Finite element modelling of asphalt concrete microstructure

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ABSTRACT

Little progress has been achieved in the past relating the mechanical behaviour of asphalt concrete (AC) to its microscopic structure. The significant influence of microstructure on the response of asphalt composite material to traffic and thermal stresses, explains the difficulties encountered in attempting to predict AC performance, based on laboratory test results. This fact is a consequence of the vast differences between the microstructure of AC constructed in the field and that produced in the laboratory (e.g., rotational position, location of aggregates, and boundary characteristics of cores or laboratory samples). The same applies to AC field performance compared to the results of laboratory testing. For these reasons, no widely accepted relationships between laboratory test results and actual field performance have emerged. Few numerical attempts have been reported in the literature to model the geometry of AC microstructure, due to the complex fabric of the material and its complicated internal material behaviour.

This paper describes a numerical approach to modelling and analyzing microstructure geometry and the characteristics of AC. This 2-D qualitative finite element (FE) model based on microstructure mesh, proved to be a very useful analytical tool for a better understanding of AC material response to various climatic and loading conditions. Examples of 2-D FE analyses are presented along with a laboratory test example.

INTRODUCTION

An examination of scientific and technical literature shows that significant progress has been made in laboratory investigations of the macro-mechanical behaviour of materials used in AC pavements. Morris
et al. [1], Wijeratne and Sargious [2], Monismith and Tayebali [3], Sebaaly et al. [4], and Button et al. [5] are examples of research relating the macroscopic mechanical behaviour of AC pavement to its microscopic functions. These studies reflect the influence of a number of microscopic factors; such as aggregate characteristics (size, shape, type, texture, orientation in concrete), properties of aggregate and asphalt matrix (i.e., bituminous binder and sand mixture), aggregate content and percent air voids. Such experimental programs carried out in many laboratories, may not include all conditions likely to occur in the field, e.g., stress and strain regime due to traffic and climatic loads, material characteristics, etc. More importantly, the essential boundary field conditions such as confining stresses and the underlying flexible granular base, subbase and subgrade are difficult to simulate in the laboratory. Thus, past experiences have shown, that predicting AC performance solely on laboratory test results is difficult. For these reasons, no universally accepted relationship between the macro mechanical behaviour and pavement micro characteristics has emerged from the reported research work as yet.

FE modelling of microstructure geometry may, however, be used as an aid to laboratory testing in order to predict AC performance, Rothenburg [6]. AC pavements are extremely complicated materials with properties affected by temperature, temperature changes (up or down), moisture, traffic loading (frequency and intensity) and aging. In addition, their complex fabric consists of separate components: bituminous binder, fine particles, sand, aggregates, fibres often, and in some new applications, waste materials, e.g., crumb rubber made from old tires, glass, plastics etc. These individual materials have different properties and behaviour. The bituminous asphalt component is highly nonlinear as well as time and temperature dependant. For example, during the manufacturing of crumb rubber asphalt, the viscosity of the resulting bitumen containing partly or completely vulcanized rubber, becomes extremely time dependent.

This paper attempts to numerically model AC in its complex microstructure geometry, and to compare it to macroscopic numerical and experimental laboratory analyses. The microscopic region is modelled as an area consisting of aggregate components, distributed randomly within the AC layer and surrounded by asphalt matrix (mixture of bitumen, small stone particles, sand, possibly fibre, etc).

FINITE ELEMENT MODEL

Assumptions
The following assumptions were used:

• the 2D plane strain condition;
• the aggregate particles were modelled as elastic, randomly shaped and distributed solids within the pavement layer and surrounded by an elastic asphalt matrix;
• material properties were constant (elasto-plasticity will be used in the next phase of the project).

Finite element mesh
Fig. 1 shows a typical flexible asphalt pavement (including material properties), consisting of AC layers, a crushed aggregate base and subbase constructed on top of the soil subgrade, underlaid by bedrock. A standard FE mesh was used for the macro model. The micro FE mesh of the area of interest, Fig. 2, was based on isoparametric quadratic elements.

Loading
By 1984 the economics of truck transportation tended to cause the average gross weight of trucks to increase such, that the majority of trucks were operating close to the legal tire pressure of 0.51 MPa. An investigation performed by Roberts and Roscon [6], however, indicated increasing tire pressure from 0.51 to 0.86 MPa. Therefore, the repetitive traffic load was modelled by an average tire pressure of 0.69 MPa in this study.

FE ANALYSIS

A typical AC pavement structure, shown in Fig. 1, was represented by macro and micro elastic FE models depicted on Fig. 2. The first analysis demonstrates the difference between the macro and micro models concerning vertical distribution of horizontal tensile stresses, while the second analysis (based on the micro mesh) illustrates effects of material properties on maximum surface deflection. It should be pointed out, however, that the non-elastic (visco-plastic) influence of bitumen combined with repetitive traffic loading (not investigated in this paper), is expected to be significantly greater than the results of this study. The purpose was to determine the most important factors by generating localized crack damage in AC pavements by, i.e., FE microstructure model.

Macro - Micro analysis
Fig. 2 shows results of analyses based on two FE meshes: a) linear macro and b) random micro mesh. The macro approach resulted in only one tensile zone located at the bottom of the base layer at the axis of symmetry (with max $\sigma_{xx} = 0.47$ MPa), while the micro approach resulted into two tensile zones located in the asphalt concrete layer (with max $\sigma_{xx} = 0.9$ MPa) and at the bottom of the base layer (with max $\sigma_{xx} = 0.46$). This finding of micro versus macro analyses is very important, since it
Localized Damage demonstrates that a micro approach can pinpoint the real location of tensile stress concentration. Furthermore, it can determine the most probable location for crack initialization, e.g., around sharp points on the surface of a crushed aggregate. Photograph, Fig. 4, shows 25 times enlargement of micro crack developed inside of the AC during thermal cooling (-30°C) of an experimental sample.

Influence of material properties - Micro random mesh analysis

Case (a): Surface deflection versus degree of compaction. The compaction of mix as a significant influence on deformation of AC pavement. To illustrate this point, air voids (AV) were simulated by imposing negligibly small values of elasticity upon some of the elements representing asphalt cement. Fig. 5 illustrates the effect of AV on the surface deflection. As can be observed, an increase in percent AV from 1 to 5% resulted in a 1.2% (from 1.63 to 1.65 mm) increase of surface deflection. Part of this deflection, in reality, can become permanent (irrecoverable) due to the viscous flow of bitumen and, therefore, the entire AC. In the field, due to a poorly compacted mix, such substantial amounts of permanent deformation may result even after a small number of repetitive applications of traffic loading.

Case (b): Surface deflection versus asphalt cement stiffness. Stiffness-temperature relationships for plain asphalt cement were investigated by Kandhal [8]. Based on his work, a temperature increase in the bituminous-sand mixture (in warm climates) will decrease its stiffness. As a result, the surface deformation potential for AC will also increase. Cold temperatures cause the opposite effect. Fig. 5 shows the effect of asphalt cement stiffness on the maximum surface deflection. As can be observed, reducing the asphalt cement stiffness from 1,000 MPa (corresponding to a mixture temperature of 4°C according to Kandhal [8]) to 250 MPa (mixture temperature at 25°C) results in as much as a 2.25% (from 1.62 to 1.70 mm) increase in surface deflection.

Fig. 5 also shows that the rate of increase in surface deflection accelerates as asphalt cement stiffness is further reduced. Structural stability was not achieved (i.e., asphalt cement flows as a result of loading) for mixture stiffness of less than 125 MPa. Numerical calculations confirmed that surface deformation can be a serious problem in warm climates, where asphalt cement stiffness can substantially decrease as a result of a rise in temperature.

Case (c): Surface deflection versus aggregate content. Increased aggregate content is simulated by imposing aggregate material properties upon some of those elements representing the asphalt matrix in the FE mesh. Fig. 5(c) shows the relationship between increased
aggregate content and maximum surface deflection. As can be observed, an increased aggregate content from 60 to 80% (or in other words, reduced asphalt matrix content from 40 to 20%) results in reduced surface deformation by as much as 4% (from 1.63 to 1.57 mm). The real long-term loading effect is, of course, expected to be much greater. Fig. 5(c) also shows that the rate of increase in surface deflection accelerates as aggregate content is reduced.

Case (d): Surface deflection versus aggregate stiffness. Fig. 5(d) shows the effect of aggregate stiffness on the maximum surface deformation of pavement structure. As can be observed, reducing the aggregate stiffness (while keeping other parameters constant) from 50,000 MPa to 10,000 MPa (two extreme values) results in a negligible increased surface deflection of less than 0.3% (from 1.63 to 1.64 mm). Comparing cases (b) and (d), it appears to be the asphalt cement and not the aggregate material properties that has the most influence, as far as the deformation behaviour of AC is concerned. However, the effect of other aggregate characteristics, such as shape, size, texture, orientation as well as content cannot be neglected and should be investigated in a localized damage concept. For example, Stone Mastic Asphalt developed some 25 years ago in Europe based on cubical shaped hard (granite) rock and stone to stone contact, is a typical example of the importance of aggregate characteristics.

Case (e): Surface deflection versus aggregate size. Results of FE analysis based on asphalt cement mixture consisting of round shaped large stones, were compared to a mixture also containing round shaped but smaller aggregates. Asphalt cement, aggregate properties and content remained the same in both cases. As a result, the maximum surface deflection was reduced by more than 3% (i.e., from 1.63 to 1.58 mm). The use of large aggregates in the mix is, therefore, shown to minimize the potential for excessive surface deflection and, in particular, rutting.

Case (f): Surface deflection versus aggregate shape. Characteristics of the aggregate in the mixture have been reported as the primary factors influencing the deformation susceptibility of AC, Button et al., [5]. For this reason, the effect of aggregate shape (round shape versus sharp edge aggregates) was also investigated. Asphalt cement, aggregate properties and content remained the same as in above cases. Reduction of almost 2% in the maximum surface deflection (from 1.63 to 1.60 mm) was obtained. This is a significant value, since deflections of a real road under traffic load is accumulated with time. The use of crushed aggregates in the mix, in place of natural round shape ones (which can easily rotate in the mix) is, therefore, a means to minimize rutting.
CONCLUSION

Results of the first analysis clearly demonstrate that a FE model constructed using a microstructure mesh (i.e., randomly spaced aggregates) is much more realistic than a linear mesh. For example, it is imperative to know the location of intensive tensile stress in the AC. This knowledge will be very important in future developments of new mixes. For example, Stone Mastic Asphalt has the great advantage of stone-to-stone contact characteristics, which naturally avoids generating excessive tensile stress.

The microstructure FE approach yielded positive qualitative results, however, several stages will be needed to achieve reliable numerical characterization of AC material performance. The 2D model should be extended to 3D with visco-plastic properties of the asphalt matrix. Traffic loading should be simulated as load repetitions and the temperature effect should also be included.

REFERENCES

Fig. 1 A typical multilayer pavement structure subjected to traffic load.

<table>
<thead>
<tr>
<th>Layer</th>
<th>$E$ (MPa)</th>
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<tr>
<td>Aggregate</td>
<td>$30,000$</td>
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</tr>
<tr>
<td>Cement</td>
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<tr>
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<tr>
<td>Subgrade</td>
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<td>$0.4$</td>
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Fig. 2 A micro FE mesh of the AC layer.

Fig. 3 Zones of horizontal tensile stress in the pavement due to macro & micro FE approaches for AC layer.

a) Macro-FE analysis for AC  
b) Micro-FE analysis for AC
Fig. 4 Microcrack in the matrix of AC (enlarged 50 times).

Fig. 5 (a) Maximum deflection v.s. percent air voids and (b) Maximum deflection v.s. asphalt cement stiffness.

Fig. 6 (c) Maximum deflection v.s. aggregate content and (d) Maximum deflection v.s. aggregate stiffness.