materials. As expected, higher displacement rates lead to higher axial stress levels inside the specimen. In each test, it has been observed that the axial stress first reaches a maximum and then decrease until the test is stopped. At the end of the tests, shear bands have been observed in the specimens, and this seems to explain the final decrease of stress. Only the first part of the tests, where the stress increases, has been represented on figure 7, and modelled with the DBN model.

Experimental results of the creep tests at constant stress level are presented on figure 8, which shows the evolution of the axial strain with time. These results show the influence of the level of stress on the strain response of the material. As expected, a higher level of stress induces higher strains and higher strain rates. For the tests performed at 0.2 and 0.4 MPa, the strain seems to stabilize at the end of the test. For the test performed at 0.6 MPa, the strain versus time curve seems to tend towards a constant slope.

6 MODELING OF THE CREEP TESTS

6.1. Description of the DBN model

The DBN model (Neifar and Di Benedetto, 2001) is a 1D thermo-visco-elasto-plastic law first developed at ENTPE. The DBN model introduces a linear viscoelastic behavior for small strain amplitudes, non-linearity for higher strain levels, and a viscoplastic flow. These two types of behavior are connected by means of a relationship initially chosen to be hyperbolic. The model thus enables describing, in a unified manner, a linear behavior (complex modulus, etc.) used in practice for computing stresses and strains within road structures, along with a non-linear and irreversible behavior appearing, for example, during pavement rutting. The temperature effect is described both at small strains, where the Time-Temperature Superposition Principle (TTSP) is supposed to be verified, and at large strains.

The model is defined by a series of n elements (see figure 5), each containing a viscous component (a dashpot characterized by its viscosity $\eta j(T)$, function of temperature) and an elastoplastic component EP, characterized by an elastic modulus Ej, and two yield stresses sj^+ (in compression) and sj^- (in tension). Given the experimental observations on bituminous mixes and, in more general terms, on geomaterials, the EP bodies describe the behaviour of the granular skeleton of bituminous materials.

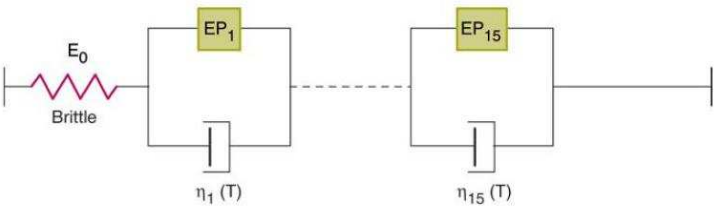

Figure 5 : Structure selected for the discrete DBN model (Olard and Di Benedetto, 2005)

The number of elements considered is not fixed. 15 elements have been chosen in our study. It is a compromise between a good accuracy and the complexity of the developments.

6.2. Calibration of the DBN model and modeling of experimental results

Calibration of the DBN model is described shortly below. The calibration procedure is explained in detail in the paper of Olard and Di Benedetto (2005).

For a given bituminous mix, the results of complex modulus tests enable calibrating the model over the small strain domain (i.e. by identification of the visco-elastic parameters Ej and ηj). Figure 6 shows the calibration results, on the complex modulus master curve at 20°C. The calibration of the plastic parameters has been empirical and needs to be improved, but simulations show that the parameters are good enough to simulate our experimental tests.

Table 2 lists the moduli Ej and viscosities ηj obtained at 20°C for the DBN model. The DBN model response is computed with the Scilab software (Le, 2009). The input data are the stiffnesses Ej, viscosities ηj, thresholds sj^+ and sj^-, temperature and stress (function of time). The output data is the strain (function of time).

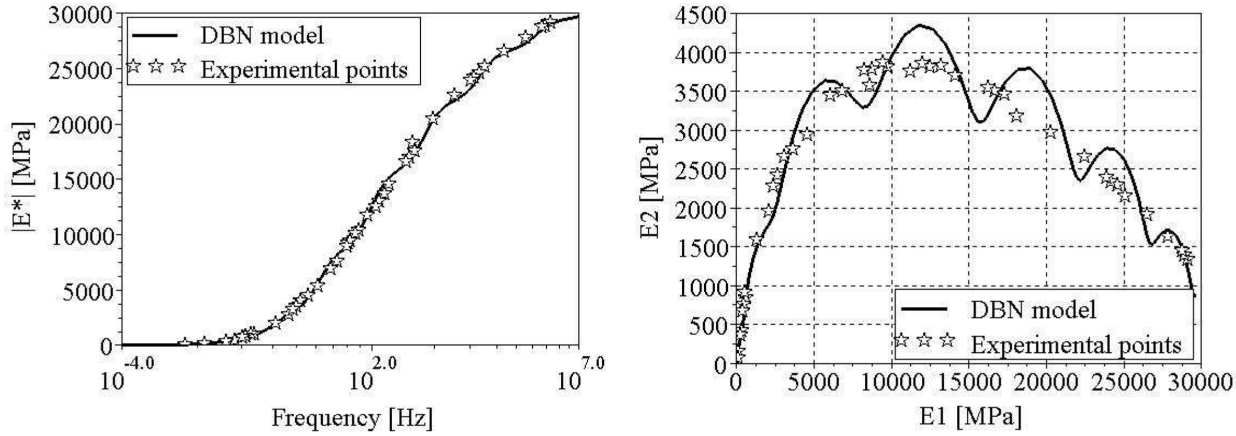

Figure 6 : Comparison of complex moduli obtained by means of the discrete (15 elements) DBN model and experimental results at 20°C.

Table 2 : Values of stiffnesses Ej, viscosities ηj and thresholds sj^+ and sj^- of the discrete DBN model obtained at 20°C

Element n0	Ej (MPa)	ηj (MPa*s)	sj^+ (MPa)	sj^- (MPa)
0	32500	-	-	-
1	1 483 800	$2.05.10^{13}$	0.46	-0.13
2	242 200	$1.40.10^{11}$	0.46	-0.13
3	4 500	$1.05.10^{8}$	0.46	-0.13
4	52	49 140	0.46	-0.13
5	83	3 209	0.46	-0.13
6	860	1 354	1.84	-0.52
7	5 600	361	2.01	-0.58
8	21 600	56	3.20	-0.90
9	57 600	6	4.16	-1.17
10	130 300	0.6	5.60	-2.57
11	280 600	0.05	7.00	-1.95
12	599 000	0.004	8.43	-2.36
13	1 244 000	0.0004	8.43	-2.36
14	2 320 000	0.00003	8.43	-2.36
15	4 095 000	0.000002	8.43	-2.36

The three creep tests at constant strain rate at 20°C have been simulated first. The values of the experimental axial stresses (function of time) have been used as input data for the DBN model. The experimental results (stress-strain curves) and the corresponding predictions obtained with the 15-elements DBN model are presented on figure 7. They show a good accuracy.

Experimental stress signals (function of time) have been used as input data and for these tests with slow strain rate, experimental signals presented some noise, and for this reason, the calculated response of the DBN model also shows this noise. All along the stress paths, the model describes well the experimental response, whatever the strain rate.

Three creep tests at constant stress level (0.2 MPa, 0.4 MPa and 0.6 MPa) and at 10°C have also been carried out. The experimental results and the corresponding predictions obtained by use of the 15-elements DBN model are shown on figure 8. Satisfactory predictions are obtained with the DBN model for this second series of tests.

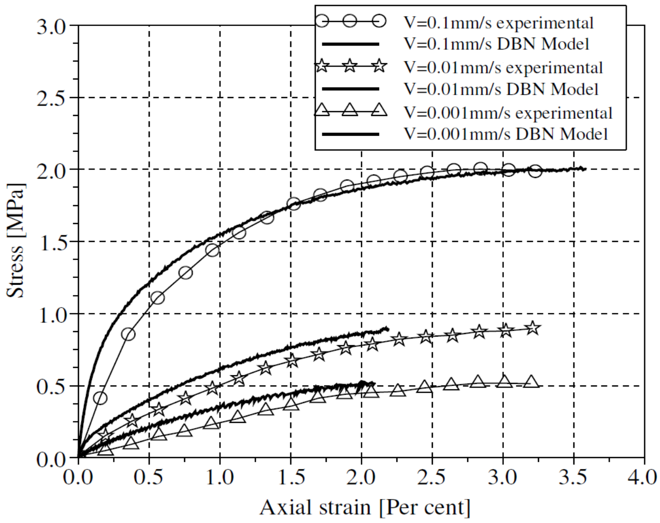

Figure 7 : Experimental creep test results at 20°C, for 3 different strain rates and corresponding predictions obtained with the 15-elements DBN model

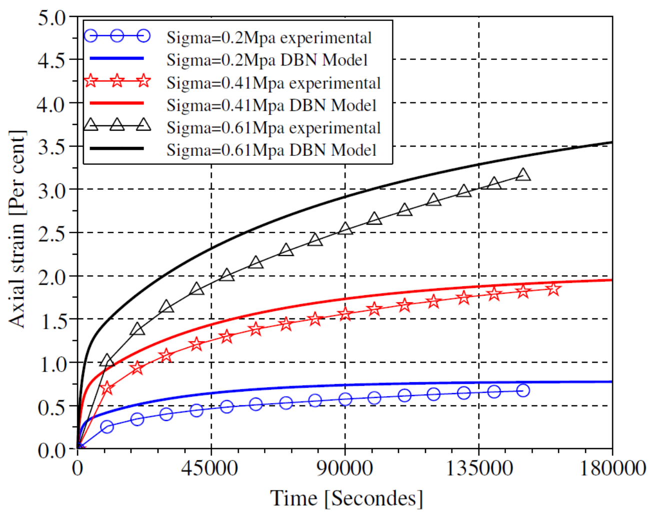

Figure 8 : Experimental creep test results at 10°C for 3 different stress levels and corresponding predictions obtained with the 15-elements DBN model

CONCLUSION

A new triaxial apparatus for bituminous materials developed at LCPC has been presented in this paper. This apparatus is equipped with a double temperature control system, consisting of a circulation of heating / cooling fluid inside the triaxial cell, plus an additional external thermal housing. On sample displacement transducers are used for the measurement of axial and radial strains. The choice of appropriate test conditions, for the study of permanent deformations has been discussed, on the basis of the modelling of stress states in pavement layers under traffic loading.

A first experimental program of creep tests at constant stress level and at constant strain rate, performed with this triaxial equipment has been presented. These results and additional complex modulus tests, have been used to determine the parameters of the DBN visco-elasto-plastic model. The capacity of this model to simulate accurately creep tests at constant stress and at constant strain rate has been confirmed. The experimental work will be pursued by studying the permanent deformation behaviour of the same bituminous mix under cyclic loading, at different levels of temperature and confining pressure.

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