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Structural Aspects of Asphalt Pavement Heating and Cooling Systems

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STRUCTURAL ASPECTS OF ASPHALT PAVEMENT HEATING AND COOLING SYSTEMS

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ABSTRACT

Systems for heating and cooling of road infrastructure provide a source of durable energy. Ooms Avenhorn Holding developed Road Energy Systems® and carries out extensive research into the structural effects of a heat conducting system on pavement performance. Laboratory tests have been performed on asphalt blocks with an embedded tube. The results of these tests have been compared with the finite element simulation of the test set-up. The conclusion is that the FE analysis is a useful tool to predict the failure mechanism and to obtain insight into the stress distribution in the specimen. Next a pavement structure, consisting of a specially developed three-dimensional reinforcing grid, a modified asphalt mix and polyethylene tubes, is modeled in the finite element system CAPA-3D and subjected to various load cases, concerning heavy duty applications like airfield platforms. The positive effect of the reinforcing grid on the response of the pavement is clearly demonstrated in numerous analyses.

KEYWORDS

heating/cooling, durable energy, reinforcement, asphalt pavements, laboratory testing

INTRODUCTION

Ooms Avenhorn Holding, Tipspit en WTH Vloerverwarming developed a system for heating and cooling of buildings and road infrastructure during the period 1997-2001. This system consists of an asphalt concrete layer with a reinforcing grid and a water-conducting medium. Because of its dark color, asphalt has a high heat absorbing capacity. The tubes are able to extract this heat in the summer time and to heat the pavement in the winter in order to keep it free from snow and ice (thereby extracting cold).

The goal of Road Energy Systems is to achieve an energy saving in the field of industrial buildings, housing and agriculture by means of storage of the extracted energy in aquifers, thereby achieving a reduction of CO_2-emissions.

Earlier research by means of finite element analyses (van Bijsterveld, 2000) showed that the presence of tubes in asphalt influences the durability of the structure negatively because of peak stresses near the tube which can lead to crack initiation. The prevention of this phenomenon was one of the reasons to develop a reinforcing grid. The goal of this research, initiated by the Research & Development department of Ooms Avenhorn Holding, is to analyze the structural aspects of the asphalt pavement heating and cooling system by means of micro mechanic finite element modeling combined with laboratory tests.

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Road Energy Systems consists of a layer of modified asphalt of 40 mm thickness. In the current design the water-conducting medium for heating and cooling consists of a specially developed, three-dimensional polypropylene grid with polyethylene pipes at a center-to-center distance of 150 mm embedded in this asphalt layer (figure 1).

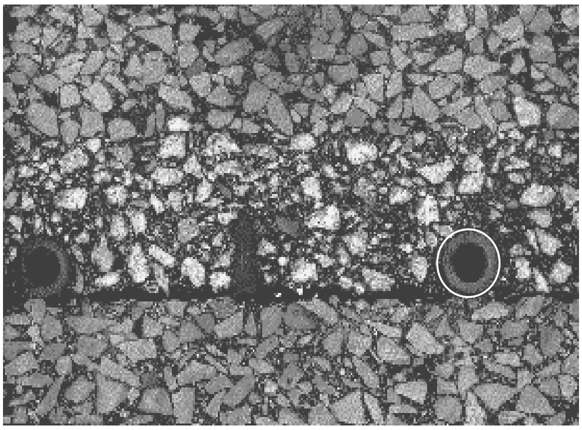

figure 1 Tubes embedded in asphalt (RES prototype at test section Hoorn, the Netherlands)

The RES asphalt contains a modified bitumen with a higher resistance against cracking. The asphalt can be applied at a lower temperature (130°C) so it will not harm the plastic pipes and reinforcing grid. Furthermore, the reinforcement pattern is designed to enhance confining and arching actions therefore reducing the need for thicker structures.

The RES asphalt layer can be applied directly on a base of concrete or asphalt. An interface layer of high quality polymer modified bitumen between the base layer and the RES asphalt layer provides a flexible but firm adhesion, which is capable of withstanding the (thermal) movements of the base layers. Depending on the expected movements the thickness of the interface can be varied between 1.0 and 3.0 mm. The grid and tubes are also sprayed with 1.5 mm bitumen to provide a good adhesion of the asphalt. The bitumen has to be of a high quality (elastomer modified) for it to remain flexible also with low temperatures thereby ensuring adhesion of the asphalt during thermal movements caused by different thermal expansion coefficients of the materials.

The specifications of the wearing course on the RES asphalt layer depends highly on the function of the complete road structure; an ultra thin wearing course of 15 to 20 mm can be applied for light traffic (e.g. parking lots for passenger cars) or a conventional wearing course of 35 to 50 mm for heavy traffic, industrial vehicles or airplanes. The wearing course can be removed and replaced (e.g. to ensure skid resistance) with the usual techniques without harming the collector.

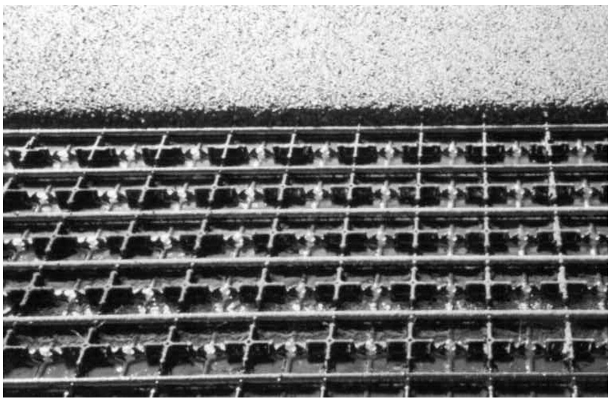

figure 2 The Road Energy System under construction

The handling of the relatively stiff polyethylene tubes does not hamper the construction process of the road. The reinforcement pattern ensures the exact position and the equal distribution of the tubes throughout the surface, causing an equal temperature distribution in the structure during heating and cooling. The grid is also designed to take the load of the asphalt paver or other construction traffic.

In Scharwoude, the asphalt pavement heating and cooling system has been applied on a public road and a parking lot (figure 2).

THE EFFECT OF TUBES IN ASPHALT

Test preparation with Finite Element Analyses

A test section with RES was built on an industrial area in Hoorn, The Netherlands (de Bondt et al, 2001). The structure consists of Topflex 10/20 with RES tubes embedded in the asphalt. Note that Topflex is a different asphalt mix than RES 0/11 in the final design (RES 0/11 is a special asphalt mixture developed for asphalt heating and cooling systems). Parts of the structure were cut out and a number of test blocks were sawn, 20 with a tube in it, another 5 without. The grid used in the test section has different properties than the current design, so it was ensured that none of the specimens had remains of the reinforcing grid enclosed. A simple compression test has been carried out in the R&D laboratory of Ooms Avenhorn Holding in a universal testing machine (UTM) with a capacity of 100 kN. Since the available number of specimens was limited, a finite element analysis of the test was carried out in order to get an idea about which test conditions would give the most information.

The analyses are linear elastic, so they are only valid for small deformations. However, it is very well possible to determine where the inelastic deformations will occur first and under which stress conditions. These are important issues for a successful test in the lab and a proper interpretation of the results.

The tube geometry is carefully modeled in CAPA 3D with 840 20 noded cubic elements. Pictures of the model are shown in figure 3.

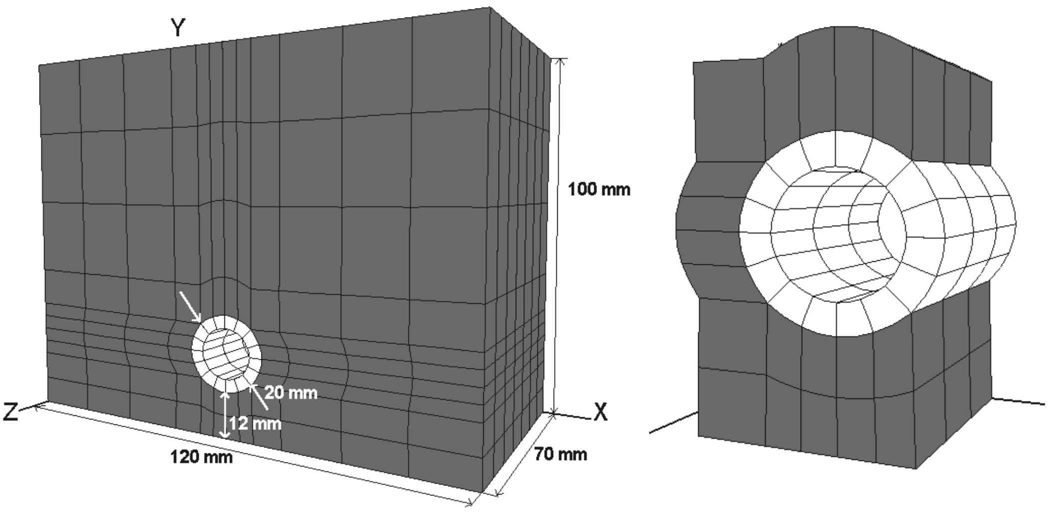

figure 3 Finite element modeling of the test specimen

The FE analyses have been carried out for temperatures of -15°C, 10°C and 35°C. The Poisson's ratios of the asphalt mix are determined according to the master curves presented by Sayegh (1967). According to this theory the Poisson's ratio is temperature and loading time dependent. Under traffic loading conditions the ratios at the given temperatures vary from 0.10 to 0.49. When performing a compression test at a relatively low strain rate and with high temperatures, the Poisson's ratios become higher than the generally assumed 0.35. The moduli of elasticity of the asphalt and the tubes have been determined for the various temperatures by means of extrapolation using charts derived from laboratory testing (de Bondt, 2002). It should be noted that the strain rate of the test (0.1 mm/s) is much lower than the available data in the charts. In table 1 an overview of the relevant material properties is presented.

table 1 Estimated material properties for strain rate = 0.1 mm/s

	test temperature		
	-15°C	**10°C**	**35°C**
E-modulus			
RES tube (MPa)	50	55	35
Topflex 10/20 (MPa)	5300	320	5.3
Poisson's ratio			
RES tube	0.3	0.3	0.3
Topflex 10/20	0.35	0.45	0.49

For the finite element analyses a displacement of the top of the specimen of 1 mm is prescribed. The theoretical linear elastic value for the vertical load that is needed to obtain a 1 mm displacement at the top for a solid block as well as the calculated loads for the block with tube are displayed in table 2. It is obvious that the loads at -15°C and 10°C cannot be applied by the UTM and the test block is likely to fail before reaching the maximum displacement. The results in table 2 also indicate that, assuming similar asphalt qualities, the "overall stiffness modulus" is hardly affected by the presence of a tube.

table 2 Computed loads at 1 mm prescribed displacement

	test temperature		
	-15°C	**10°C**	**35°C**
without tube (kN)	445	26.9	0.445
with tube (kN)	416 (93.5%)	25.4 (94.5%)	0.426 (95.8%)

Laboratory compression test

For the compression test 14 test specimens were selected. The density of 5 specimens without tube is determined by means of weighing the specimens under and above water. The results are mentioned in table 3.

Blocks 1.4, 1.5 en 3.1 are used to determine the stiffness of the material at 35°C. The test set-up is shown in figure 4. The top and bottom of the block are treated with soap and a thin plastic sheet to minimize friction. Displacement transducers (LVDTs) are installed to measure the horizontal deformations of the specimen. A summary of the results of the test is given in table 4. The stiffness is determined by drawing a tangent line to the linear part of the curve in a stress-strain diagram. The strength is an overall strength of the block and is calculated by dividing the maximum force of the UTM over the area of the loaded surface. It should be noted that this does not represent the maximum stress in the specimen and therefore not the strength of the material. Due to the more complex geometry an uneven distribution of stresses occurs in the specimen.

figure 4 Test set-up compression test

table 3 Properties of the 5 specimens without tube

Blocknr.	height [mm]	width [mm]	length [mm]	density [kg/m^3]
1.4	102	71	117	2233
1.5	100	71	116	2201
3.1	100	69	119	2176
2.1	101	71	122	2217
2.2	101	71	121	2220

table 4 Results compression test 35°C

block	Fmax [kN]	E mod [MPa]	strength [MPa]
1.4	7.9	35	1.1
1.5	6.2	34	0.86
3.1	5.0	17	0.73

table 5 Blocks with pipe, 35°C

block	Fmax [kN]	E mod [MPa]	strength [MPa]
0.1	6.7	44	0.94
4.1	4.3	18	0.64
4.2	4.8	30	0.69
average	5.3	31	0.76

table 6 Blocks with pipe, 10°C

block	Fmax [kN]	E mod [MPa]	strength [MPa]
5.1	25.5	174	3.73
7.1	24.4	148	3.61
7.4	24.6	166	3.57
average	24.8	163	3.64

table 7 Blocks with pipe, -15°C

block	Fmax [kN]	E mod [MPa]	strength [MPa]
1.2	92.1	619	13.2
5.2	86.6	609	12.4
7.2	80.7	411	11.8
average	86.5	546	12.5

table 8 Specimen without pipe, -15°C

block	Fmax [kN]	E mod [MPa]	strength [MPa]
2.1	91.7	560	13.1

Though the variation in the results is large (mainly thought to be caused by the large aggregate/specimen size ratio), it can still be concluded that the behavior of the specimen at 35° is stiffer than expected from the material parameters originating from testing on laboratory prepared specimens (de Bondt, 2002). The results of the tests with tube at -15°C, 10°C and 35°C are summarized in table 5 to table 8. It can be seen that at 10°C and 35°C the stiffness of the specimen is lower than the assumed values (table 1). This can be explained by the low deformation rate of the test. The stress-strain diagram for the tests at 10°C is displayed in figure 5. The course of the test is shown with pictures in figure 6a to e.

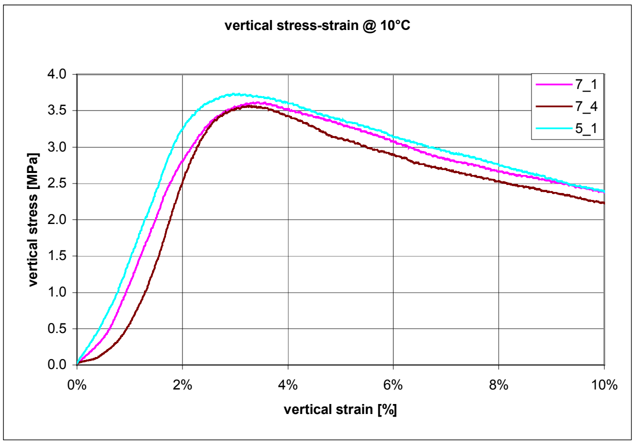

figure 5 σ-ε-diagram for specimen with tube at 10°C

The bigger the difference in stiffness between the asphalt and the tube, the more pronounced is the damage pattern. In case of a temperature of about 35°C cracks develop throughout the specimen whereas at -15°C cracks develop in the area next to the tube until failure. One of the specimens developed a crack from the right side of the tube upwards through the center and lost all coherence. This kind of behavior is inherent to the grain size (10/20 mm) with respect to the specimen size (100 mm * 120 mm).

This series of photos shows a compression test at 10°C. The first picture shows the specimen close after the start of the test.

Soon the first cracks can be observed. The specimen starts to bulge (poisson effect) and a slight ovalization of the tube occurs.

The specimen has failed. Parts of the material are being pushed out to the sides and the tube is flattened. This stress pattern was also predicted by the FE analyses (see figure 7).

Notice that the material above the tube is intact. The tube deforms and the material next to the tube takes the load and fails.

When the load is removed the relatively thick tube springs back elastically and thereby pushing itself through the thin asphalt layer under the tube (note that the block is upside down in the picture). Later the asphalt has been removed from the tube and no structural damage to the tube was found. In the final design of Road Energy Systems the reinforcing grid should prevent this phenomenon.

figure 6a-e Photos of a compression test on a specimen at 10°C

Result interpretation with finite element analyses

The FEM analyses of the test have been repeated after the test with new parameters derived from the measurements. This means the measured modulus of elasticity of the asphalt and the deformation at break were used in the parameters. With these analyses more information is obtained about the stress distribution in the specimen. An important difference in the deformation pattern is caused by the absence in the model of horizontal friction in the top and bottom of the specimen. The specimen in the lab bulges whereas the FE model remains straight.

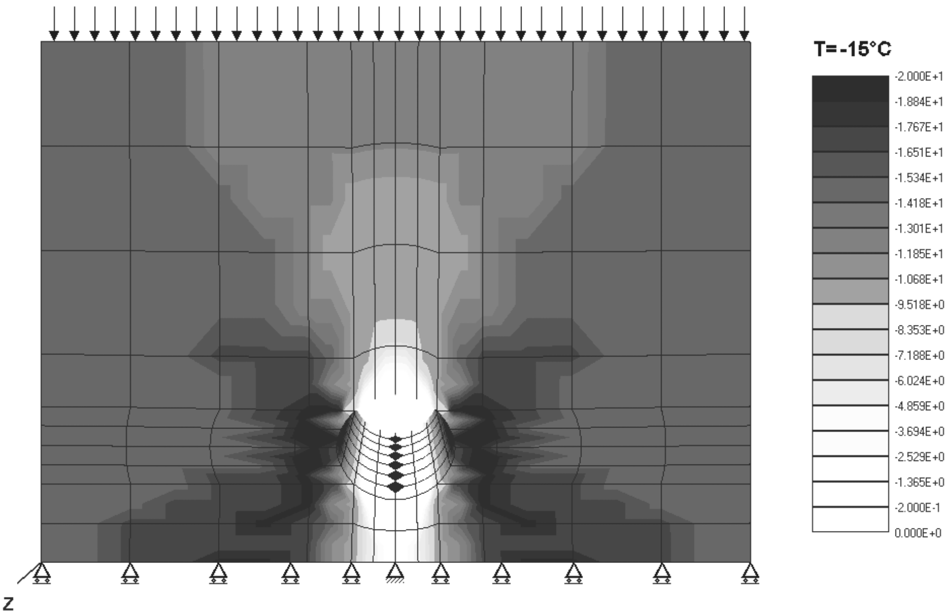

figure 7 vertical stresses in specimen at 15°C

In figure 7 the vertical stresses are displayed graphically. Note that the original pictures are in full color and that therefore the stress level is not always apparent from this picture. For color pictures reference is made to de Bondt (2002). Diagonally from the tube to the sides of the specimen a stress path develops. Above and under the tube the stresses are very low because the tube hardly carries any load. Although the values change with the temperature, the phenomena are similar. This can be explained by the relatively low stiffness of the tube compared to the asphalt. Even at higher temperatures, where the stiffness of the asphalt is almost equal to the stiffness of the polyethylene, the geometry of the tube (the opening) causes a flexible behavior.

From the orthogonal and shear stresses the principal stresses have been calculated. The results show that the maximum principal stress is roughly 50% higher than the average vertical stress in the block. At –15°C and 10°C this value occurs in the asphalt, at 35°C the maximum stress occurs in the tube.

table 9 FE analyses results

	temperature		
	-15°C	**10°C**	**35°C**
F_{max} (kN)	-119	-38.5	-8.6
Principal tensile stress (MPa)	4.2	1.35	0.78
Principal compressive stress (MPa)	-21.5	-6.24	-1.63
Average vertical stress (MPa)	-14.1	-4.58	-1.02

The analyses after the laboratory tests have been performed with two distinct models. In the first model the tube elements are directly connected to the surrounding asphalt. In the second mesh the tube and the asphalt are separated by an interface layer, which allows easy sliding of the asphalt along the tube. In reality the tube is also sprayed with a 1.5 kg/m^2 polymer modified bitumen. This is for reasons of improvement of heat transfer, asphalt adhesion and allowance of movements due to differences in coefficients of thermal expansion. In the finite element model, the horizontal interface shear stiffness is assumed 0.1 (N/mm)/mm^2, the vertical shear stiffness is set to 55 (N/mm)/mm^2. The difference in the deformation pattern is shown in figure 8.

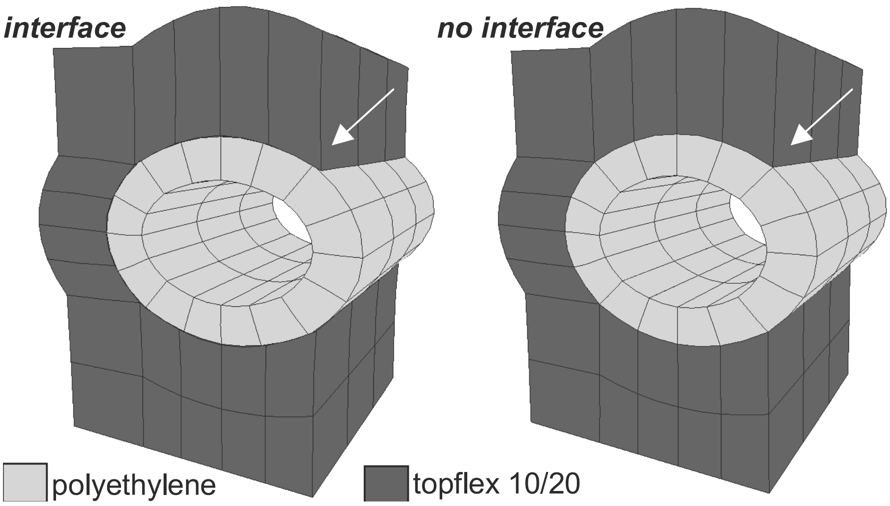

figure 8 Deformation patterns with and without interface between tube and asphalt.

It can be noticed that visually the deformation pattern of the mesh with interface provides a better match with the laboratory tests. The presence of the interface layer results in higher stresses in the tube and in the asphalt surrounding the tube. There are pronounced stress paths from the tube to the bottom of the specimen. The response of the whole structure is less stiff than without interface layer.

Conclusions from the laboratory tests

From the laboratory compression tests on asphalt with an embedded tube and the interpretation of the results using finite element analyses, the following can be concluded:

- The presence of a tube in the asphalt results in principal stresses approximately 50% higher than the mean vertical stress.
- The presence of an interface layer around the tube in the FE element model results in slightly higher peak stresses and a less stiff behavior of the structure. This model seems closer to reality.
- Despite the limitations, a linear elastic finite element model can be useful in the preparation of a laboratory test and the interpretation of the results, provided that the material properties are estimated for the test conditions (temperature and strain rate).

All in all, the laboratory tests and their finite element simulations have resulted in a model which is thought to be accurate enough for pavement design and optimization purposes.

FINITE ELEMENT ANALYSES FOR HEAVY DUTY APPLICATIONS

Situation description

Pavement heating and cooling is especially interesting on large rectangular areas, such as airport platforms. For these heavy duty applications special analyses have been carried out. In this case the base of the structure consists of concrete slabs. Over the slabs and joints a stress relieving system, consisting of 3 mm high quality PMB, is applied and then the RES-system. In these analyses not only the high loads (30 tons per wheel with a contact pressure of 1.4 MPa, 500 mm diameter) but also relative vertical movements between the slabs and horizontal movements of the joint due to temperature differences are relevant (de Bondt, 1999). For each of the load conditions the calculations are made with and without a reinforcing grid. The goal is to determine whether the system can resist the loads and to get insight into the confining effect of the reinforcing grid.

Finite element mesh

For this analyses emphasis is put on the detailed design of the reinforcing grid including the tubes. Therefore only a small part of the structure is modeled, just enough to be able to model all the details of the structure and to analyze a number of relevant load cases. A characteristic part of the mesh is shown in figure 9. The figure shows a part of the concrete base, the reinforcing grid and the tube. The total mesh, consisting of 2640 20-noded cubic elements and 240 16-noded interface elements, also represents the stress relieving system, the RES asphalt (0/11) in the reinforcing grid and the wearing course. The boundary conditions of this micro mechanic model are of extreme importance. In some cases the symmetry planes result in peculiar load cases, which are unlikely to occur in reality. For the purpose of this research however, the conditions are adequate and minimize disturbance by boundary effects within the area of interest.

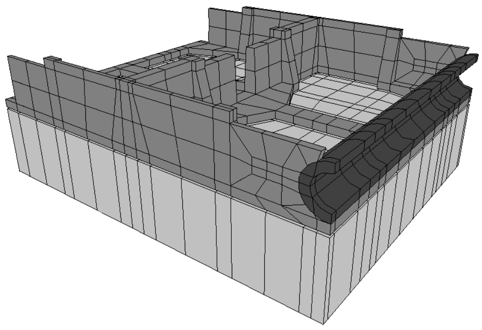

figure 9 Characteristic part of FE mesh

Load cases

The finite element analyses consist of more than 20 different cases, deriving from combinations of variations in temperatures, loading times, support conditions and loads. A selection of a few illustrative cases will be presented here, for details again reference is made to de Bondt (2002).

Traffic loading (confining pressures in reinforcement)

Three distinct load cases for traffic loading on a solid concrete base (without joint) have been analyzed of which one will be dealt with here. Half of the mesh is loaded on the side of the tube as shown in figure 10. Goal is to see the effect of confining effect of the reinforcement. This means that a higher horizontal stress in the asphalt and less horizontal strain is expected in the mesh with reinforcing grid compared to the mesh without grid. This effect should be the most obvious in summer circumstances since under those circumstances the reinforcing grid has an significantly higher stiffness than the filling asphalt. The material properties are estimated for a temperature of 35°C and slow moving traffic (10 km/h). The surface

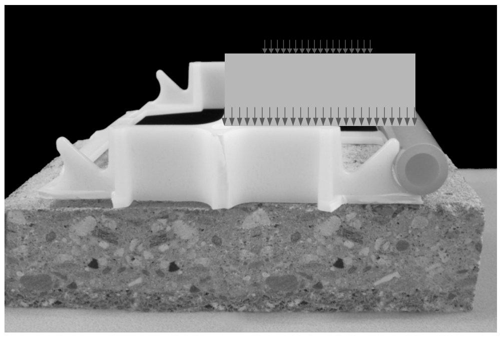

figure 10 Traffic loading

load is representing the pressure under the wheel of a McDonnell Douglas MD11 aircraft before take off. It is noted that without compression/confining RES 0/11 cannot sustain this load (table 5).

The deformed mesh (figure 12) shows that the loaded part of the mesh tends to widen and this movement is restrained by the grid. In figure 11 the horizontal displacements (along the white line in figure 12) of the mesh with grid and without grid are compared; the effect of the grid is clearly visible.

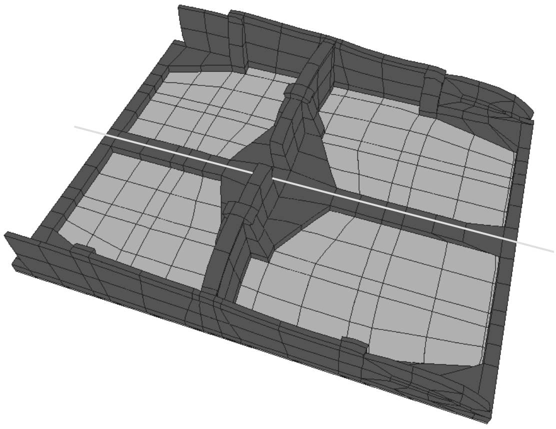

figure 12 Deformation of the grid due to traffic

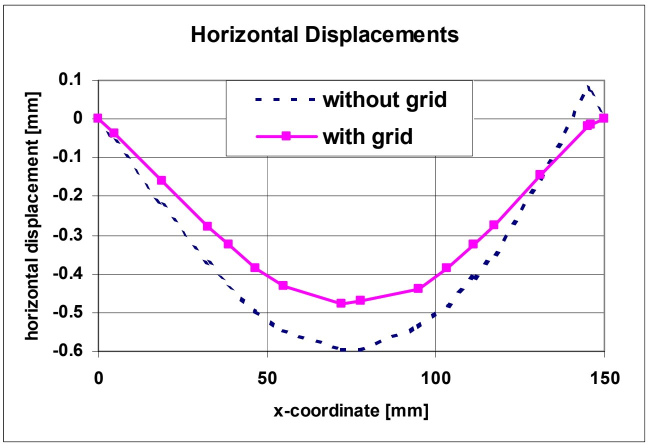

figure 11 horizontal displacements in bottom of RES asphalt layer, with and without grid

Also the strains in the RES asphalt show the expected phenomena. In the corner of the reinforcing grid a compressive horizontal strain occurs which indicates confinement. The horizontal strains in general are slightly lower in the mesh with grid reinforcement. There is a significant reduction of strains in the tube due to the presence of reinforcement (see figure 13).

Also when looking at the vertical stresses next to the tube, the positive effect of the reinforcement is considerable (see figure 14).

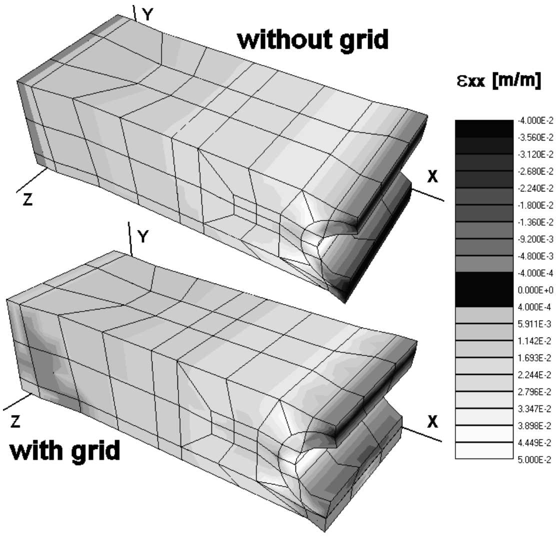

figure 13 Horizontal strain in RES layer

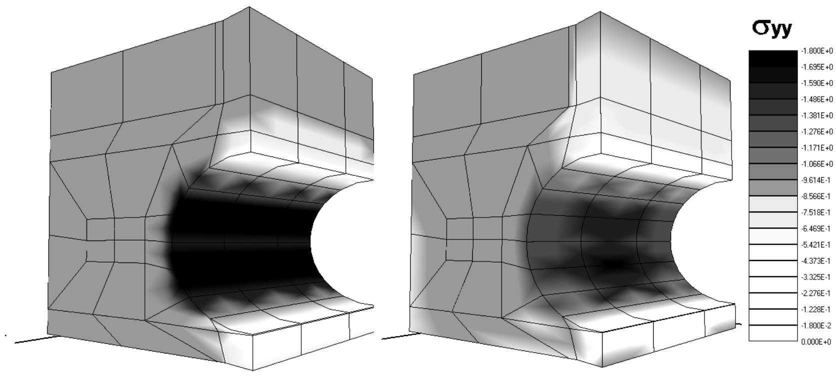

figure 14 Vertical stresses in the RES asphalt next to the tube. Left without and right with reinforcement.

Traffic loading on joint

In these cases a joint is simulated by replacing some of the concrete elements with a material with very low stiffness. In addition, the support conditions under the load are adjusted in such a way that a realistic relative vertical movement at the surface of the concrete of the joint occurs (i.e. about 0.5 mm). This movement has been measured with a falling weight deflectometer. Two cases have been considered; a joint perpendicular to the tube direction and a joint parallel to the tube. In both cases the joint is situated in the middle of the mesh. The difference in stresses and strains are small. However, when looking at the deformations and displacements some differences can be observed. The deflection of the concrete slabs is transferred more smoothly by the reinforcing grid as shown in figure 16 and figure 17.

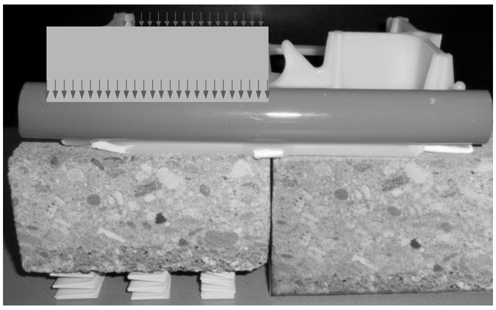

figure 15 traffic on joint

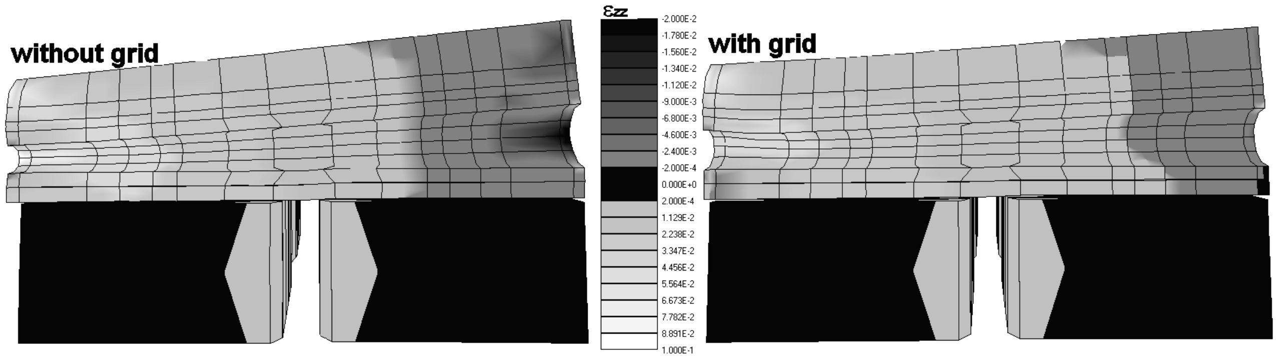

figure 16 Deformation and horizontal strains in the grid and tube.

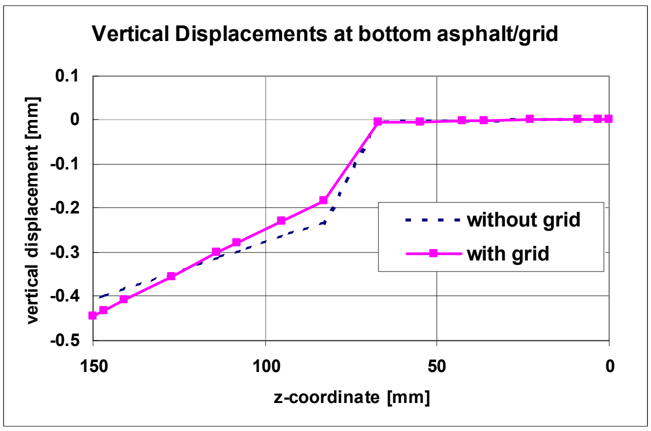

figure 17 displacements just above the joint

Thermal loading on joint

Due to temperature variations the joint width varies with the change of the season. From the slab dimensions and the mean temperature difference between summer and winter a maximum horizontal displacement of the joint of 12 mm was calculated. This displacement has been simulated with the finite element mesh for a structure with and without grid reinforcement. Measurements in the field indicate that this is a realistic value for exceptional cases.

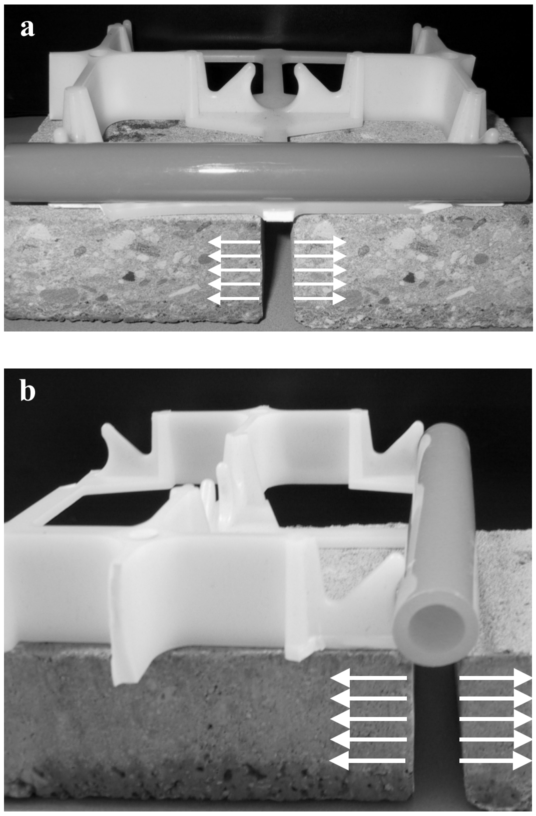

figure 18 thermal movements of the slabs

Two distinct cases as shown in figure 18 have been analyzed. The results are presented in a number of pictures and graphs. First the effect of the grid and the tube is visualized in figure 19. The pictures give a view from the bottom of the reinforcement, where the light colored elements are the filling asphalt and the dark elements form the reinforcing grid. Note that the most right pictures, where no grid is present, have a larger deformations and the tube is functioning as reinforcement (which is not wanted). In figure 20 the horizontal displacements in the bottom of the RES asphalt layer are plotted for both cases. The effect of the reinforcing grid is more than apparent. Finally the horizontal strains in the grid, the RES asphalt and tube are presented in figure 21 and figure 22. Especially in the case where the tube is perpendicular to the joint, the reduction of strains in the tube is considerable.

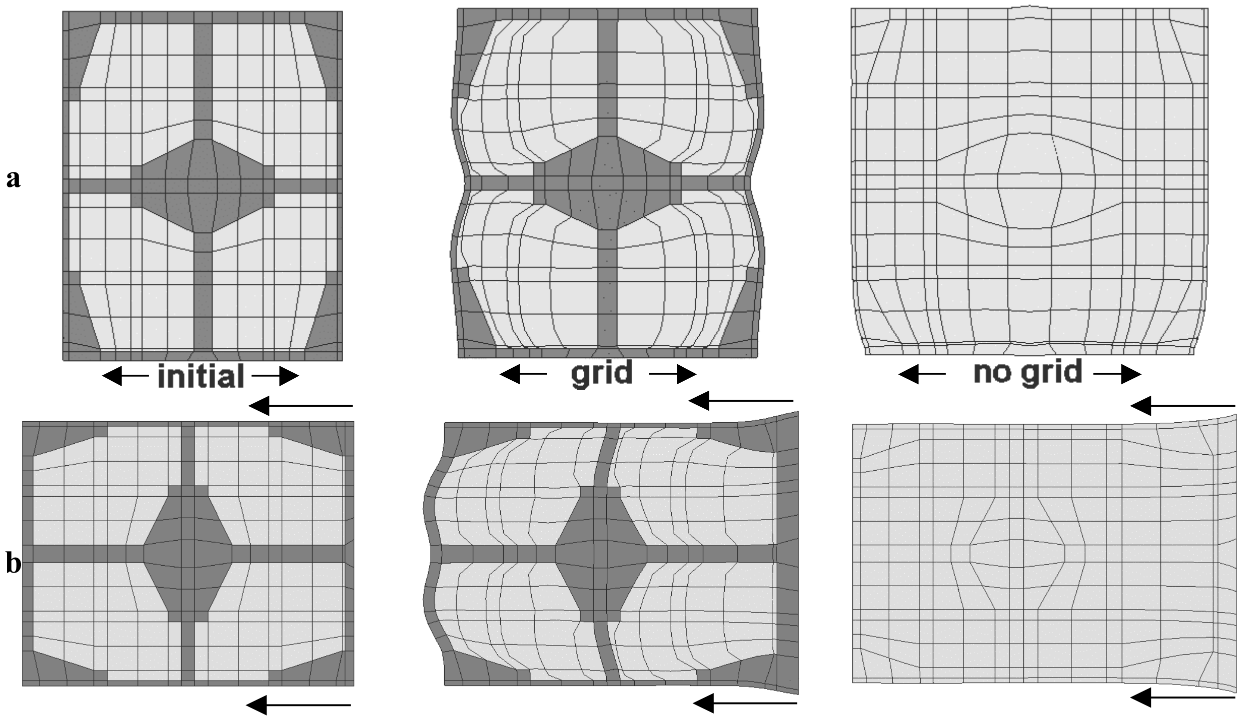

figure 19 Deformation of the mesh with and without grid due to thermal movement of the concrete slabs

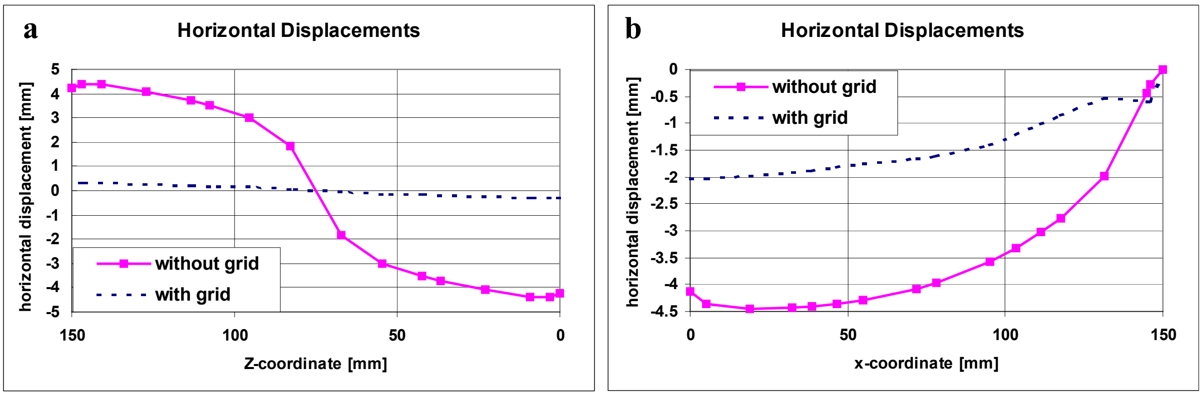

figure 20 Horizontal displacements in bottom of the RES layer with and without grid for both thermal cases (see figure 18 a and b)

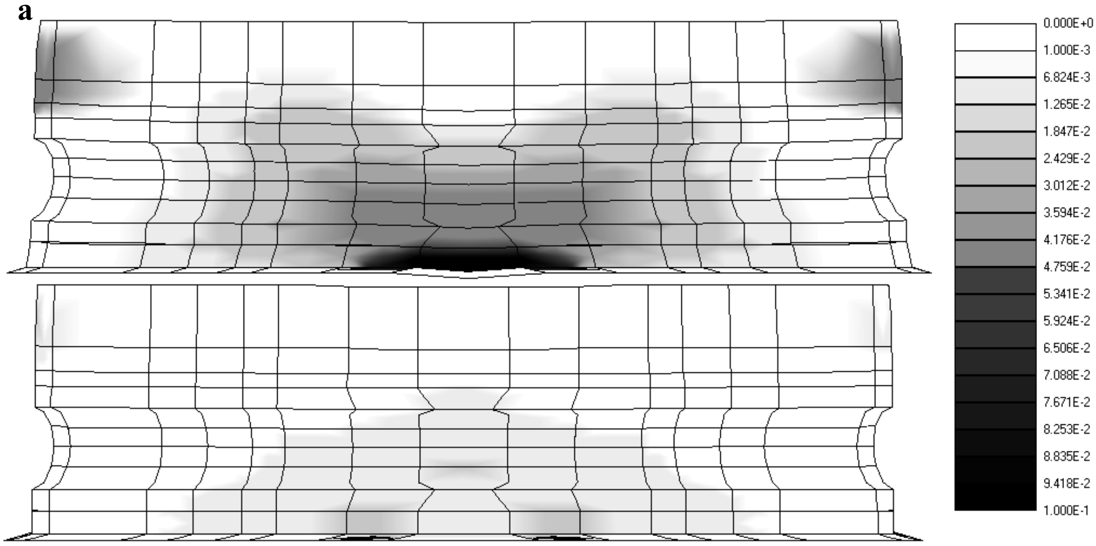

figure 21 Deformations and horizontal strain in the tube due to thermal movement of the slabs. Above without reinforcing grid, beneath with reinforcing grid (see also figure 18a)

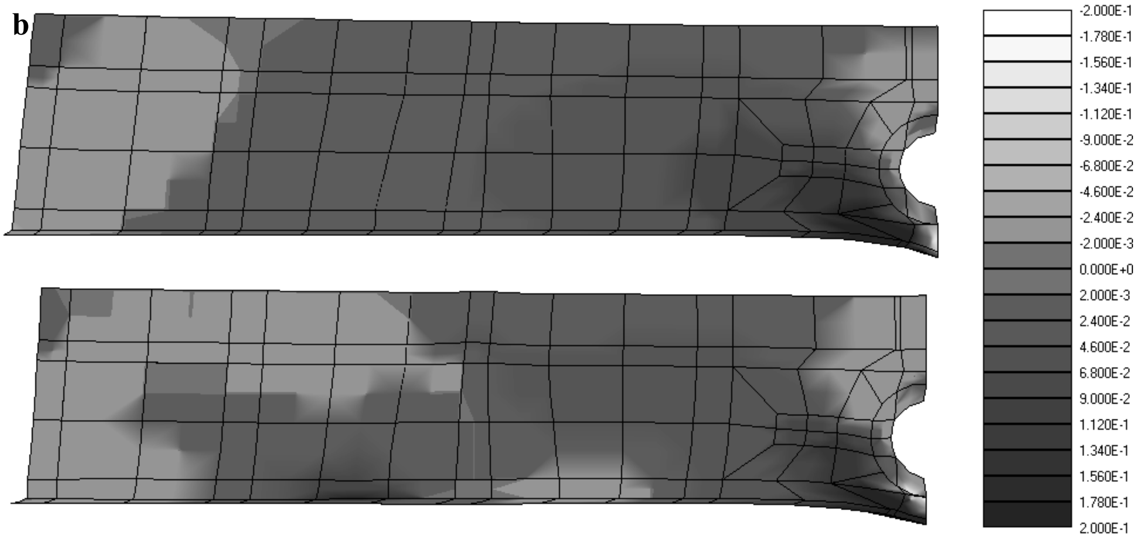

figure 22 Deformations and horizontal strain in the tube due to thermal movement of the slabs. Above without reinforcing grid, beneath with reinforcing grid (see also figure 18b)

CONCLUSIONS AND RECOMMENDATIONS

After numerous finite element analyses, combined with laboratory tests, the following can be concluded with respect to the structural aspects of asphalt heating and cooling systems:

- The presence of a tube in asphalt results in a complex distribution of stresses and strains with peak stresses around the tube. This will reduce the lifetime as compared to pavements without tubes.
- The RES reinforcing grid enhances confinement of the asphalt and reduces the stresses around the tube. In combination with the modified flexible RES asphalt the negative effects of the tube are strongly diminished.
- The grid is very effective in reducing excessive strains in the asphalt due to horizontal movements in underlying jointed pavement layers due to temperature variations.

Further research is being carried out by Ooms Avenhorn Holding on aspects such as:

- Analyses of other load cases and quantification of the effects on long-term pavement performance.
- "Equivalent" average stiffness modulus values to be used for pavement thickness design purposes.
- The effect of the heating and cooling process itself on rutting, cracking and raveling.

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