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3D finite elements analysis of a pavement structure with an open joint in the EPS sub-base

M. Duškov
Road and Railroad Research Laboratory, Delft University of Technology, Netherlands

A. Scarpas
Section of Structural Mechanics & Road and Railroad Research Laboratory, Delft University of Technology, Netherlands

ABSTRACT: The behaviour of pavement structures with an EPS sub-base and a relatively thin asphalt toplayer due to a 50 kN falling weight load is analyzed by means of a three-dimensional finite elements model with a single vertical interface layer. The position of the vertical interface layer was chosen next to the loading area. In this way an open joint between the EPS blocks at the most critical position with respect to the loading area can be modelled and the effect of such a joint on the structural pavement behaviour can be determined. Calculations have been carried out for pavement structures with only unbound base layers on top of the EPS sub-base and for pavements with a cement-treated loadspreading layer above the EPS. Finally the calculated deformations, asphalt strains and vertical stresses in the EPS sub-base are presented.

1 INTRODUCTION

In situ measurements [1,2] and numerical analyses with linear elastic multi-layer systems [3] have contributed to acquire a better insight of the structural response of pavement structures with an EPS sub-base. Among others the in-time development of surface deflections was measured (on various types of pavement structures) and the development of strains at the bottom side of the asphalt layer (in one flexible pavement). By this means both, the effective stiffness of the individual pavement layers and the overall condition of the pavement structures after several years of traffic were studied. The measurements indicated some locations of weakness in the pavement structures with high surface deflections and rutting. In the case of a pavement in Rotterdam with a thin asphalt toplayer even longitudinal cracking occurred. This last instance was the initiation point for the analysis presented in this contribution.

The above-mentioned longitudinal cracking in the flexible pavement structure of the Matlingeweg in Rotterdam occurred within a month after completion of the first reconstruction phase and before overlaying [1]. It illustrates the potential dangers associated with the inadequate design and/or construction of pavements with an EPS sub-base. Out of in-situ observations at the time it became apparent that the cause was wide gaps in the joints of adjacent EPS blocks. The location of these longitudinal joints in the cross section coincided with the position of the wheel track. Simulation of these events and in particular of the influence of the presence of joints between the EPS blocks on the load transfer mechanisms of the pavement structure constituted the initial motivation for the pavement analysis that will be presented in this contribution.

Simulation of open joints and cracks implies the implementation of discontinuities in the pavement layers. By default this is impossible in the available pavement analysis programs based on the linear elastic multi-layer theory. For this reason the three-dimensional finite elements system CAPA-3D (Computer Aided Pavement Analysis) developed at Delft University of Technology [4] was utilized. In CAPA-3D simulation of joints between EPS blocks and/or cracks can be achieved by means of the so called "interface" finite elements which, because of their formulation, are capable of capturing the discontinuous deformation characteristics of these regions.

In following sections the geometry, the material properties and the load characteristics of the simulated pavement structures are reviewed. Three different stages of crack development in the body of the pavement have been simulated by means of the CAPA-3D program. The deformations, stresses and strains at critical pavement locations for every one of these cases are presented. On the basis of these, design suggestions are made for pavement structures with an EPS sub-base.

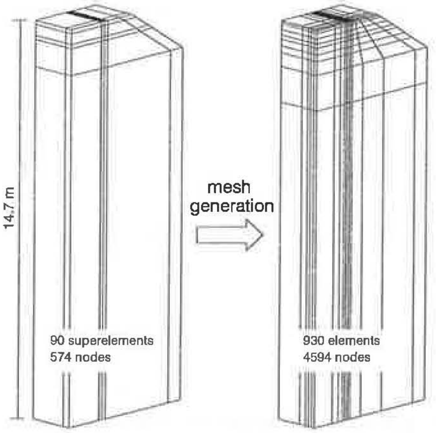

Figure 1. Generation of the CAPA-3D final mesh from the initial 3D mesh consisting of superelements.

2. CAPA-3D FINITE ELEMENT MESH

The initial and final CAPA-3D finite elements meshes of the pavement model are shown in Figure 1. The final mesh is generated from the initial mesh that consists from the so-called 'superelements'. Within superelements only one material type can be implemented. The generated mesh is composed of 930 elements with 4594 nodes, obtained by division of the initial mesh with 90 superelements and 574 nodes. The element division, fine in the loadspreading area, becomes coarser with increasing distance from the load center.

The boundary conditions are defined in the nodes of the superelements where the displacements in horizontal and vertical directions can be restrained. The dimensions of the mesh are 14.7 m by 5.55 m (3.0 m at the top). Such a large vertical dimension of approximately 15 m is chosen to prevent any influence of the rigid bottom on the loadspreading inside the pavement model. The height of the mesh is approximately equal to the dimensions recommended in the literature [5] for pavement finite element models. For the same reason, on the one hand, and taking account dimensions of a real road cross-section, on the other, the horizontal dimension of the mesh is taken as 5.5 m. The dimension in the longitudinal direction is 1.8 m which coincides with the distance between the load center and the last geophone belonging to the standard configuration of a falling weight deflectometer. In this way it was possible to draw complete deflection bowls at the pavement surface in the cross and longitudinal direction of the road.

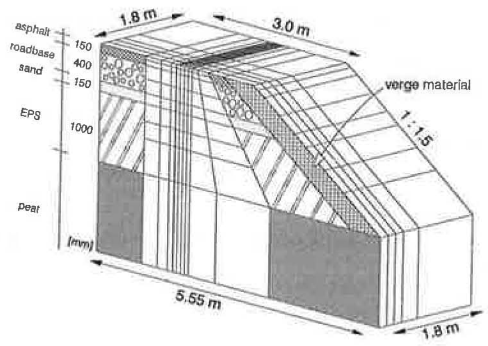

Figure 2. Pavement materials and corresponding layer thickness values in the CAPA-3D pavement structure model with a single vertical interface layer.

2.1 *Analyzed pavement structure*

The layer thicknesses in the pavement model have been chosen such that they are close to those of the mentioned existing asphalt pavement in the Matlingeweg in Rotterdam. On the considered pavement structure with an EPS sub-base severe rutting and cracking developed within a month after the first stage of reconstruction and before planned overlaying [1].

The toplayer of asphaltic concrete has a thickness of 150 mm, the thickness of the unbound base layer and the sand layer is 400 mm and 150 mm respectively, and the sub-base consists of a 1.0 m thick EPS layer. The lay-out of the modelled pavement structure is shown in Figure 2.

2.2 *Materials parameters*

The materials parameters, E moduli and Poisson's ratios of the model layers, are assumed to be similar to the back-calculated values in the existing pavement structure with EPS [1]. Only for the peat a somewhat lower value of 30 MPa is assumed. The E-modulus of EPS has a value of 5 MPa which is usually applied in design calculations for EPS20. The E-values for the sand, base material and asphalt layer are equal to 100, 300 and 10500 MPa respectively, while the Poisson's ratio, identical for all these materials, has a set value of 0.35. The Poisson's ratio for EPS, $\nu_{EPS}=0.1$, was found in the performed materials research [6].

2.3 *Modelled loading and vertical interface elements*

The modelled loading corresponds to a 50 kN falling weight load through a circular loading plate with a diameter of 300 mm. Because of symmetry only half of the described loading is really modelled as it is

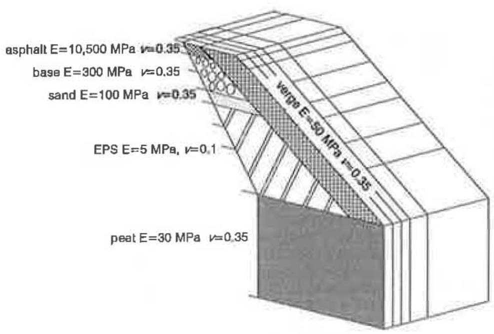

Figure 3. Material parameters, E moduli and Poisson's ratios of the layers of the modelled pavement structure.

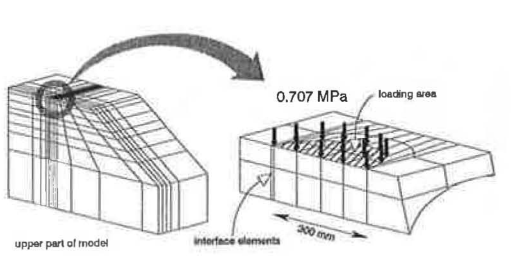

Figure 4. Modelled 50 kN load through a circular loading plate with a diameter of 300 mm.

shown in Figure 4. The representative contact stress of 0.707 MPa is applied on the upper edges of the eight elements next to the vertical interface layer. The position of the vertical interface layer direct next to the loading area represents the most critical configuration which can appear in situ. In the vertical interface layer also a joint between the EPS blocks is modelled so that the load lays exactly above the longitudinal open joint. Therefore the pavement structure is loaded where the unbound base materials are not properly supported because of the open joint in the layer below. This situation leads to an improper support of the asphalt toplayer by the roadbase. The observed result in the case of the Rotterdam's road was longitudinal cracking of the asphalt.

By means of the implemented interface elements, besides an open joint between the EPS blocks, it also possible to create a crack in the asphalt layer and to create no-tension response of the unbound materials in the base layers. This can be achieved by the specification of low horizontal stiffness for the used interface corresponding to the unbound materials and the cracked asphalt layer.

Furthermore, it is possible to model the interface elements with a behaviour identical to the surrounding elements. In such a way the influence of the presence of interface elements can be excluded and the pavement structure with neither cracks nor open joints can be modelled.

3. RESULTING PAVEMENT STRUCTURE DEFORMATIONS

In the following, the resulting deformations obtained in the modelled pavement structure are presented for three essentially different situations. The first case describes the situation with no crack in the asphalt toplayer and a monolith EPS sub-base. In the second case an open joint is modelled in the EPS layer. At the same time the unbound character of the base material and the sand in the layers above the EPS sub-base is simulated by reduction of their horizontal stiffness. In the third case the pavement structure is analyzed with an open joint in the sub-base, a crack in the asphalt layer and the no-tension response of the unbound materials.

The calculated deformations in the first case without 'active' interface elements are presented in Figure 5. The model contains no discontinuity in the load spreading area and only a very small deformations due to a 50 kN loading occurs in the pavement structure.

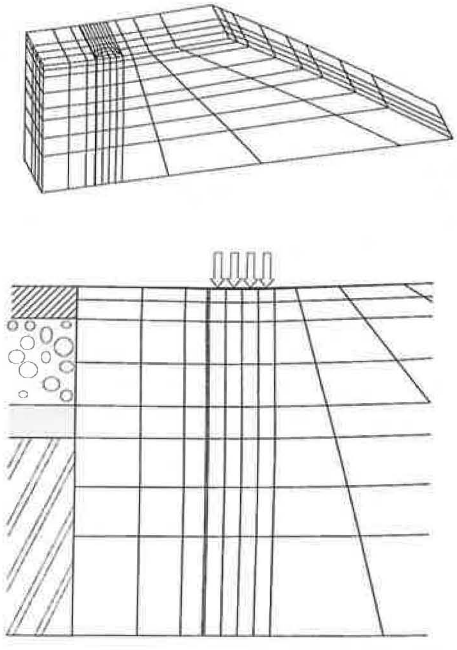

Figure 5. Deformed mesh due to the 50 kN load where neither an open joint between EPS blocks nor a crack in the asphalt layer are modelled.

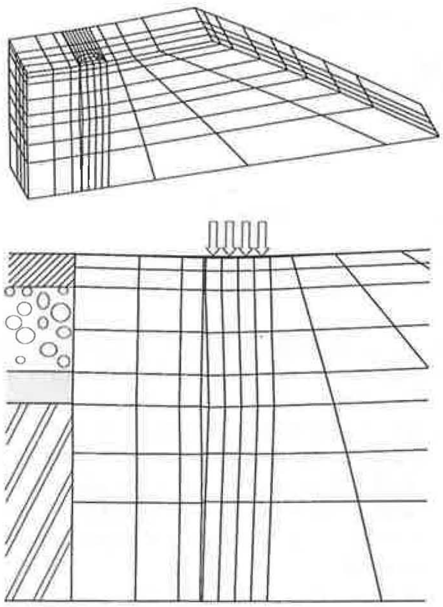

Figure 6. Deformed mesh due to the 50 kN load of the pavement model where an open joint between EPS blocks but not a crack in the asphalt layer are modelled.

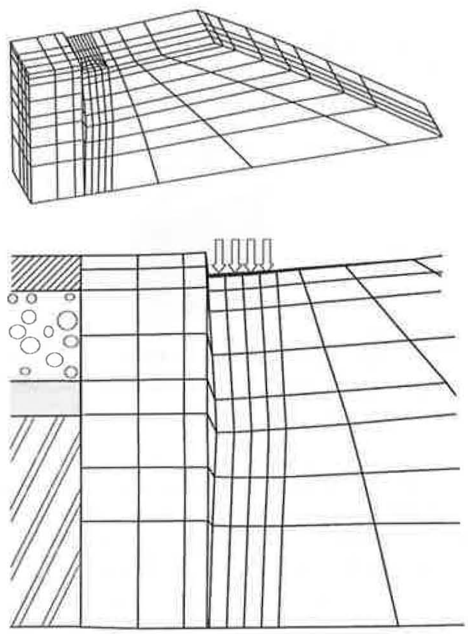

Figure 7. Deformed mesh due to the 50 kN loading of the pavement structure with both an open joint between the EPS blocks and a crack in the asphalt toplayer.

Resulting deformations in the pavement structure with an open joint between the EPS blocks and the no-tension response of the unbound materials in the layers above the EPS sub-base are shown in Figure 6. The asphalt layer was modelled to be continuous without cracks next to the loading area.
The obtained deformations due to a 50 kN loading are reflected in widening of the interface elements in the unbound roadbase as a result of appearing tensile stresses. The implemented interface elements have a low horizontal stiffness and can not resist the tensile deformations (which corresponds with the actual behaviour of the unbound materials). The most significant result is additional widening of the joint between the EPS blocks. The support of the EPS sub-base to the above laid roadbase is reduced due to the further opening of the existing joints between the EPS blocks. The insufficient support to the unbound base reflects further in the insufficient support of the roadbase to the asphalt layer. Consequently, higher stress and strain values occur in the asphalt layer under the load.

Calculated deformations caused by a 50 kN loading in the pavement structure with both an open joint between the EPS blocks and a crack in the asphalt layer are graphically presented in Figure 7. The cracking in the asphalt layer leads to big differences in deformations between the 'loaded' and 'unloaded' part of the pavement structure. The differences in vertical deformations of the adjacent EPS blocks result in relatively bigger vertical permanent deformations in the block below the load than on the other side of the joint, and differences in level between those blocks as observed on the Matlingeweg in Rotterdam [1].

4. CALCULATED STRESS AND STRAIN VALUES

In this paragraph the horizontal stress (ϵ_{xx}^{asph}) and strain values (σ_{xx}^{asph}) at the bottom of the asphalt layer and the vertical stress values at the top of the EPS sub-base (σ_{zz}^{EPS}) are listed for the cases described in the previous section (❶). Additionally, the analyses were repeated for pavement structure models with, on the one hand, a cement-treated layer instead of a sand layer above the EPS sub-base (❷) and, on the other hand, with a somewhat heavier EPS type in the sub-base (❸).

❶ Unbound base and sand layer above EPS sub-base

	ϵ_{xx}^{asph} [µm/m]	σ_{xx}^{asph} [MPa]	σ_{zz}^{EPS} [kPa]
⇨ neither an open joint between EPS blocks nor a crack in the asphalt layer	108	1.76	4.96

➪ an open joint between EPS blocks but no crack in the asphalt layer

138 2.14 6.03

➪ both an open joint between EPS blocks and a crack in the asphalt layer

\- - 11.91

❷ Cement-treated layer above EPS sub-base (E=11,000 MPa, ν=0.35)

ϵ_{xx}^{asph} [μm/m]	σ_{xx}^{asph} [MPa]	σ_{zz}^{EPS} [kPa]

➪ neither an open joint between EPS blocks nor a crack in the asphalt layer

89 1.45 3.86

➪ an open joint between EPS blocks but no crack in the asphalt layer

90 1.47 3.90

➪ both an open joint between EPS blocks and a crack in the asphalt layer

\- - 5.66

❸ Unbound base layers above heavier type EPS (E_{EPS}=10 MPa instead of E_{EPS}=5 MPa)

ϵ_{xx}^{asph} [μm/m]	σ_{xx}^{asph} [MPa]	σ_{zz}^{EPS} [kPa]

➪ neither an open joint between EPS blocks nor a crack in the asphalt layer

106 1.73 6.09

➪ an open joint between EPS blocks but no crack in the asphalt layer

128 2.02 7.49

➪ both an open joint between EPS blocks and a crack in the asphalt layer

\- - 15.75

5. CONCLUSIONS

❑ Presence of open joints between the EPS blocks in the sub-base significantly affects the behavior of pavement structures with an unbound roadbase. The wide joints make impossible mutual support of the blocks and, at the location directly above the open joint, the proper support of the EPS layer to the above-laid unbound base. The insufficient support to the unbound base reflects in the insufficient support of the roadbase to the asphalt layer. Consequently, higher stress and strain values occur in the asphalt layer under the wheel load with, as a final result, a shorter design life of the pavement structure. If the strain values become critical this leads to cracking in the asphalt. After the cracking of the asphalt layer, a wheel loading at one side of the surface asphalt crack will result in a relatively bigger vertical deformations in the EPS block below the load than those on the other side of the joint.

❑ Implementation of a cement-treated layer above the EPS sub-base neutralizes the (negative) influence of the block joints on the pavement behavior. Such a cement-treated layer insures enough support to the unbound roadbase layers above this layer. This is valid also in the case of existing open joints between the EPS blocks and, therefore, an insufficient support from the EPS sub-base below. Construction of a cement-treated layer contribute to a significant increase of the pavement design life as well.

❑ Application of a heavier EPS type with a somewhat higher elasticity modulus in the sub-base has only very limited influence on the horizontal strain values at the bottom of the asphalt layer and, therefore, on the overall behaviour of the pavement structures with the EPS sub-base.

6. ACKNOWLEDGEMENT

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