3D Finite Element analysis of accelerated pavement test results from New Zealand's CAPTIF Facility

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ABSTRACT: A nonlinear elastic model for unbound granular materials that was developed from the results of multi-stage Repeated Load Triaxial (RLT) Tests is described in this paper. The model was implemented in the 3-D FE-program FALTFEM. To check the validity of the model, comparisons were made with the results from accelerated pavement tests at Transit New Zealand's CAPTIF Facility. The stresses and elastic strains within the test pavement at different depths were measured. A comparison was carried out to assess the accuracy of the elastic model by comparing the results of calculated elastic responses from the model using the nonlinear elastic DRESDEN Model and elastic solutions against the measured values. In addition an empirical approach was formulated and calibrated to determine basecourse plastic strain rate using data from RLT and CAPTIF tests of two different materials. From results of laboratory tests a good correlation was found to exist between the elastic strain rate and the plastic strain rate as long as the shear stresses within the basecourse material are sufficiently small. However, by comparing the elastic/plastic relationship from RLT tests and the elastic/plastic relationship from CAPTIF tests differences could be observed. Shift factors were determined for the materials investigated, to predict the plastic strain rate in the field from RLT test results.

KEY WORDS: Accelerated pavement test, non-linear elastic plastic deformation, RLT test, 3D-FE calculation.

1 INTRODUCTION

This paper presents the validation of a laboratory-based model with results of accelerated pavement tests undertaken at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) in Christchurch, New Zealand, which is owed and operated by Transit New Zealand. CAPTIF (Figure 1) is a 58 m long circular track (contained within a 1.5 m deep by 4.0 m wide concrete tank) where the wheel paths of two vehicles can be separated to assess the relative damaging effect of loading parameters on pavements and surfacings. Mounted on a centre platform is a sliding frame that can move horizontally. This radial movement enables the wheel path to be varied laterally to simulate vehicle wander and can be used to have the two "vehicles" operating in independent wheel paths.

From 1999 to 2001 the first stage of Transfund funded research project (PR3-0404) investigated axle load limits at CAPTIF. The aim of the project was to compare the effect of mass on pavement wear for a range of pavements which are typical of those found in New Zealand. Different basecourse materials were used to construct different sections in the test track (Figure 1).

The two “vehicles” at CAPTIF, which are known as Simulated Loading and Vehicle Emulators –(Figure 2), were configured with identical suspensions but with different axle loads. One was loaded to 40 kN to simulate the current 8 tonne axle load limit, while the other was loaded to 50 kN to simulate a increase to a 10 tonne axle load limit. A lateral wander of ± 5 cm was simulated in the test.

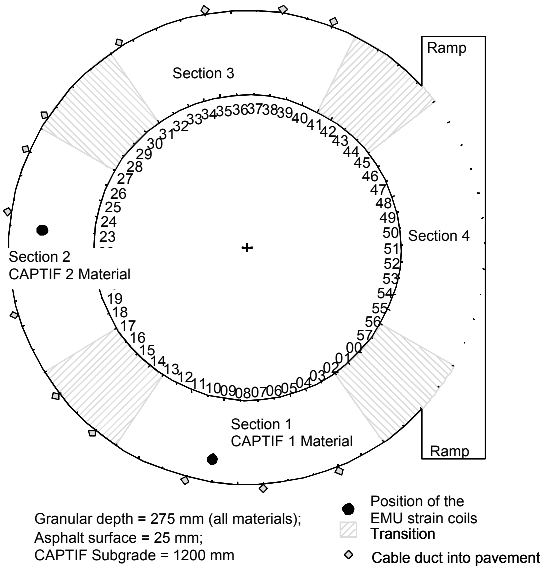

Figure 1. Plan view of CAPTIF PR3 - 0404 test

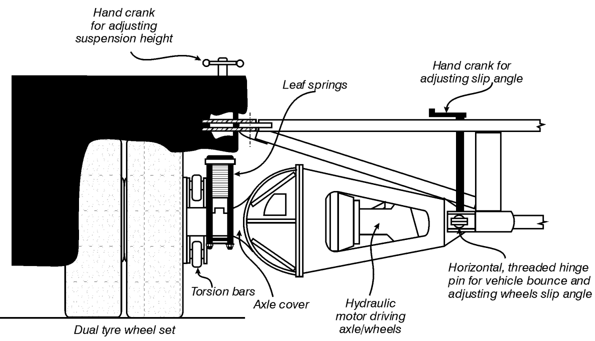

Figure 2: CAPTIF Simulated Loading and Vehicle Emulators

In particularly the paper presents research that is focused to find a relationship between the elastic and plastic deformation response of unbound granular layers in pavements. The aim is to predict the plastic strain rate as a function of the elastic strain rate within the Unbound Granular Layers (UGL). The results of laboratory (RLT) tests and CAPTIF tests on same materials where compared to determine a shift factor between laboratory and field.

2 TEST PAVEMENT AND INSTRUMENTATION

The four pavements tested were thin-surfaced (25 mm Asphalt) unbound granular pavements (275 mm deep) each with different granular materials. Table 1 and Figure 3 shows the characterization of granular materials investigated.

One subgrade soil, a silty clay, with a thickness of 1200 mm was used during the tests. The subgrade was compacted in layers 150 mm thick to ensure the uniform compaction over the full depth of the layer.

The pavement instrumentation included EMU soil strain coils for measurement of vertical, transverse and longitudinal strains in 3 of the 4 pavement segments (station 9 – CAPTIF 1 material and station 23 – CAPTIF 2 material) (Figures 1 and 4). Vertical stress was measured at subgrade surface level using Dynatest stress gauges. The transverse profile at each station of the test track was measured with an automatic profile beam using a LVDT and a jockey wheel rolling across the pavement surface.

Table 1: Characterization of basecourse materials

		CAPTIF 1	CAPTIF 2
Basecourse		Greywacke	Greywacke
Fine Content < 75 µm	[%]	5	10
Density	[g/cm^3]	2,32	2,36
Moisture content	[vol. %]	2,07	2,76
Degree of compaction	[%]	97	97
Opt. moisture content	[vol. %]	6,0	4,8

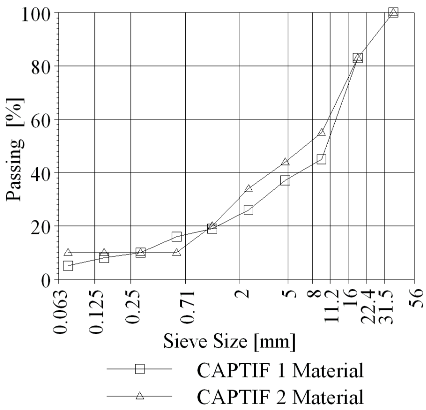

Figure 3: Grading of the basecourse materials

3 3-D FINITE ELEMENT MODEL

3.1 Finite Element Mesh

For a detailed investigation of rutting, a 3-dimensional computational model is required. FALTFEM, a 3D-Finite Element (FE) program was used to carry out this investigation. A half model was developed, to reduce the computational effort, by making use of symmetry in the geometry. Due to the restricted number of elements in the FE Program, the subgrade was modeled with a thickness of 300 mm. The length of the FE section was 2.4 m (2 x 1.4 m). Figure 5 shows the finite element mesh. The subgrade was modeled by 2 elements, each 150 mm height, the basecourse was modeled by 4 elements, each 68.75 mm height and the asphalt layer was modeled by 2 elements, each 12.5 mm high. Smaller elements in the loading area (66.7mm x 66.7 mm x height) were used. The rigid boundaries of the concrete tank were simulated in the FEM, the bottom of the subgrade and the sidewalls are prevented from axial movement in the three directions.

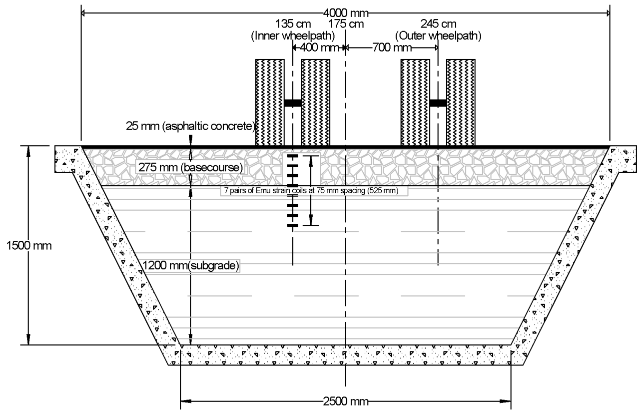

Figure 4. Pavement cross-section and wheel path locations - CAPTIF 404 2001 test

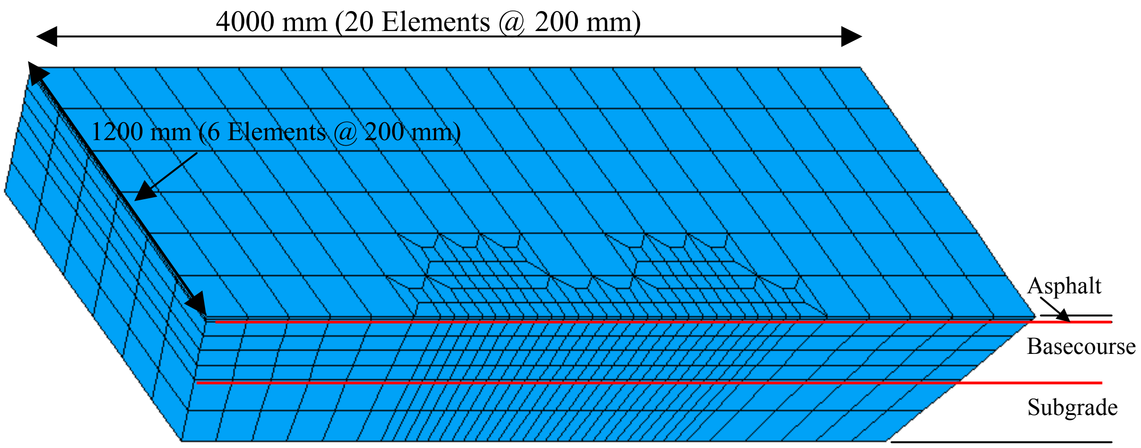

Figure 5. Finite element mesh

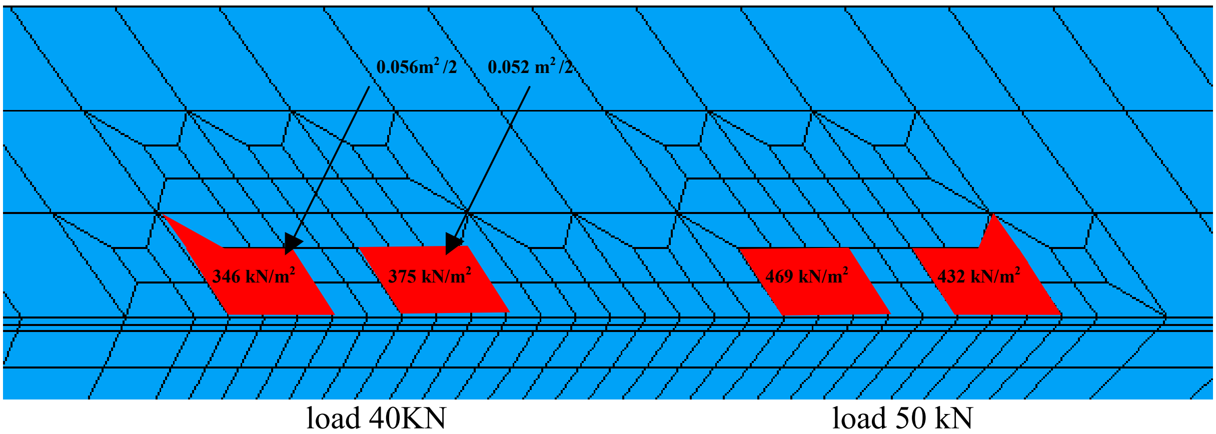

Figure 6: Finite element mesh - detail loading area

In order to determine the contact area of the tire for use in the pavement modeling stage of this research, the tire footprints were measured. The dimensions of the tire footprint were approximately rectangular, 230 mm long and 215 mm wide for vehicle A (each wheel) loaded to 40 kN and 250 mm long and 215 mm wide for vehicle B (each wheel) loaded to 50 kN. The loaded area for vehicle A is 0.0495 m^2 (each wheel) and for vehicle B is 0.0538 m^2 (each wheel). However, these areas could not be modeled identically in the version of the FE Program (FALTFEM), which was used in this study. The loaded area of both vehicles composed of 2 by 3 elements (each wheel 0.056 m^2 / 0.052 m^2) according to Figure 6.

4 MATERIAL MODEL

4.1 Asphalt

The asphalt layer was treated as linearly elastic ($\mu = 0.35$). An E-value of 5,500 N/mm^2 was assumed. It should be noted that the 25mm thick asphalt layer does not provide significant structural capacity to the pavement (Saleh 2003).

4.2 Nonlinear DRESDEN Model for UGL

In the Repeated Load Triaxial (RLT) testing, three distinct types of behavior were observed (which we name Range A, B and C). In Range A there are stable conditions (low increase of plastic deformation). In Range B (higher increase of plastic deformation than in Range A) failure was observed at high number of cycles and in Range C an incremental collapse was observed at a low number of load cycles (Werkmeister 2003, Arnold 2004).

On the basis of these investigations an empirical nonlinear elastic-plastic deformation design model (DRESDEN Model) was formulated. This model has been implemented into the FE Program. In this section only a short overview on the modelling of the UGM is given. Further details are available elsewhere (Gleitz 1996, Werkmeister 2003, Oeser 2004). This non-linear elastic model (valid for Range A and B) is expressed in terms of modulus of elasticity E and Poisson's ratio ν as follows:

$$E = p_a \left(Q + C \cdot \left(\frac{\sigma_3}{p_a} \right)^{Q_1} \right) \cdot \left(\frac{\sigma_1}{p_a} \right)^{Q_2} + D \qquad (1)$$

$$\nu = R \cdot \frac{\sigma_1}{\sigma_3} + A \cdot \frac{\sigma_1}{p_a} + B \qquad (2)$$

where σ_3 [kPa] minor principal stress (absolute value); σ_1 [kPa] major principal stress (absolute value); D [kPa] constant term of modulus of elasticity; Q, C, Q_1, Q_2, R, A, B model parameters. On the basis of the multi-stage RLT tests documented in (Arnold 2004) it is possible to determine the parameters of the model. Results for both elastic and plastic strain components have been obtained.

The elastic model includes a stress independent stiffness dependant upon the residual in-situ confining stress. The residual stress has the effect of reducing the strains at small stress levels. The parameter D is mainly influenced by macroscopic parameters like the degree of compaction of the UGM, content of fines, shape of the grains and water content. The RLT results do not allow determination of the parameter D because the residual stress needs some time to develop in a real pavement construction. Using the CAPTIF results it was possible to determine the value of stress independent stiffness for the materials investigated.

4.3 Subgrade

To overcome the limitation of the depth of the FE model the subgrade was modeled as a linearly elastic material with an E-value of 25 N/mm^2 and a μ-value of 0.4.

Table 2. Parameters for the elastic DRESDEN-Model

Material Elastic DRESDEN-Model		CAPTIF 1 Greywacke 0/40	CAPTIF 2 Greywacke 0/40 (high fine content)
Q	[-]	14,004	11,849
C	[-]	6,540	16,161
Q_1	[-]	0.346	0.226
Q_2	[-]	0.333	0.333
D	[kPa]	65,000	55,000
R	[-]	0.035	-0.015
A	[-]	-0.002	-0.0045
B	[-]	0.388	0.226
p_a	[kPa]	1	1

5 RESULTS OF ANALYSIS

5.1 Elastic strains

Figures 7 and 8 show the results of the linear and nonlinear elastic finite element analysis. Figure 7 shows a good agreement between the strains calculated using the nonlinear Dresden Model and those measured in the basecourse layer. The linear model tended to underestimate the strain at the top of the basecourse layer. Accounting for the non-linearity of the basecourse layer improved the solution, as it is clear in Figures 7 and 8 with the DRESDEN Model providing results close to the measured elastic strain values. In addition the nonlinear solution for the basecourse provided a better match for the subgrade strains than the completely linear elastic solution.

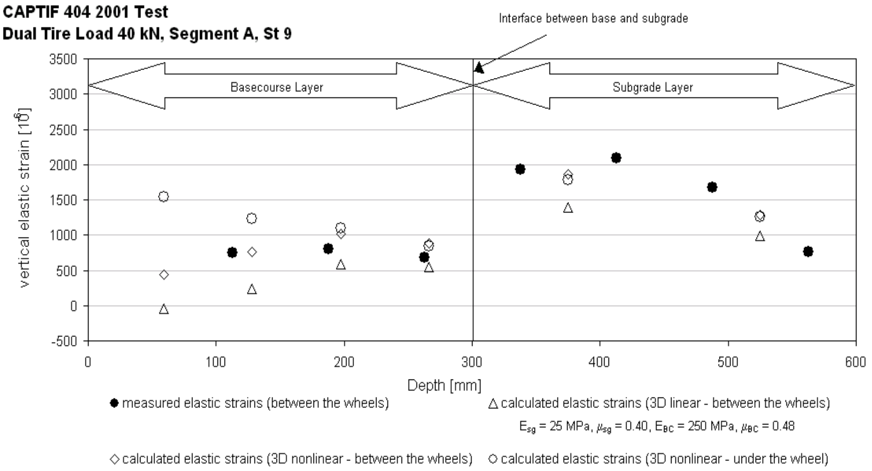

Figure 7: Comparison of predicted and measured strains at different depths for P = 40 kN

As already described in the paper, the nonlinear elastic parameters were determined using multi-stage RLT test results. However the determination of the stress dependent component of the Elastic Modulus, D is only possible using field test results. During the nonlinear back-calculation process, the measured basecourse strains where matched with various sets (different D values) of calculated strains. The value of D was chosen from the result set that gave the best approximation to the measured strains.

The vertical stresses measured by using a calibrated loading cell at the interface between the base course and subgrade layers for different loads are shown in Figure 9. There is a good agreement between the measured and the predicted values.

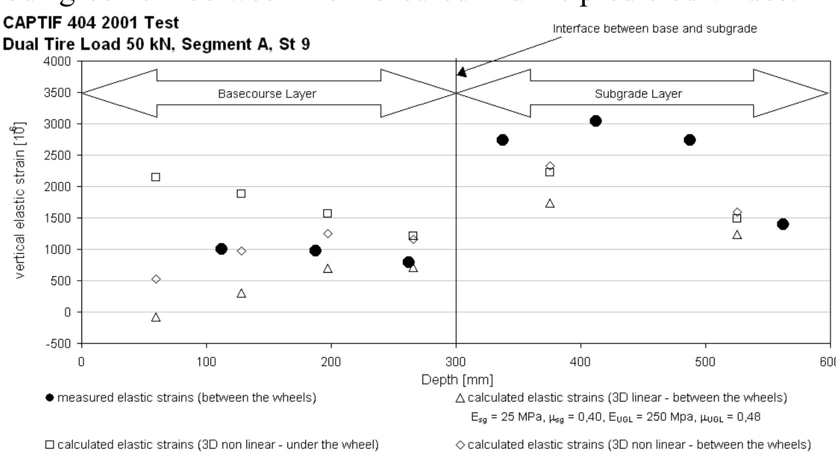

Figure 8: Comparison of predicted and measured strains at different depths for P = 50 kN

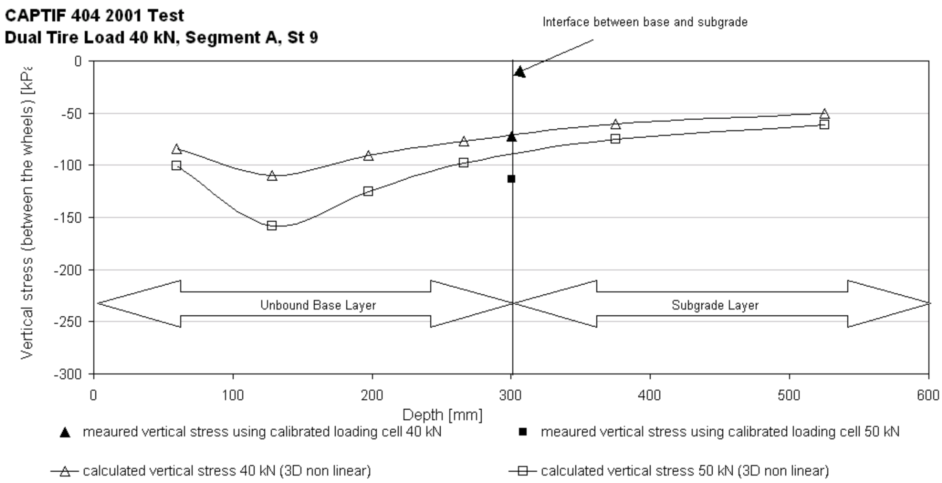

Figure 9: Comparison of predicted and measured stress for P of 40 and 50 kN

6 ANALYSIS OF ELASTIC AND PLASTIC BASECOURSE DEFORMATION RESPONSE

The pavement structure, which is common in New Zealand, is usually divided into three zones;

- The sprayed chip seal, which is typically 2.5 to 4 cm thick, is the primary waterproof wearing layer.
- The structural pavement layer (basecourse layer) that is subjected to high bulk and shear stress conditions and therefore requires high crushing and shear strengths. This layer distributes the high input stress intensity and protects the pavement subgrade.
- The subgrade usually comprises of the in situ subgrade. At this level, the shear stresses are assumed to have dissipated and the relatively low quality subgrade should be subjected to shear stresses well below the shear strength of the material for any given confinement.

This section of the paper presents an approach to determine the plastic strain rate from the elastic strain values for the basecourse layer. A similar design approach was suggested by Theyse (Theyse 2004) for the pavement subgrade from Heavy Vehicle Simulator results. However the subgrade deformation will not be taken into account in this paper. The CAPTIF trench profiles show, that the amount of plastic deformation that comes from the subgrade will be much lower, compared to the plastic deformation within the basecourse (de Pont 2001).

The CAPTIF elastic data consists of direct measurements of the elastic strains between the two wheels (Figure 4). A laboratory based calculation with the 3 D FE program FALTFEM was used to determine the elastic deformation directly underneath the wheels (Figures 7 and 8). The average of these vertical basecourse strain values was taken for the determination of the CAPTIF elastic strain values shown in Figure 10. These vertical strains represent the response of the basecourse material to the applied stress.

The analysis of the CAPTIF plastic data consisted of direct profile measurement at the pavement surface (Steven 2005). On the basis of the rut depths (plastic deformation) the plastic strain rate in the wheel path at certain stations (where the trench profiles where available) of the test track was determined. It has been observed, that after the initial loading, the plastic strain rate settles into a linear rate. Only this linear rate of plastic strains after completion of post compaction was taken into account.

In addition multi-stage RLT tests (constant confining pressure tests) at different stress levels were conducted on samples of the basecourse materials used in the test track (Arnold 2004). For each stress path 50,000 load cycles were applied. The deviatoric elastic strain and plastic strain rate after completion of post construction compaction was calculated. Figure 10 shows a linear relationship between the deviatoric elastic strain and plastic strain rate per load cycle (RLT test results) on a log (ε_p) vs. log (ε_{el}) plot.

The following relationship between the elastic strain and plastic strain rate could be determined, as long as the shear stresses within the basecourse material are sufficiently small and the material behaviour corresponds to either Range A or B.

$$\varepsilon_p = A \cdot \varepsilon_{el}{}^{B} \qquad (3)$$

where ε_p [10^{-3}] plastic strain rate, ε_{el} [10^{-3}] elastic strain, A, B [-] material parameters.

By studying the elastic/plastic relationship out of RLT tests and the elastic/plastic relationship out of CAPTIF tests differences can be observed. There are two obvious factors; the insufficient simulation of the field conditions within the laboratory test (CCP – constant confining pressure tests) and the lateral wander, which help to explain the difference between laboratory test results and those in the test pavement where lower plastic deformations are obtained, uncertainty in the proportions of plastic strain occurring in the base and the subgrade is also a factor. Only the deviatoric elastic strains out of the RLT tests could be taken into account. However, better correlation between RLT and field test results may be achieved by using VCP (variable confining pressure) RLT test results.

It was possible to calculate the shift factor according to the basecourse material type. Two sets of data where analyzed and the following values were obtained (Table 3).

$$S = \frac{\varepsilon_{p\,lab}}{\varepsilon_{p\,\mathrm{field}}} \qquad (4)$$

where S [-] shift factor, $\varepsilon_{p\ lab}$ [-] measured plastic strains out of RLT test results and $\varepsilon_{p\ field}$ [-] measured plastic strains in the wheel path out of CAPTIF tests.

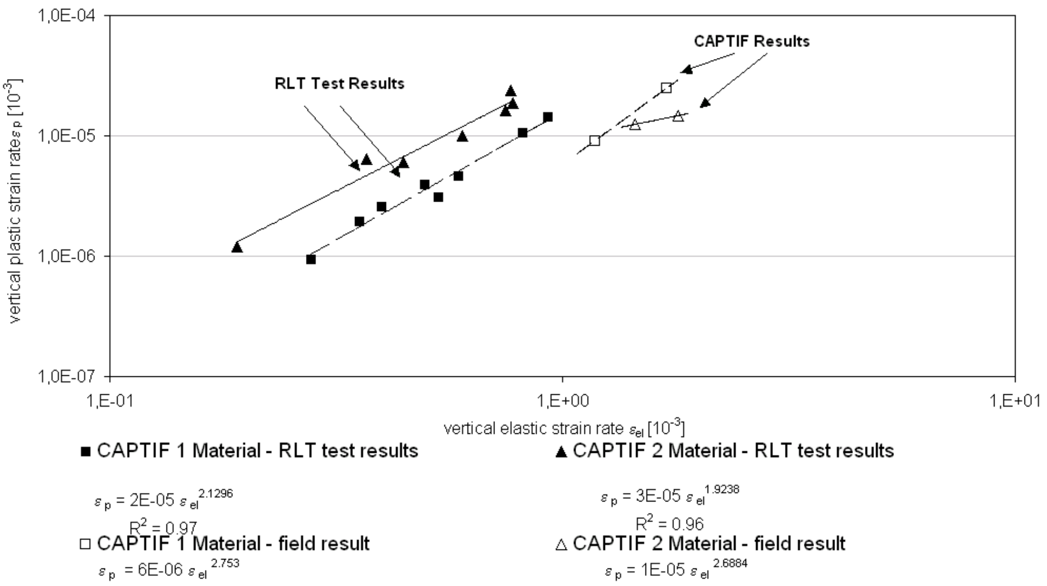

Figure 10: Elastic strain versus plastic strain rate, results of RLT and CAPTIF tests

Table 3. Shift factors S for CAPTIF 1 and 2 Material

	CAPTIF 1 Material Station 9	CAPTIF 2 Material Station 23
Loading 40 kN	3.3	5.5
Loading 50 kN	2.9	7.0

The value for the shift factors varying between 2.9 and 7 (Table 3). One reason for the variation is that the value of the shift factor is likely to be material dependant. By looking at the shift factors for a specific material, a lower variation of the shift factors is observed. However also of concern is the different slope between the laboratory and field tests seen in the CAPTIF 2 results. To get more information about the scattered range of these shift factors for basecourse materials further investigation of CAPTIF test results are necessary.

7 CONCLUSIONS AND RECOMMENDATIONS

The nonlinear elastic Dresden model and a linear elastic solution implemented in the 3D-FE Program FALTFEM were validated against CAPTIF test results. The determination of the stress independent component of the Elastic Modulus D of the DRESDEN Model was possible from the field test results. The nonlinear approach provided a much better solution than the linear elastic approach. The stresses predicted from the nonlinear model were quite close to the measured values.

In addition an empirical approach was formulated and calibrated to determine basecourse plastic strain rate using data from laboratory (RLT) and field (CAPTIF) tests for two different materials.

From results of laboratory tests a good correlation was found to exist between the elastic strain rate and the plastic strain rate as long as the shear stresses within the basecourse material are sufficiently small and the material behaviour corresponds to either Range A or B.

The CAPTIF test results showed a similar tendency between the elastic strain rate and the plastic strain rate to the results of laboratory tests. However, by comparing the elastic/plastic relationship out of laboratory tests and the elastic/plastic relationship out of field tests differences could be observed. There are two obvious factors; the insufficient simulation of the field conditions within the laboratory test and the lateral wander, which help to explain the difference between laboratory test results and those in the test pavement where lower plastic deformations are obtained, uncertainty in the proportions of plastic strain occurring in the base and the subgrade must also be a factor and CAPTIF’s Emu system is being improved to so these proportions can be more accurately determined. Shift factors were determined for the materials investigated to enable the prediction of the plastic strain rate in the field from the laboratory test results. Further investigations are necessary to confirm these predictions.

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