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). Zaghoul 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 (Zaghoul, 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 viscoelastic 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). Pirabaroonan, 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
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.
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:

\[ E = E_0 - k \sum \ln(N), \]

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:

\[ \Delta = \sum_{i=1}^{n} (E_{n}^{exp} - E_{n}^{mod})^2 \rightarrow \text{min}, \]

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

|          | AC11   | SMA11  |
|----------|--------|--------|
| Strain, \( \mu m/m \) | \( E_0, MPa \) | \( k \) | \( \Delta \) | Strain, \( \mu m/m \) | \( E_0, MPa \) | \( k \) | \( \Delta \) |
| 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

|          | AC11   | SMA11  |
|----------|--------|--------|
| Strain, \( \mu m/m \) | \( E_0, MPa \) | \( k \) | \( \Delta \) | Strain, \( \mu m/m \) | \( E_0, MPa \) | \( k \) | \( \Delta \) |
| 75       | 5994   | 30.9   | 440 396 070 | 150 | 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 diameter 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

| Layer   | $E$, MPa | $\eta$ | $\rho$, 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
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 4. Scheme of the road structure](image)

![Figure 5. Dependence of the vertical displacements on time](image)
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

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**Table 4. Use of experimentally applied fatigue models**

| 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                                                  |                                             |                                                       |

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**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).

\[ E = E_0 - k \sum \ln(1000N) \]  

(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](image-url)  

**Figure 8.** Dependence of vertical displacement on 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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