Micromechanical Behaviour of Asphalt Concrete Based on X-ray Computed Tomography Images and Random Generation of Heterogeneous Aggregates Skeleton

Y El Haloui¹,*, F F Tehrani²,³, J Absi⁴, F Courreges⁵, M Elomari¹, F Allou² and Ch Petit²

¹ Université Cadi Ayyad, UCA, FSSM LAEPT, Boulevard Prince My Abdellah, P.B. 2390, 40000 Marrakech, Maroc.
² Université de Limoges, GC2D, boulevard Jacques Derche, 19300 Egletons, France.
³ Conservatoire national des arts et métiers Paris, 292 Rue Saint-Martin, 75003 Paris, France.
⁴ Université de Limoges, IRCER, UMR CNRS 7315, 12 Rue Atlantis, 87068 Limoges, France.
⁵ Institut de Recherche Xlim, UMR CNRS 7252 - 123, avenue Albert Thomas - 87060 Limoges Cedex, France.

*Corresponding author: yassine.elhaloui@edu.uca.ac.ma

Abstract. The main objective of this work is to investigate the influence of the microstructure characteristics on the mechanical behaviour of asphalt concrete. The heterogeneous microstructure of an asphalt concrete is influenced by the aggregate content, shape, orientation and contacts. In previous works, the asphalt concrete is treated as homogeneous material and its heterogeneous microstructures are ignored. While the distribution of its heterogeneous microstructure can strongly influence the intensity of deformation at local scale. Therefore, it is important to create more precisely a micromechanical model containing information on heterogeneous microstructure. A comparison study has been done between the microstructure issues from X-ray computed tomography (CT) and digital models of random aggregate generation. The dynamic modulus of the viscoelastic matrix and elastic properties of aggregates are used as input parameters in the numerical simulations. The obtained results at global scale (complex modulus and phase angle) and at local scale (local strain intensity) of each model are compared. This comparison leads to confirm the feasibility of the proposed heterogeneous random generation of aggregate skeleton at global and local scales. These results provide the basis for an interesting discussion on material design optimization in order to increase the durability of the road pavement materials.

1. Introduction

An asphalt mixture is a composite material that comprises aggregates, binder and air voids [1]. Aggregates usually take up about 85% of the volume of asphalt concrete with different sizes, irregular shapes and random locations. Bituminous materials can be modelled at different length scales, i.e. from bitumen scale to asphalt mixture scale [2]. Its mechanical behaviour is considered as viscoelastic and depend on temperature and loading frequency. The associated characteristics are usually described through use of the dynamic modulus and phase angle [3]. In the most previous studies, the asphalt
concrete is treated as homogeneous material and its microstructures are ignored [4,5]. However, it has been reported that the deformation and strength of asphalt concrete are not only influenced by volume fraction of its components but also affected by the spatial distribution of its microstructures [6]. Thus, to investigate the mechanical behaviours of asphalt concrete, it is imperative to notice more accurately a micromechanical model containing information of components and microstructures.

The X-ray computed tomography (CT) method is a digital image processing technology which can be used to capture the internal microstructure of composite materials like asphalt mixture. Two dimensional (2D) or three dimensional (3D) numerical specimens are generated based on slices capture. In general, X-ray CT involves three steps as following: 1) Images acquisition. 2) Images processing. 3) Images analysis. X-ray CT has been used to paid attention for asphalt mixture in the past 15 years. For example, Dai in [7] constructed 2D and 3D micromechanical models using X-ray CT to predict the dynamic modulus and phase angle of asphalt mixture. It was concluded that the 3D model offered a high prediction of mechanical behavior of asphalt mixture than the 2D model.

2. Scope and objective
In this paper, asphalt mixture is modelled as heterogeneous material contains irregular aggregate skeleton localised in random position and bonded with asphalt mastic. The X-ray computed technology and random aggregate generation have been respectively applied for acquisition and generation of the internal microstructure of material. In this work, the aggregate images were taken from an X-ray tomography of a real asphalt mixture samples (see figure 1). In parallel the virtual microstructure of the material was generated from a custom software (called "MOA", French acronym for Random Object Modeler) developed in our laboratory. The finite element modelling is performed with the commercial finite element code ABAQUS [8]. The viscoelastic properties of the bitumen and mastic are calibrated with the laboratory experimental measurement and introduced into a user material subroutine within ABAQUS code. Thereafter the viscoelastic mastic is combined with elastic aggregates to predict the properties of asphalt mixture.

![Figure 1. Illustration of gray image acquired by X-ray CT and segmentation process](image)

3. Materials and experimental results
The asphalt mastic is defined as the combination of a 50/70 penetration grade asphalt bitumen and limestone filler sieved between 63 and 100 µm. A laboratory test was conducted by Delaporte et al [9]. Bitumen, mastic and asphalt mixture exhibit a thermo-rheological simple behaviour: the data (φ, |E*|) have a unique curve in Black space. The dynamic modulus and phase angle master curves obtained at a reference temperature of 10°C are shown in figure 2. In this study, the asphalt mixture is composed of aggregates as inclusions and mastic as matrix. To be specified in numerical simulation, the viscoelastic properties of mastic should be calibrated based on figure 2 and then defined in ABAQUS like Prony parameters. The step of calibration can be performed by Viscoanalyse code [10]. First, the complex modulus |E*| and phase angle φ are input in a normalized file recognizable by Viscoanalyse code; then, the Prony parameters can be adjusted by specifying the number of Maxwell elements.
The type of aggregate used in this study was limestone. In general, aggregates are assumed to behave elastically. In this study, an estimated aggregates elastic modulus of 70 GPa and Poison's ratio of 0.15 were considered. These properties will be used as input parameters of simulation to define the mechanical behaviour of aggregates. In the other hand, the aggregate size distribution in asphalt mixture concrete is given in Table 1. This gradation was used in the formulation of the considered asphalt mixture specimen. It will be used also to generate the internal microstructure of this materials through use the heterogenous generation method by MOA code. This part is detailed in the following section.

Table 1. Particle size distribution in an asphalt mixture

| Sieve size (mm) | 12.5 | 10  | 8   | 6.3 | 4   | 2   | 1   | 0.5 |
|-----------------|------|-----|-----|-----|-----|-----|-----|-----|
| Passing percentage (%) | 100  | 92  | 68.9| 52.7| 42.2| 32.1| 21.7| 15.4|

4. 2D and 3D micromechanical modelling of bituminous composites

The MOA program, developed in our laboratory in C++ language, is an original software capable of automatically generating samples derived from a matrix with a given percentage of air voids and containing a known number of inclusions featuring different shapes, extending from spherical to polyhedral and randomly placed in the volume defined by the matrix in the form of a rectangular prism or cylinder.

To avoid a situation in which the distance between two randomly created objects becomes less than the minimum resolution of the FEM code, the generator imposes a minimum inter-object distance (equal to one-tenth of the smallest acceptable radius). Moreover, the inclusions might intersect the external surface of the container, which could provide an accurate representation of the final sample obtained by cutting from a larger fabricated sample. Then, a Boolean operation serves to differentiate the inclusion part from the matrix part. Once such geometries have been imported into the ABAQUS code, a fully cohesive state at the matrix/inclusion interface is imposed on the entire inclusion surface by use of the "tied contact" function, which has been preloaded in the FEM code. [11,12]

As shown in figure 3, 2D and 3D microstructure of numerical models, that includes aggregates and matrix, were generated from MOA software as a rectangular and a rectangular prism specimen, respecting the gradation curve of the materials.
It is noteworthy that direct aggregate to aggregate contact is neglected in the current study. However, the existence of a thin bitumen and mastic film is assumed between each aggregate and the other, which simulates to some extent the adsorption of aggregate to some of the bitumen phase and mastic phase. This asphalt film allows to simulate a viscoelastic contact condition between different aggregates. The minimum element size in the generated finite element model was adapted in function of the minimum thickness of the bitumen and mastic between the adjacent separated aggregates.

On the top surface of the digital models, a uniaxial tension-compression cyclic load is applied. Cyclic strain (sinusoidal signal) with several frequencies (0.1, 1, 10 and 100 Hz) corresponding to the experimental tests have been used. The strain magnitude should not exceed $10^{-4}$ in order to remain in the linear viscoelastic domain of bituminous materials [13].

5. Numerical simulation results

5.1. Global scale
The dynamic modulus $|E'|$ and phase angle $\varphi$ are the most required parameters to describe viscoelastic materials like bituminous composites. To obtain these parameters, four methods can be used: i) Experimental tests, ii) rheological models, iii) analytical formulations and iv) numerical simulations. In this research, numerical simulation method has been considered to determine $|E'|$ and $\varphi$. The magnitude of the dynamic modulus was calculated using the last two cycles for each frequency, with the equation:

$$|E'| = \frac{\mid \sigma_{\text{max}} - \sigma_{\text{min}} \mid}{\mid \varepsilon_{\text{max}} - \varepsilon_{\text{min}} \mid} \quad (1)$$

The phase angle was calculated by tracking the computation points of maximum/minimum stress and strain. For each cycle, 100-time increments (computation points) were used to achieve a high resolution.

Figure 4a and figure 4b present the master curves of the complex modulus and phase angle of asphalt mixture obtained respectively by the random aggregate generation and X-ray computed tomography methods. It can be observed that the results obtained by both approaches agree reasonably. The average difference between simulation results at global scale is less than 4 % for complex modulus and 3 % for phase angle. In order to evaluate the influence of microstructure on the mechanical response of material at local scale, the intensity of strain at different zones of numerical models were obtained and compared to global imposed strain ($\varepsilon = 10^{-4}$).
5.2. Local scale

The distributions of local vertical strain obtained respectively by X-ray computed tomography and random aggregates generation methods are presented in Figure 5a and figure 5b. It can be observed that the deformation intensity ratio depends generally on the position and the thickness of the thin viscoelastic layer of matrix. As it is shown, the intensity of strain at local scale can be reached up to 10 times greater than imposed global strain.

5.3. Final discussion

In this study, numerical investigations of the mechanical behaviour, at global and local scale, of asphalt mixture through the use of X-ray CT and heterogenous generation were conducted. The effect of inclusions shape irregularity was shown in our previous study [6]. Two categories of aggregates shape were used: polygonal inclusions and spherical inclusions. At global scale, the corresponding complex modulus of each type of aggregates were determined. The values corresponding to the spherical inclusions were situated just below those of the polygonal inclusions. In addition, both master curves display a regular variation versus the frequency. Therefore, the shape of aggregates does not affects the overall mechanical behaviour. At local scale, stress values of polygonal inclusions were found greater than that of spherical inclusions due to the high angularity of polygonal aggregates in compression in comparison to the case of spherical aggregates. Thus, considering heterogeneous models rather than homogenous ones can makes sense. In fact, by ignoring the microstructure of asphalt mixture, the intensity of strain within the equivalent media of this material will be close to the global applied strain ($10^{-4}$). However, it was found that, taking into account biphasic model, the level of strain is 10 times greater than the initial imposed strain ($\varepsilon=10^{-4}$). This large variation affects various local phenomena within asphalt mixture such as self-heating.
6. Conclusions
In this paper, we developed a heterogeneous numerical approach able to calculate the mechanical properties of hot mix asphalt from the properties of its components. The microstructures of the material were obtained by two methods: random aggregates generation and X-ray computed tomography. In order to investigate the influence of microstructure into mechanical response of asphalt mixes, the complex modulus and phase angle issue from the two methods under study, were compared and a good agreement was observed. Moreover, the intensity of deformation within the viscoelastic matrix at local scale was investigated and again an interesting and converged results were obtained. In summary, the proposed heterogeneous numerical approach, yields very acceptable results for highly heterogeneous media of asphalt mixes at global and local scales in comparison to those issues from X-ray method.

7. References
[1] Masad E, Muhunthan B, Shashidhar N and Harman T 1999 Quantifying laboratory compaction effects on the internal structure of asphalt concrete Transportation Research Record: Journal of the Transportation Research Board 1681 179-185
[2] Fakhari Tehrani F, Absi J, Allou F and Petit C 2016 Micromechanical modeling of bituminous materials complex modulus at different length scale International Journal of Pavement Engineering 19 1-12
[3] Di Benedetto H, Olard F, Sauzéat C and Delaporte B 2004 Linear viscoelastic behaviour of bituminous materials. From binders to mixes Road Materials and Pavement Design 5 (1) 163-202
[4] Huang B, Shu X, Li G and Chen L 2007 Analytical modeling of three-layered HMA mixtures *International Journal of Geomechanics* 7 (2) 140-148

[5] Shu X and Huang B 2008 Micromechanics-based dynamic modulus prediction of polymeric asphalt concrete mixtures *Composites Part B: Engineering* 39 (4) 704-713

[6] Fakhari Tehrani F, Absi J, Allou F and Petit C 2013 Heterogeneous numerical modeling of asphalt concrete through use of a biphasic approach: Porous matrix/inclusions *Computational Materials Science* 69 186-196

[7] Dai Q 2011 Two- and three-dimensional micromechanical viscoelastic finite element modeling of stone-based materials with x-ray computed tomography images *Construction and building materials* 25 (2) 1102-1114

[8] Hibbitt K 2007. ABAQUS version 6. 7: theory manual, users’ manual. verification manual and example problems manual

[9] Delaporte B, Di Benedetto H, Chaverot P and Gauthier G 2007 Linear viscoelastic properties of bituminous materials: From binders to mastics *Proc of the Technical Sessions. Asphalt Paving Technology: Association of Asphalt Paving Technologists* 76 455-494

[10] Chailleux E, Ramond G, Such, C and de La Roche C 2006 A mathematical-based master curve construction method applied to complex modulus of bituminous materials *Road Materials and Pavement Design* 7 (1) 75-92

[11] Fakhari Tehrani F, Absi J, Allou F and Petit C 2016 Viscoelastic properties of bituminous composites using multiscale heterogeneous numerical simulation and micromechanical analytical self-consistent model *Rilem bookseries* 13 133-138

[12] Fakhari Tehrani F, Absi J, Allou F and Petit C 2013 Heterogeneous numerical modeling of asphalt concrete through use of a biphasic approach: Porous matrix/inclusions *Computational Materials Science* 69 186-196

[13] Airey G D and Rahimzadeh B 2004 Combined bituminous binder and mixture linear rheological properties *Construction and Building Materials* 18 (7) 535-548