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Microstructural Characterization of Oolitic Rocks and Numerical Evaluation of Their Effective Elastic Properties

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Abstract

The present work focuses on the characterization of the geometry of the microstructure of porous oolitic rocks. These rocks are constituted by an assemblage of porous grains (oolites), pores and inter-granular crystals. X ray 3D Computed Tomography is used to identify the different components of these rocks by applying an algorithm based on grayscale values. This analytical method allows the characterization of the porous network (size, spatial distribution, and volume fraction), oolites and inter-oolitic crystals. The microstructure of these porous rocks has a significant effect on their macroscopic behavior. This micro-macroscopic relationship is taken into account in micromechanical models developed within the framework of the homogenization theory (e.g., Maxwell scheme) of random heterogeneous media. X ray tomography images showed that pores have irregular shapes, so the micromechanical modeling based on analytical solution is not relevant. Then, pores are approximated by ellipsoids using principal components analysis (PCA) method, which allows us to obtain the geometrical properties such as length of semi-axes and orientation of ellipsoids. To validate mechanically this approximation, we compared the contribution of irregularly shaped 3D pores and ellipsoidal pores to the effective elastic properties. The relative error due to this ellipsoidal approximation is then estimated. The compliance contribution tensors of irregular 3D pores are evaluated numerically using finite element method while those of approximated ellipsoidal pores are obtained analytically and numerically. The same procedure of approximation is applied on oolites. Shape and spatial parameters, such as the volume, radius and center of each oolite are also determined. The sphericity of the approximated oolites is calculated. The obtained values are close to 1, so oolites can be reasonably approximated by spheres.

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Keywords: Compliance contribution tensor; Microstructural analysis; Finite element method; 3D irregular shape inhomogeneities

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1. Introduction

In this paper, we characterize the geometry of porous oolitic rocks that are modeled as a heterogeneous material composed by an assemblage of porous grains (oolites), pores and inter-granular crystals (cement). We used a simplified model within the framework of Maxwell homogenization scheme described in [1]. Three scales are then identified. First is the microscopic scale that corresponds to the intra-oolitic pores. Second is the mesoscopic scale that corresponds to the oolites, the inter-oolitic cement and pores. Third is the largest scale and corresponds to the representative elementary volume (REV) which is considered large compared to the oolites size, the intra and inter-oolitic pores. The first homogenization step concerns intra-oolitic pores of spherical or ellipsoidal shape within oolites using Self Consistent Approximation [2]. It allows the transition from the microscopic to the mesoscopic scale. The second step allows the transition from the mesoscopic to the macroscopic scale using Maxwell homogenization scheme. As in [1], at the mesoscopic scale we consider that the heterogeneous medium is formed by three phases: the porous oolites approximated by spheres, inter-oolitic cement and irregularly shaped pores approximated by ellipsoids with randomly distributed orientation. This Maxwell model and its reformulation based on contribution tensors are discussed in [3, 4, 5, 6]. Indeed, this method has been used by [7] for the calculation of effective parameters of poroelastic composite materials. This method has also been extended in [8] to the case of viscoelatic microcracked materials. In our study, we considered an oolitic limestone as heterogeneous material. To verify the homogenization method, we approximate the rock components by the PCA method presented in [9] as follows: oolites are approximated by spheres and interoolitic pores are approximated by ellipsoids. The microstructure of the material was observed using 3D X-ray nano-computed tomography and scanning electron microscopy. We analyze then the X-Ray images using image processing software in order to distinguish the different components of the material. The procedure for the geometry analysis of oolites and pores is presented in section 2. To validate the approximation, we evaluate the contribution of irregularly shaped 3D pores and ellipsoidal pores to the effective elastic properties. Our work is based on the previous calculation of compliance contribution tensors of 3D pores of irregular shape in carbon/carbon composites [9]. Analytical method based on Eshelby solution for ellipsoidal shapes are usually used to evaluate the contribution of pores to effective elastic properties. However, in our case, this solution is not relevant due to the high irregularity of the pores, so numerical methods such as finite element method (FEA) is used. The FEA procedure for the evaluation of the contribution tensors of irregular shape pores and their corresponding ellipsoids is presented in section 3. Then, we evaluated analytically the contribution tensors of the ellipsoids and we estimate the relative error due to this approximation.

2. Microscopic observations of a porous oolitic limestone (Lavoux, France)

2.1. SEM observation

Lavoux limestone is a middle Jurassic (Callovian) oolitic limestone, located in the southwest of the Paris Basin, in Vienne, France [10]. To observe the microstructure of the rock, two techniques were used: SEM (scanning electron microscope) (Fig. 1) and 3D X-ray nanotomography. The microstructure of oolitic limestone observed under SEM is described in [11].

Chemical characterization performed on the limestone Lavoux by the EDS method (Energy Dispersive X-ray Spectroscopy) showed that the material is mainly composed of calcite (98%) and contains also a very small fraction of clays and dolomite [11]. So it is almost a mono-mineral limestone.

Within the homogenization framework, this description allows us to consider the microstructure of the limestone as an assembly of grains (oolites) and inter-oolitic pores. Indeed, there are two scales in the microstructure of the material:

- The mesoscopic scale (sample level) is primarily that of oolites and inter-oolitic meso and macro pores.
- The microscopic scale is that of the micro-pores in oolites.