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STUDY OF ASPHALT-CONCRETE PAVEMENT FATIGUE MODELING

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Abstract. Deterioration of asphalt pavements due to fatigue cracking is one of the most common highway pavement failure types. If the fatigue cracks are allowed to develop and grow, the driving comfort and safety, i.e., serviceability of the pavement, decreases. Pavement fatigue behaviour is not a straightforward mechanism and involves many factors and effects, thus computational methods are developed in order to help understand how the pavement works. This paper explores the accuracy and applicability of a less computational resource demanding procedure that uses transient material mechanical behaviour to model the long-term behaviour of a pavement structure. First, the mechanical and fatigue properties of asphalt were determined at the laboratory. Then a four-layer finite-element model was created using Ansys software. Two different models – with and without infinity elements – and two different fatigue simulation procedures – full and simplified – were considered. Material parameters were obtained by the

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laboratory tests and material properties degraded over time. Cyclic surface loading was applied to simulate the passing of a truck – 6 million fatigue cycles were simulated.

Keywords: asphalt, fatigue, finite element analysis, pavement, structural health monitoring.

Introduction

Deterioration of asphalt pavements due to fatigue cracking is one of the most common highway pavement failure types. Fatigue damage is caused by repeated traffic loading that creates a series of connected cracks. They initiate at the bottom of the asphalt layer and then grow to the surface and in the longitudinal direction. Initially, the cracks are thin and sparsely distributed, but if further development is allowed the longitudinal cracks connect and many separate asphalt prisms form. Moreover, the formed cracks allow moisture to infiltrate in the road structure, which leads to an even faster deterioration. Passing vehicles can pull out these asphalt prisms from the pavement or they break down completely. In either case, a pothole in the road pavement forms, which reduces the driving comfort by increasing the noise level, decreases safety by reducing tire friction and making the pavement surface more uneven, which may also increase the costs of vehicle maintenance Vanelstraete & Francken (2014).

Computational modelling is commonly used to reduce the number of required experiments and thus reduce costs. Several different approaches have been used by researchers to model road structures. Kutay, Chatti and Lei (2011) developed the layered viscoelastic algorithm to model flexible pavements based on quasi-elastic theory proposed by Schapery (1969), (1974). Zaghloul and White (1993) used a three-dimensional FE model to investigate pavement response to moving loads. They employed a visco-elastic material model for AC, extended Dricker-Prager model for the granular road base and Calm Clay model for the soils in the subgrade (Zaghloul, 1993). Kim (2000) showed that Drucker-Prager plasticity model is not suitable to model nonlinear unbound layers, and adopted Uzan model for the granular materials and cohesive soils with the Mohr-Coulomb failure criterion in the nonlinear FE analysis. Erlingsson (2002) used a linear elastic model in a three-dimensional FE analysis of low volume road pavements. Elseifi, Al-Qadi, and Yoo (2006) compared visco-elastic and elastic models and found that viscoelastic constitutive models increase accuracy. Yin, Stoffels, and Solaimanian (2008) used viscoelastic 3D FE model that showed a reasonable prediction of strain response in the field. Onyango (2009) used nonlinear creep models to model permanent deformation of hot-mix asphalt-concrete (HMA). Pirabarooban, Zaman, and Tarefder (2003) developed an elasto-viscoelastic creep model that represents the time-dependency of asphalt mixtures to evaluate their rutting resistance. Huang (1995) showed that nonlinear viscoelastic and viscoplastic models are capable of capturing the pavement response under different temperatures. A nonlinear time-hardening creep model to simulate a large number of loading cycles was proposed by Huang (1995) and further improved by Hua (2000) and Al-Qadi *et al*. (2009). Studies by Fang *et al*. (2004) and Al-Qadi *et al*. (2009) showed the effectiveness of using a nonlinear time-hardening creep model to compute permanent deformations. Leonardi (2015) modelled runway pavement using nonlinear time-hardening creep model for HMA surface layer and a linear elastic material model for the granular layers, the results showed good correlation between simulation results and the field measurements. Varma and Kutay (2016) developed an analytical solution and compared it to the FE solution that used viscoelastic material for the AC layer and nonlinear material model for the unbounded road base and subgrade soils. Mulungye, Owende, and Mellon (2007) simulated a road structure using two (one for longitudinal, one for transversal direction) 2D FE models with viscoelastic material models.

Additionally, there is a clear need for new and open computational modeling and simulation techniques and approaches as noted by the roadmap issued by the European Materials Modeling Council (The European Materials Modeling Council, 2018). Moreover, need for new modelling software particularly for engineering applications, such as uncertainty quantification, risk analysis and decision in engineering, has been recognized by the Council of the European Union in its decision that established the Horizon 2020 program (European Commission, 2013).

1. Methods

1.1. Determination of elastic and fatigue material properties

Initial elastic and fatigue properties of asphalt concrete materials (AC11 and SMA11) were determined by 4-point bending fatigue test method according to EN 12697-24 Annex D standard using Large Hydraulic Four Point Bending Machine by Cooper

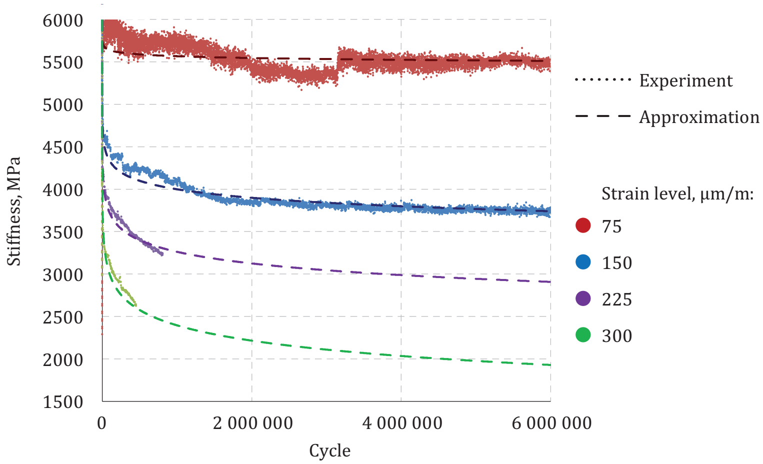

Figure 1. Fatigue curves of AC11

Technologies (experimental equipment). Specimens with dimensions 380 × 50 × 50 mm were tested to 4-point-bending with effective length of 355.5 mm. Symmetric bending at frequency of 10 Hz and constant strain amplitude of 75, 150, 225 and 300 µm/m (for AC11), and 150, 250, 300, 350 and 450 µm/m (for SMA11) was applied to determine dependences of materials stiffness modulus on the loading cycles. The obtained dependences are presented in Figure 1 and Figure 2 for AC11 and SMA11, respectively.

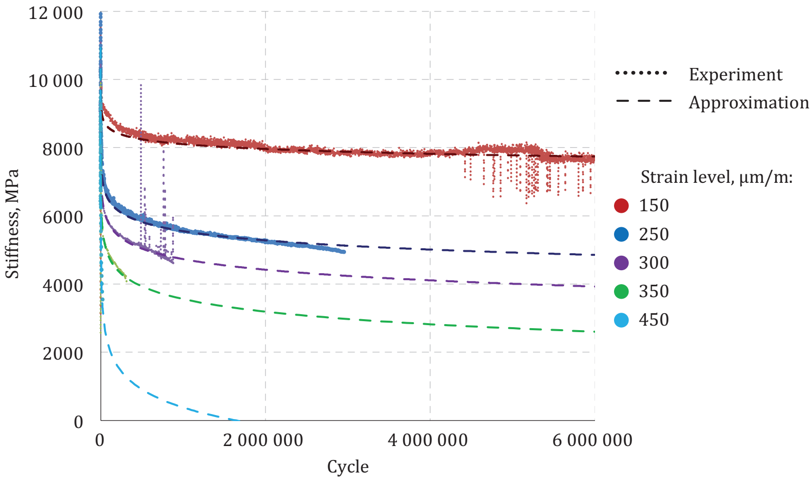

Figure 2. Fatigue curves of SMA11

Experimentally obtained fatigue curves were approximated for further use in the numerical model. Logarithmic equation was taken for approximation of fatigue curves for both asphalt-concrete materials:

$$E = E_0 - k\sum \ln(N), \tag{1}$$

where E_0 is initial stiffness modulus, N is cycle number, k is regression coefficient.

Coefficient of approximation function E_0 and k for each experiment were obtained by regression analysis applying the least squares method:

$$\Delta = \sum_{i=1}^{n} \left(E_n^{exp} - E_n^{mod}\right)^2 \rightarrow \min, \tag{2}$$

where n is the number of sampling points.

For the initial regression analysis, both E_0 and k were taken as variable parameters. The obtained values of coefficients are presented in Table 1. Then the average value of E_0 for each material was set as a

Table 1. Results of the initial regression analysis

AC11				SMA11			
Strain, µm/m	**E_0, MPa**	***k***	**Δ**	**Strain, µm/m**	**E_0, MPa**	***k***	**Δ**
75	6793	86.0	263 165 146	150	11 531	244.6	546 586 512
150	6173	156.7	48 975 287	250	11 822	454.3	359 087 300
225	5675	170.6	29 292 093	300	10 893	445.8	120 915 060
300	5334	199.0	44 867 956	350	10 507	491.4	300 096 292
Average	5994			450	9862	597.5	43 761 312
				Average	10 923		

Table 2. Results of the regression analysis with fixed initial stiffness

AC11				SMA11			
Strain, µm/m	**E_0, MPa**	***k***	**Δ**	**Strain, µm/m**	**E_0, MPa**	***k***	**Δ**
75	5994	30.9	440 396 070	150	10923	204.1	662 290 714
150		144.4	57 852 779	250		388.9	553 748 846
225		197.8	48 044 398	300		448.2	121 085 953
300		260.5	115 050 404	350		533.0	225 141 135
				450		763.3	96 721 973

constant coefficient and the regression analysis was repeated. Results of this analysis are presented in Table 2 and Figures 1 and 2 together with the experimentally obtained curves.

1.2. Model description

A four-layer road structure consisting of the bound surface (SMA11, 3 cm), bound base layer (AC11, 6 cm), subbase layer (gravel, 15 cm) and subgrade (sand) was considered in this research. Elastic material properties are presented in Table 3. Time-depending load with the maximum value of 5 t and frequency of 10 Hz simulating load from truck wheel was applied through a circular metal plate with dimeter of 30 cm. The profile of the corresponding surface load in time domain is presented in Figure 3, and the scheme of the considered domain – in Figure 4.

Commercial finite element software ANSYS Mechanical was used to build a 2-D numerical model according to the scheme presented in Figure 4. 13 148 Plane182 elements defined by four nodes having 2 translational degrees of freedom at each node with characteristic size

Table 3. Material properties

Layer	*E*, MPa	η	ρ, kg/m^3
SMA11	11 000*	0.35	2420
AC11	6000*	0.35	2300
gravel	450	0.27	2600
sand	230	0.3	2000

* initial value of stiffness modulus

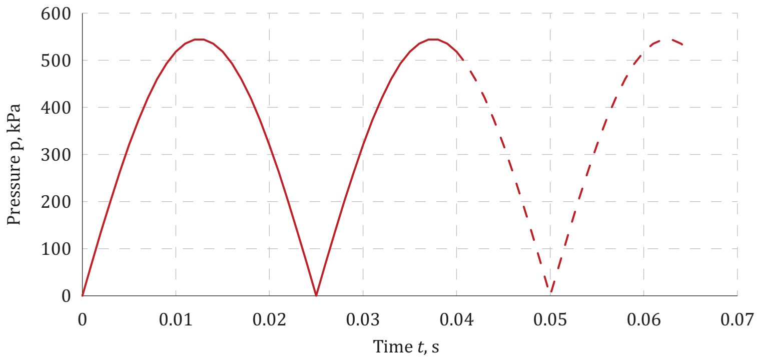

Figure 3. Time-depending surface load

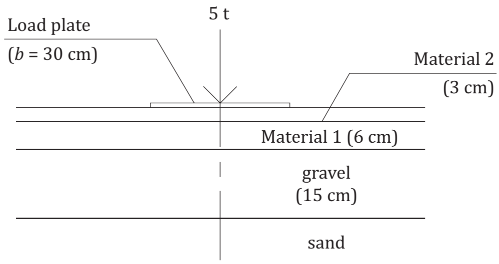

Figure 4. Scheme of the road structure

of 1 to 6.5 cm depending on element location (smaller elements were used closer to load attaching place) were used to represent all layers of the road structure. A single layer of INFIN257 elements located at the sides and the bottom of the finite simulation domain was used to represent infinity domain. This was done to avoid non-physical reflections of the elastic waves caused by time-dependent external load from the boundaries of the finite simulation domain obtained in the transient analysis of the structure and presented in Figure 5.

As mention before, the transient analysis was used to simulate time-dependent behaviour of the structure. The following procedure presented in Figure 6 have been developed and successfully applied to simulate fatigue of the asphalt concrete materials of two upper layers of the road structure. Initially, elastic properties of these materials were set as constants presented in Table 4 and no fatigue model was applied. After calculation of several loading cycles necessary to obtain steady amplitudes of displacements (Figure 5) and, accordingly, strains, the solution was stopped and the amplitude values of strain intensity in each element were acquired. These values were used to match the fatigue models for finite elements. It is assumed that

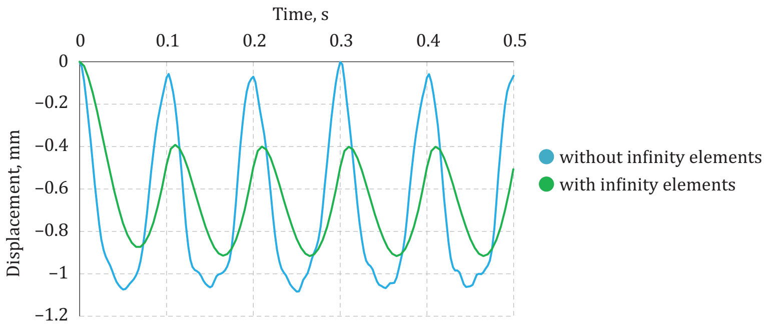

Figure 5. Dependence of the vertical displacements on time

Table 4. Use of experimentally applied fatigue models

AC11		SMA11	
Strain intensity in the finite element, μm/m	**Fatigue model experimentally obtained for strain, μm/m**	**Strain intensity in the finite element, μm/m**	**Fatigue model experimentally obtained for strain, μm/m**
< 50	no fatigue	< 50	no fatigue
50... 112.5	75	50... 200	150
112.5... 187.5	150	200... 275	250
187.5... 262.5	225	275... 325	300
> 262.5	300	325... 375	350
		> 375	450

no fatigue behaviour is observed in the element if strain is less than 50 μm/m. For greater values of strain experimentally obtained fatigue models were applied according to Table 4. After change of material models the solution was continued. Since strains in the elements increase over time due to decrease of elastic properties caused by fatigue, it is possible that after some time it is necessary to change fatigue model for some elements. Thus, the procedure that consists of interruption of solution, analysis of the strain level in the elements and material model change with consequent continuation of the solution was repeated during the simulation.

In order to evaluate the effect of this simulation with progressive change of fatigue models, a simpler algorithm was utilized. Only initial

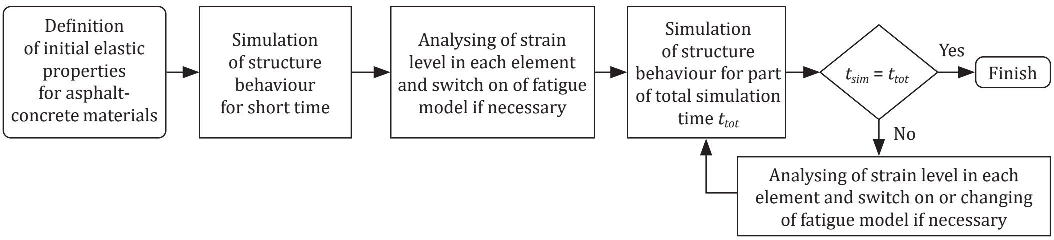

Figure 6. Simulation procedure for fatigue behaviour

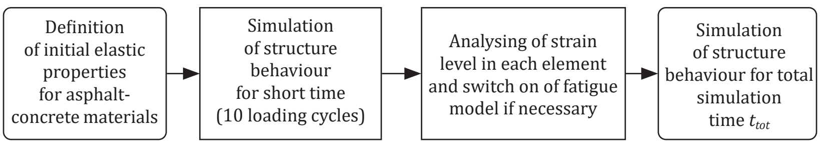

Figure 7. Simplified simulation procedure

definition of fatigue models after obtaining the steady displacement amplitudes, was used (Figure 7).

Since transient analysis of multi-cycle loading of the structure is a very time and memory consuming process, the degradation of material stiffness properties depending on the number of loading cycles was accelerated 1000 times. It means that one simulated loading cycle is equivalent to 1000 loading cycles in reality. In this case, the previously developed material models (Eq. (1)) with coefficients presented in Table 1 could be used in a slightly modified form as presented in Eq. (3).

$$E = E_0 - k\sum \ln(1000N) \tag{3}$$

2. Results and discussion

Simulation results obtained by full and simplified (Figure 8) procedures showed considerable difference. As it is shown in Figure 8, increase of the point located at the top of the road structure under the centre of the loading plate, vertical displacement due to fatigue of asphalt concrete materials obtained by the full simulation procedure is 0.032 mm after 6 million loading cycles. The value obtained by the simplified procedure is 0.017 mm or 1.9 times smaller. Dependences of absolute values of strains in vertical and horizontal directions obtained by both simulation procedures in the point located between Material 2 and Material 1 under the centre of the loading plate are presented in Figure 9. Smooth and slow increase of strains caused by fatigue behaviour according to the once defined fatigue model is observed in case of calculation by the simplified procedure. The

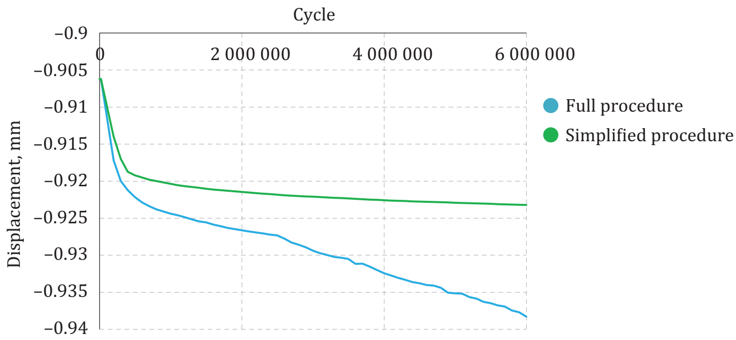

Figure 8. Dependence of vertical displacement on loading cycles

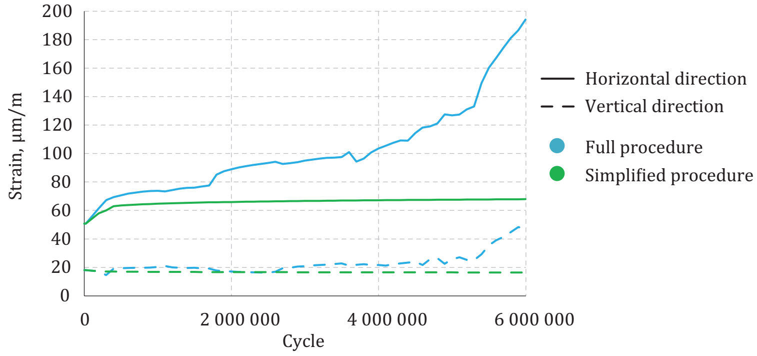

Figure 9. Dependence of strains on loading cycles

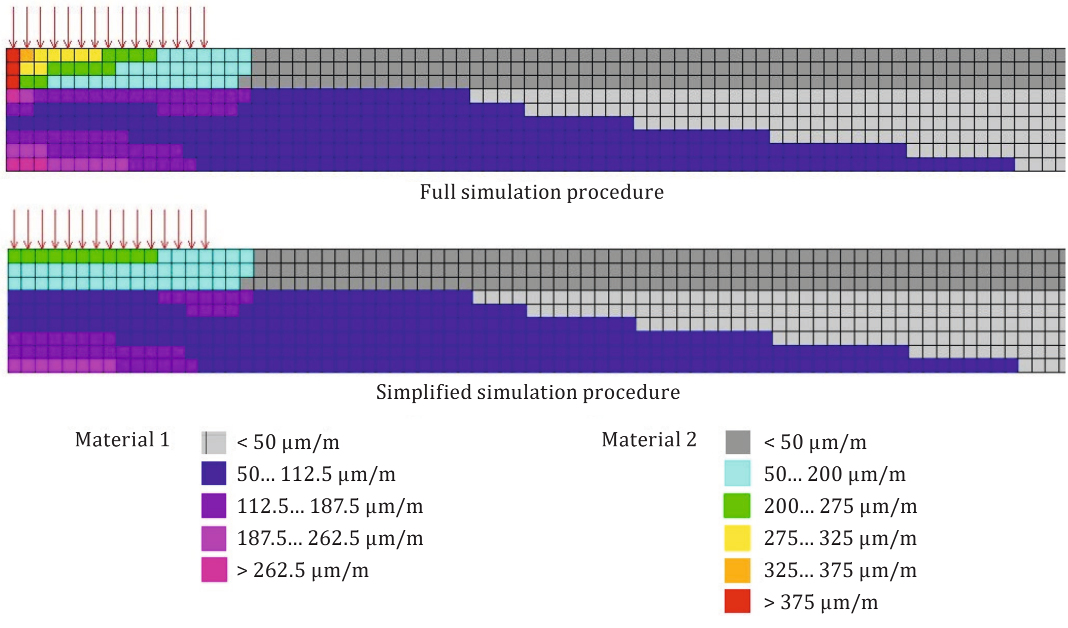

Figure 10. Distribution of fatigue models after 6 000 000 loading cycles

curves obtained by full simulation procedure are considerably more irregular and the values of strains are greater in comparison with those obtained by the simplified procedure. This phenomenon is explained by progressive change of fatigue models during simulation. Fatigue models applied after 6 million loading cycles are presented in Figure 10.

Conclusions

The pavement structural fatigue material model has been presented in this study. The transient analysis has been used to simulate time-dependent behaviour of the structure – rapid procedure has been developed and successfully applied to simulate fatigue of the asphalt concrete materials of two upper layers of the road structure.

Elastic properties of these materials initially obtained in the course of laboratory fatigue tests were successfully integrated in this material model.

The boundary conditions are used to represent infinity domain. This is done to avoid non-physical reflections of the elastic waves caused by time-dependent external load from the boundaries of the finite simulation domain obtained in the transient analysis of the structure.

Material models in this procedure were changes and the solution of the task was continued. Since strains in the elements increase over time due to the decrease of elastic properties caused by fatigue, it is possible that after some time it is necessary to change the fatigue model for some elements. Thus, the procedure that comprised interruption of solution, analysis of strain level in the elements and material model change with consequent continuation of the solution was repeated during the simulation.

In order to evaluate the effect of this simulation with progressive change of fatigue models, a simpler algorithm with only initial definition of fatigue models was tried. However, since the curves obtained by full simulation procedure were considerably more irregular and the values of strains were greater in comparison with those obtained by the simplified procedure, it is clear that the full procedure has to be used.

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