Development of the Non-linear Finite Element Program NOLIP for Concrete Block Pavement

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Summary

A research program is performed to gain more knowledge about the development of permanent deformation in concrete block pavements, caused by traffic loadings. For this research a good insight into the stresses introduced to the pavement structure by wheel loadings is needed. A Finite Element Model is developed in order to get this insight. Special attention is given to the representation of the concrete block layer.

A Concrete Block Pavement has a discontinuous top layer that is generally placed over unbound base and sub-base materials which have a non-linear stress dependent behaviour. Both this non-linear stress dependency and the discontinuity cause the need for a Finite Element Model.
Often an axial symmetric model of the pavement structure is used in order to limit the number of elements (degrees of freedom). However an axial symmetric representation of the three dimensional concrete block layer shows a behaviour which is different from the behaviour of a real concrete block layer.
First of all such a model has a self confining property. Expanding forces in the block layer are as a result absorbed by the blocks themselves so that the model will not explain the need for kerbs.
Furthermore the individual blocks within the axial symmetric block layer can not rotate freely. As a result, the modelled layer is stiffer than the layer it is representing and (what is even more important) tensile stresses are introduced in the bedding sand layer.
Using modified axial symmetric elements, which do not develop tangential stresses, the disadvantages of an axial symmetric representation of a concrete block layer are overcome to a large extent. A more realistic representation of a concrete block pavement is now obtained. As a result of the freedom of block rotation and translation, the model no longer results in tensile stresses in the bedding layer. Firm expanding joint forces are now calculated. Since the modelled block layer does no longer have a self confining property, the need for an adequate edge restraint (kerb) is now shown by the model.

1 Introduction

At the Delft University of Technology a research program is performed to gain more knowledge about the development of permanent deformation, introduced by traffic loadings, in concrete block pavements. For this research a good insight into the stresses introduced in the substructure of a concrete block pavement is needed. To obtain this insight a Finite Element Model, FEM, for concrete block pavements is developed.

Modelling a concrete block pavement practically means modelling the concrete block layer. In The Netherlands the blocks in this layer are mostly placed in herringbone bond. It is clear that a concrete block layer in this bond shows a complex geometry which does not show axial symmetry, but is truly three dimensional. As a result the ultimate FEM for concrete block pavements is a 3D model.
Such a model however has two major disadvantages. First of all it will have an enormous amount of elements compared with an equally large and fine-meshed axial symmetric model. The second disadvantage is that it will show a very complex geometry.
Since an axial symmetric model does not show these disadvantages, such a model is preferred over a 3D model. Using axial symmetry, the representation of the concrete block layer however becomes very poor. By a modification of the physical properties of the axial symmetric elements, used to model the concrete block layer, the quality of this representation is strongly increased.

2 The concrete block layer

2.1 Block rotation and the development of stresses in the joints

The concrete block layer of a block pavement structure consists of individual concrete blocks. In The Netherlands these blocks are mostly placed in herringbone bond, see figure 1.
These individual blocks can rotate and translate in any direction, as is shown by the paviour while manipulating the blocks before putting them into the correct position. As a result the individual blocks do not contribute to the stiffness or bearing capacity of the total concrete block pavement.

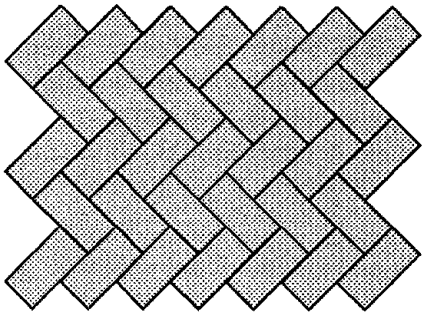


Figure 1 Herringbone bond.

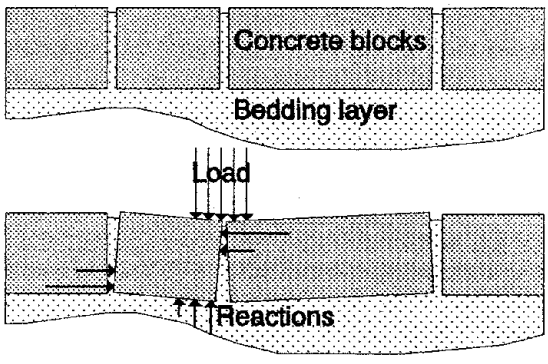


Figure 2 The effects of rotation of concrete blocks as a result of a loading.

The individual blocks are interlocked however by means of joints filled with sand. As a result of the sand-filled joints, a rotation or translation of any single block will result in reactive stresses in the joints, as shown in figure 2. Of course stresses will also develop in the bedding layer. Some load transfer between neighbouring blocks thus occurs so that the concrete block layer in total obtains a certain stiffness.
Stresses are also introduced in the concrete blocks themselves. These stresses are not a result of the rotation or translation itself, but are introduced by the contact pressure of the load and the reactive stresses in the bedding layer and the joints.

2.2 Model of the concrete block layer

As discussed in the previous paragraph, the joints have an interlocking effect on the blocks in the concrete blocks. As a result of this interlocking effect the concrete block layer obtains a certain stiffness.

This interlocking effect of the joints between the blocks can be modelled by means of normal and shear springs, see figure 3. As is the case in reality, rotation and translation of a block will now result in joint reactions. As a result concrete blocks will interact so that the concrete block layer obtains its stiffness.

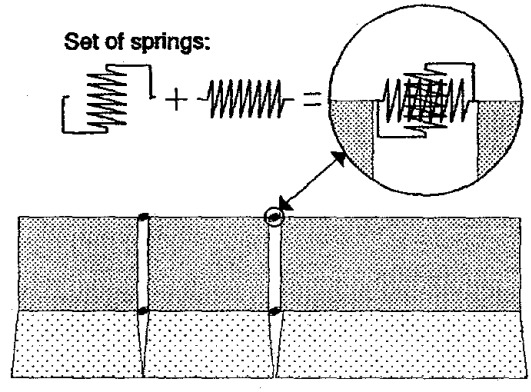


Figure 3 Modelling the joints by means of springs.

Figure 3 thus gives an usable representation of the concrete block layer for a three dimensional model. In such a model blocks can rotate and translate freely.

Axial symmetric elements however are really rings around the central axis of a model. As shown in figure 4 these rings have to deform in order to rotate around the Θ axis. Translation of a ring in the radial direction requires a change of the ring diameter. It might be clear that these deformations will result in stresses in such an axial symmetric element.

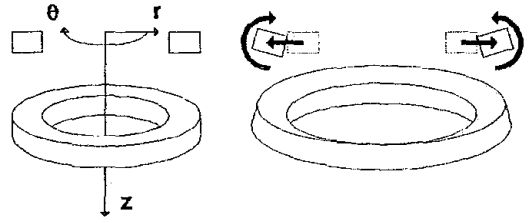


Figure 4 Axial symmetric elements show internal resistance against rotation around the Θ axis and against translation in r direction.

A concrete block layer modelled by these elements would show an internal confining property. Translation of a modelled block in the radial direction now increases the diameter of the axial symmetric elements within this block. As a result tensile stresses will develop in these elements, confining the concrete block layer. Such a model would thus not show the need for kerbs.

Furthermore the concrete blocks would have an internal resistance against rotation around the Θ axis. As a result, the development of expanding joint forces now remains too small. As shown later tensile stresses are now introduced in the bedding layer.

It might be clear that the behaviour of such a concrete block layer does not equal the expected behaviour of a real block layer.

In order to come to a better axial symmetric representation of the concrete block layer the properties of the elements used for modelling this layer are modified. The elements are given the freedom of rotation around the Θ axis and translation in the radial direction by preventing the development of tangential stresses '$\sigma_{\theta\theta}$' within

these elements.
Stresses within these elements are now only introduced when their cross section is deformed. This implies that the blocks modelled using modified elements can rotate and translate freely as is the case in reality. As a result, the modelled concrete block layer will no longer show self confining properties. Rotation and translation of blocks will result in reactive joint forces giving the block layer its stiffness.
Using the modified elements to model the concrete block layer a far better representation of this layer is obtained than when using non-modified axial symmetric elements, as shown in the next paragraphs.

3 The model of a complete concrete block pavement structure

3.1 Description of the model

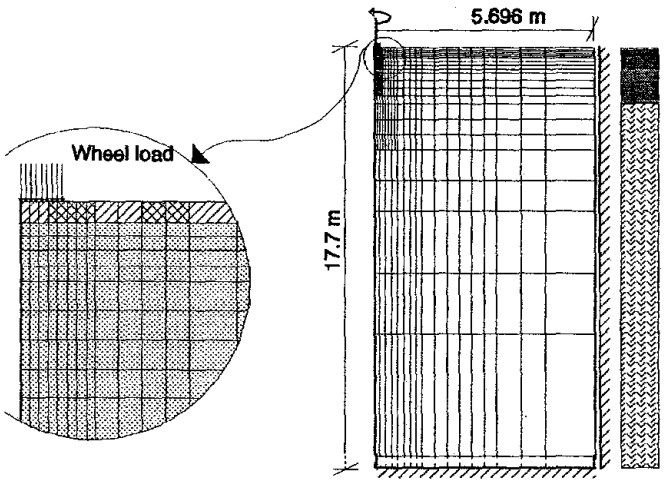


Figure 5 The complete axial symmetric model of a concrete block pavement structure.

The axial symmetric model for concrete block pavements, discussed in this paper, is given in figure 5. The radius of the model is almost 5.7 m and the depth equals 17.7 m.
In radial direction the dimensions of the elements are: 8 x 32 mm, 4 x 80 mm, 4 x 160 mm, 6 x 320 mm, 2 x 640 mm and 1 x 1280 mm starting at the central axis. The first set of joint springs is located 96 mm from the central axis, so that the radius of the central block equals 96 mm. The adjacent seven blocks have a width of 160 mm, so that the modelled blocks near the central axis consist of several elements.
Dutch concrete blocks have horizontal dimensions of 105 x 211 mm^2. Considering a joint width of 2 mm this becomes 107 x 213 mm^2, the earlier mentioned 160 mm thus equals the mean of these figures. With a further increasing distance from the central axis the dimensions of the concrete blocks increase too.
In the vertical direction the dimensions of the elements are: 1 x 70 mm, 4 x 50 mm, 4 x 100 mm, 4 x 200 mm, 2 x 800 mm, 2 x 1600, 1 x 3200 and 1 x 6400 mm. The height of the first layer of elements equals the thickness of the modelled concrete blocks, in this case 70 mm.
At larger depths in the model the wheel load only causes minor (vertical) strains. If these small vertical strains are integrated over a large height a substantial contribution to the deflection at the top of the model is obtained. As a consequence, the large depth of the model i.e. the very large elements at the bottom of the model, is needed in order to obtain correct deflections (2).
The load area plotted in figure 5 has a radius of 150 mm and thus equals the load area of a falling weight deflectometer. Using the model shown in figure 5 some

calculations are made. For these calculations the model was loaded by a 50 kN load. The results of these calculations will be discussed hereafter.

3.2 Effects of the modified properties of the concrete block elements

In order to show the effects of the described modification of the axial symmetric elements used to model the concrete blocks, two linear elastic calculations are performed. One of these calculations refers to a block layer modelled by non-modified elements while the other one refers to a concrete block layer modelled using the modified elements. Both these calculations consider a concrete block pavement with 70 mm thick concrete blocks. The blocks are directly placed over a 1400 mm thick sand subbase.
Using the model with modified elements for concrete blocks, the deflection curve measured on such a pavement was back-calculated. A good match between measurement and calculation was found using the input shown in table 1.

Layer	Thickness [mm]	E-modulus [MPa]	Poisson's ratio [-]	Joint normal stiffness [N/mm²]	Joint shear stiffness [N/mm²]
concrete blocks	70	35000	0.2	400	15
sand subbase	600	142	0.35	---	--
sand subbase	800	250	0.35	---	--
subgrade	16230	70.7	0.35	---	--

Table 1 Properties of the various layers within the axial symmetric model of a concrete block pavement.

The joint spring stiffnesses given in table 1 refer to the compressive joint stiffness. By applying negligible tensile joint spring stiffnesses the development of tensile joint forces is prevented.
Figure 6 gives the results of the calculation described above. This figure clearly shows the effects of the freedom of rotation and translation of the concrete blocks modelled by the modified elements. As was discussed earlier this extra freedom results in a reduction of the stiffness of the concrete block layer. As shown in figure 6 this stiffness reduction has a large influence on the deflections at a short distance from the load centre. At a larger distance the deflections are not so much influenced by the mentioned stiffness reduction of the concrete block layer.
The reduction of the stiffness of the concrete block layer, caused by the modification of the elements used to model the concrete blocks, is not the goal which was aimed for. This goal is a representation of the concrete block layer in such a manner that a realistic behaviour is obtained. A (wheel) load on the blocks is introduced into the substructure by the concrete block layer. As a result a realistic behaviour of this layer is needed in order to calculate realistic wheel load stresses for the substructure.
As shown by the bottom plot in figure 6 this goal is largely achieved. Using non-modified elements, the concrete blocks can not rotate freely which results in small

block rotations and thus in small normal joint forces. Furthermore these expanding joint forces are not transferred to an adjacent modelled block, but are reduced by tensile stresses within the blocks. These tensile stresses in the modelled blocks operate to confine the block layer.

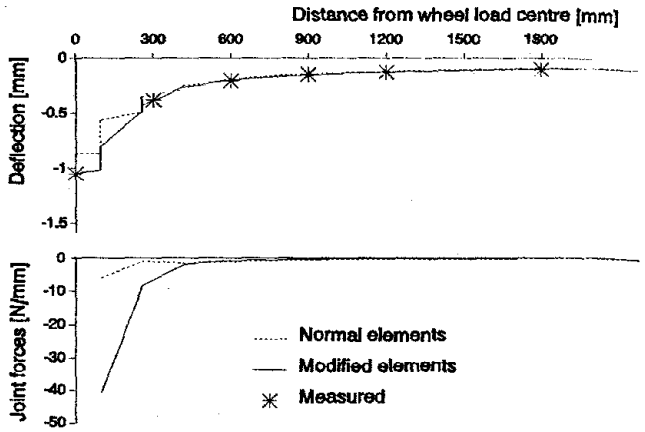


Figure 6 The calculated and measured deflection curves (top) and the calculated normal joint forces (bottom).

The lack of freedom of rotation of the blocks modelled by non-modified elements furthermore causes tensile stresses directly underneath the blocks, see figure 7. This figure gives the effects of the deflection of the individual concrete blocks on the development of stresses in the bedding sand at a depth of 25 mm below the blocks. As shown in this figure tensile stresses are calculated when concrete blocks do not have the freedom of rotation and translation, see left side of figure 7.

If the blocks are given the freedom of rotation and translation then they will rotate, strongly reducing the tensile stresses in the bedding sand, see right side of figure 7. Of course this rotation is limited by the development of joint forces. As a result small tensile stresses might still be calculated when using the modified elements.

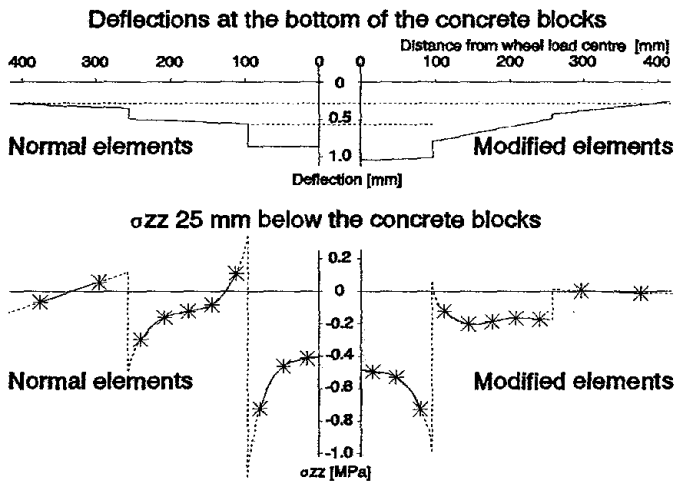


Figure 7 The deflection curve at the bottom of the concrete blocks and its effect on the development of stresses within the bedding sand.

The normal joint forces limiting block rotation operate to expand the concrete block layer. Since the blocks can now translate freely, these expanding forces are transferred to adjacent blocks and have to be absorbed by an adequate edge restraint (kerb), as is the case in reality.

3.3 A non-linear calculation

In the previous paragraph two calculations including linear elastic sub-base and subgrade materials were discussed. The linearity of these calculations made it easy to show the effects of the modification of the elements used to model the concrete

blocks. In order to give an impression of the results which are obtained using non-linear material models, a third calculation is performed. Within this calculation the 1400 mm sand layer is modelled by the widely used Mr-Θ model (3).

Using this model the resilient modulus of the sand is defined as: $Mr = 9.8\ \Theta^{0.54}$ MPa, where Θ equals the sum of the principal stresses [kPa].

The stiffness modulus of the subgrade was increased from 70.7 MPa to 73 MPa, all other input equalled the input for the linear calculations, given in table 1. The first figure considering the non-linear calculation gives the stiffness of the sand sub-base, figure 8. It appears from this figure that the stiffness of the sand is highly influenced by the stresses introduced by the wheel load. Resilient moduli up to almost 500 MPa develop directly underneath the edges of the central modelled block.

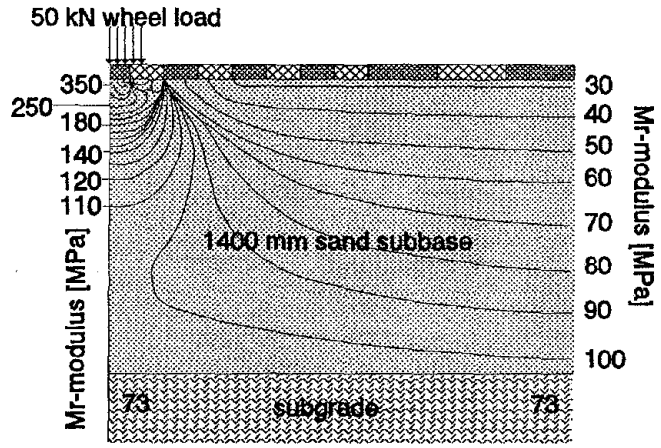


Figure 8 Distribution of the resilient modulus within the 1400 mm sand sub-base (50 kN wheel load).

At larger distance from the central axis the resilient modulus is mainly determined by the dead weight of the sand and the concrete blocks. Since the distribution of stiffness within the sand sub-base differs strongly from the distribution in the linear calculations, the deflection curve is not equal to the earlier calculated curve, as shown by comparing figure 9 with figure 6.

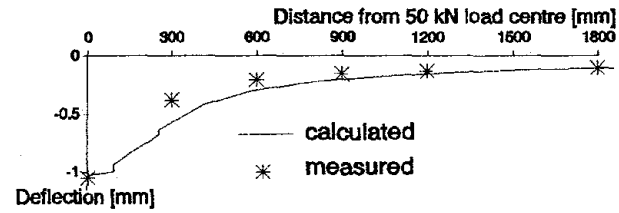


Figure 9 The deflection curve calculated using the Mr-Θ model for the sand.

Figure 9 shows that the deflections at the load centre and at a distance of 1800 mm are almost the same as the measured deflections. The other calculated deflections however are larger than the measured ones and larger than the deflections in the linear calculation. The explanation of these differences is found of course in the stiffening area around the central axis, see figure 8.

As a result of the freedom of rotation of the modelled blocks, combined with the properties of the material model, no tensile stresses are calculated in the bedding sand. Up to a depth of 75 mm below the concrete block layer (z = 145 mm) the effects of the discontinuous top layer are clearly reflected in the vertical wheel load stresses. With increasing depth these reflections become smaller and smaller, see figure 10.

The typical distribution of the vertical stress directly underneath the concrete blocks has its effects on the distribution of the vertical stresses at the central axis of the model. Directly underneath the top layer the vertical wheel load stresses seem too small. A vertical stress of somewhat less than 0.7 MPa is expected since the load introduces a stress of 0.707 MPa. The stress calculated directly underneath the middle of the central block nevertheless is much smaller. Larger vertical stresses are however found at the edges of the central block as shown by the top left plot.

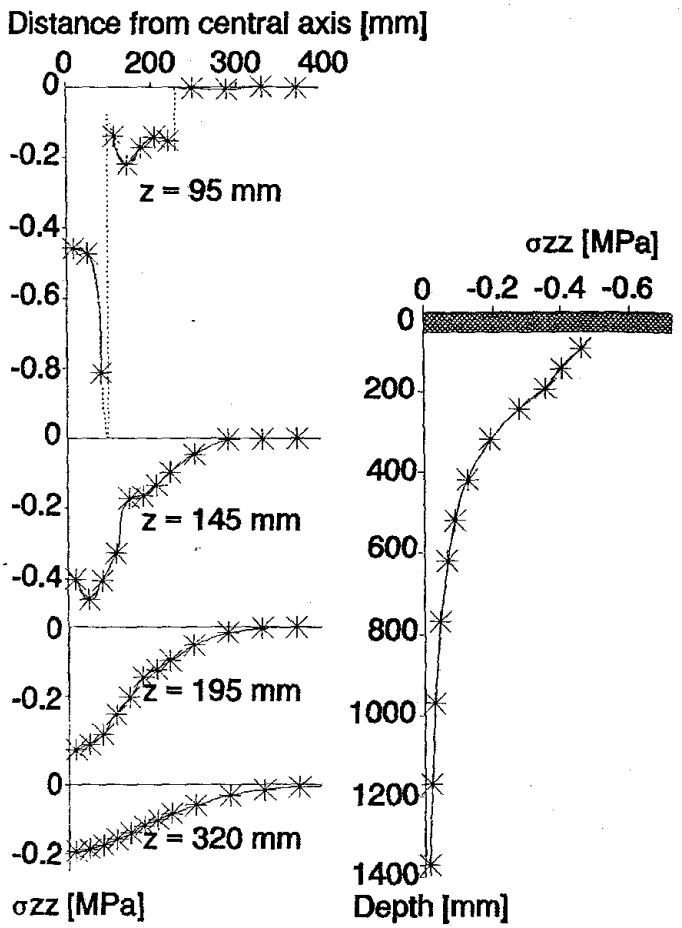


Figure 10 The vertical wheel load stresses in the sand sub-base (50 kN wheel load).

3.4 Forces on the kerbs

As stated earlier a concrete block layer modelled by the modified elements does no longer have the self confining property found when using non-modified elements. This implies that the kerbs have to withstand the expanding forces which develop in the concrete block layer as a result of block rotation.

The axial symmetric model does not contain kerb elements, nevertheless the forces applied to the kerbs can be determined on the basis of calculations using the presented model. For this purpose it is assumed that the stiffness of the kerbs equals the equivalent stiffness of the concrete block layer. In other words, it is assumed that the development of joint forces in a very wide concrete block layer equals the development of joint forces in a concrete block layer bordered by kerbs. Using this assumption it is a simple mater of goniometry to calculate the joint forces applied to the kerbs, figure 11.
The upper part of this figure explains the situation which is referred to. In the bottom part of the figure the results of two calculations are shown. The first calculation refers to the concrete block pavement with 70 mm thick concrete blocks, as discussed in the previous paragraph. The second calculation refers to a similar concrete block pavement constructed using 140 mm thick concrete blocks. The joints between these block now are twice as high so that the springs representing the joint material must become stiffer. The spring stiffnesses were increased by a factor two, deducted from a

pure bending situation in the block layer.
As shown by figure 11 the joint forces applied to the kerbs are now much larger. The increased stiffness of the concrete block layer reduced the deflection at the load centre from 1.023 to 0.915 mm.
As shown by figure 11 the forces applied to the kerbs decrease as the transverse distance between the kerbs and the wheel load increases. This is caused by the fact that horizontal forces in the concrete block layer are partly absorbed by the bedding layer directly underneath the concrete blocks.
Figure 11 shows that behaviour of the modelled concrete block layer is quit realistic. Increasing the thickness of the blocks results in an increasing stiffness of the concrete block layer. The effect of this increasing stiffness on the deflections is small since the wheel load is largely carried by the substructure. In this case the reduction of the maximum deflection is about 10.6%.

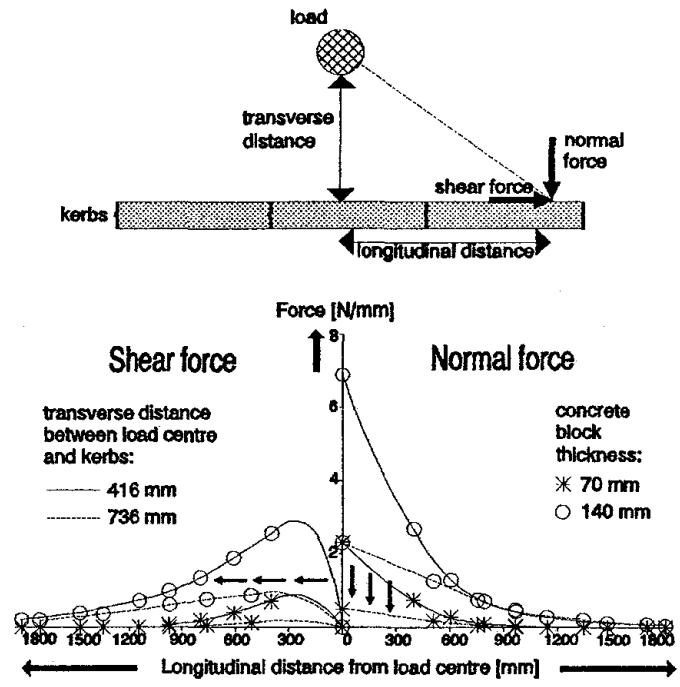


Figure 11 The forces applied to the kerbs as a result of the expanding forces in the concrete block layer.

In order to obtain this small increase of the stiffness of the total structure the joint forces increased strongly resulting in a substantial increase of the expanding forces applied to the kerbs. In this case the maximum normal expanding force applied to the kerbs increased form 2.3 N/mm to 6.9 N/mm when the load is located 416 mm from the kerbs. The previous figures show an increase of the expanding forces to be absorbed by the kerbs of 198%.
When the wheel load is applied 576 mm from the kerbs this percentage becomes 258% and when the transverse distance between the load and the kerbs equals 736 mm this percentage increases to 369%.

5 Conclusions

In order to get more insight into the wheel load stresses in the substructure of a concrete block pavement a Finite Element Model is needed. The concrete block layer of a real pavement structure transverses the wheel load applied on the blocks to the substructure. As a result the behaviour of this layer is of influence on the wheel load stresses which develop in the substructure. A Finite Element Model of a concrete block pavement can thus only offer the insight needed if it has a realistic representation of the concrete block layer.

It is concluded that the axial symmetric model as discussed previously, offers the insight needed. As shown, detailed information about the stress-distribution in concrete block pavements is offered by the model.
This goal could only be reached by modifying the properties of the elements used to model the concrete blocks. As a result of this modification these elements show a behaviour which is expected from real concrete blocks. The self compressive behaviour of normal axial symmetric elements is lost and block rotation can occur without the development of block stresses. Using the modified elements it is possible to create a realistic axial symmetric representation of the block layer of concrete block pavements.
This axial symmetric representation yields the behaviour which is expected from the concrete block layer in reality. The need for kerbs, absorbing the expanding forces in the concrete block layer, is shown by the calculations.

The effects of the joint stiffness and concrete block thickness are as expected. Thicker blocks result in a small decrease of the maximum deflection and an increase of the joint forces. The increase of the expanding joint forces to be absorbed by the kerbs as a result of an increase of the block thickness is enormous.

The model presented here seems very useful as a tool for further research concerning concrete block pavements. It has coped with the major disadvantages of axial symmetric models of concrete block pavements. Nevertheless a 3D model of a concrete block pavement remains the ideal model of such a structure. The model presented in this paper however forms a good alternative for a 3D model and clearly shows the behaviour expected from a 3D concrete block pavement structure.

8 Literature

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