Possibilities for material characterisation and FEM simulation of compaction processes of asphalt pavements

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Scientific knowledge about how compaction processes of asphalt roads can best be managed in order to achieve homogeneous compaction results hardly exists. In particular when road construction takes place under poor external weather conditions this can be problematic. During these circumstances the workmen experience and professionalism have to be relied upon for realising quality in compaction. The research discussed here attempts to fill a lacuna in knowledge by simulating the compaction process with help of FEM methods. Because there is no model for the description of the mechanical behaviour of non-compacted asphalt concrete, a "Critical State" model out of soil mechanics is adopted. In the paper results of a first roller pass, based on an ALE approach, will be discussed. The calculations show a realistic stress and strain pattern in the asphalt mixture. For quantifying the parameters of the FEM material model, material measurements have to be carried out. For this activity standard laboratory equipment is not sufficient and therefore modifications of an existing piece of equipment will be proposed. In the project, a field experiment has been set up to validate the model.

Keywords: **Asphalt concrete material model compaction, FEM Simulation**

1 Introduction

Maintenance of flexible paved roads is faced increasingly with time constraints and spatial limitations. As a consequence, rather often, the maintenance process has to be carried out under less favourable circumstances, e.g. adverse weather conditions and/or small working area. In the road construction branch on different levels the quality of the under these circumstances achieved work became a point of discussion in the first half of the nineties. This was the time that the questions like; "how do less favourable circumstances affect the quality of work?", and, "how should the operating procedure of the maintenance process be adapted to unexpected or changing conditions?" were raised. This was also the occasion for a start in 1992 of a research project at the University of Twente on the effects of external circumstances during construction of asphalt road works.

Inventory of submitted articles on conferences and in international magazines shows that topics like the design of asphalt mixtures, its material characterisation and the development of performance based specifications have received the most attention in research in the last decades. This is some-

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what amazing since the true mechanical quality of the mixture, once it is laid, heavily depends on the quality of the construction in general and the level of compaction in particular.

The degree of compaction is a crucial factor, but only little detailed knowledge is available on how to get there. There are no validated material models available for describing the behaviour of non-compacted asphalt concrete. There is also a lack of understanding about which external conditions influences the compaction results and to what extent. Analysing the compaction process and developing a tool to manage the process efficiently can therefore lead to better mechanical characteristics and improve quality management of road works. Other approaches to predict compaction results that were found in literature, are based on empirical methods which makes it uncertain to generalise the results and use them for predicting compaction progress of new materials. The existence of a compaction simulation tool will make it easier to perform a parameter study or sensitivity analysis of the compaction process. During the research project an attempt is made to develop a method that can deduce the effort of the compaction process on an arbitrarily asphalt concrete mixture more scientifically. For realising this goal different more or less separated steps have to be taken. A part of these steps will be the topic of discussion in this contribution.

The outline of this paper is as follows; to emphasise the importance of compaction is, in the second section of the paper, the effect of insufficient compaction on mechanical specifications discussed. To gain knowledge about the compaction process a modern tool like the FEM method is chosen for simulating the process. The characteristics of an asphalt mixture during compaction are in between that of a solid and a liquid. On the other side the compaction process is a forming process where relatively large deformations can arise. Both matters of facts, however, require a non-standard FEM approach. This approach will be discussed in section 3.

When using FEM methods for calculating the behaviour of a construction (or piece of material) there must be a fundamental model that describes the relevant material behaviour. Because such a model is not available for asphalt concrete mixtures during compaction in combination with the existence of an analogy between hot asphalt mixes and wet soils, a model out of soil mechanics is adopted for this purpose. This "Critical State" material model and the here out resulted constitutive relations will be discussed in section 4. However when a suitable model is selected as a framework for the mechanical material behaviour still material measurements have to be done to fill in the parameters of the model. Again because the relevant material takes the middle between a solid and a fluid this measurements can not be carried out with standard available equipment. For the measurements a test apparatus is modified and in the fifth section the modification and the way the measurements can deliver the specific parameters will be the object of discussion. Because material characteristics are not fully available in this ongoing research (July 2000) the results of first calculations of a simulated single roller pass are presented in section 6. Finally, the set-up of a validation study is given, and conclusions are drawn.

2 Influence of the compaction rate on mechanical properties

The compaction of an asphalt layer is probably one of the most crucial stages during construction and it governs largely the structural performance of the entire pavement construction (1). Knowledge of the variation in compaction is important because road deterioration starts at the weakest link (2). Leech and Powell showed also that the distribution of the degree of compaction over road sections is quite inhomogeneous. They investigated the relation between the average density and the applied distribution of the roller passes in the width direction of a test section. The nearside wheel path approximately 0.9 m from the edge of the lane, received less than half of the roller passes that where applied to the middle of the lane. The corresponding densities in this wheel path turned out to be about 3 per cent lower than the maximum density in-between the wheel paths, as is illustrated in figure 1.

In the Netherlands a significant part of the construction work is carried out under less favourable weather conditions. These conditions might result in an inferior degree of compaction due to a fast cooling down process of the hot asphalt, which deteriorates the road quality. To test this hypothesis a validation study was carried out which showed that the degree of compaction for work performed under "poor" conditions was about 1.6 per cent less than for work carried out under "good" conditions (3). Poor conditions for example are; rain, high wind velocities and/or low environmental temperature.

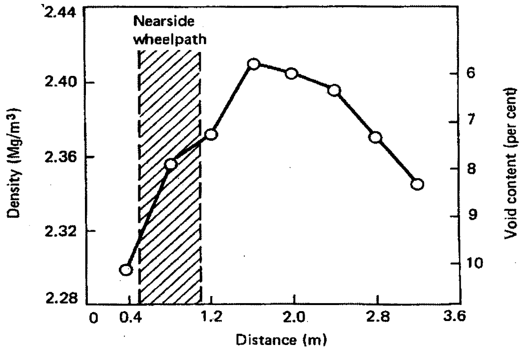

Fig. 1. Variation of density across the laid width after compaction of a Dense Bitumen Macadam road base (5).

The dynamic stiffness of asphalt concrete is a key factor in controlling pavement performance. Powell and Leech (4) showed that this stiffness increases with 30% if the void content of the material is reduced with 3%. Linear elastic analysis of the construction showed that thereby the thickness of the construction could be reduced with 8%. Moreover, a higher compaction level will increase the fatigue resistance of the material. The third advantage of adequate compaction is the increase of the resistance to the permanent deformation. An increase of 3% in compaction leads to a reduction of the permanent deformation of about 50% after 1000 passes, measured with a pneumatic tired wheel-tracking machine.

Improving compaction results in a significant improvement of load spreading, resistance to fatigue cracking and resistance to deformation of asphalt concrete mixtures. These improvements undoubtedly result in extended pavement life (1).

3 A FEM approach of the compaction process

To increase the knowledge about the compaction of asphalt concrete mixtures simulation methods can be used. Here the choice is made to use a FEM method. Because the behaviour of the material during the compaction stage is in between that of a solid and a liquid, relatively large deformations can arise which requires a non-standard FEM approach; the Arbitrary Lagrangian Eulerian (ALE) method. Another reason that makes selection of a specific FEM tool relevant, origins caused by the use of a soil mechanical model for describing the material behaviour. Not in every FEM code a suitable material model is foreseen. The material model adopted from soil mechanics for describing the behaviour of hot laid asphalt will be proposed. Because the analysis is a 2D one, edge effects and the effect of the width of the roller drum are not taken into account.

Within FEM two approaches can be used based on different principles, the Eulerian formulation and the Lagrangian formulation.

Eulerian formulation

The Eulerian formulation is a FEM approach that fixes the finite element grid in the space. The finite element grid is not coupled on the material and the borders of every element are defined in such a way that material can flow in, out and even through the elements. In stead of the Lagrangian formulation where equilibrium of forces is prescribed for every boundary, in the Eulerian formulation the fundamental equations at the boundaries concerns the material flow in and out the element. If it concerns a porous media the nett flow is related to the pressure (gaseous phases) or to the specific density of the material inside the element. In the Eulerian formulation it is possible to model only a relevant part of the workpiece and let material flow into the mesh at the entrance and out of the mesh at the exit. Its characteristics make the formulation notably suitable for fluid mechanical problems. In simulations of (semi-) continuous processes such as rolling, the mechanical deformations occur in an area that is very small compared to the length of the workpiece.

Lagrangian formulation

The Lagrangian formulation, which couples the element grid to the material, is often used in structural disciplines. In a Lagrangian analysis, a material point is followed in time. The deformations that the material point experiences can influence the constitutive behaviour. If the displacements remain small the difference between the non-deformed and the deformed geometry can be ignored and a geometrically linear analysis will be sufficient. If however, the displacements become larger, the notion of stresses and strains depends on the choice of a reference frame. In this case a geometrically non-linear analysis must be performed (6).

In a finite element analysis the stresses and strains are usually determined only in the integration points. During the complete Lagrangian analysis an integration point represents the same material point. The Lagrangian formulation is usually adopted for solids. Material behaviour that is history dependent is easily solved in a Lagrangian analysis (7).

Arbitrary Lagrangian Eulerian (ALE) analysis.
Because asphalt concrete can flow heavily during a rolling process it seems logical to use an Eulerian approach for simulating this process. On the other side is the currently material behaviour dependent of the currently compaction stage and thus of the history of stresses on the relevant part of the material. This can be realised through integration of the relevant quantities along the streamlines, which necessitates deducing of the path dependent material behaviour. A second shortcoming of using a fixed element grid for modelling a rolling problem origins by the fact that the boundaries perpendicular to the process flow (for example; the free surface at the top of the layer) not are known in advance. Summarising can be posed that an Eulerian approach of the compaction of asphalt concrete mixtures is not applicable for because of the in space fixed discretisation, the boundaries of the modelled piece of material can not change its form which is essential.

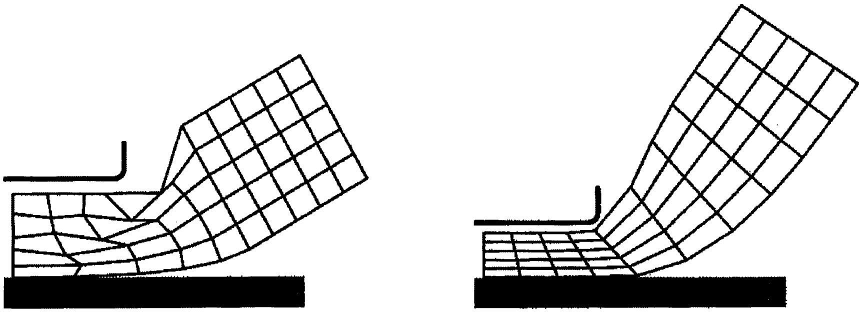

Fig. 2. The deformed Finite Element mesh as a result of a forming process in an Lagragian calculation (left) and in an ALE calculation (right) (7).

For processes with large deformations at limited area, like forming processes, the Lagrangian formulation is not favourable because large mesh distortions can easily occur. To overcome these shortcomings researchers developed the Arbitrary Lagrangian Eulerian (ALE) approach, a combination of both the Eulerian and Lagrangian method. In this method the computational grid is disconnected from the material and can have any displacement. It can be used to keep the mesh more or less regular and let the material flow partly through the mesh and at the same time to keep track of the material boundaries. One of the implications of this method is that a material point is not represented by one and the same integration point during the analysis but by adopting special measures history dependent material behaviour can be taken into account. The implications of an ALE method on the structure of the element mesh during the calculation is clearly illustrated in figure 2.

For modelling the interaction between the roller and the asphalt concrete, contact or interface elements are used. In this case the nodes of the elements of the two connected bodies have to be lined out with each other. This can be arranged easily in the ALE method because the method takes care of the control capabilities of the mesh deformations.

Contact elements

The contact elements are regulating the normal and shear stress, and the normal and shear strain between the two components (material and workpiece). The size of the contact element in the thickness direction (i.e. perpendicular to the direction of the contact plane) can be zero (the contact element is closed) or can be larger than zero (there is a gap between the two bodies i.e. the contact element is open). The contact behaviour in the normal direction, perpendicular to the contact surface, can be represented by an elastic spring parallel to a damper as shown in figure 3. The damper can be activated or not. The damper is used to smooth the opening and closing of the contact element.

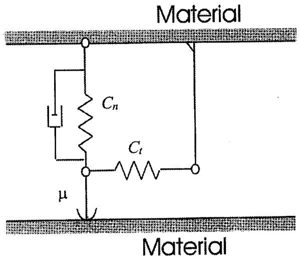

Fig. 3. *Model of behaviour of a contact element (9).*

The thickness of the contact element can also become negative, in which case the contact element is turned inside out and one is talking about an overlap between the contacted bodies. In fact the overlap is limited and can be adjusted with the input parameters (8).

For modelling the shear stress between the two bodies, the contact element contains an elastic spring parallel to the contact plane. If Coulomb friction is modelled, the maximum shear stress is limited and depends on the normal stress in the element. Depending on both shear and normal stress, stick or slip occurs in the contact plane. Stick-slip behaviour plays an important role especially in modelling rolling processes. For this reason the parameters that represent the phenomenon have to be chosen with care (9).

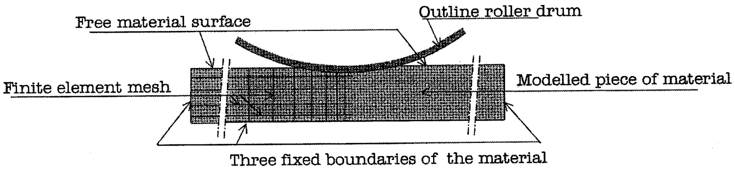

Fig. 4. *The element mesh and the boundaries of the modelled piece of the material related to the roller drum.*

Element mesh and boundaries

Three boundary conditions of the modelled material (except that for the free surface) are fixed. The nodes laying on the edges are geometrically coupled and the deformation of the boundaries is prescribed (zero in vertical direction and a specific value per step in horizontal direction). By this prescribed geometrical displacement the considered piece of material is forced through under the roller drum. When there is contact between material and roller drum the edge of the drum constitutes a fourth boundary of the material, when there is no contact the top is a free surface. The assumption is made that the roller drum does not deform during the compaction process. The edge of the roller drum is modelled in such a way that it can turn free around its centre but can not move in vertical direction.

Because the material is driven through under the roller drum, the simulation can be seen as a rolling process with a prescribed deformation result. Out of the calculation results the relation "roller drum weight" versus "compaction progress" can be analysed. This kind of calculation is preferred above one in which the roller drum weight is prescribed because this latter approach is an unstable one.

4 Constitutive relationships

The behaviour of asphalt concrete mixtures during compaction is mainly plastic and partly elastic and viscous (10). The plastic behaviour is mainly due to the particle reorientation that occurs during the compaction process of aggregate composed materials like non-compacted asphalt and soils. Because the analogy between soil and asphalt concrete and the fact that no good model exists that describes the material behaviour of asphalt concrete an attempt is made to use a model out of soil mechanical disciplines. In the used FEM approach, DiekA, there is a material model implemented that operates in accordance with the "Critical State" principles. This model is the "Rock" model.
A fundamental theory describing the behaviour of soil is the Critical State theory. The principles of this theory are used for modelling the material behaviour of asphalt concrete during compaction.

Critical State theory

In Critical State theory, often use is made of p' and q as stress parameters and v as a parameter for the specific volume of the material. p' is the isotropic normal stress on the solid parts of the material. This total normal stress reduced with the fluid pressure in the material if there is one. q is the deviator stress in the material.

Because many important mechanical properties of soil are depending on the closeness of the particle pattern the state of the soil can be described by the specific volume parameter, v, by

$$v = V/V_s \quad [\mathrm{m}^3/\mathrm{m}^3]$$

where V is the volume of a sample containing a volume V_s of soil grains (11). One of the aspects of the Critical State theory that is used for the modelling of the compaction process of asphalt concrete is the limitation of possible stress-specific volume states in the $p':q:v$ space which is known as the State Boundary Surface (SBS). In theory it is assumed that every specific volume of the material is coupled to a yield locus, which is a criterion that indicates at which stress elastic deformation in the material is switched over to elastic-plastic deformation. The well-known Mohr-Coulomb criterion is a similar relation with the difference that this criterion is not "closed". It means that no plastic volume change due to isotropic compression takes place, which is a reasonable assumption for dense particle patterns but not for loose ones. Schwartz and Holland coupled a Mohr-Coulomb criterion to a so called "closure cap" and created this way a closed yield locus (12).

If there is no shear stress in the material, $q/p' = 0$, and the material is "isotropic normal compressed". A line in the $p':v$ space can represent this situation, which line is known as the Normal Compression Line (NCL). At a specific stress combination of q/p' the material is in a so known Critical State. This Critical State of the material is defined as a situation in which the material deformation increases constantly at a constant volume and a constant combination of stresses. The line that the critical state points connects is known as the Critical State Line (CSL) and when it is drawn in the $\ln p':v$ space, it has the same slope λ as the NCL. The surface between the NCL and the CSL is of specific interest for compaction because in this situation a closer particle pattern (i.e. compaction) occurs. The surface between the CSL and the NCL can be seen as the "closure cap" of the yield locus (figure 5). This situation is known in soil mechanics as on the wet side of critical. The part of the SBS that corresponds to the wet side of critical is also known as the Roscoe surface (13). On the part of the yield locus left form critical there is dilation caused by shear. This part of the SBS is in soil mechanics known as the Hvorslev surface. The governing stress situation here is known as "on the dry side of critical".

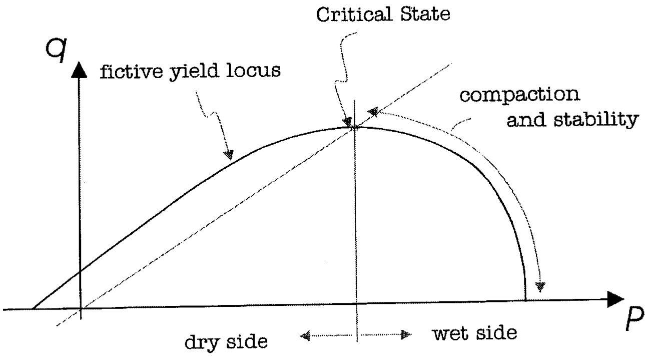

Fig. 5. The yield locus of an elastic plastic material model.

To characterise a material model the shape of the yield locus has to be determined. In the original Cam Clay theory this model was a logarithmic spiral, later on in Modified Cam Clay (MCC) theory it became an ellipse. As an extension of the Cam Clay theory several yield loci have been developed. Some of them fit better with experimental measured data and others are more practical to implement in a mathematical model (14).

Another characterisation of granular material is the progress in which a material gets stronger. In fact this can be determined from the slope λ of the CSL and the NCL in the $ln\ p':v$ space. This progress in strength of the material is also known as the hardening relation. The proportion of the plastic shear strain, ε_s, versus the plastic volumetric strain, ε_v, as a result of the stress ratio q/p', is an important material characteristic. If both quotients are equal in number, one is speaking of associated flow and the yield locus coincides with the plastic potential, which is the line that indicates the direction of plastic deformation. In this case plastic strain is directed perpendicular to the yield locus. This is the case for the closure cap of the Rock model, which is described in the sequel.

Nature of deformation asphalt mixes during compaction

Although in an asphalt concrete mixture the volume of bitumen is small in relation to the volume of the aggregate, the characteristics of the bitumen are of significant importance on the mechanical characteristics of the total mixture. Figge (10) concludes that in mixes with a mineral aggregate and a bitumen component, the aggregate has clearly the biggest influence. Nevertheless the characteristics of the bitumen also influences the characteristics of the total mixture significantly. During compaction the largest part of the deformation is due to non-reversible particle reorientation and fracture, which causes plastic deformation. During the compaction process, the elastic component increases whereas the plastic component decreases. The viscous rate of the deformation is almost constant during the entire compaction process.

The DiekA Rock material model

The Finite Element calculations are carried out with the DiekA FEM code, a code that consists of an ALE calculation method and in which a suitable material model, the "Rock" model, is implemented. The "Rock" material model is developed for calculations of dredging activities in soft rock. With its closed yield locus and its hardening and softening possibilities, it is applicable for asphalt concrete mixtures.

The model describes elastic plastic material behaviour. The transition between elastic and plastic behaviour is modelled with the use of a yield locus as described for Critical State theory. For the elastic part of the material behaviour the model uses the modulus of elasticity E and the Poisson's ratio ν. For hardening caused by compaction in the isotropic compression side of the $p':q$ plane (high p'/q ratio) a hardening parameter can be defined. For softening caused by shear a softening parameter will be used. Hardening and softening parameters determine how fast the yield locus grows or shrinks when the specific volume changes. The right values have to be determined through calibration. A with use of a FEM code reconstructed yield locus based on fictitious material properties is illustrated in figure 5.

5 Material characterisation with modified Hveem StabiloMeter

In the preceding sections it became clear why a material model out of soil mechanics will be used for modelling the behaviour of asphalt concrete. But also, if a material model is selected, measuring material characteristics and calibration of material properties is needed in order to be able to apply the (FEM) material model for practical purposes.

The Critical State theory is in principle a framework that couples the strength of a granular material (shape and size of the yield locus) to the specific volume of the material. Inside the selected FEM material model parameters have to be quantified in such a way that the model describes the specific material behaviour for the external conditions (temperature and compaction level). Furthermore the shape of the yield locus has to be modelled, with respect to the possibilities inside the selected material model, and also hardening and softening parameters have to be determined. The task of measuring and material properties validation will be carried out with help of an existing piece of equipment the Hveem StabiloMeter (HSM) that will be modified. In this section the standard HSM will be discussed as well as how it will be modified.

Critical State model and tri-axial testing equipment

The Critical State theory makes use of the possibilities that occur when soils are tested with the tri-axial test equipment. During such a test the primary mechanical characteristics of an axial symmetrical sample can be deduced out of the measured quantities which are the vertical loading force, vertical deformation, radial loading stress (confining pressure) and the change of volume (if the sample is saturated, for details see [13]). Besides of this, through the flexibility in regulating the vertical force and confining pressure on any wished individual level, almost every stress path in the $q{:}p$ space can be followed while testing the material.

The parameters needed for utilisation of the Critical State theory could be determined by the possibilities the tri-axial test equipment furnishes. It seems that theory and test equipment is suited for each other. But there are limitations; the sample has to be saturated because the fluid in the sample (water) is used for measuring the volume change. This is a problem for using the test method on asphalt concrete since asphalt concrete mixtures are normally not saturated. An additional obstruction is that the viscosity of the bitumen is not low enough that it can be used for measuring the volume changes of the sample.

For testing the stability of asphalt concrete samples Hveem introduced in the thirties his StabiloMeter (HSM). Hveem developed his Stabilometer based on the thought that materials that are build up out of particles can be characterised by deducing their ability to resist loading without deformation. Basically the idea was that the rate in which a vertical loading stress is turned over into a horizontal stress in a sample when this sample is horizontally supported, is an inverse measure for the resistance of the material against deformation. This quantity, the ability to carry a loading without deformation, is defined as the stability. Hveem developed the Stabilometer to measure stability-values of a material.

The HSM is just like the tri-axial test apparatus a piece of equipment that can measure stresses and stains on axial symmetric samples. The loading stresses can be applied independent of each other in radial and vertical directions. The HSM makes use of an external loading facility to apply the vertical load. For measuring vertical deformation of the sample an external measuring device has to be placed. Inside the HSM a rubber diaphragm separates the sample from an oil/air mixture that is taking care of the confining pressure on the sample. The oil/air mixture is locked into the HSM body and the compressibility of the air lock in this mixture creates in combination with the oil that surrounds the sample an elastic confining boundary of the sample. On the HSM a pressure gauge is placed with which the pressure of the air/oil mixture can be read out.

There are also clear differences between the tri-axial test equipment and the HSM. This equipment is a predecessor of the tri-axial equipment and the way it creates the radial confining stress on the sample is quite different. Also the geometry of the sample is different. In the tri-axial test equipment the height/diameter ratio is about 2.5 where in the HSM the same ratio is approximately 0.6. Because of the high height/diameter ratio the sample in the tri-axial test equipment can create freely shear surfaces during the test which is not the case in the HSM. The possibilities of origination of free shear surfaces are important if the test sample is loaded to high shear stress situations. Nevertheless FEM calculations have shown that this stress situations do not occur during rolling. The equipment is still in use, in parts of the USA, as a design tool for mixtures of ac. In this original set-up there is poor volume control of the sample during the test. When volume control of the sample during the test is wanted the equipment can be modified. This will be discussed below.

Modification of HSM

The main problem of using the HSM in unmodified form, for deducing compaction characteristics of an asphalt concrete mixture is the lack of control over the volume of the sample during the test.

In the standard HSM the confining stiffness around the sample is strong progressive because of the in the oil confined airlock behind the diaphragm of the Stabilometer body. It gives advantages when this confining stiffness would be linear dependable of the radial deformation and adjustable. This realises a more wanted stress situation on the involved sample (higher deviator stresses). By modifying the HSM this can be realised. The modification changes the confined airlock out for a piston combined with a mechanical spring in a supplementary cylinder. In this modified situation a radial deformation of the sample generates a displacement of the new involved piston. This piston displacement wills, because of a change of spring length, also changes the confining pressure on the sample. And because of the fact that the radial volume change of the sample has to correspond with the volume change of the piston, out of piston displacement the changes of volume of the sample can be determined. Translation of the piston will be measured during the test. Because the spring stiffness is linear the confining stiffness of the sample will also be linear to the radial deformation. By changing out the spring for a stiffer or a softer one the confining pressure can, between certain limits, be adjusted. The physical construction of the modification of the HSM will not further be discussed here.

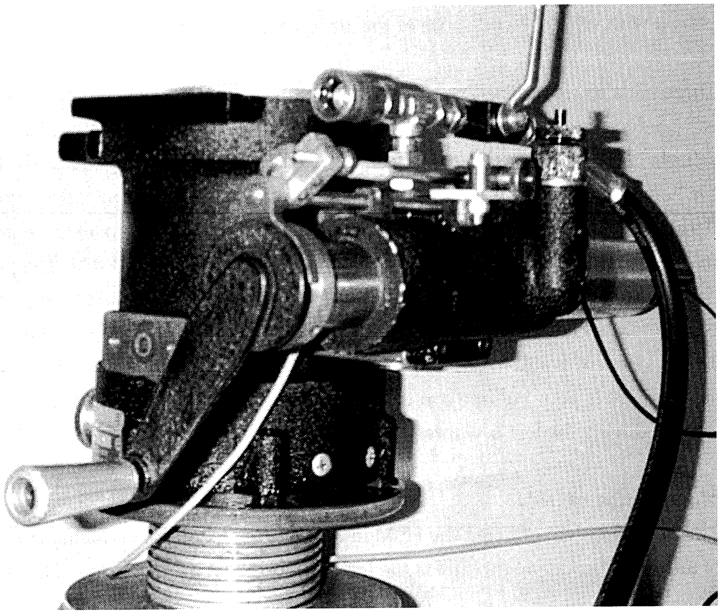

Fig. 6. de Modified Hveem StabiloMeter (MHSM) under an external loading facility.

A test with the modified HSM furnishes the following primary sample quantities; the axial loading force [kN], axial deformation [mm], radial stress [MPa] and piston displacement of the HSM modification [mm]. Out of the axial loading and deformation the axial stress; σ_{ax}, and axial strain ε_{ax}, can be calculated directly. The radial stress, σ_r, is directly measured, and the radial strain, ε_r, can be calculated out of the piston displacement and the starting radius of the sample. The modified Hveem StabiloMeter can be seen in figure 6.

Results out of modified HSM measurements

The information about the mechanical material behaviour that will be gathered with the tests concentrates on; the specific volume where elastic deformation is turning over in elastic-plastic deformation (p and q) for different q/p ratio's, and, the speed with which the yield locus is growing both during elastic deformation (slope κ), and during elastic plastic deformation (slope λ). The relations can supply information about the E modulus, Poisson's ratio v, the hardening parameter, the shape and size of the compression cap (part of the yield locus on the wet side of critical).

6 Calculation results

Calculations have been made with fictitious values for material properties of an asphalt concrete mixture. The parameter values are roughly estimated from results found in literature (10). In the near future calibration of parameter values is foreseen based on experimental material measurements with the modified Hveem Stabilometer described in section 5.

The simulation is carried out using a roller drum diameter of 1000 mm and a start value of the layer thickness of 50 mm. For stability reasons of the calculation, the layer thickness reduction is fixed here on 2.5 mm, which brings the progress of compaction to approximately 5 per cent measured in specific density. The simulation corresponds to one single roller pass, which can be expected at the start of the compaction process. The total vertical reaction force on the material (or the total vertical force on the roller drum) is calculated on 70.1 N/mm^1. So a roller drum weight of 7010 kg/m leads to a compaction (specific density) progress of about 5%, in this specific situation.

Analysis of plastic deformation of the material at different depths

The plastic deformation (i.e. increase in compaction) of the material is analysed at various depths in the material. These depths are;

- level 0 = the top of the layer,
- level 1 = on 18 % depth in the layer,
- level 2 = on 30 % depth in the layer, and,
- level 3 = on 100 % depth or the bottom of the layer.

In figure 7 the progress of compaction at levels 0 to 3 is shown as a function of the distance to the centre of the roller drum. The progress of the compaction rate at the top of the layer (level 0) is bigger than the progress at the bottom of the layer (level 3). Furthermore, a strong progress of compaction is reached at the point where the roller drum makes contact with the material (vertical position –43 mm), around the centre of the drum no significant progress the material, extra progress of compaction takes place.

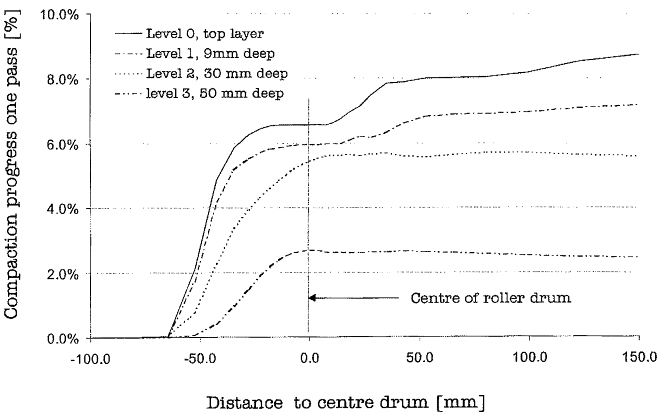

Fig. 7. Compaction progress on four horizontal levels.

Analysis of vertical stresses in the layer

The distributions of the vertical stresses on both bottom and top of the layer as a result of the compaction process are illustrated in figure 8. From these vertical stresses the total vertical force of the roller drum can be calculated, in this case 7010 kg/m width.

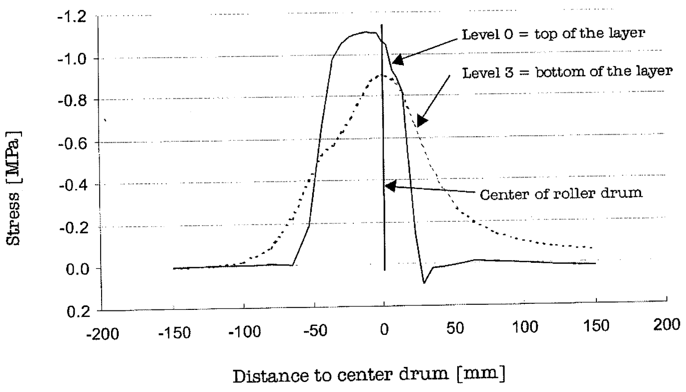

Fig. 8. Vertical stresses level 0 (top of layer) and 3 (bottom of layer).

Out of comparison of stresses on top and at the bottom of the layer, the spreading of stresses in the asphalt layer can be calculated on a slope of approximately 1:1. This corresponds to what roughly can be expected from a rule of thumb estimation of such a material. The length of the surface between roller drum and material can be derived from the calculation, which was about 81 mm. Out of this the mean vertical stress on the material can be calculated at approximately 0.87 MPa.

Horizontal stresses in the material

The horizontal stresses in the material are calculated. Roller cracks can occur when the rolling process is carried out poorly. These cracks can be the result of small tension stresses in the material. The horizontal stresses applied to the surface are the main cause for the tensile stresses in the material. The calculation reveals that tension stresses originate at the top of the layer just in front and behind the roller drum, and sometimes (depending on material properties) on the bottom of the layer below the centre of the roller drum. The horizontal stresses are illustrated in figure 9. The figure gives also notion of the set up of the Finite Element mesh.

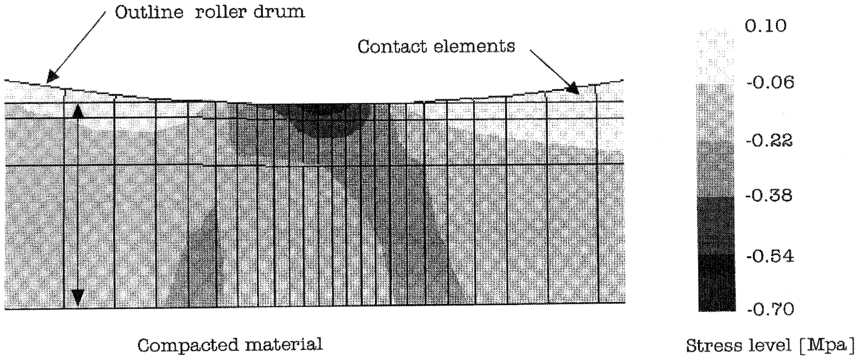

Fig. 9. Horizontal stress distribution below the roller drum.

Adjusting viscosity of bitumen
Material temperatures of asphalt concrete during compaction are approximately between 70 and 140 °C. So in fact the test samples have to be hot for deducing the governing material parameters under compaction. Testing hot materials in a HSM is not possible and also (simple) modifications can not make this work. The rubber diaphragm used in the HSM would be damaged at high temperatures and also the sensors in the equipment do not give accurate measuring results at temperatures higher than approximate 70°C. As a method of approach within this research is assumed that mainly the viscosity and the amount (volume) of the bitumen are responsible for the difference in compaction resistance of the material. The mixtures that will be used for deducing the material characteristics of the non compacted hot asphalt concrete will be modified in such a way that it simulates the behaviour of the originally hot material at approximate room temperature.

7 Validation of theory

The compaction process simulated with the FEM approach needs validation. Therefore the results of the simulations will be compared with the results of a field experiment.

For this purpose an experimental section has been constructed in 1998 at the test facility of the Road and Railroad Laboratory of the Delft University of Technology. The experimental test section has been constructed with three layers of Dense Asphalt Concrete on an existing road base. The layers were approximately 30 m long and 2.80 m wide. The thickness of every layer was planned to be 50 mm after compaction. The roller used was a tandem roller with a total weight of 7240 kg and drums of 1100 mm diameter and a width of 1400 mm. During the construction of the test section the following measurements have been collected for each layer:

1. the decrease of the thickness of the layer on 16 measuring points after every roller pass,
   a.) with a levelling rod,
   b.) with the Stratotest equipment,
2. the nuclear density increase on 4 measuring points after each roller pass,
3. the variation of the density in thickness direction with a gamma ray scanner on 16 cores drilled out of each layer,
4. the progresses of the cooling of the hot spread asphalt concrete with build in thermocouples. These temperature measurements will not further discussed here.

The validation study, the next stage within the project, will be performed on the basis of these measurements.

8 Conclusions

A FEM approach is presented to simulate the compaction process of asphalt concrete mixtures in an elastic-plastic way. Within this FEM approach use is made of a material model that originates from soil mechanics. Essential features are; an ALE method, the implementation of contact elements and an elastic-plastic material model with closed yield locus and hardening possibilities. Measuring material characteristics and calibration of material properties is needed in order to be able to apply the FEM approach for practical purposes. Modifications of an existing piece of equipment are proposed and worked out for deducing material characteristics during compaction in accordance with a "Critical State" theory.

A first FEM calculation is made to deduce stress and strain patterns in the material during compaction. From a theoretical point of view it turns out that plausible stress, strain and deformation patterns on the material can be produced. By means of the FEM tool, it should be possible to get grip on the compaction process in a fundamental way, which is necessary for improving quality management of road works. All other approaches to predict compaction results found in literature, are based on empirical methods which makes it difficult, though not impossible, to generalise the results and to adapt these for new materials. The described tool makes it also easier to perform a parameter study or sensitivity analysis. The developed tool looks promising and powerful, and further research is undertaken to validate the approach using extensive measurements of a field experiment.

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