Using critical state theory and Modified Hveem Stabilometer for modelling asphalt material behaviour.

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Summary

The correct compaction level is crucial for the realisation of high quality asphalt roads. However, reaching the correct compaction level requires knowledge of the material behaviour during compaction; the material change from just slightly compacted into densely compacted. The paper discusses how a material model adopted from soil mechanics is tested for modelling the material behaviour of asphalt mixes. In the first part of the paper the Hveem Stabilometer is discussed, an existing test device that is modified to make it capable to measure material parameters during asphalt compaction. The second part of the paper discusses the results of a laboratory-measuring programme. Mixes with round material, different bitumen viscosity (equivalent to material temperatures) were tested under different applied stress combinations.

Introduction

In road construction practice compaction of the material asphalt is a key element in establishing the final quality of the road. Compaction (rolling) of asphalt is mainly based on experimental knowledge. From experiences with compaction of asphalt mixes gained in the past, it is possible to estimate the results when comparable mixtures are compacted under similar circumstances. Operating outside the experience domain makes it impossible to predict the results of compaction. At present this is often the case since regularly roads are maintained under adverse conditions and new types of mixtures are being used.

It was reckoned that the ability of simulating the compaction process for asphalt layers would have several advantages. It allows one to predict under what conditions a particular mixture can be compacted. Moreover it provides an indication as to what rollers are suitable for specific mixtures and how the rolling process should be managed in order to reach a desired compaction level. Finally, simulation can show the impacts of constructing under adverse conditions.

The research project proposes to develop a tool for simulation of compaction processes of asphalt [1]. A potentially useful option is the use of Finite Element

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Methods to simulate compaction. However, when using such a method the constitutive information about the material must be available. For asphalt mixtures in a hot just loosely compacted state, this is not the case. Therefore in the research project the following issues were addressed:

a.) identifying a constitutive model that can describe the behaviour of asphalt mixes during the compaction process,
b.) identification, design and composition of equipment that can quantify the parameters for a material model as a result of a.) and deduction of those parameters for an asphalt mixture by performing a laboratory test programme.

Similarities between soil and loosely compacted asphalt mixtures

Detailed investigation of the mixture composition of soils and HMA, illustrates that although there are a lot of differences between both materials, there are also many similarities. One of these similarities is the material behaviour when a relatively loose compacted mixture is subjected to a mechanical load. The material behaviour is based on particle reorientation and a theoretical framework that describes such behaviour is the *critical state* theory [2].

The idea to apply soil mechanics principles was born from the analogy between the internal structure of sandy soils and asphalt. Both soil and asphalt are mixtures of particles, fluid and air voids. It is thought that because of these similarities between both materials (mixtures) it would be possible to use the framework of the soil mechanical model as a tool to describe the behaviour of the asphalt mixture during compaction. The soil mechanics model that is selected for this purpose is from the critical state family of models [3]. To validate if such a critical state model is really suitable for the task a measuring tool is selected (developed) and laboratory test programme is designed. Both issues will be addressed in this paper.

Use of the Modified Hveem Stabilometer

To deduce material properties from asphalt mixtures during compaction the suitability of different equipment was considered. One of the equipment tested was the Hveem Stabilometer (HSM) [4]. The equipment uses axial symmetric samples of 4” (101.60 mm) in diameter and around 2.4” (60.96 mm) height. The basic principles of Hveem’s equipment are very useful for compaction; the material is vertically loaded while the magnitude of the confinement stresses is related to the radial deformation. However, the HSM omits an adequate volume control over the sample during a test, a definite pre-requisite for deduction of critical state parameters.

Therefore possibilities were investigated to modify the HSM without disturbing the basic principles and without developing a complete new testing apparatus. The modification should improve the volume control over the sample and it should make the confining stress-strain relation better adjustable. The principles of this Modified Hveem StabiloMeter (MHSM) are illustrated in Figure 1.

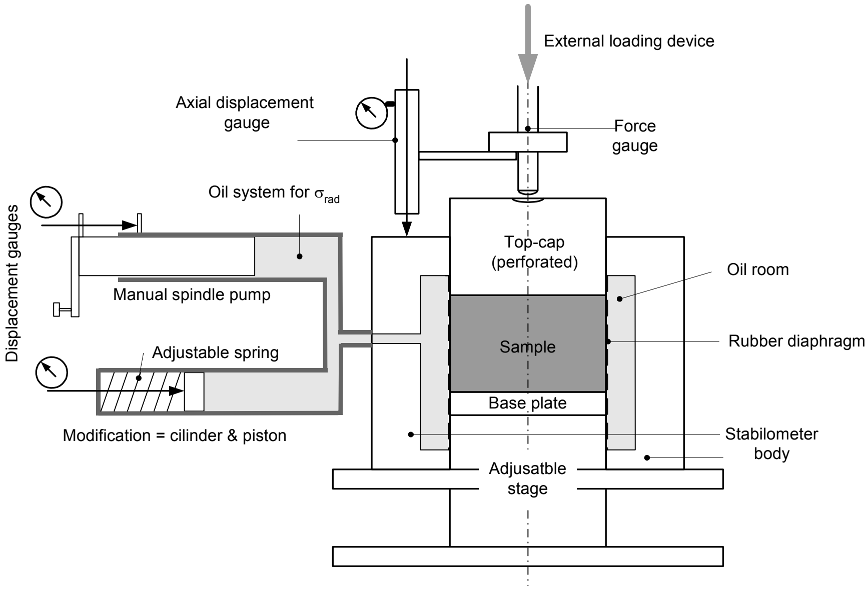

Figure 1. The principles of the Modified Hveem StabiloMeter.

The basic principles of the MHSM are the same as the HSM; a vertical load on the sample generates a radial displacement and this radial displacement generates a radial confining stress on the sample. In the MHSM the radial deformation of the sample generates a displacement of the installed piston and alternates the spring length and force. Therefore the piston displacement will alternate the oil pressure and thus the confining pressure on the sample. The radial confinement stress-strain relationship is adjustable by changing the spring stiffness. Due to the modification, the confinement stress strain relationship on the sample is approximately linear. Additionally, because the oil is free of air, the radial expansion volume of the sample is equal to the translation volume of the involved piston and can be measured accurately. Deduction of the radial expansion of the sample, together with the measured axial deformation, provides volume control over the sample during a test.

Quantities measured in a Modified Stabilometer test

A test with the MHSM provides the following measurements:

- axial load [kN],
- axial deformation [mm],
- radial stress [MPa],
- piston displacement of the HSM modification [mm].

From these MHSM test signals the axial and radial stresses and strains can be determined.

Axial load and displacement;	Measurement of axial load and displacement is similar to the standard HSM. The axial stress σ_{ax}, and axial strain ε_{ax}, can be calculated from the axial load and axial displacement.
Radial confinement stresses & strains;	In the MHSM set up the radial confinement stress-strain relationship can be adjusted by changing the spring in the additional cylinder. Due to the nature of the MHSM the magnitude of the confinement stress on the sample is almost linear to its radial deformation. A pressure gauge measures the radial stress, σ_{rad}, during the test. Radial deformations (and strains) cannot be measured directly, they have to be calculated from the piston displacements and other factors.

The required quantities for realising the material relation between *p'*, *q* and *VMA* (or v)[3], can be calculated at any stage during the test from the primary stresses and strains.

Use of the MHSM for deduction of material parameters

Compactibility results are discussed in this section. The section will start by explaining how the results from MHSM tests can be used to achieve critical state parameters. The suitability of the equipment to measure material compaction characteristics was tested, based on the REF[4], RM and LBC test series and based

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[3] The terms *p', q* and v used here are also often used in soil mechanics. *p'* = the effective normal compression stress, *q* = the deviator stress, v = the specific volume of the material. *VMA* = the voids in the mineral aggregate a term from road construction branch, it expresses the volume of the material, equal to v.

[4] The meaning of the used codes (REF, RM etc.) are addressed in table 0.12

on MTM, HTM and SP1 material tests series, parameters for a DAC 0/11 were obtained.

LABORATORY TEST PROGRAMME						
1	2	3	4	5	6	7
REF	78	27.0	6.35	1.3 (2)	25	reference mix
RM	78	27.0	6.35	1.3 (2)	100	more round sand
LBC	141	0.34	5.35	1.3 (2)	25	less bitumen
MTM	94	5.6	6.35	1.3 (2)	25	medium viscosity
HTM	141	0.34	6.35	1.3 (2)	25	low viscosity
SP1	78	27.0	6.35	1.8 (1)	25	stiffer confining

Note:
1 = mixture code
2 = imitated temp. [° C]
3 = viscosity fake bit. [Pa sec]
4 = bit cont. [% $^{m}/_{m}$]
5 = confinem. stiffness [N/mm^2]
6 = perc. round [% $^{m}/_{m}$]
7 = remark

Table 1 Test programme of the DAC 0/11 mixture.

For every test the progress of sample compaction is achieved in *p' & VMA* values and the calculated *p'-VMA* path is plotted, see also Figure 2. The path indicates the ease at which a material can be compacted. It expresses the extent of required stress levels for achieving compaction improvement, given the material conditions (i.e. pre-compaction state and temperature). Comparing these test-paths can explain differences in compactibility between, for example, round and more angular materials.

Deduction of critical state parameters

The material test programme provides the relationship between the volume of the sample (in terms of *VMA*) and the governing stress conditions in *q* and *p'*. Both from the critical state theory and from the material measurement programme, it follows that a particle based material shows a bi-linear loading behaviour when such a material is tested over a sufficient wide loading range and the results are expressed in the *VMA - log p'* space [5].

For each of the test series (one material constitution, temperature or loading condition) six samples were tested. Each test yielded one single loading line. Within such a test series two tangents were deduced by using statistical techniques; one representing the recoverable behaviour[5] and one representing the irrecoverable behaviour. The tangents are deduced by estimating the slopes and intercept for the best straight lines that can model the recoverable and irrecoverable part of material behaviour in the *VMA-log p'* plane. In order to be able to do this it must be estimated how much data could be used to calculate those slopes (because between the straight ends of the line there is a curved section which cannot be used to calculate both tangents). The results of the loading lines from the Reference test series and the estimated tangents are shown in Figure 2.

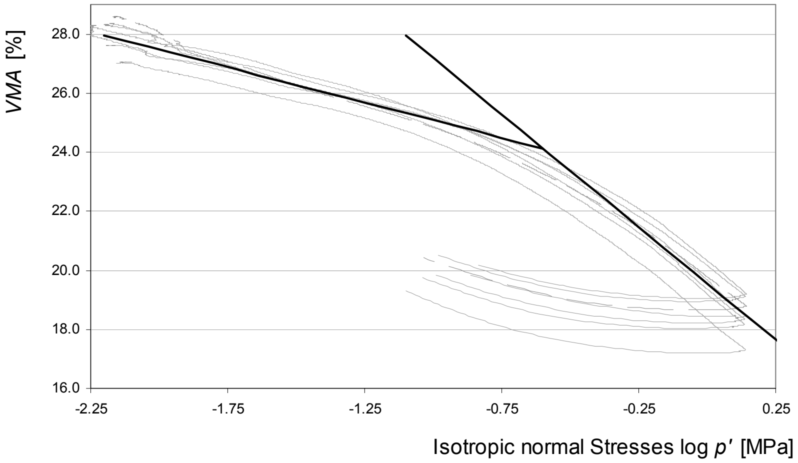

Figure 2 The 7 individual test results from the reference (REF) series including the composed mean curve.

Besides numerating the two tangents, also the stress ratio q/p' and deformation ratio $\varepsilon_{sh}/\varepsilon_{vol}$, have to be calculated from the test data. We need this information to model the deformation behaviour during plastic flow.

The results obtained by the laboratory test programme resulted in different “compactibility” lines for different material compositions respectively the REF, MTM, HTM, RM, LBC mixtures.

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[5] Before this was done the specific volumes (i.e. *VMA* values) of the sample were first of all normalised to the *VMA* starting value. So when using the calculated slopes and intercepts they have to multiplied by the mean *VMA_I* values within that specific test series.

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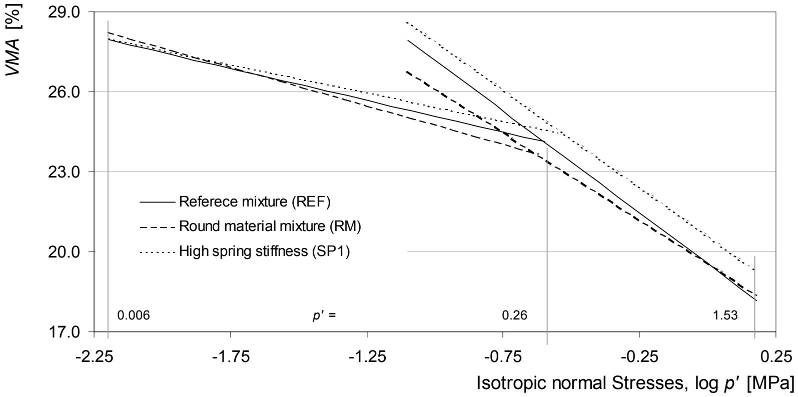

Figure 3 The mean *p'-VMA* curves for the mixtures with a low bitumen content (the LBC mixture) and for that the reference mixture, the HTM mixture (bitumen with lowest viscosity; 0.34 Pas, 141°C) together with the results for the mixtures tested at the changed confining stiffness (SP1 tests).

The SP1 test series sample was subjected to a higher confining stiffness (related to REF). From the position of all other lines related to the REF test series expressed in the log *p'* - *VMA* space conclusions of the compactibility of the mixtures could be drawn. A higher position of the line (e.g. the HTM line related to the REF line, see Figure 4) or a stiffer slope of the plastic tangent of the line (see Figure 4) implies that an easier compactable mixture or material composition under the assumption that the *q/p* ratio during testing was kept equal.

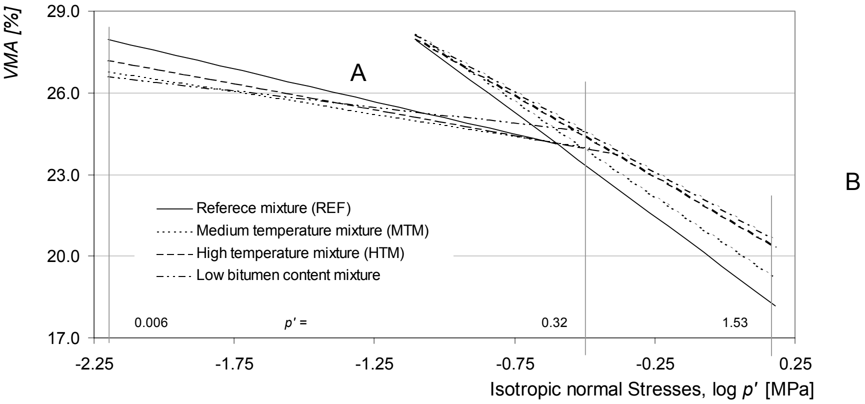

Figure 4 A view on the mean elastic (A lines) and mean plastic (B lines) tangents for the REF, MTM, HTM en LBC test series.

The results of the SP1 test series indicate that a higher position of the line does have nothing to do with the mixture itself but the effect is caused by the larger *q/p'* ratio subjected to the sample. The results imply that a higher deviator stress has a positive effect on the compactibility of the sample, which is a plausible result. Analysis of the results show that an surplus of round sand makes a mixture more easy to compact, whereas more or less bitumen did have no effect in terms of *VMA*. The results further indicate that a higher viscosity of the bitumen (lower temperatures) results in better compactibility. Especially this latter result contradicts to common expectation. In road-building practice it is thought that HMA mixtures are easier to compact at higher temperatures (lower bitumen viscosity). Further research is needed to explain these results.

Conclusions

From the results discussed in this paper the following conclusions can be drawn:

- a material model from soil mechanics (from critical state theory) is tested and proved to be suitable to model the constitutive behaviour of Hot Mix Asphalt (HMA) at compaction temperatures,
- a new method / equipment is proposed for measuring fundamental material properties (i.e. critical state material properties) of an asphalt mixture during compaction,
- differences in compactibility could be obtained for bitumen viscosity (equal to bitumen temperature), roundness of the sand in the mixture and confining stiffness of the sample during a test.

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