

# Modelling the time dependent behaviour of asphalt and pavement permanent deformation under a rolling wheel

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## 1 Introduction

The primary function of the structural layers of a pavement system is to spread the vehicle load efficiently so that individual layers are not overstressed and deteriorate prematurely. Pavement design begins with a study of response of the structure to the transient loads generated by traffic. For this the calculation of the stress history of each layer is a prerequisite for the calculation of the long term performance of the road in terms of cracking and deformation. A successful mechanistic pavement model is crucial to maximise the life of the pavement and to design maintenance treatments to minimise traffic disruption resulting from road works.

Earlier work at TRL (Nunn *et al.*, 1997) led to the development of the concept of long-life asphalt pavements. This demonstrated that deterioration in well constructed asphalt pavements above a threshold thickness is generally confined to the surface layers, in the form of top-down cracking and rutting. This was contrary to conventional theory which predicted that structural deterioration results from fatigue cracks propagating up from the road base and structural rutting in the subgrade. The development of an advanced mechanistic model of the system comprising the tyre and pavement structure will help to improve our understanding of the deterioration processes taking place close to the pavement surface and it will assist with the design of pavement maintenance and choice of materials. It could also be used to quantify such things as the damaging effect of tyre type and vehicle overloading.

The aim of the research described in this paper and funded by the Transport Research Foundation (TRF) was to develop an advanced mechanistic model of an asphalt pavement. The main objectives were to develop a constitutive model to characterise the elasto-visco-plastic response of asphalt and then develop a finite element model system comprising the tyre and the pavement. This model would be capable of predicting the stress and strain response of the pavement more realistically. An output of this model will be the prediction of permanent deformation. It will also predict the stress and strain response of the pavement which could be used in the development of models for any load associated deterioration mechanism.

In pavement research there is an over reliance on linear elastic theory. For example, Huhtala (1990) has

demonstrated that the assumption that the pavement response to dynamic loading is elastic is inadequate which becomes increasingly questionable at higher pavement temperatures. At high temperature the viscous and plastic characteristics of the material control the deformation behaviour of the asphalt layers. Models involving elastic, viscous and plastic components have the potential to predict a realistic pavement response under a rolling wheel load.

The effect of vehicle speed is not fully understood. It is a dynamic effect and current analytical procedures generally involve successive static analyses that are not representative of a loaded rolling wheel. Laboratory results show that the stiffness of the asphalt falls to very low values for frequencies of loading equivalent to those of slow vehicles. However, this does not represent the true behaviour of the pavement as vehicles can be parked for long periods without undue damage to the road. Obviously the stiffness of the material is an important parameter. What is clear is that the load spreading ability is different for an elastic material and a plastic material, and therefore the quantification of the load spreading ability for an elastic material should be corrected to take into account the plastic response.

In addition to using a constitutive equation based on elasto-visco-plastic theory as an input to describe the behaviour of the asphalt layers, the mechanical model developed consists of a rolling wheel on a pavement structure. No assumptions are made about the stress interaction between the wheel tyre and the pavement. The complex three dimensional nature of the contact stresses are predicted by the model. This is an important aspect of the model. The contact stresses are likely to be important for deterioration processes, such as rutting and top-down cracking, which occur close to the wheel tyre. Conventional models (COST Action 333, 1999) generally represent a moving vehicle as a quasi-static problem with the interaction between the tyre and pavement being represented unrealistically by a uniform normal stress on a circular contact area.

The elasto-visco-plastic model for the asphalt pavement adopted in this study should help address the issues mentioned above. In this paper, the model is described and its predictions are compared with measurements carried out in the TRL Pavement Test Facility (TRL-PTF). A detailed verification programme is required to fully validate the model.

## 2 Brief description of the model

### 2.1 Preliminary

An asphalt pavement is a multi-layered structure that consists of the foundation and several layers of asphalt. The foundation generally consists of the subgrade and a layer of unbound granular material, while the asphalt layers consist of a thick base, the main structural layer, a binder course and a relatively thin surface course, which is required to have good friction characteristics for high speed traffic. In the model described in this paper, an elasto-visco-plastic constitutive model was developed for the asphalt layers by carrying out laboratory tests on samples of asphalt, while elastic theory was used to model the behaviour of the foundation layers. These descriptions of material behaviour were fed into a finite element program that modelled the system comprising the tyre and the pavement structure. This model predicted the stress and strain distribution in the pavement as well as its rutting behaviour.

The predicted load spreading ability and the magnitude of load induced strains in the pavement system will depend greatly on the accuracy with which the stiffness moduli of the different layers forming the pavement can be defined. Traditionally the stiffness modulus is assumed to be dominated by elastic behaviour but this is not the case for asphalt material. At very low temperature the asphalt behaves in a brittle manner and the assumption of elasticity is acceptable, but at high temperature the viscous component dominates which will make the pavement more prone to permanent deformations.

The stiffness modulus is generally influenced by temperature, rate of loading, level of stress, plastic flow and damage to the material. This suggests that a more general description of stiffness is required that should include dependency on stress ( $\sigma$ ), temperature (T), plastic strain ( $\epsilon^p$ ), which is a combination of plastic flow and plastic creep), and a damage factor (D) defined as the ratio of the difference between a damaged and undamaged material.

For asphalt material the relationship for the stiffness modulus should be able to capture:

- The reduction of stiffness due to plastic flow.
- The increase of stiffness when the rate of loading increases.
- The occurrence of increased plastic flow at higher pavement temperatures.
- The occurrence of plastic creep that is dependent on stress and temperature.
- Damage accumulation.

The development of the elasto-visco-plastic model is based on the classical theory of plasticity (Hill, 1950) and the following assumptions are made:

- The strain tensor can be represented by an elastic ( $\epsilon^e$ ) and plastic ( $\epsilon^p$ ) part, as follows:

$$\epsilon = \epsilon^e + \epsilon^p \quad (1)$$

- The elastic domain is bounded by a frontier defined by a function F called the yield criterion which constrains the admissible stress state ( $\sigma, \chi$ ) to lie in the region defined by :

$$F(\sigma, \chi) \leq 0 \quad (2)$$

Where,  $\sigma$  is the stress tensor depending on ( $\epsilon, \epsilon^p$ ) and  $\chi$  is the tensor of internal variables which are functions of the plastic strain  $\epsilon^p$  and the position of the yield surface  $\alpha$  in the stress space.

- The irreversibility of the plastic flow is defined by the following equations of evolution for  $\epsilon^p$  and  $\chi$ , called the flow rule and hardening law, respectively;

$$\frac{\partial \epsilon^p}{\partial t} = \lambda R(\sigma, \chi) \quad (3)$$

$$\frac{\partial \chi}{\partial t} = \lambda H(\sigma, \chi) \quad (4)$$

Where, R and H are prescribed functions which define the plastic flow and the type of hardening.

### 2.2 Implementation procedure

The components of the elasto-visco-plastic model for asphalt are shown in Figure 1. The model assumes that visco-plastic strain will occur until the stress  $\sigma$  is greater than the yield stress, which defines the onset of irrecoverable plastic strain.

The model is defined by assigning values obtained from laboratory tests to determine:

- 1 The elastic parameters in terms of the Young's modulus and the Poisson's ratio.
- 2 The yield stress.
- 3 The viscous parameters of a power law relating the strain rate to stress.
- 4 The hardening modulus.
- 5 The kinematic hardening parameter.

The model parameters were determined by carrying out laboratory compression tests at several strain rates and at

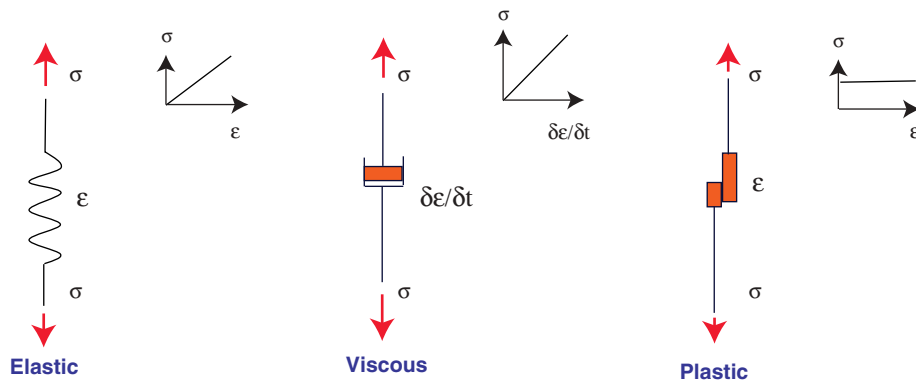


Figure 1: Components of the elasto-visco-plastic model for asphalt

two temperatures on test specimens cut from slabs of asphalt that were compacted in the laboratory to a density representative of material in the field.

The elastic modulus was obtained from the initial slope of the stress-strain curves of laboratory test specimens subjected to a uniaxial stress, and a value of 0.35 was assumed for Poisson's ratio. The yield stress was obtained directly from stress relaxation curves. The viscous parameters were obtained by fitting the predicted plastic flow to experimental data, using a non-linear least squares algorithm and assuming a Von Mises equivalent stress yield criterion and a non-linear kinematic hardening rule (Hill, 1950). The hardening modulus was obtained from the relationship between visco-plastic strain and stress level. The kinematic parameter is assumed to be equal to zero.

The material identification parameters for the asphalt investigated were used to calculate the numerical stress-strain curves describing the mechanical response of the asphalt at two temperatures 20°C and 40°C. For example,

Figure 2 compares theoretical predictions with the experimental results of compression tests performed under uniaxial stress conditions on Heavy Duty Macadam (HDM) for three strain rates:  $\partial\epsilon/\partial\tau=0.3\%$ ,  $\partial\epsilon/\partial\tau=0.07\%$  and  $\partial\epsilon/\partial\tau=0.004\%$  at a temperature of 20°C. A good agreement was observed between the theoretical predictions and the experimental results.

### 2.3 Model of tyre-pavement interaction

The model consists of the wheel/pavement system shown in Figure 3. Since the system is symmetrical in the vertical, longitudinal plane passing through the centre of the tyre, only half of the tyre and pavement structure is represented. This reduces the number of finite elements required to represent the system and this improves the computational efficiency of the model. The wheel is in contact with the surface of the road and it turns at a speed compatible with the tracking speed of the loaded wheel in the TRL-PTF (20 km/h). A value of the friction coefficient between the wheel and the surface was chosen to prevent slip.

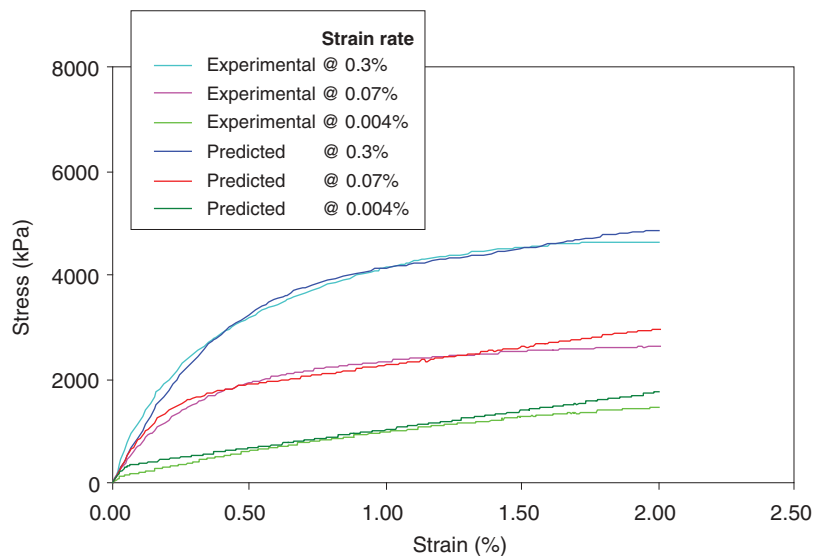


Figure 2: Comparison of predicted and measured behaviour in the compression test (20°C)

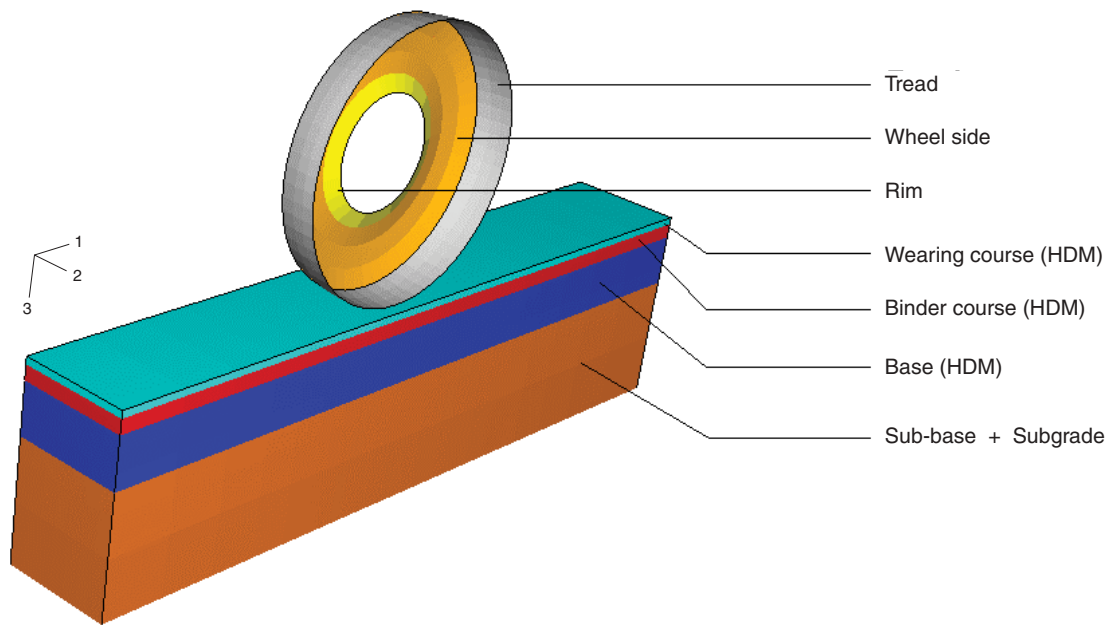


Figure 3: Finite element discretisation of the tyre/pavement interaction model

The three-dimensional model finite element mesh of the wheel is generated by revolving a cross-section of the wheel discretised with shell elements. The wheel is assumed to be a deformable tyre in contact on a rigid rim centered on the axle. The entire circumference is discretised in order to accommodate the changing contact conditions while the wheel is rolling over the pavement surface.

The pavement structure constructed in the TRL-PTF (Sanders and Nunn, 2005) was modeled. This consisted of four material layers. The first layer is a 400mm granular sub-base on top of a subgrade with an infinite thickness, the second layer is a 210mm thick asphalt base, the third layer is a 60mm asphalt binder course and the fourth layer is a 30mm asphalt wearing course. All asphalt layers were assumed to consist of the same elasto-visco-plastic material. The subgrade is restrained horizontally in all directions to represent the constraint of the surrounding soil and the infinite thickness of the subgrade was modeled using infinite elements. All layers are assumed to be fully bonded to one another.

The loading was applied in stages in which the wheel was first inflated and then brought in contact with the pavement surface, loaded and then a velocity was applied to the wheel axle and the axle was allowed to turn and move forward.

Figure 4 shows the inflated wheel in contact with the pavement surface. The displacement field depicted in this figure represents the deformation state of the tyre from the unloaded condition to the condition after the tyre is inflated, brought into contact with the pavement and a load of 40kN applied. This is the loading condition used in the TRL-PTF.

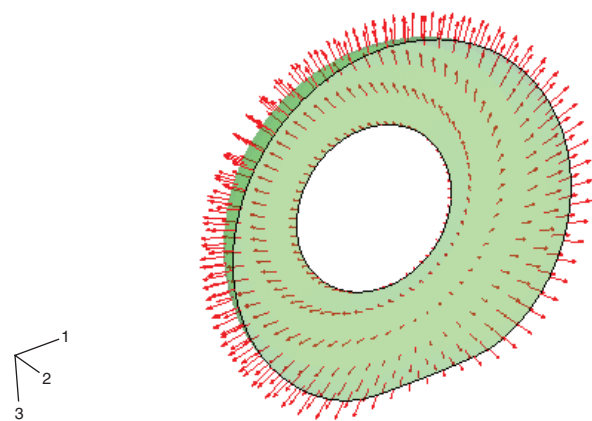


Figure 4: Field displacement in the deformed wheel model

The resulting vertical contact pressure at the base of the wheel is shown in Figure 5. The highest stresses are depicted by red and the lowest by blue. The model also predicts that there will be horizontal components of the contact stresses. This illustrates that the 3-dimensional, non-uniform nature of the tyre contact stresses are more complicated than the circular patch of uniform vertical pressure that is assumed by most models (COST Action 333, 1999). The high level of stresses in the asphalt close to the tyre, are crucial to the development of load associated deterioration in the form of rutting or top-down cracking. These are influenced by the nature and magnitude of the stress interaction between the tyre and the pavement surface. The assumption of a uniform normal stress will result in unrealistic stress conditions in the asphalt close to the surface.

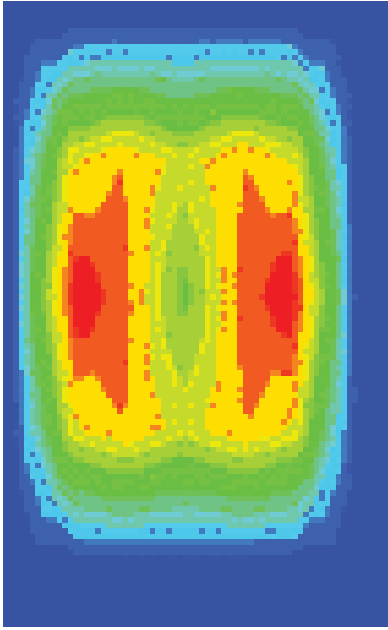


Figure 5: Foot print of a tyre when in contact with the pavement surface

An example of the output of the model is given in Figure 6. This shows contours of the first stress invariant or volumetric stress defined as  $p = (\sigma_1 + \sigma_2 + \sigma_3) / 3$  in the asphalt layers of the pavement. A maximum value for  $p$  of 0.5MPa occurs at the pavement surface (red zone) which decreases gradually with depth. This illustrates the high level of stresses induced in the surfacing layers of asphalt. A similar plot could be determined for the second stress invariant (deviatoric stress) which is a measure of the shear stresses occurring in the pavement.

### 3 Comparison of predictions and observations

An experimental pavement built in the TRL-PTF, shown in Figure 7, was subjected to repeat cycles of a 40kN wheel load while the pavement was maintained at a temperature

of 40°C (Sanders and Nunn, 2005). The wheel was tracked forward and backward at 20 km/h for 30,000 passes in blocks of 840 passes with a lateral Gaussian distribution. The transverse deformation profile was measured after each block of passes. The pavement structure is defined in Section 2.3.



Figure 7: The TRL Pavement Test Facility (PTF)

The time taken to carry out the computations for a deformable tyre rolling over a deformable pavement meant that it was impractical to simulate 30,000 wheel passes. Also to reduce the computational time, the longitudinal tracking distance was reduced. The following two computer simulations were carried out:

- 1 A total of 840 load passes were simulated in which the wheel was rolled forward and backward over a distance of 0.45m.
- 2 This simulation was identical to Simulation 1, but with the exception that 423 passes were applied with the wheel rolling forward and backward over a distance

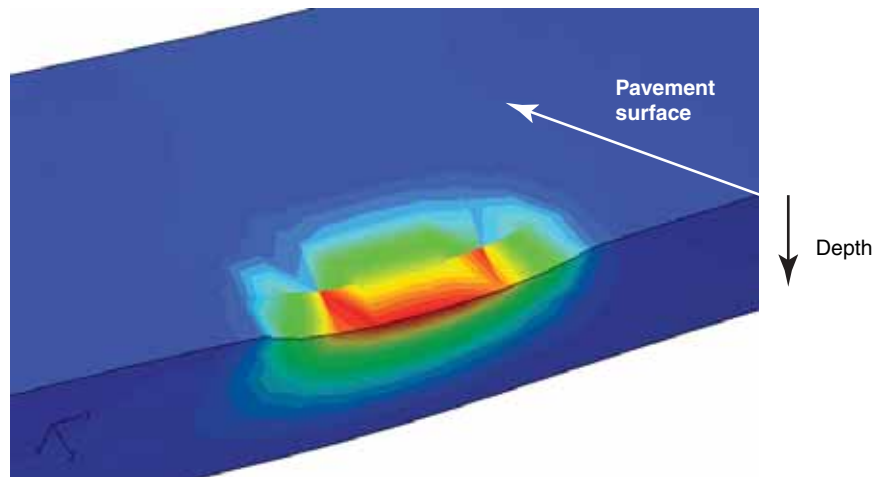


Figure 6: Contour of distribution of the first stress invariant in the asphalt layers

of 1m. This simulation was performed to determine whether tracking over a distance of  $\pm 0.45\text{m}$  was representative of a longer distance.

The shapes of the transverse rut profiles using Simulation 1 and Simulation 2 predicted using the finite element model are given in Figure 8. As observed, both simulations resulted in similar transverse rut profiles after 423 wheel passes, which confirms that the movements in Simulation 1 were sufficient to load and unload a small element of the pavement.

The measured transverse rut profile, after 840 wheel passes, from the experiment in the TRL-PTF is also plotted in Figure 8. The rut depth predicted by the numerical model and the rut depth measured in the TRL-PTF are in reasonable agreement, bearing in mind the experimental errors in defining the elasto-visco-plastic material properties and in the measurement of *in situ* rut depths. The rut profile in the TRL-PTF is asymmetric about the centre line. There was no obvious reason for this but it demonstrates the variable nature of the asphalt.

The resulting displacement field due to the wheel rolling backward and forward through several cycles, is shown in Figure 9. In the large depression caused by the accumulation of visco-plastic strain, the displacement vectors are vertical in the plane of symmetry; the displacement vectors rotate progressively with decreasing magnitude away from the plane of symmetry in the transverse direction. This material rotation results in some heave just outside the area loaded by the rolling wheel. This is clearly observed in Figure 9 in the zone where the vector displacements are pointed slightly upwards. This heave is comparable to the heave that occurred to the left hand side of the rut in the TRL-PTF shown in Figure 8 but smaller than the heave on the right hand side. This variability is attributed to the variable nature of asphalt and it demonstrates that a single comparison is insufficient.

Most rutting originates in the upper layers of asphalt of thick asphalt pavements (Nunn *et al.*, 1997). This model supports this observation as demonstrated in Figure 10, which shows the predicted variation of vertical plastic strain

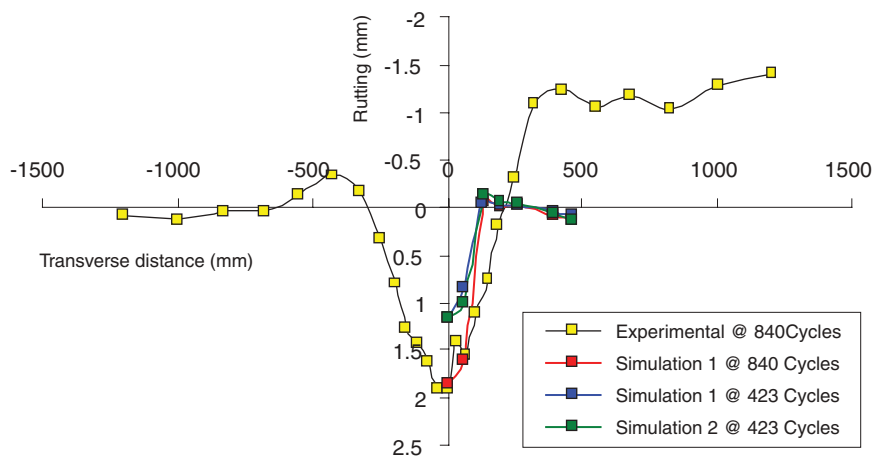


Figure 8: Comparison of predictions between experiment and the finite element model

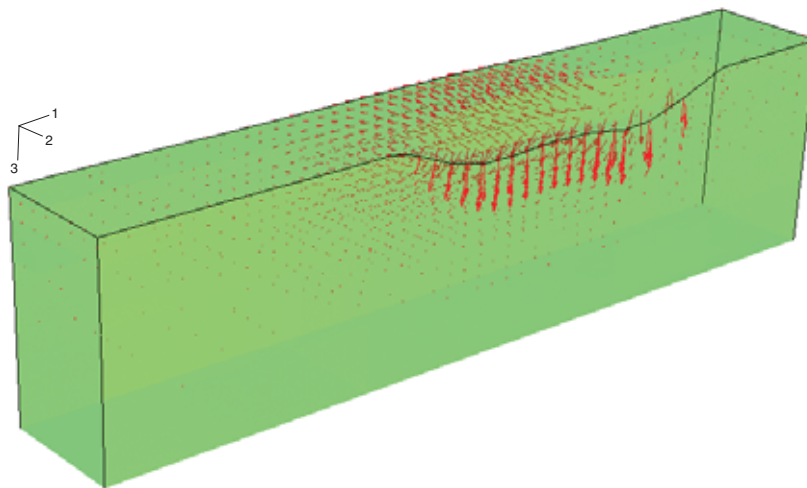


Figure 9: Field displacements in the rutted pavement

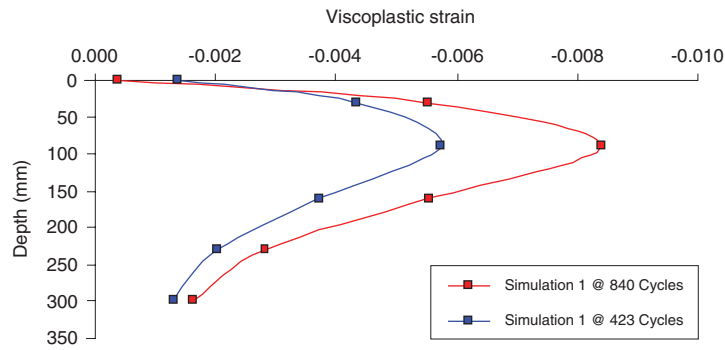


Figure 10: Variation of plastic strain with pavement depth

with depth after 423 wheel cycles and 840 wheel cycles. In both cases the plastic strain reaches a peak value at a depth of 90mm below the pavement surface and then decreases gradually with depth. This suggests that the majority of the permanent deformation will occur in the upper asphalt layers of the pavement and agrees with the experimental observation that rutting is non structural provided that the foundation supporting the upper layers is sound.

The integration of vertical plastic strain with depth gives the distribution of vertical deformation with depth as shown in Figure 11 for both simulations. For comparison an elastic based analysis was also carried out, and this suggests that the deeper layers in the pavement will experience deformations as significant as the upper pavement layers.

#### 4 Future developments

The numerical model described in this paper is still under development. The finite element model was able to predict the important characteristics of rutting in the TRL-PTF. However, further work to refine and validate the model is required.

Additional trafficking studies in which rutting is achieved in instrumented pavements under controlled conditions are required to assist with this validation. Predictions using the model should be compared with the deformation

behaviour of these test pavements. This will need to be supported by a laboratory test programme to establish constitutive equations for the materials involved, and to calibrate the model using realistic strain paths as they occur in the field.

The three dimensional nature of the contact stresses between the wheel and the pavement should be investigated, in particular the area of contact between the wheel and the pavement, the wheel characteristics, the degree of adherence of the wheel to the pavement surface and the friction mechanism between the wheel material and the pavement material.

#### 5 Conclusions

An analytical model has been developed that simulates a system that comprises a wheel rolling on a pavement structure. The interaction between the wheel and the pavement is modelled as two deformable bodies in contact. A model of this type is able to predict the complex three dimensional contact stress interaction between the tyre and the pavement. It could also be used to evaluate the damage caused by overloaded vehicles, tyres inflated above and below the correct pressures and new generations of commercial tyre.

The constitutive model developed can simulate non-linear response of asphalt material. The constitutive model, based

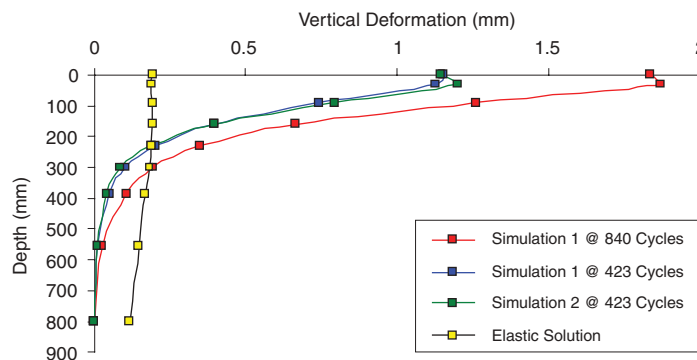


Figure 11: Integrated vertical deformation

on elasto-visco-plasticity, is able to take into account the dependency of the mechanical behaviour of asphalt on the rate of loading and temperature. This constitutive model is unique in the sense that it is able to predict several features which are characteristic of the mechanical behaviour of asphalt using a single set of parameters. The material model has six temperature dependent parameters: the Young's modulus, the elastic limit, the visco-plastic parameters of a power law relating strain rate to stress, the hardening modulus and the kinematic hardening parameter. These parameters can be identified from appropriate compression tests carried out over a range of strain rates at a given temperature.

The modelling of the pavement structure in the TRL-PTF subjected to tracking by a wheel load gave reasonable quantitative and qualitative results when compared to experimental observations. The model successfully predicted the level of rutting and that the majority of the deformation originated in the upper asphalt layers of the pavement.

## 6 Acknowledgements

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## 7 References

**COST 333 (1999).** Development of new bituminous pavement design method. Final report of the action, Brussels, Luxembourg.

**Hill R (1950).** The mathematical theory of Plasticity. London: Oxford University Press.

**Huhtala M, Alkio R, Pihijamaki J and Halonan P (1990).** Behaviour of bituminous materials under moving wheel loads. *Journal of the Association of Asphalt Paving Technologists*, **59**.

**Nunn M E, Brown A, Weston D J and Nicholls J C (1997).** *Design of long-life flexible pavements for heavy traffic*. TRL Report TRL250. Wokingham: TRL Limited.

**Sanders P and Nunn M (2005).** *Investigation into the properties of a 20mm EME binder course for use on heavily trafficked roads*. TRL report (*In preparation*)