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Using Critical State Theory for Modelling of Asphalt Mix Compaction

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Abstract: This paper focuses on modeling of Hot Mix Asphalt (HMA) material behavior during compaction. During compaction the particle configuration inside the HMA is changing from a relatively loose into a denser one while the bitumen is fluid. Initially particle reorientation is easily possible due to the HMA's loose configuration. The material behavior predominantly falls in the elastic-plastic domain. Critical state theory from soil mechanics is proposed as a basis for modeling this behavior. An extensive laboratory testing program was undertaken using a modified Hveem stabilometer as a tool for parameterization. The program included: different mixtures, different stages of mixture density and different material temperatures. In this paper, we discuss how well the critical state principles suit HMA behavior, and what the critical state material parameters are for HMA with respect to different material temperatures, different compaction stages and different stress states. We show that HMA compaction behavior can be modeled using the critical state theory and that material behavior is bi-linear in the *p':q* stress space.

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***Key words**: Asphalt; Compaction; Critical state theory; Hveem stabilometer; Material parameterization; Pavement.*

Introduction

It is difficult to construct an asphalt road with a consistent compaction level that is close to optimum density. Although adequate compaction of Hot Mix Asphalt (HMA) in road construction is of major importance for producing flexible pavements with sufficient bearing capacity and a long life span. Hassan *et al.* [1], for instance, indicated that different methods for compacting HMA mixtures is leading to different orientations of particles in the mixture, and, as a result of that, different mix performances. During such situations it seems to be an advantage to be able to model compaction processes. Figge [2] and Gauer [3] both reported on the 5 parameter model of Krass [4] to describe the behavior of HMA. Gauer describes the three basic rheological models: 1) elasticity, Hooke's law, 2) plasticity by St. Venant and 3) viscosity by Newton. These models describe material behavior in general as we observe it in laboratory tests. Micaelo et al. [5] applied these techniques in a (two dimensional) discrete element model (DEM) [6] method to study compaction processes of HMA. His research led to plausible stress situations as a result of compaction and is useful in starting to understand material behavior. However for reliable results the third dimension cannot be neglected. Altogether, these models and tools cannot be used for more sophisticated simulation experiments. Even a literature review [7] shows that currently no fundamental tools exist for simulating the behavior of HMA under compaction. Simulation and modeling has significant advantages when testing new compaction equipment or new asphaltic mixtures, and for understanding, analyzing and improving compaction processes.

Here, in this paper we want discuss preliminary steps in developing models and testing them on HMA compaction behavior. We think that as an underlying model a soil mechanical model could be used. We therefore have to make the comparison between the materials "soil" and "hot, partly compacted asphalt mixtures". We think this is correctly because both "mixed" materials (wet soils vs. HMA) consists out of a solid component (stone/sand), a fluid component (hot bitumen vs. moisture), and, a gaseous component; the air filled voids. During compaction effort applied on the material particles are pushed together and squeezed along each other. The viscosity of the fluid and the number and size of voids deduces the ease compaction progression is taken place. We did tests on real asphalt mixtures using real asphalt test equipment, the underlying used soil mechanical theory is the critical state theory [8-11].

The paper starts with a brief introduction of the basic principles of the critical state theory (CST). Then we describe an existing instrument that is capable to do a limited material parameterization on lab scale; the Hveem StabiloMeter (HSM). We continue in the next section with the material testing program for estimating the asphalt material parameters. In the next section we analyse material behaviour and compactibility based on material data plotted in graphs. In the last section we end by summarising the most important conclusions.

Literature Review

Several research groups studied compaction processes of HMA in order to improve the process and to realize longer life spans of roads. It is shown that the temperature of the mixture during compaction is very important but underestimated and a very complex process. It does not need much imagination that during such situations homogeneous compaction levels close to target density is uncertain in many cases. From such perspectives the use of thermo graphic imaging and GPS technology in asphalt paving is becoming

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common practice to support compaction processes of HMA. According to Stroup-Gardiner [12], Read [13] is credited with the initial observation that temperature differentials in the HMA during construction is a strong indicator of a segregated mix. Further, there have been several industry-aided research efforts for the development of state-of-the-art technologies for real-time locating and positioning systems for construction operations in order to be sure that compaction effort is applied at the right temperature and thus at the right moment during lay down operations [14]. Li et al. [15] reported on a system to map moving compaction equipment and to transform the result into geometrical representations. They investigated the use of Geographic Information System (GIS) technology to develop a graphical illustration depicting the number of compactor passes. Oloufa [16] described the development of a GPS-based automated quality control system for tracking pavement compaction. Timm et al. [17] indicated that both temperature of the mixture and moment of compaction are very important for achieving a proper compaction stage and the most desirable mechanical specifications. Timm and Decker [18] showed that material temperature and cooling behavior are dependent upon mixture composition, meteorological conditions (wind speed and moisture content), and the temperature of the sub-layer on which will be paved.

Hence, it appears that several innovative technologies and experiments have been introduced during the recent years, in order to compact HMA mixtures at suitable temperatures. Much effort is being invested in systems that correlate the compaction effort (number of compaction passes and temperature of the mixture while being rolled) and its impacts.

But, still the need of knowledge about material behaviour related to external conditions is missing. Hence a fundamental material model must be developed. The studies described above make at least clear what factors do affect HMA compaction; mixture temperature while being rolled and the compaction energy applied (i.e. the number of roller passes applied). It seems that Koshla et al. [19] and Picados Santos et al. [20] felt this omission and studied different compaction methods to make specimens of Hot Mix Asphalt in a laboratory and compare those specimens to mixtures compacted in situ. As another aim to model HMA material behavior we mention the work of Xia and Pan [21]. They tried to understand the behaviour of HMA vibratory compaction by numerical simulation. For doing so they selected a “crushable foam type material model”. A model that makes use of a yield locus for indicating the turnover from elastic deformation into plastic deformation, this model comes the most close to the model described here in this paper.

Studies like these are very common in HMA research because the lacking of a fundamental model that describes material behaviour during compaction. Without such a material model, or, a one to one match between laboratory and field compaction, the effects of compacting HMA mixtures can only be derived from full scale laboratory tests. Such an approach may provide much information but does not increase our knowledge on what in detail happens inside the material and are very expensive and time consuming. For this purpose we suggest a newly developed material model particular for being able to simulate HMA compaction.

In general we can conclude that many aspects of compaction of HMA mixtures already have been addressed: temperature during compaction, moment of rolling, weather conditions, cooling of the material, and also some elementary material modeling. However, it must be stated that still a lot of work needs to be done before reliable computer simulations of the compaction process of HMA’s are available. And thus before the process can be further improved and automated. The research topic addressed here aims to contribute to this development. First, proper theoretical concepts are needed to describe the material response behavior as a result of external loading. This paper uses the analogy between soils and HMA (both built up out of particles) and selects a model of soil mechanics for describing the transformation of the material from a fluid-like into a more solid like response.

Mechanical Material Behavior

The mechanical behavior of HMA’s during compaction is derived from the behavior of the bigger particles inside the material just as is the case in a soil. In both, soils and HMA’s, part of the mixture is fluid (bitumen versus moisture) and consists of air filled voids. Ter Huerne [7] makes the assumption that compaction of HMA is mainly caused by particle re-orientation. The hypothesis is that in loosely-compacted granular materials (i.e. soils) and hot loosely-compacted HMA’s similar mechanisms govern the material behavior during compaction. Both materials are composed of solid particles, voids and a fluid. Obviously, the viscosity of the bitumen in a HMA is different from the viscosity of moisture in a soil. However, volume changes and progression in densification will be achieved largely by the sliding of particles along each other and the way particle skeletons are developed. The ease of progression in densification depends mainly on the fluid in the mixture. Because of similarities in behavioral principles of asphalt mixtures and granular materials it makes sense to use similar models for their mechanical behavior. This argument led to the use of a soil mechanical model to test its applicability to describe the behavior of HMA’s during compaction.

A soil mechanics model that uses elastic-plastic principles is found in the critical state theory, developed at Cambridge University around 1968. In this section a brief description of the principles of this theory is given. For more details we refer to Atkinson, Schofield, Wood or Roscoe [8-11].

Critical state theory works with stresses p' (isotropic normal compression stress) and q (deviatoric stress). For axial symmetrical situations, like a tri-axial test, these stresses can be calculated using the following equations

$$p' = {}^{1}/_{3}\sigma'_{ax} + {}^{2}/_{3}\sigma'_{\mathrm{rad}} \tag{1}$$

$$q = \sigma_{\mathrm{ax}} - \sigma_{\mathrm{rad}} \tag{2}$$

in which, σ_{ax} = axial stress applied on the sample; σ_{rad} = radial stress applied on the sample.

Depending on the stress situation and the pre-compacted state of the material the theory describes when the material shows elastic (recoverable) or plastic (irrecoverable) behavior. The transition from recoverable to irrecoverable behavior is indicated by what is called a “yield locus”.

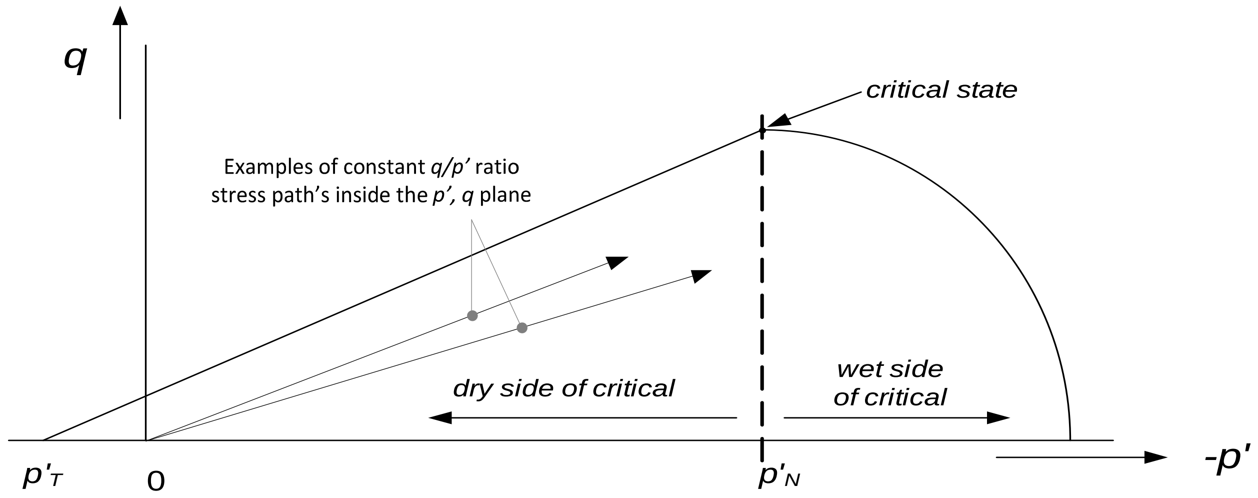

Fig. 1. An Example of the Shape of the Yield Locus of a Critical State Material Model.

The theory distinguishes between three stress situations if a material is deformed irrecoverable. These situations are coupled to the critical state stress situation, which implicitly is one of the states itself. The critical state situation is defined as the ultimate condition of perfect plasticity in which irrecoverable shearing can continue indefinitely without changes in volume of effective stresses [9]. It is the highest level of q at $p' = p'_N$ (Fig. 1). It must be seen as a combination of isotropic compression and shear stress at which the sample deforms ongoing, while the total volume of the sample stays equal: i.e. nor compaction nor expansion of the material sample takes place.

Furthermore, there exist stress situations that are called "on the dry side" and "on the wet-side" of critical state. In case the stress situation is on the wet side of critical state (i.e. p' higher than $p'_{\text{critical state}}$,) the material tends to compact. It is a situation in which there is more isotropic compression stress and less shear as compared to the critical state. The specific volume of the material decreases and the material becomes stronger. Due to the strength increase the yield locus increases too.

In case the stress situation is on the dry side of critical state (i.e. p' lower than $p'_{\text{critical state}}$), the material tends to shear (Fig. 1). It is a situation in which there is less isotropic compression stress in combination with still a high level of shear stress, again compared to the critical state: the material is shearing off. The volume increases (expansion) and the material becomes less compacted and less strong. Due to this, the yield locus, that represents the material strength, decreases as well.

In accordance to critical state theory a particular amount of a granular material can have any volume (of course within certain limits). For every specific volume the material does have a particular yield locus which corresponds to a material strength. Material in a loose state has high Voids in the Mineral Aggregate (*VMA)* values and a low strength; materials in a densely compacted state have low *VMA* values and a higher strength. It is plausible that the theory is suitable for modeling the mechanical behavior of asphalt concrete mixtures.

Fig. 1 illustrates an example of a yield locus. Critical state models may use different shapes (for example see Van Eekelen and Van den Berg [22], Schofield and Wroth [9] or Vermeer [23]). For practical reasons, we focus on the material model and corresponding yield locus that is available in the FEM approach DiekA [24]. It is recommended to do further research to compare different yield loci shapes and to assess what models fit HMA compaction behavior best. However, this is not the objective of this paper.

The compaction process of asphalt mixture is characterized by the material flow, in which the air voids are expelled and the material becomes compacted. In this paper, however, we do not study material behavior on a microscopic level, but assume it to be homogeneous on a meso level. The compaction of the asphalt mixture is explained to be caused by plastic deformation.

Developing the Modified Hveem Stabilometer

The assumptions about the material behavior require verification and a material parameterization study in the laboratory to derive parameters for particular mixtures. In a pursuit to model HMA compaction Scarpas [25] stated that

1. No laboratory tests exist for asphalt mixtures at compaction temperature to determine model parameters
2. There is no laboratory method to test asphalt mixtures at compaction temperatures

For parameter quantification purposes one requires tri-axial type of testing equipment. In this compaction research the Hveem StabiloMeter (HSM [26]) was selected. Previously the Hveem StabiloMeter was used as test equipment in a design procedure for asphalt mixtures. However here we use it for research purposes. The most important argument to choose HSM is the fact that the radial pressure on the specimen is the result of the radial deformation of the material. This is very similar to the way stresses develop during HMA compaction in the field. To derive the critical state parameters, the apparatus had to be modified. Hence as a spinoff of the project we developed the Modified Hveem StabiloMeter (MHSM). For more details about the modification of the Hveem we refer to Ter Huerne [7].

Inside the Hveem a test sample is surrounded by a rubber diaphragm and behind that diaphragm incompressible oil is enclosed inside the MHSM body (Fig. 2). In the test the sample inside is loaded axially by use of an external device. The sample deforms axially and radially, and caused by the radial deformation a confining pressure on the sample is built up. This confining pressure is equal to the oil pressure inside the MHSM and, due to this, the piston inside the modified part of the apparatus is moving.

A test with the MHSM provides the primary 'sample' quantities:

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

From the known piston displacement the radial sample deformation can be calculated. From the radial and axial stresses and strains the soil mechanics quantities *p'*, *q* and the strains ξ_{vol} and ξ_{sh} can be derived. The *VMA* value of the sample can be calculated since the total volume of the sample and the amount of aggregate is known. From this data the *p'-q -VMA* relation could be derived.

Set up of the Test Program

In the laboratory testing program we have tested materials at three different temperatures. We used three different material compositions and two stress combinations (*p'* versus *q*). For explaining the material behavior of an asphalt mixture in practice we distinguish two different material modes:

1. The "operating mode", typically when vehicles are driving over it. In this mode the material is cold (between -20 and 60℃) and highly compacted, therefore there is almost no particle sliding inside the material; the material behavior is mainly viscous-elastic [27].
2. The "construction mode"; in this mode the material is warm to hot (between 60 and 180℃) and partly or not at all compacted; in this mode particle sliding and changes in the particle skeleton may occur easily, material behavior can be defined as mainly plastic.

It is expected that at high temperatures, corresponding to low bitumen viscosities, hardly any cohesion will develop in the binder (Fig. 3). At lower temperatures, when cohesion plays a role, it is necessary to introduce viscous-elastic behavior. Below temperatures of 70˚C, general cohesion becomes very important where in most cases the compaction process has already been finished [2].

During HMA compaction, as a rule, the material cools from approximately 140˚C to 70˚C. These compaction temperatures were also found during construction of a compaction test section. However, there is evidence that the temperature of road sections constructed in the field vary widely because there is a wide range of environmental factors that affect the cooling process of the mixtures [28].

Whilst developing the set-up of the test program, variations in mix composition and applied stresses have to be taken into account. These variations involve/include

- tests at different temperatures, or more explicitly different bitumen viscosity's,
- tests with different confining stress-strain relationships,
- tests at different compaction rates.

The conceptual MHSM is equipped with two different spring stiffness's. The two springs enables one to vary the confining stress on two levels. This is done by running and comparing the two test series RM and SP1 (see Table 1). The tests were not really executed at different temperatures but the used bitumen was modified in such

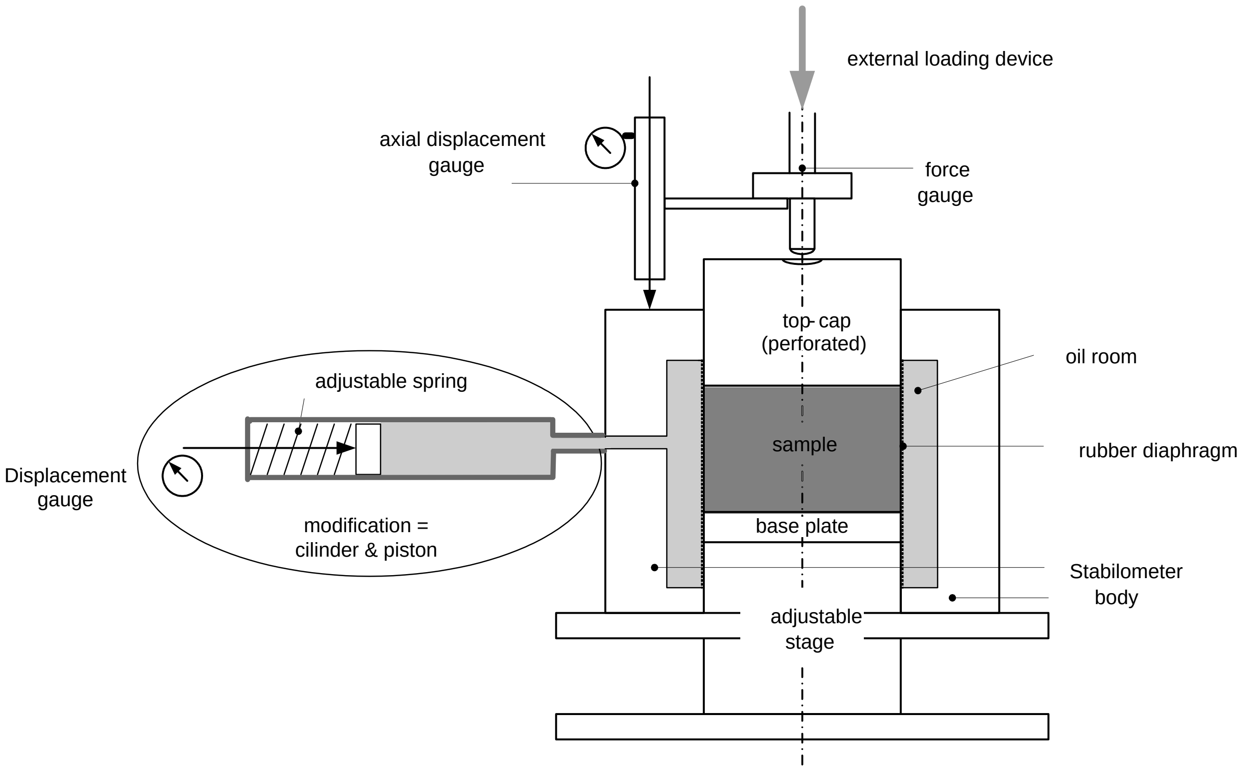

Fig. 2. The Modified Hveem StabiloMeter (MHSM).

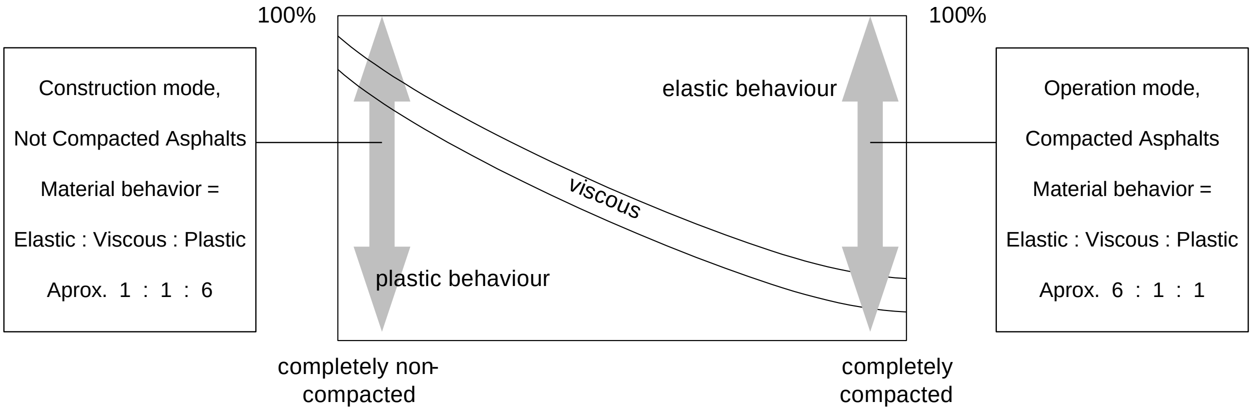

Fig. 3. Rheological Behavior of HMA During Compaction, Elastic – plastic – viscous [13].

Table 1. The Set-up of the Laboratory Material Testing Program.

Test Series [-]	Code [-]	Initial (Simulated) Temperature [˚C]	Bitumen Viscosity During test [Pa.s]	Bitumen Content [%]	Confining Stiffness [N/mm^3]	Percentage Round [%]	Remark
A	RM	80	27.0	6.35	1.3	100	More Round Sand
B	LBC	140	0.34	5.35	1.3	25	Less Bitumen
1	REF	80	27	6.35	1.3	25	Reference Mix
2	MTM	95	5.6	6.35	1.3	25	Medium Viscosity
3	HTM	140	0.34	6.35	1.3	25	Low Viscosity
4	SP1	80	27.0	6.35	1.8	25	Stiffer Confining

a way that tests could be done with different bitumen viscosities at 20℃. For more details we refer to [7].

While running a test on the initially non-compacted asphalt mixture inside the MHSM, the material will be compacted automatically because stress levels increase during such a test from *p’* levels 0.01 MPa until around 1.4 MPa. During the test the *q/p’* ratio was on such a number that sample behavior was on the wet site of critical state. Testing the material at different compaction rates is therefore implicitly achieved during the test.

An increase in the use of rounded aggregate and an increase of bitumen in a mixture lead to more easily compactable mixtures [3]. To test this relationship, two test series were added to the laboratory testing program. Series A contained a surplus of round aggregate in the sand fraction (below 2 mm), whereas the B series mixtures were prepared using a smaller amount of bitumen. The specifications of the tests are shown in Table 1.

Results of the Test Program

Compilation of the Average *p’-VMA* Stress Path’s.

Most of the tests were carried out using one and the same particular spring. It resulted in a constant stress *q/p’* ratio for five different test series (all test series except the SP1 test series). If a test is applied loading the sample with a constant *q/p’* ratio, stress conditions are in such a way that the ratio between *q* and *p’* is fixed during that test, see also Fig. 1. For each test series the progress of compaction was obtained and the *p’-VMA* path could be plotted. An example of such a curve is shown in Fig. 4. This path corresponds to the stress path ac (Fig. 5).

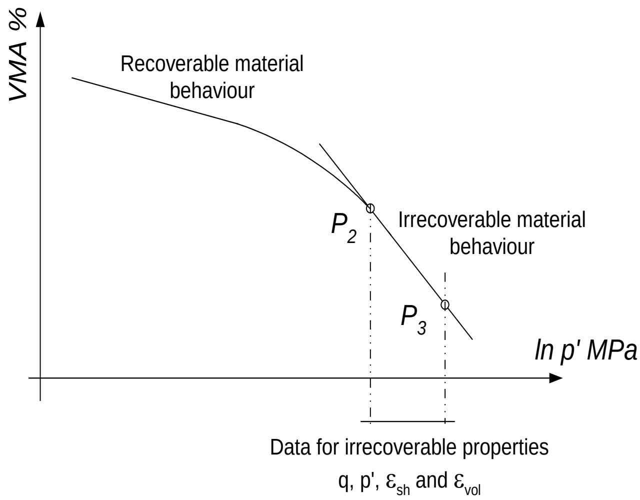

Fig. 4. The Course of an MHSM Test in the *VMA;p’* Plane for a Certain *q/p’* Ratio.

The position of the path indicates the amount of energy needed to further compact the material. It expresses how large the stress level on the sample should be for achieving on-going compaction, given the particular material properties, pre-compaction state and temperature. Six individual tests were done per test series and all the individual *p’-VMA* paths were plotted in one graph. Per test series an average curve is estimated from the 6 individual *p’-VMA* curves. For the reference test series (coded REF) this curve is shown in Fig. 6. The same procedure has been followed for all the test series of Table 1.

A comparison of the average curves per test series shows

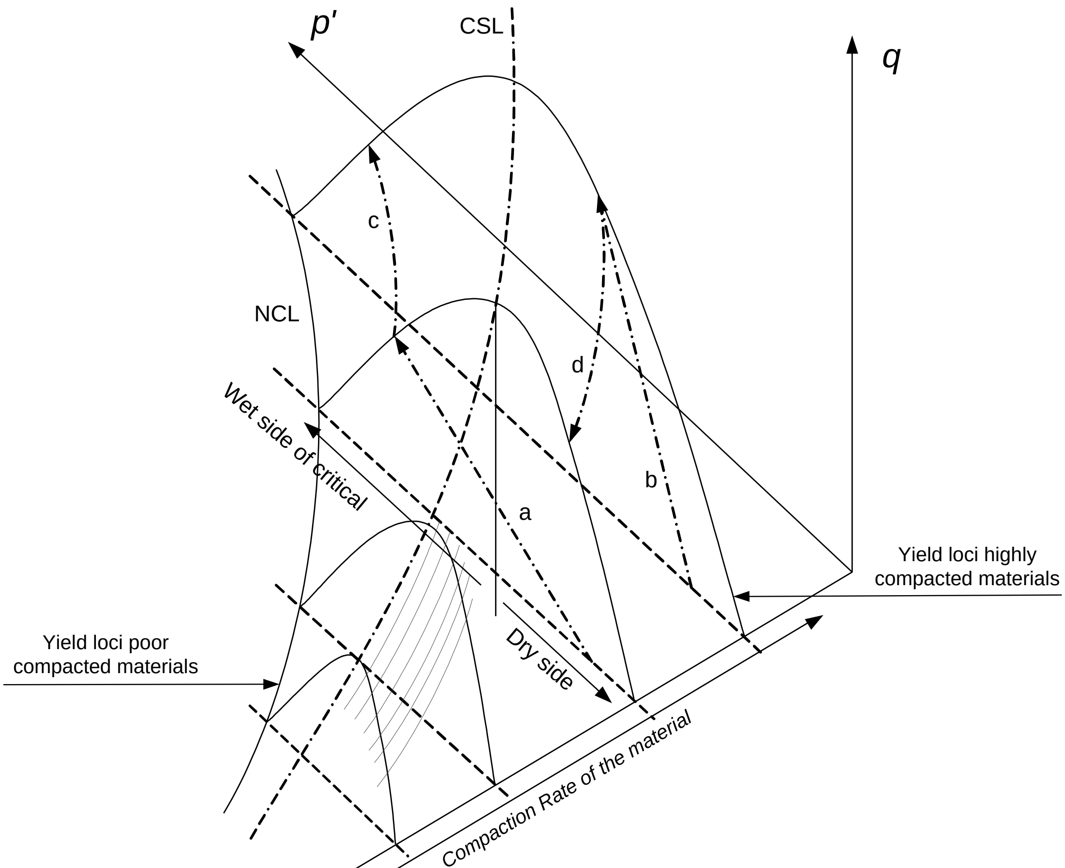

Fig. 5. Four Yield Loci for a Material as a Result of Different Compacted States and Two Elastic – plastic Stress Paths Plotted in the *p'*-*q*-*VMA* Space.

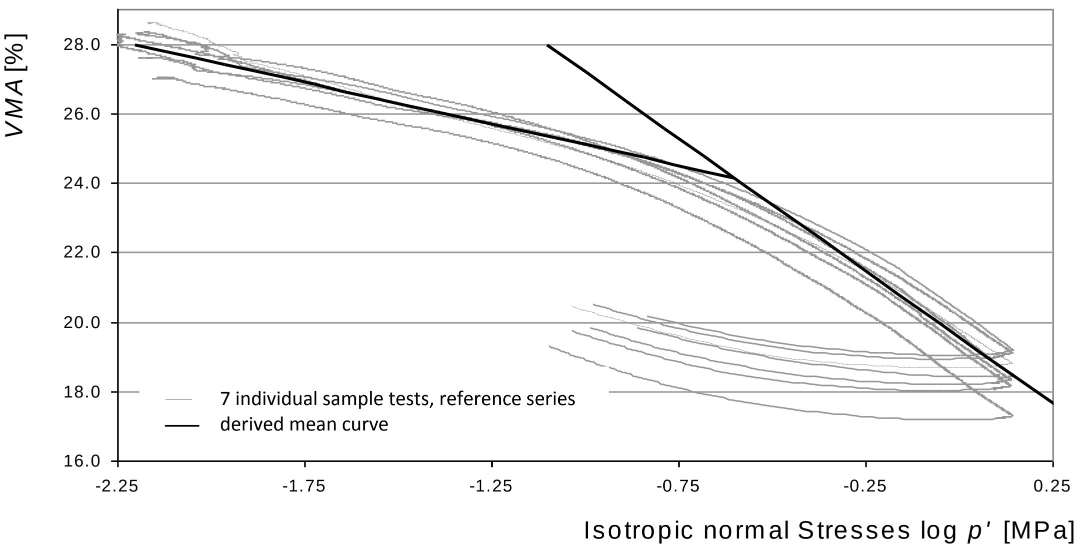

Fig. 6. Test Results for the Reference Series (REF) and the Derived Mean Curve.

differences in compactibility. The average curves for the REF, the RM and the SP1 test series are shown in Fig. 7. Finally, measured values for the material parameters should be transformed into parameters that can be used straight in a simulation tool (Ter Huerne [29]). The slopes in Figs. 7 and 8 provide useful information about the ease a material can be compacted at a specific *q/p'* ratio. The lines are straight because they are plotted in the *log p'*-*VMA* space. This result corresponds to the critical state theory. The flat line

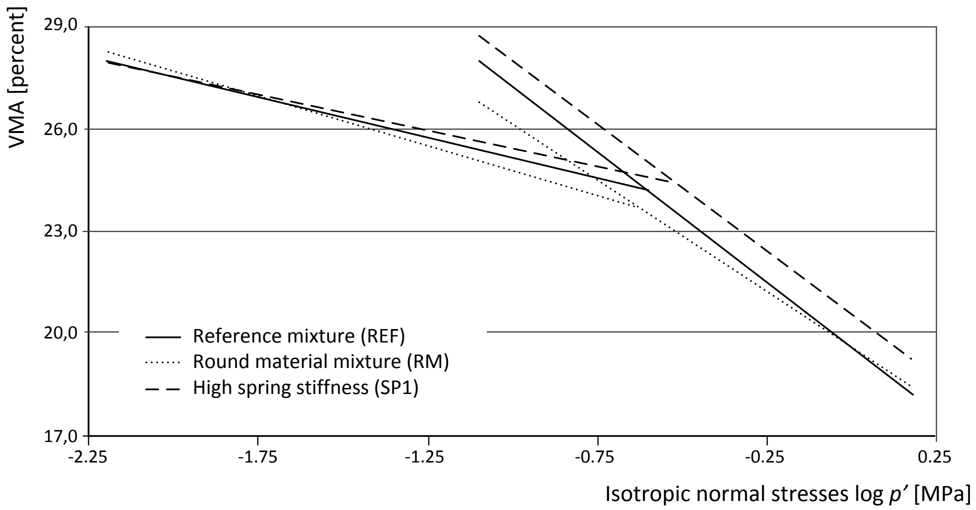

Fig. 7. The Mean *p'-VMA* Curves of the Reference Mixture, the Stiffer Confining and Surplus of Round Material (Codes REF, SP1 and RM).

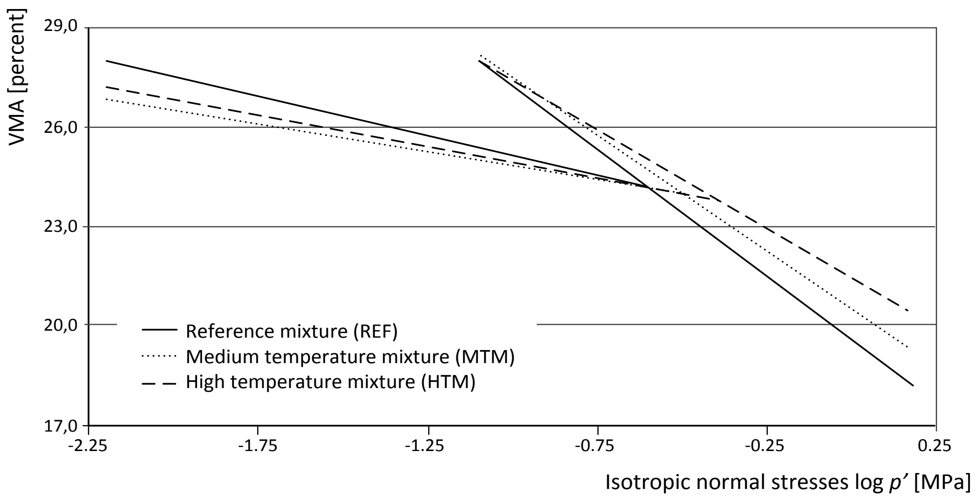

Fig. 8. The Mean *p'-VMA* Curves of the Reference Mixture, at Three "Material Temperatures" or Bitumen Viscosities (codes REF, MTM and HTM).

corresponds to material behavior that has a loading history. We can compare this to an intermediate situation during asphalt rolling. If the asphalt pavement has been loaded until a specific earlier achieved load level (earlier roller pass), no on-going compaction will take place when the loading will not become bigger than the earlier applied loading level. This implies also no particle reorientation if no on-going compaction will take place. Because of that we call such behaviour "elastic or recoverable", the material springs back to its original form and volume when unloaded. The steep slope indicates the zone where particle reorientation occurs, and because of that compaction of the material takes place. The behavior of the material can be seen as mainly irrecoverable. When the material gets unloaded the sample does not spring back to its original form and volume but a new particle arrangement has been found. The intersection point of the two lines marks the position where particle reorientation starts to occur. In reality it is not a single point but a transition curve (Fig. 4).

Bi-linearly estimated average curves are plotted for the test series REF, HTM and MTM. Fig. 8 expresses the effect of temperature whereas Fig. 7 expresses the effect of material constituents and stress conditions. The "reference curve" is plotted in both graphs because it is the benchmark for all the other test series.

Analysis of the Results, Surplus of Round Aggregate

From road building practice as well as compaction studies (i.e. [3], [30]) it is known that more round aggregate in the mixture results in an easier compactable HMA. The data measured with the MHSM show that the round material (RM) results in a lower *VMA* in most stress situations (Fig. 7). This corresponds to higher compaction values at equal stress levels. More confinement (SP1) results in lower shear stress and a mixture that is more difficult to compact. More confinement means a lower *q/p'* ratio, i.e. lower shear stress levels applied on the sample. This is in agreement with critical state theory in which under such conditions higher *p'* levels are needed to reach equal compaction stages. Fig. 7 shows that this result is also found in the testing program.

Effects of Bitumen Viscosity on Compactibility

The test results obtained at different temperatures indicate that mixtures with a low viscosity bitumen are more difficult to compact. It is illustrated in Fig. 8 and contradicts with common expectation. In practice, it is known that HMA mixtures are easier to compact at higher temperatures. Is this because the bitumen can flow more easily from one void into another one during compaction? Or is it because of the thinner bitumen film around the particle that less lubrication results in a harder re-arrangeable particle skeleton? What factor should have the most impact during rolling and during testing a sample inside the Stabilometer? It seems clear that further investigations must be done.

Another result of the testing program is that equivalent mixtures with different bitumen viscosities do have a specific sequence when compactibility is considered (Fig. 8). Regarding to those tests it is found that mixtures at 95˚C are harder to compact than mixtures at 80˚C and in turn, mixtures at 140˚C are harder to compact than mixtures at 95˚C. It implies a consistency in the results of the measured compatibility of the samples at different test temperatures, however, those measured effects were not understood completely and are hard to explain. It might indicate earlier stone to stone particle contact when bitumen has a lower viscosity (at lower compaction stress levels). That earlier stone-to-stone contact would cause a rise of internal friction (less lubrication), which in turn results in a mixture that is more difficult to compact. Within this field we want to refer to the research of Bahia [31] who introduced related to this topic “lubrication” effects of bitumen in stone tot stone contact planes. It is hard to model and forecast precise impacts of bitumen viscosity effect on compatibility of asphalt mixtures in different situations. It is clear that although a lot work already has been done on this topic still this phenomenon needs further research.

The effects of bitumen “temperature” or viscosity are difficult to explain. Analysis of these results indicate that *p’*, *q* parameters are suitable for modeling plastic material behavior, and enables one to develop ideas about what might happen inside the sample.

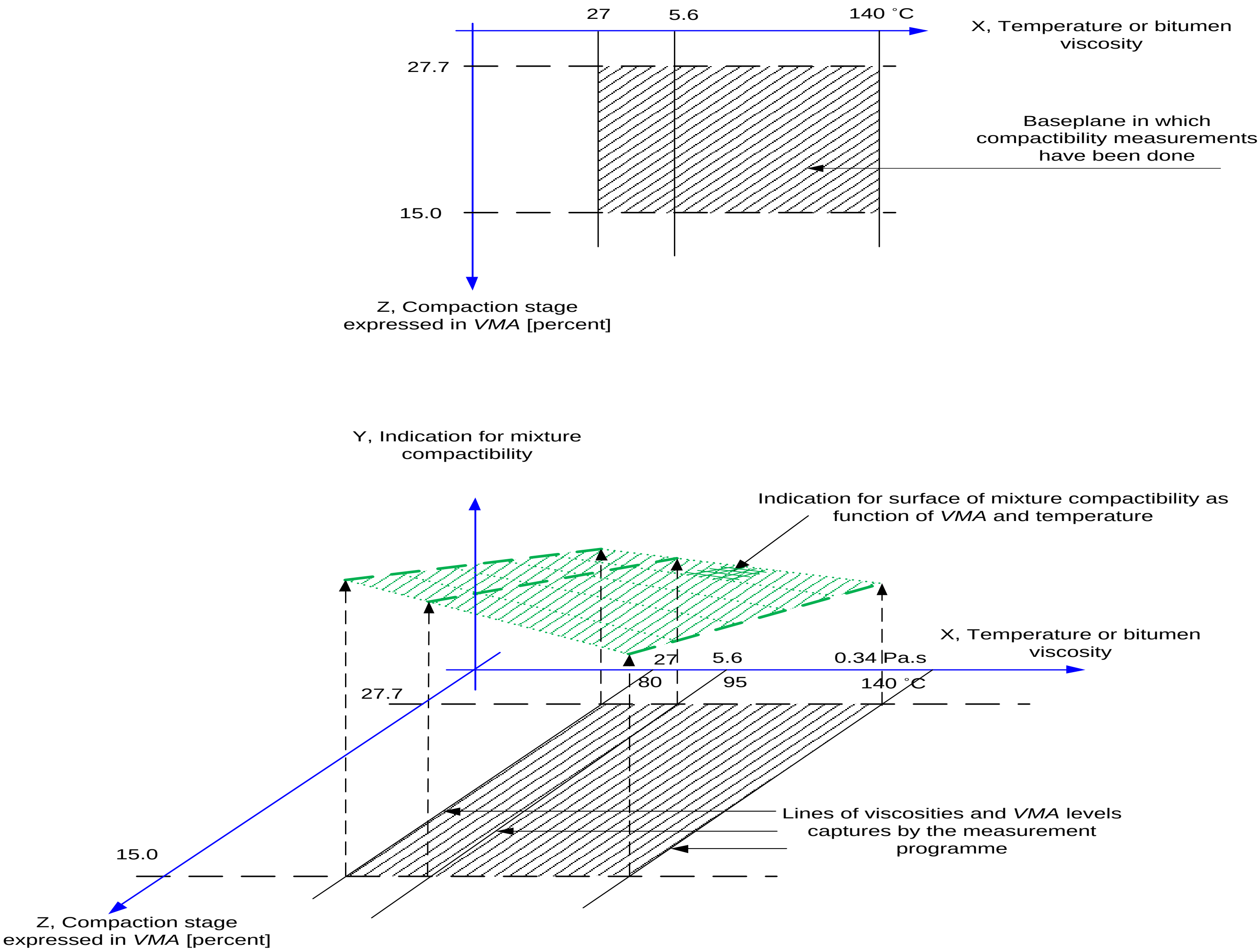

Fig. 9. Material Specification as a Function of Bitumen Viscosity and Compaction Level.

It appears to be not quite clear whether in general higher temperatures in asphalt mixtures make compaction easier or not. The research indicates that hotter mixtures are harder to compact. From common practice on compactibility issues it is known that dense asphalt concrete mixtures are easier to compact at higher material temperatures whereas stone skeleton mixture behave relatively independent from material temperature. The mixtures mentioned in this paper were dense asphalt mixtures. Altogether, evidence for a relationship between material temperature and compactibility of the asphalt mixture is still very difficult to find in scientific literature. In addition FEM simulations of compaction processes were performed (for example see [7] or [29]). For that purpose the material model parameters as the yield locus sizes and hardening parameters for different mixtures were derived. Fig. 9 presents the visualization of the material properties as a function of the compaction stage and the bitumen viscosity. It illustrates an HMA specification (as for example compactibility) as a function of bitumen viscosity and compaction level.

Conclusions

Based on the results of the test program, the following conclusions can be drawn:

1. The critical state theory, derived from soil mechanics, appears to be applicable for modeling and analysing HMA behavior under compaction. It provides new insights and challenges for simulating HMA material behavior.
2. Fundamental stress and stain material parameters of HMA during compaction can be extracted using the Modified Hveem StabiloMeter. The results of the tests indicate that the way the material behaves corresponds to critical state model behavior. The Modified Hveem StabiloMeter appears to be appropriate and accurate for doing tests on initially non-compacted asphalt concrete samples.
3. Comparison and analysis of the tests results show that there is a specific sequence in material characterization regarding to material temperature or bitumen viscosity. It implies that there is consistency in the results of the measured compatibility of the samples at different test temperatures. The precise effects measured are hard to explain.
4. The results also show that mixtures with more rounded aggregate compact more easily than mixtures with more angular material. It is in line with expectations.

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