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# Viscoelastic Properties of Bituminous Composites Using Multiscale Heterogeneous Numerical Simulation and Micromechanical Analytical Self-consistent Model

F. Fakhari Tehrani, J. Absi, F. Allou and C. Petit

**Abstract** In this work, detailed study is carried out to develop heterogeneous micromechanical modelling based on multiscale technique to investigate complex response of asphalt mixture. The mechanical behavior of this material is very complex and one must take into account the geometry of the microstructure and the mechanical behavior of the different phases. The properties of such heterogeneous material are highly dependent on the volumetric fraction of bitumen, aggregate structure, air void distributions and interfacial bonding strength between bitumen and aggregates. In this study, the considered bituminous composites are mastic, mortar and asphalt mixes. These composites are treated as biphasic composites, composed of a viscoelastic bituminous binder and an aggregate skeleton with linear elastic properties. In the developed multiscale approach, the homogeneous equivalent properties of biphasic composite are transferred from one scale of observation to the next higher scale of observation. The dynamic modulus of the matrix and elastic properties of aggregates were used as input parameters into micromechanical finite element models qualified by heterogeneous micromechanical models. The

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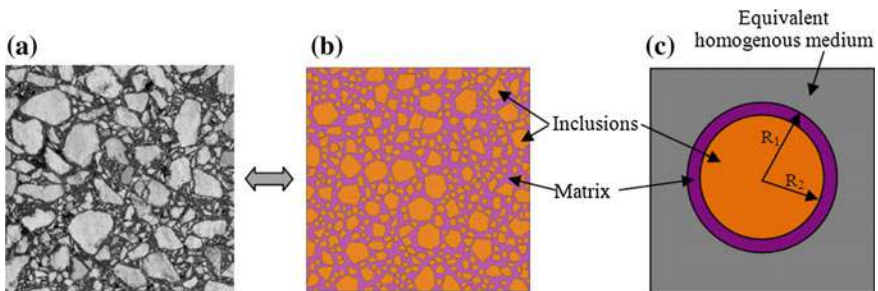
complex modulus and phase angle were compared to experimental measurements and analytical values obtained by Generalized Self Consistent Scheme (GSCS).

**Keywords** Micromechanical modelling · Multiscale approach · Self-consistent scheme · Numerical calculation

## 1 Introduction

Granular skeleton of an asphalt mixture is composed of different combination of aggregates distributed in a size from coarse aggregate to the fraction of fine aggregate (Yin et al. 2011). In this gradation the amount of fine particles is thousand times or even more that of coarse aggregates. This distribution requires a huge computational capacity to construct a numerical model of asphalt concrete with the complete gradation. Therefore, in order to realize the balance between the model fidelity and the computational efficiency, it should be districted several homogenization scale for granular gradation.

In this study, from mastic to asphalt mixes, three scale of observation have been distinguished. At the lowest scale, mastic is composed of filler, i.e., aggregates with a diameter  $<100 \mu\text{m}$  are embedded in a bitumen matrix. At the next higher scale, commonly called mortar scale, the mastic is considered as the matrix whereas sand, with a diameter ranging between  $100 \mu\text{m} < D < 2 \text{ mm}$ , is used for the inclusions. Finally, at the last scale, asphalt can be treated as a biphasic material, with a matrix of mortar and inclusions of aggregates having a size between  $2 \text{ mm} < D < 10 \text{ mm}$ . The primary objective of this work is to present a numerical micromechanical modeling based on multiscale technique using digital biphasic models for predicting the dynamic modulus of bituminous materials such as mastic, mortar and asphalt mixes. Then the obtained values will be compared to those obtained with the micromechanical model called Generalized Self Consistent Scheme and with experimental results. (Fig. 1). This model (GSCS) is recognized among the high sophisticated micromechanical model (Christensen and Lo 1979, 1986) which is based on a three-phase model: A spherical inclusion is embedded by a matrix,



**Fig. 1** Schematic representation of micromechanical modeling of bituminous materials

which in turn is embedded in an infinite equivalent medium of the composites. In the last part, stress and strain distribution, within the heterogeneous model, will be presented to reveal the potential region of cracking development.

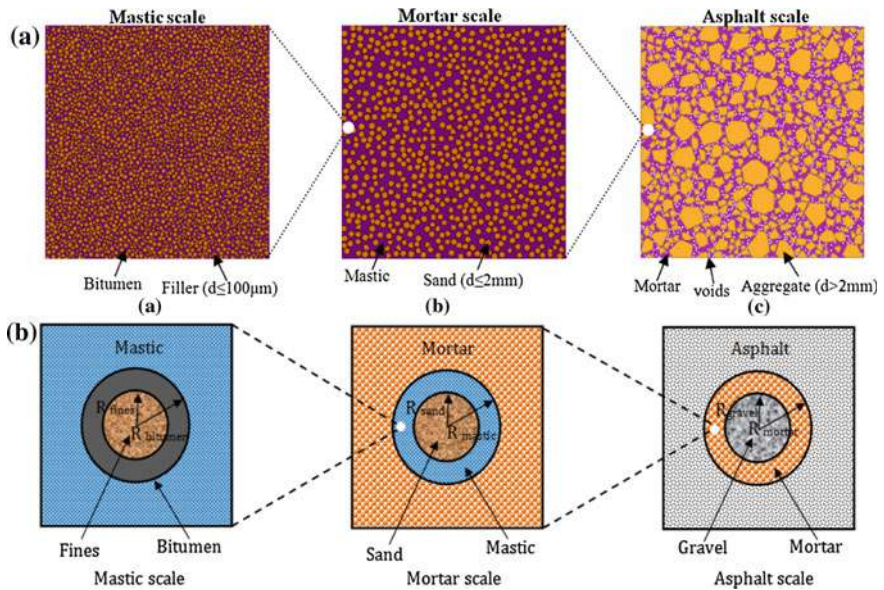
## 2 Numerical and Analytical Upscaling Method

In this study, four components are used to construct the coming numerical models. The used mechanical characteristics are issue from Delaporte experimental investigations (Delaporte et al. 2005).

Digital models are obtained from a random generation by using M.O.A. software which is developed in our laboratory in C++ language. The efficiency of this software was studied previously (Fakhari Tehrani et al. 2013). As hypothesis, separated particles are generated to represent a perfect embedding of aggregates by a thin layer of matrix.

The numerical predicted dynamic modulus of bituminous composites were compared to analytical results issues from GSCS micromechanical model. (Christensen and Lo 1979, 1986). The corresponding constitutive equation is:

$$A \left( \frac{G_c}{G_m} \right)^2 + B \left( \frac{G_c}{G_m} \right) + C = 0 \quad (1)$$



**Fig. 2** Multi scale modeling of asphalt mixes using heterogeneous numerical method (a) and the generalized self-consistent model (b)

where A, B and C are the model parameters which depend on the Poisson ratio of matrix and the volume fraction of inclusions.  $G_c$  and  $G_m$  are the shear modulus of composite and matrix respectively. By taking into account the four phases for asphalt mixes (bitumen, fines, sand and gravel), the self-consistent model applied is considered in three scales (see Fig. 2).

### 3 Results and Discussions

Figure 3a, b show respectively the comparison between numerical, analytical and experimental measured dynamic modulus (Delaporte et al. 2005) and phase angle of mastic at  $T = -10\text{ }^\circ\text{C}$  and  $T = 0\text{ }^\circ\text{C}$ . It is observed that the predicted numerical and analytical results followed the same trend as experimental measurements. However the 3D numerical complex moduli are situated below the original experimental curve. Therefore, to avoid having any cumulative uncertainty of simulation, the experimental measurement of mastic is used as the input for mortar scale.

Figure 4a, b represent respectively the numerical and analytical dynamic modulus and phase angle obtained for mortar scale at different temperatures. As expected, it is observed that the dynamic modulus values are depending on

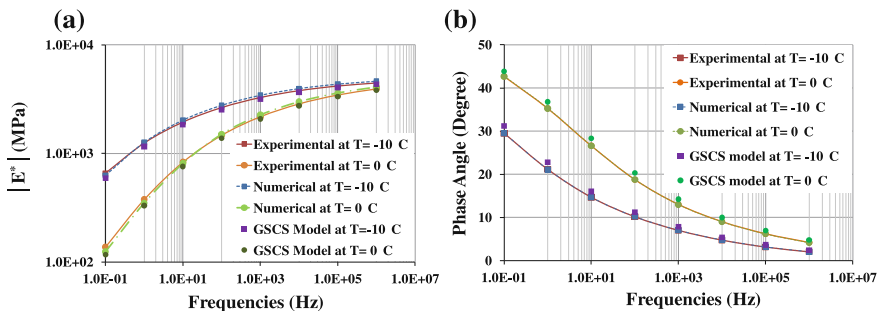


Fig. 3 Numerical and analytical phase angle and master curve of mastic 30 % compared to experimental one at different temperature

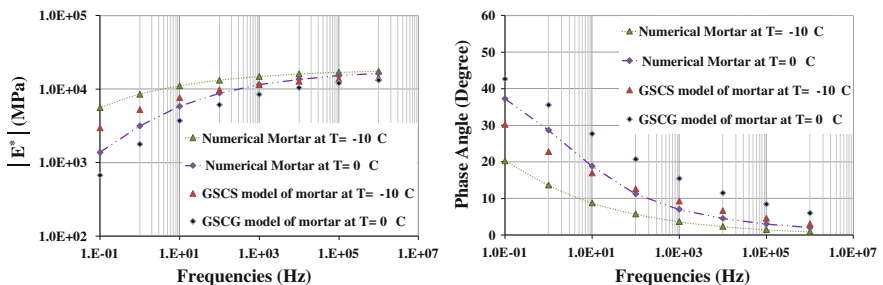
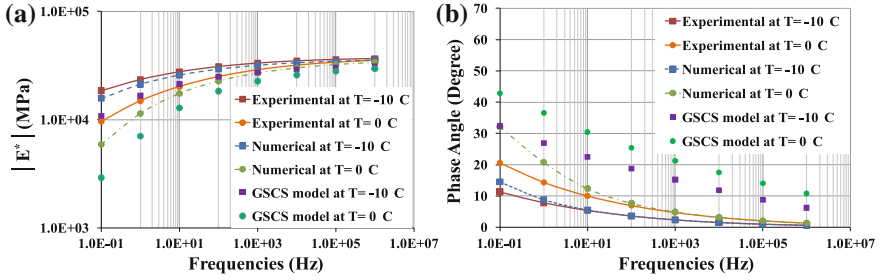


Fig. 4 Numerical and analytical phase angle and master curves of mortar at  $T = -10\text{ }^\circ\text{C}$  and  $T = 0\text{ }^\circ\text{C}$

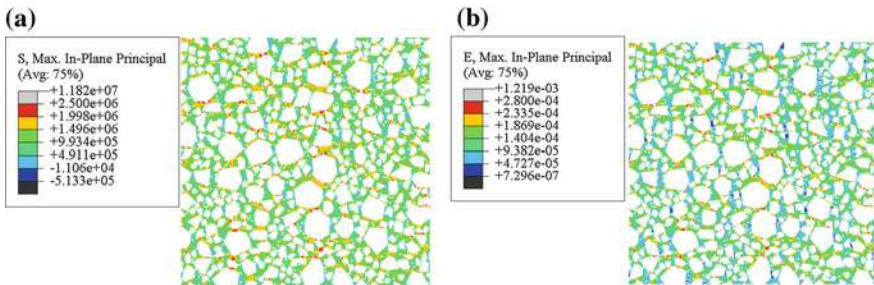


**Fig. 5** Numerical and analytical phase angle and master curves of asphalt mixture compared to experimental one at  $T = -10$  °C and  $T = 0$  °C

temperature. When temperature increases, the dynamic modulus values decrease over the entire studied frequency range. However these values become progressively closer when the frequency values increase.

To evaluate the accuracy of our heterogeneous numerical modeling, we compared the dynamic modulus and phase angle master curves obtained by the numerical procedure and analytical model with the homogeneous asphalt mixture laboratory parameters. This comparison is shown respectively in Fig. 5a, b.

It is observed that for high frequencies, the numerical and analytical results give good prediction values of complex modulus of asphalt mix scale in comparison to the experimental ones. However, analytical results are systematically situated below the finite element results. This observation can be explained by the weakness of the analytical models in the case of a high filling rate (almost higher than 40 %) (Buttler et al. 1999, Yin et al. 2008) for the numerical results issue from  $T = 0$  °C under frequencies loading almost lower than 100 Hz, there is an important gap between the predicted numerical results and experimental measurements. An underlying parameter behind this gap, may be related to the moduli contrast ratio between the mortar matrix phase and the granular phase. According to this assumption, it can be estimated that an increasing of the contrast between the aggregate and mortar moduli from 12.7 ( $E_{\text{inclusions}}/E_{\text{mortar}}^* = 12.7$ ) at  $T = -10$  °C and  $f = 0.1$ –38.9 Hz at  $T = 0$  °C under frequency loading of 0.1 Hz, can influence



**Fig. 6** Distribution of stress and strain within a heterogeneous model

the numerical results obtained at  $T = 0$  °C. Another reason of this gap between predicted numerical results and experimental measurements can be attributed to the limitation of aggregate-aggregate contact in numerical models and lack of considering of the interlock effects between the aggregates, which can play an important role in load transfer between the particles. Figure 6a, b show respectively the stress and strain distribution within the heterogeneous model which reveals the potential region of cracking development.

## 4 Conclusion

In this work, an attempt has been made to develop a finite elements model to predict the mechanical behavior of bituminous composites. Our approach is based on a homogenization of characteristics obtained from intermediate scales. These intermediate steps represent a progressive technique used to construct the final asphalt mixture model. The major advantage of this technique is that, the larger scale structure, that exhibits complex geometry and constitutive behavior, can be simulated based on material properties on a much smaller scale.

The predicted dynamic modulus of asphalt mixture was compared with that of the experimental test data for different temperatures. It was observed that at low temperature (here  $-10$  °C) the numerical values are slightly less than the experimental measurements values. With increasing in temperature the difference between predicted numerical results and experimental data increases. This observation can be related to the increase of the contrast modulus between matrix and inclusions at high temperature. Another reason can be related to the limitation of aggregate-aggregate contact in the numerical models and lack of interlock effects consideration between aggregates.

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