An Evaluation of the Springbox test for Unbound Materials

Coni M.
University of Cagliari, Department of Land Engineering

Thom N.H.
University of Nottingham, School of Civil Engineering

Isola R.
University of Nottingham, School of Civil Engineering

Edwards J.P.
Scott Wilson Pavement Engineering, Nottingham

Synopsis

The Springbox is a relatively new piece of equipment, designed to generate realistic values of modulus for use in pavement design. The specimen, which can be of soil, granular or lightly stabilized material, is a 17cm cube, confined by steel sides, two of which are spring-loaded and free to move during the test. Repeated load is applied vertically through a full-face loading plate. Detailed descriptions are given elsewhere, but this paper will include an overview of the equipment. However, the principal content of the paper concerns an evaluation of the true meaning of the test based both on comparisons between Springbox data and on finite element analysis (FE) of the stress conditions within the specimen. The comparative test data are obtained on three different granular materials (Clay soil, Sub-Base and Cement Treated Base). The FE analysis was performed using experimentally obtained values of resilient modulus and Poisson's ratio and comparing the simulation with the real test in terms of longitudinal and vertical strain in order to assess the FE model. Reference is then made to the FE analysis of the equipment in order to explain the material's local behaviour inside the specimen with respect to the global mechanical behaviour, which is evaluated during the test by means of point measurements, which are, therefore, assumed to be representative of the stress and deformation state of the material. The model is able to take into account the effect of friction between the steel sides and the material (cf = 0.4), which can highly affect the interpretation of results. Moreover, a FE parametric study was carried out under different static and dynamic load conditions on unbound materials with different characteristics. Finally, conclusions are drawn regarding the potential use of the equipment in generating values of stiffness modulus for design.

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In recent years, there has been a strong tendency throughout civil engineering to move away from traditional "recipe and method" specifications and towards those that are "performance related" (Fleming, P.R., Rogers, C.D.F., Thom, N.H., Armitage, R.J. and Frost, M.W. 2000). The determination of fundamental engineering properties of materials is key to their inclusion within analytical or mechanistic pavement designs.

Specialist tests are available such as the Repeated Load Triaxial (RLT) test and Hollow Cylinder Apparatus (HCA), as are much simpler techniques such as the California Bearing Ratio (CBR). Simplistic index and relationship tests, in particular the CBR for foundation layers, have stood the test of time in terms of continued widespread use, and have been correlated with pavement performance over a number of years. However, it is widely recognized that the CBR does not fundamentally measure the performance of a pavement foundation material (Brown, S.F, 1996). Increasing policy towards the use of performance based specifications (Chaddock, B.C.J., and Merrill,2004 and Fleming, P.R., Rogers, C.D.F., Thom, N.H., and Frost, M.W., 2003), adoption of European wide aggregate standards (Rockcliff, D., and Dudgeon, R., 2004), and sustainable construction pressures, all strongly imply the need for performance assessment of a wider range of materials than previously used. In addition, the design of upper pavement structures in the UK, Italy and several other countries is currently independent of the quality of the road foundation.

A need was therefore identified for a relatively simple test which was capable of generating the required mechanical properties for input into analytical pavement design, most notably stiffness modulus, but also resistance to permanent deformation. The need for this test relates to conventional unbound materials (soils, capping, granular sub-bases), but is perhaps more critical in the case of less well understood materials, in particular stabilised soils, hydraulically-bound cappings or sub-bases, and cement bound materials. In some of these cases, there is a clear need to be able to obtain information on specimens at different stages of curing.

A new laboratory test for the characterisation of unbound and weak hydraulically bound mixtures under repeated loading was therefore developed at Scott Wilson Pavement Engineering Limited. The Springbox has been designed to fill the gap between relatively complex research-based laboratory tools and the more empirical test, as a relatively simple and practical tool, but one which is capable of generating scientifically meaningful data. Economical accelerated testing of unbound material performance can only be undertaken within laboratory conditions, especially when properties under varying loading and moisture conditions must be defined.

This paper's main target is to evaluate the stress-strain state within the specimen and to investigate how the operating conditions can influence the results. The FE model has been developed in ANSYS code using 3D Solid elasto-plastic elements, which allow the evolution of a Springbox test to be simulated, using a cubic granular specimen of 17 x 17 x 17 cm.

The simulation has been first conducted by static analysis and then applying harmonic cyclic loads.

The model gives the possibility to analyse the stress-strain state locally and to evaluate aspects that are not evident at the global level.

The parametric study involved: resilient modulus, material density, Poisson's ratio, damping factor, wall-specimen friction, internal friction and cohesion, moisture content and different materials.

The input data used for the analysis have already been presented elsewhere (Edwards, J.P., and Thom, N.H., and Fleming, P.R.).

THE SPRINGBOX EQUIPMENT AND TEST PROCEDURES

The Springbox equipment (shown in Figure 1) is loosely based around the principle of a variably confined test, similar to that adopted in the mechanically more complex K-Mould that originated in the U.S. before being modified and adopted in South Africa (Semmelink, C.J., and de Beer, M, 1995). The equipment utilizes the standard Nottingham Asphalt Tester (NAT) load frame, software and hardware. The only significant amendment to the NAT apparatus, which is widely used throughout UK material testing laboratories, is the utilization of four Linear Variable Differential Transformers (LVDT's), rather than the standard two used in asphalt testing. The key elements of note are that the test applies a repeated vertical load to a cube of material and allows horizontal strain of the specimen in one direction, with these sides restrained by springs. In the other horizontal direction the sides are fully restrained.

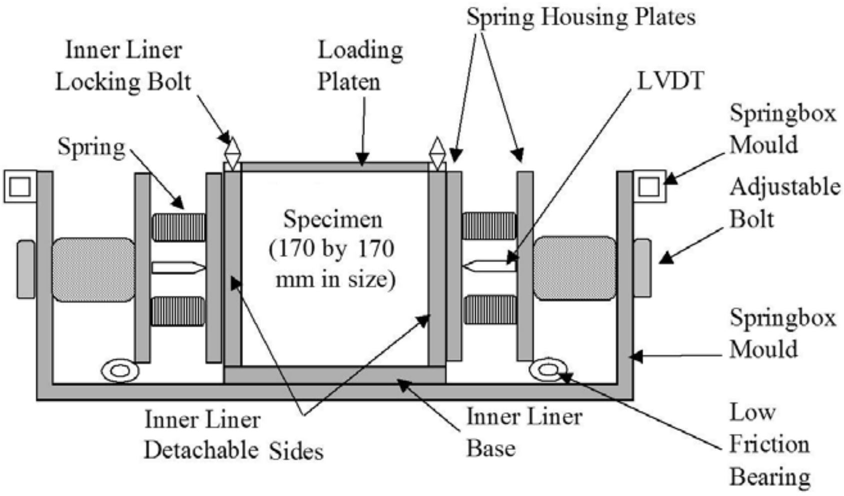
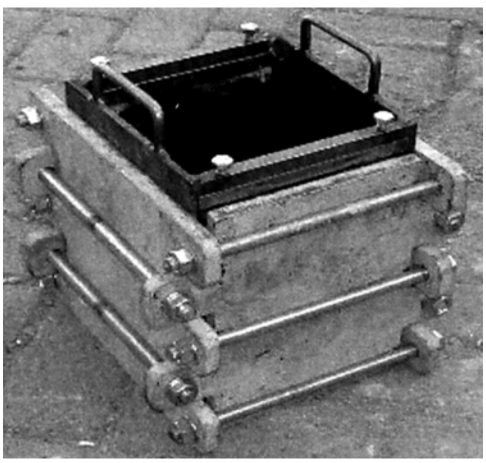


Figure 1 The Springbox **Figure 2 Longitudinal section through Springbox apparatus**

The spring housing plates, shown in Figure 2, have been designed to accommodate a range of spring sizes with varying spring rates, allowing material-specific spring selection. These plates are adjusted to the moveable inner liner sides, which can then be released by unlocking the top locking bolts, allowing horizontal straining of the sample under repeated load. Additional rigidity is given to the inner liner during compaction by placing it within a fully adjustable compaction jacket. This jacket is removed after compaction and the movable liner sides are fixed in place with the locking bolts, until set up in the Springbox testing mould. The springs have been selected based on the amount of strain, which is desirable in a test. Since granular materials under simple stress conditions tend to reach peak stress at a strain of around 1-3%, it was considered sensible to allow movement of at least this level (Edwards, J.P., and Thom, N.H., and Fleming, P.R, 2004). With a specimen dimension of 170 mm, this equates to a movement of around 2 mm at each spring. The vertical load level to be applied to the specimen is variable, but is likely to be a maximum of 300 kPa. This, it is suggested, could generate a horizontal stress of around 150 kPa under repeated load, equating to a little over 1 kN per spring (four are used). Thus a spring stiffness of around 375 to 570 N/mm is considered appropriate for the test.

A standardized test procedure was adopted to allow direct comparison of results between selected materials. Unbound materials typically display a non-linear stress dependency. The test procedure therefore applied a range of stresses to each material, simulating conditions at different levels in the pavement. As with the more mechanically complex K-Mould (Semmelink, C.J., and de Beer, M, 1995), the Springbox automatically increases the lateral restraint to the specimen as horizontal strain accumulates during the test.

A loading frequency of 1 Hz has been selected with an approximately haversine pulse shape. The following test procedure is usually applied to the specimens: apply 500 load applications at a low stress level (50 kPa), apply the same number at an intermediate stress level (100 kPa) and repeat at a high stress level (170 kPa). Prior testing (10) of unbound materials had shown permanent deformation to be approaching an asymptotic value at around 400 cycles. The choice of 500 load cycles was made following this initial testing.



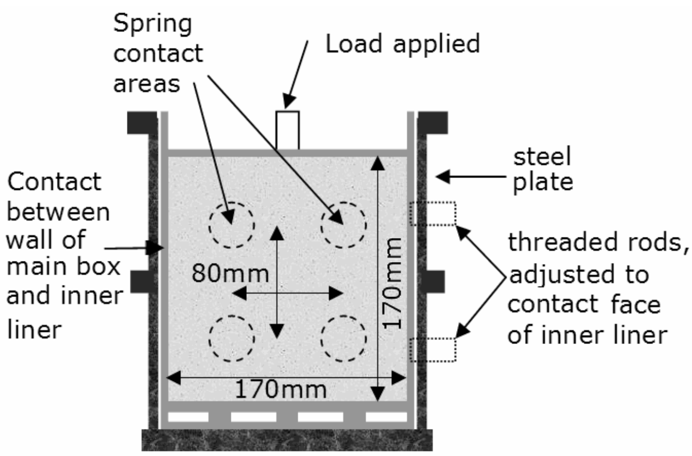


Figure 3 Sample inner liner and adjustable compaction jacket **Figure 4 Springbox details**

The test samples are prepared within the Springbox stainless steel test liners . A maximum aggregate size of up to 40 mm for broadly graded aggregates has been utilized. This partially results from boundary condition assessments undertaken during the equipment development trials, but also reflects a maximum aggregate size relative to the compaction procedure (layer thickness related to maximum aggregate size).
Samples are compacted to densities similar to those determined in standard laboratory tests, by utilizing a vibrating hammer methodology. The vibrating hammer is mounted within a vertically adjustable frame, thus controlling the horizontal level of the finished sample surface and the level of the static load applied during compaction. The compaction foot applies full surface loading. The static load applied was calculated proportionally from that used with the relatively smaller CBR compaction foot. The standard procedure of building up the sample in three layers, and applying the compaction force for between 80 and 100 seconds, produced suitable samples without unrealistic sample degradation occurring (Edwards, J.P., and Thom, N.H., and Fleming, P.R, 2004). Some care was taken to avoid placing the largest aggregate particles near the corners of the inner liner, to prevent bridging and the creation of a macro void. This practice is not dissimilar in nature to the care required with sample preparation in the RLT apparatus around the on-sample instrumentation studs.
Materials are generally compacted at their optimum moisture content (OMC) as determined using a vibrating hammer. The effect of variation in moisture content on stiffness modulus and resistance to permanent deformation can be explored over a range of moisture contents and also by soaking the samples, by placing the sample in a water tank for a 24-hour period. Water ingress is permitted through the base of the liner, a head of water equivalent to the upper surface of the sample is maintained throughout. The sample is then removed for immediate testing. Drainage of samples is permitted throughout the sample preparation and subsequent testing.

FINITE ELEMENT ANALISYS

The FE model, shown in Figure 5, considers, apart from the cubic specimen, also the loading plate, the steel walls in direct contact with the specimen and the spring system.

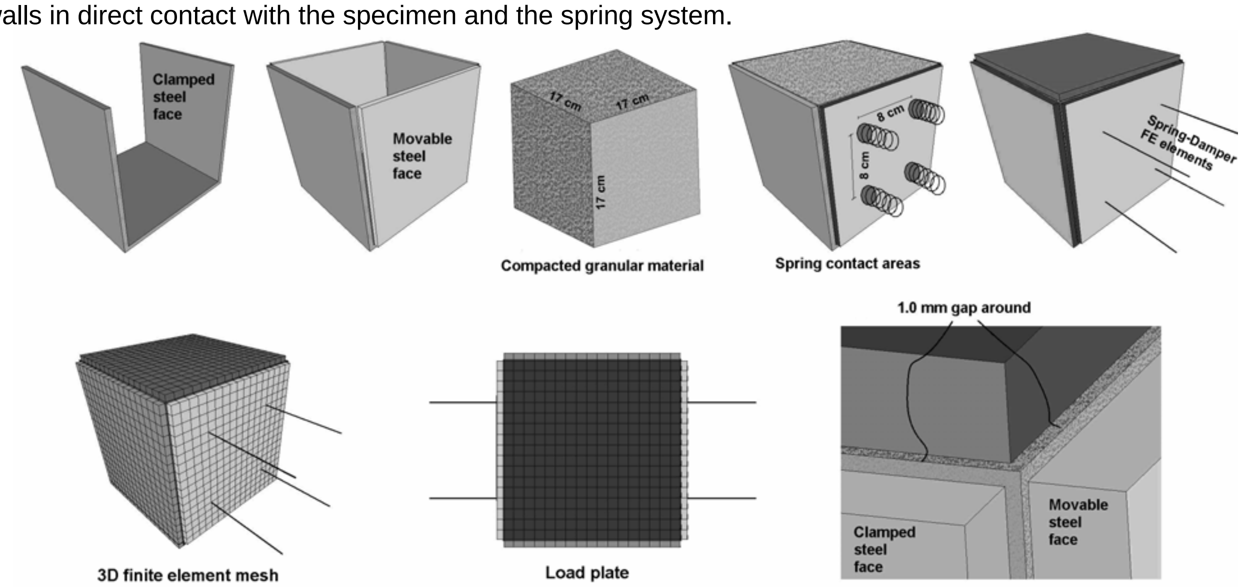


Figure 5 Springbox FE model developed

The mesh used is based on a regular three-dimensional square grid with elements of 10 mm. In total, 5491 Solid 3D elements have been used to model the specimen, while for the rest of the steel parts 1734 elements of the same kind were necessary. Finally, Spring-Damper elements were used to model the 8 lateral springs.
The FE model developed reproduces the boundary conditions that the specimen is subjected to in the Springbox cell. To better simulate these boundary conditions, the presence of a 1 mm gap has been considered around the loading plate in order to allow its movement. Table 1 shows the different material characteristics.

Table 1 Material proprieties

Material	E	μ	γ	damping
Steel	206 GPa	0.20	7850	0
Granular material	30 MPa ÷ 300 MPa	0.30÷0.40	2000	0.05

	K			Cv
Spring-Damper	375.000 N/m			0

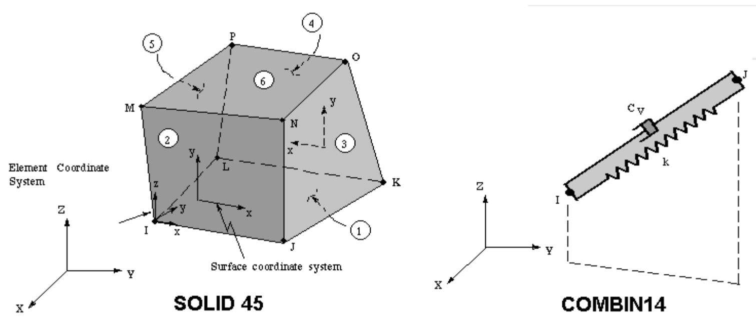


Figure 6 Finite element used in Springbox model

The FE package ANSYS was available to perform all FE simulations. The library element SOLID45 was used. It was developed for modelling three-dimensional solid structures, and also allows the input of different material characteristics. A constant equivalent viscous damping ratio of ξ = 0.05 was introduced in the material during dynamic analysis. Modal analysis was first carried out and subsequently harmonic analysis was performed for each mode so that modal damping could be assessed, and each time the value of a corresponding resonance frequency was calculated. In the harmonic analyses forced vibration excitation was applied with a one point sinusoidal force applied on the load plate. The system is governed by the expression:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\}$$

where:

[M] = structure mass matrix	$\{u\}$ = nodal displacement vector
[C] = structure damping matrix	$\{\dot{u}\}$ = nodal velocity vector
[K] = structure stiffness matrix	$\{\ddot{u}\}$ = nodal acceleration vector
[F] = time-dependent forcing function	

In this paper, structural damping was included. Modal analysis is used to determine the natural frequency and mode shapes of a structure. Free, undamped vibrations are assumed in ANSYS (F(t)={0} and [C]= 0). A modal analysis should precede any other dynamic analysis. The governing equation then is:

$$[M]\{\ddot{u}\}+[K]\{u\}=\{0\}$$

For a linear system, free vibration will be a harmonic of the form, $\{u\}=\{u_0\}\cos\omega t$. For the non-trivial solution, the determinant $\left|[K]-\omega^2[M]\right|=0$.

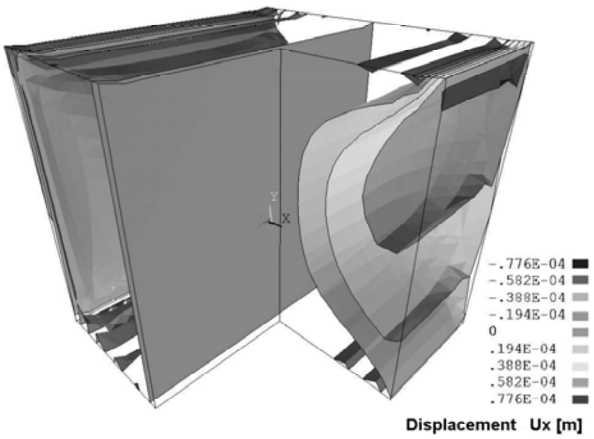
This is an eigenvalue problem, whose solutions are the eigenvalues and the corresponding eigenvectors. The eigenvalues represent the natural frequency of the system and the eigenvectors the corresponding mode shapes. Harmonic analysis is used to determine the response of a structure to harmonic sinusoidally varying forces. The function F(t) is a periodic value of known amplitude and frequency. The equation of motion, therefore, can be solved to obtain displacements as a function of frequency.
The model calibration has been conducted comparing the results obtained from the simulation of three different materials (Clay soil, Sub-Base and CTB) with the respective experimental Springbox results. Table 2 shows this comparison and the percentage differences between simulations and tests. As can be observed, the FE model results are much more accurate in determining the vertical strains than the lateral ones, where errors up to 35% were obtained. This leads to the possibility of deriving sufficiently trustworthy E values but more uncertain Poisson's ratios.

Table 2: Model calibration from experimental Spring-box test and FE ANSYS simulation

Material (example specimen of each)	E MPa	μ	σ_v kPa	Vertical Strain ($\mu\varepsilon$)			Lateral Strain ($\mu\varepsilon$)		
				test	ANSYS	Δ %	test	ANSYS	Δ %
Mat.1 - Clay soil	30	0.32	99.6	2550	2492	2.3%	-694	-601	-13.4%
Mat. 2 - Sub-base	114	0.30	103.8	735	705	4.1%	-135	-164	21.4%
Mat. 3 - CTB	369	0.34	95.0	194	208	7.2%	-53	-72	35.8%

RESULTS

The following images illustrate the distribution of the displacement, stress and strain fields. Moreover, the Von Mises equivalent tensional state within the specimen is also reported. In order to give a clearer visualization, a quarter of the specimen has been removed.



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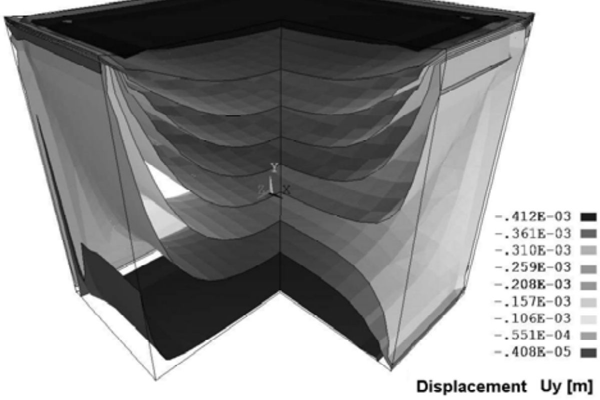

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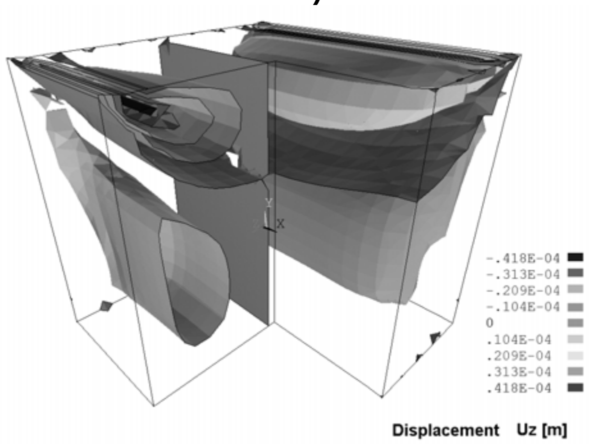

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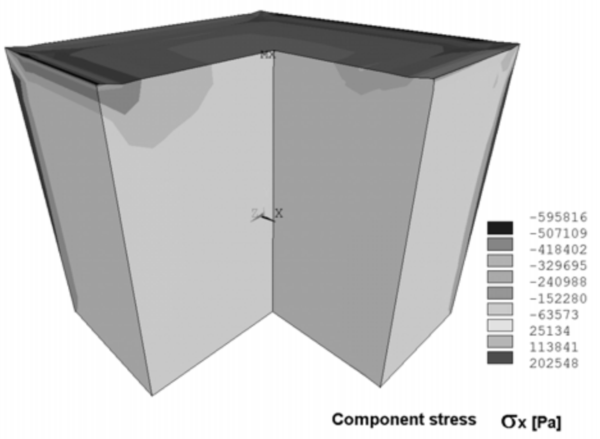

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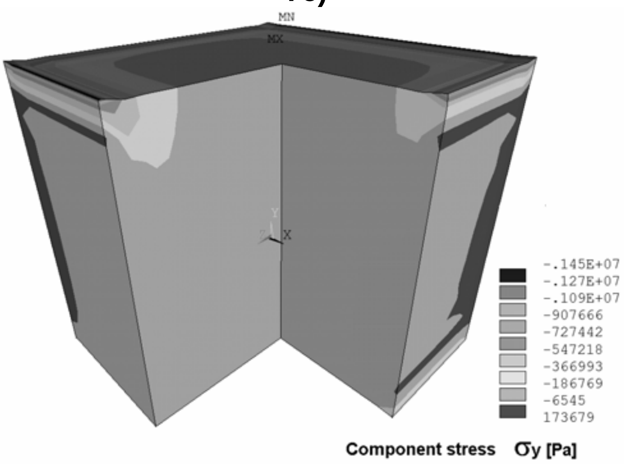

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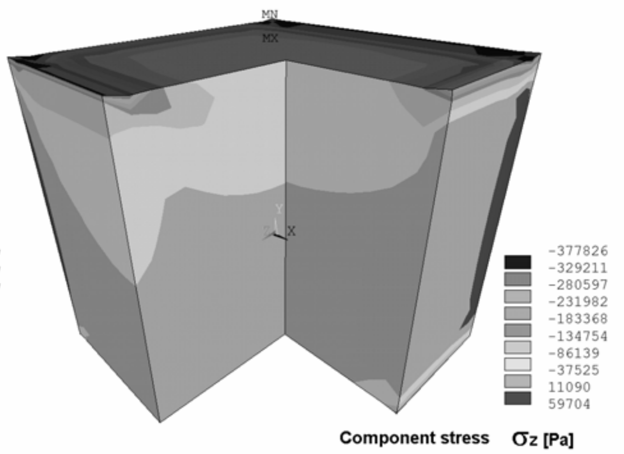

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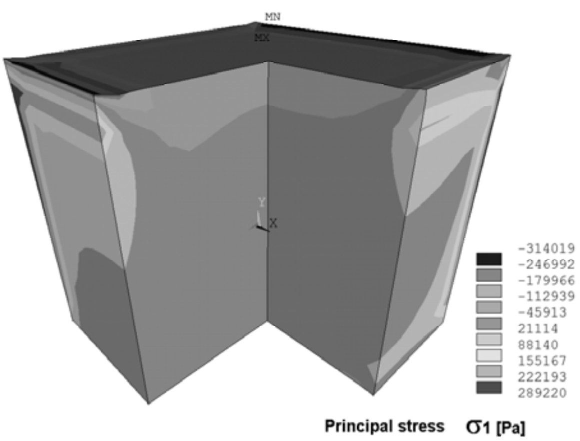

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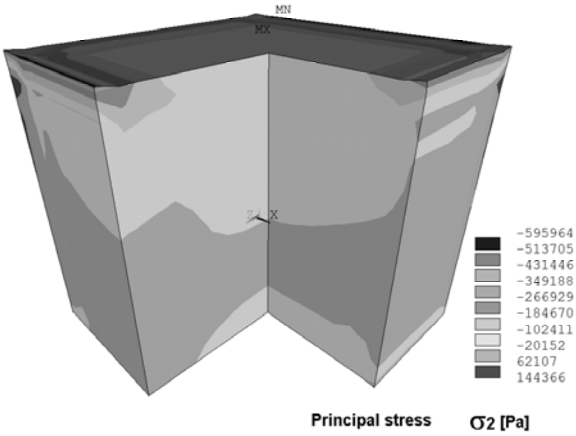

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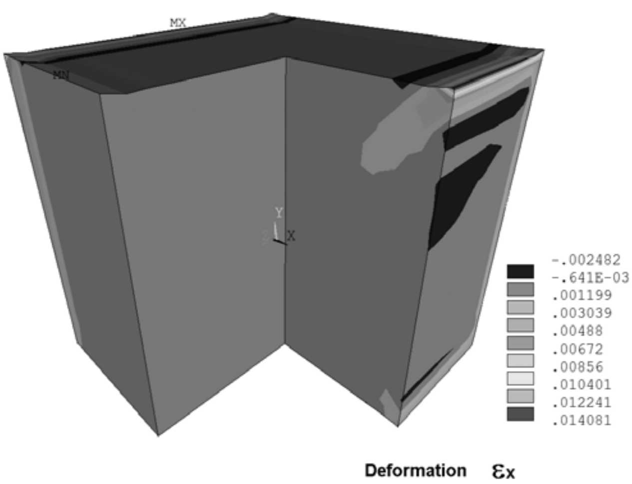

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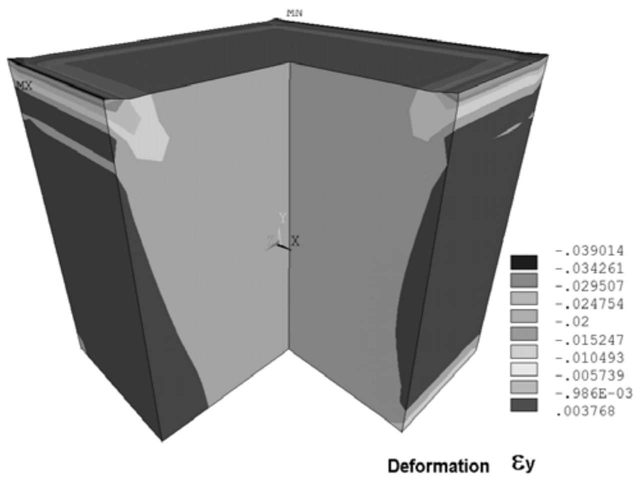

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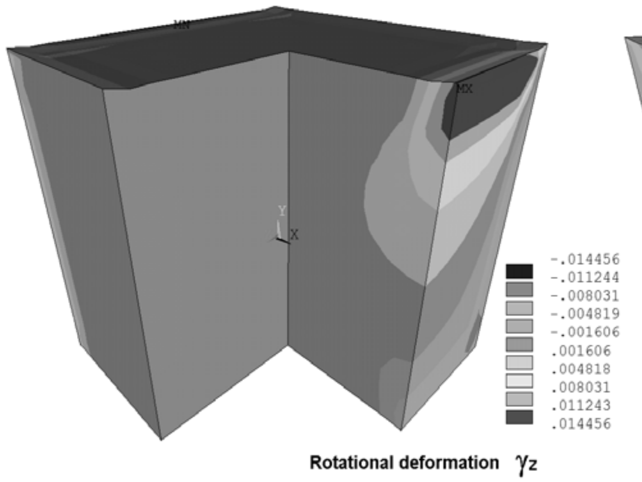

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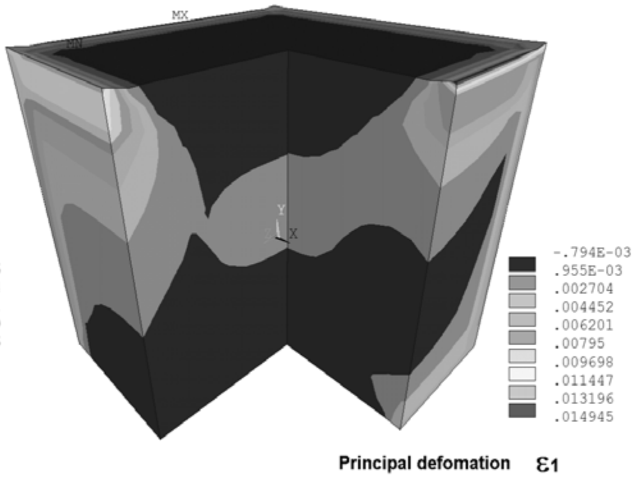

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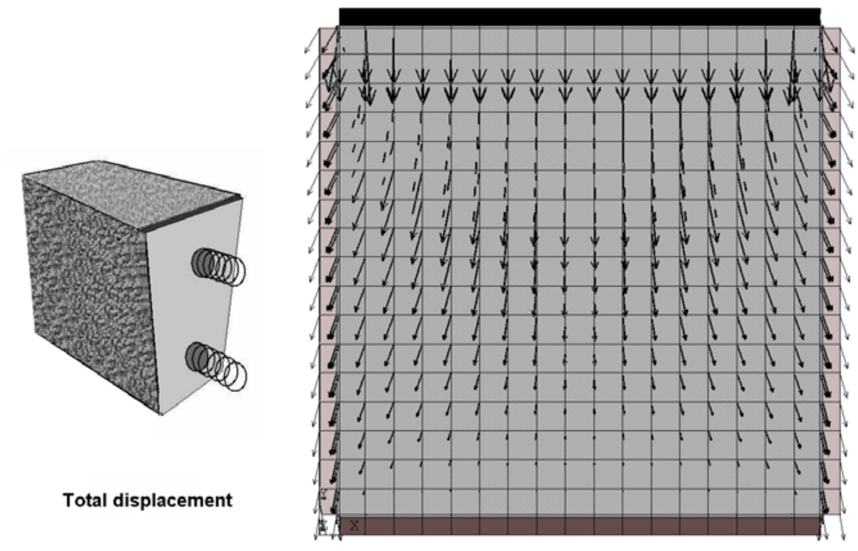
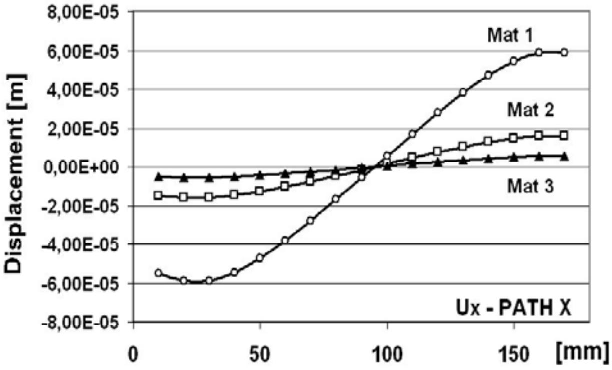


Figure 7 Displacement, stress and deformation component inside the material



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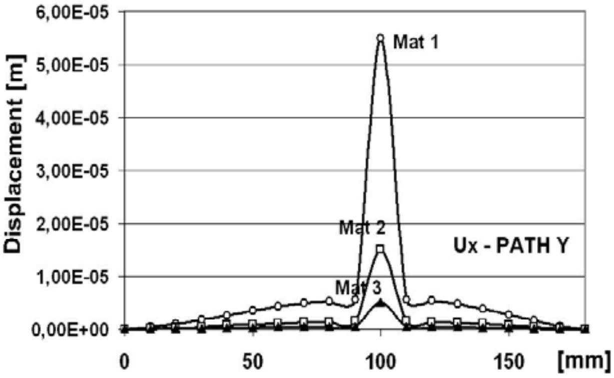

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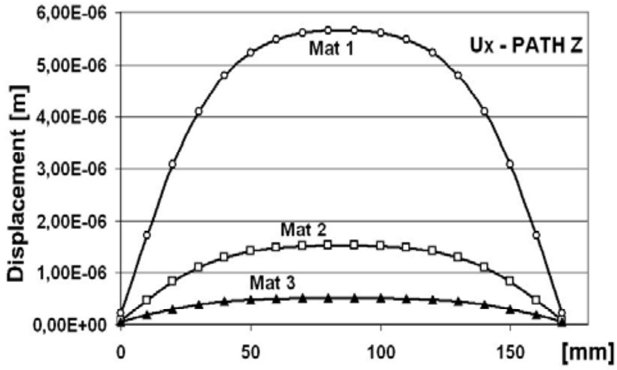

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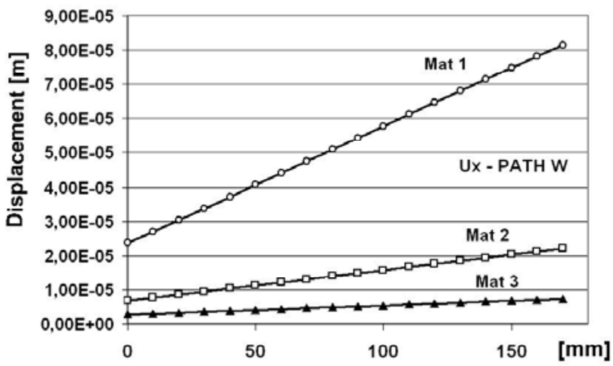

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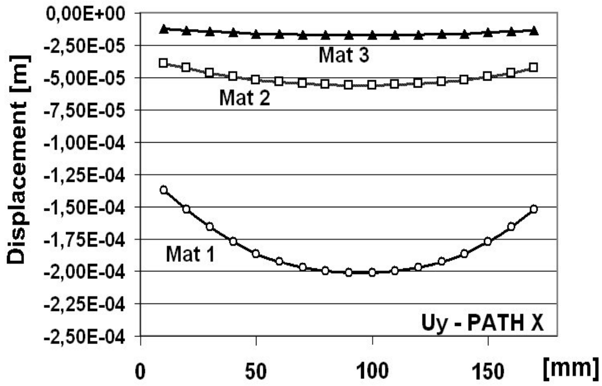

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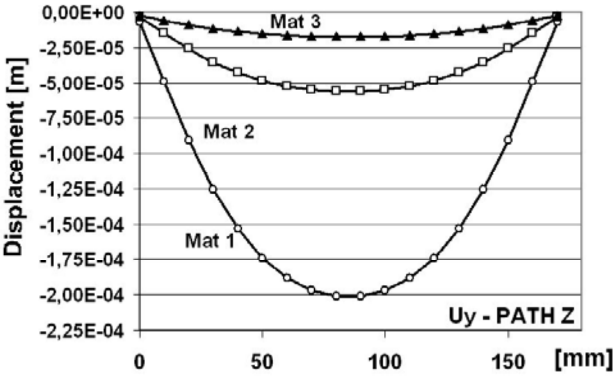

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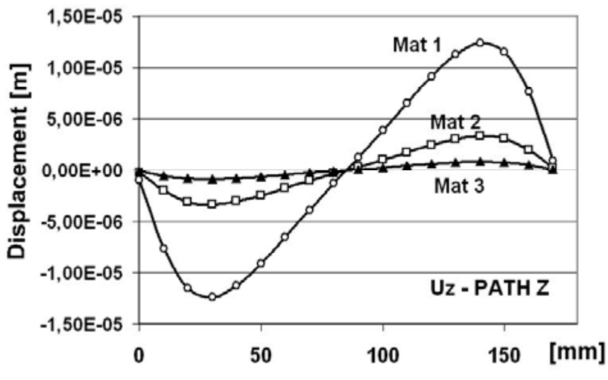

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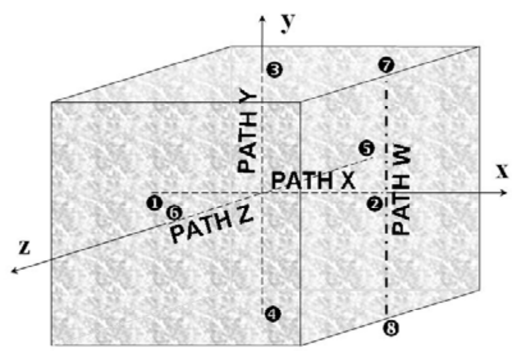

8h)

Figure 8 Displacement on PATH X, Y, Z and W.

In Figure 7 it is possible to observe that the longitudinal displacements in the x direction corresponding to the movements of the spring-loaded plates are not uniformly distributed but linearly increase from the base towards the top (see Figure 8d). Therefore, the spring-loaded plates rotate in a measure that is inversely proportional to the resilient modulus. An opposite relation appears for the Poisson's ratio. Therefore, the placing of the LVDTs at the specimen's mid-height to measure x displacements is important. It must be noted that, in reality, the material is not homogeneous as assumed in the FE analysis, and this can explain the lower precision, reported in Table 2, in evaluating longitudinal deformations.
Figure 8 shows the displacement distribution for 3 different materials through 4 paths: the first three, indicated as PATH X, PATH Y, PATH Z are perpendicular to each other passing through the origin; the fourth represents the internal line of the Springbox specimen immediately adjacent to the spring-loaded walls, indicated as PATH W.
The displacements have their maximum in the x direction at the centre.
Despite what might be expected from a global analysis of the system, the material is subjected to articulated and non-negligible displacements in the z direction, which reach their maximum at a distance of 1/4th of the specimen's side and few centimetres underneath the loading plate, decreasing towards the fixed walls (Figure 8g).
The deflection basin in the vertical direction reaches its maximum value in the centre of the loading plate and decreases much more in z direction rather than in x direction (Figure 8e and 8f).
Stresses and strains are found to be very homogeneously distributed, with the exception of the upper borders where, due to the presence of a 1 mm gap between the moving and fixed plates, stress spikes occur that, in the experimental equipment, become more relevant as the tested material becomes finer. For this reason, it could be interesting to evaluate how the presence of possible discontinuities (i.e. particles of excessive dimensions) can affect the test's results and the corresponding FE simulations.

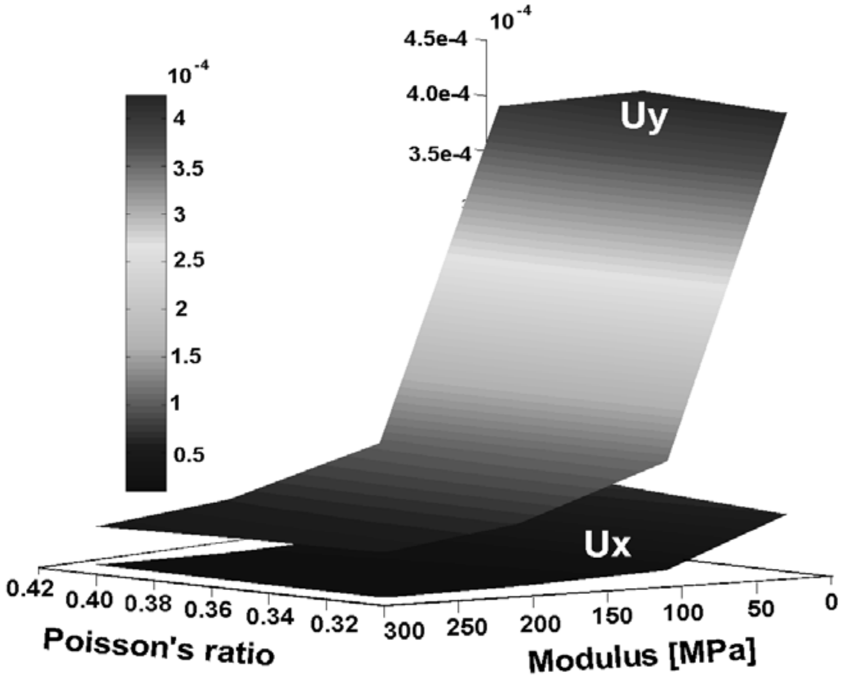

Figure 9 Parametric FE analysis: vertical dispalcement at centre of load plate (uy) and longitudinal displacement at the centre of movable plate (ux) versus modulus and Poisson's ratio

CONCLUSIONS

The FE model implemented by ANSYS code and conveniently calibrated by comparison with 3 different materials allowed the investigation of a number of detailed aspects of the stress-strain state that develops within the specimen during the Springbox test. These aspects, not evident at the macroscopic level, are filtered by the experimental measurements taken at points that were found to properly represent the average deformational state. For example, the transverse displacement field, in the direction of the fixed walls, assumes meaningful values distributed in a consequential way.
This study, utilizing a FE evaluation of the newly developed Springbox, confirmed some already known conclusions, and provided evidence that:

- the Springbox apparatus provides a relatively rapid and economic accelerated test method for determining resilient modulus (Er) and resistance to permanent deformation;
- higher uncertainties are present in the Poisson's ratio's measurement;
- reliability assessment of the Springbox and the range of results produced for unbound materials gives confidence that the Er results are suitable for material characterization in pavement design;

- ranking of materials in terms of Er does not directly correspond to the ranking for resistance to relative permanent deformation;
- the stress distribution is very homogeneous with the exception of the top borders where the gap between sides and loading platen creates stress spikes that may become more relevant as the particle dimension decreases. On the other hand, the presence of particles of large dimensions might be expected to affect this homogeneous distribution, particularly when these particles are in contact with the spring-loaded plates.

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