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Effect of Porosity on the Mechanical Properties of Materials

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.**Abstract.** The mechanics of heterogeneous materials is a discipline of the mechanics of materials which is in full expansion. In general, it is interested in structural materials that have heterogeneities that influence their behavior and that cannot be considered homogeneous.

The goal of this discipline is the determination of mathematical forms respecting the fundamental principles of physics and describing the constitutive law of materials with heterogeneities such as different types of pores. This contribution proposes a micromechanical analysis of the damage by meso cracks by highlighting a new homogenization method applied to the porous media to arrive at an effective Young's modulus which we exploited in a thermal shock application.

Keywords: Heterogeneous materials, micromechanics, porous medium, effective Young modulus

Introduction

The interesting theoretical and experimental work has been published on the effect of inclusions or pores dispersed in an isotropic and continuous matrix. This work led to several laws linking elastic characteristics and porosity.

An analysis was developed by KNUDSEN and then taken up by WANG, based on the fact that a porous material can be considered as a stack of spheres with more or less large contact surfaces, and an elongation in tension. This consideration has led to an approximate solution [1,2,3]

In the case of micro cracking, theoretical work was first carried out in the field of geophysics for the prediction of earthquakes. A more recent approach has been made by Budiansky and O'connel by the salt consistency procedure in the case of randomly arranged and randomly oriented fissures in a locally isotropic material. The analysis of the damage of the granular materials in general passes by the understanding of the relation between the microstructure and the macroscopic phenomena[4]. Thus, several authors after theoretical and experimental studies, have tried to model this behavior[5].

Case of micro cracking

Theoretical work was first carried out in the field of geophysics for the prediction of earthquakes.
The expressions are as follows, for circular cracks of radius a:

$$\frac{E}{E_0} = 1 - \frac{16}{45}\frac{(1-\nu_0^2)(10-3\nu_0)}{2-\nu_0}\varepsilon \tag{1}$$

$$\frac{G}{G_0} = 1 - \frac{32}{45}\frac{(1-\nu_0)(5-\nu_0)}{2-\nu_0}\varepsilon \tag{2}$$

ε : Crack density parameter.

If the cracks are circular with radius a: $\varepsilon = N \times moy(a^3)$

N: number of cracks per unit volume.

The most used expressions to express the relation between these mechanical properties and the porosity, p, are:

$$E = E_o e^{-ap} \tag{3}$$

$$\sigma = \sigma_o e^{-bp} \tag{4}$$

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E is the Young's Modulus, E_o the Young's Modulus without porosity, p Porosity, the stress at break, the breaking stress without porosity.

In the case of refractory materials, Bradt (1993) uses the same expressions. Thus, for this category of materials, stiffness and breaking stress decrease as porosity increases.

On the other hand, in the case of breaking energy, very few authors are interested in the question. Apart from the classical relations of fracture mechanics that show the influence of microstructure such as equation 3 rare are the authors who considered the effect of porosity.

$$\gamma_{wof} = \gamma_s + \gamma_p + \gamma_r = \gamma_{eff} + \gamma_r \qquad (5)$$

In this equation is the energy of rupture, the surface energy, the surface energy due to the inelastic phenomena, the surface energy due to the interactions with the microstructure and the effective surface energy. Among these authors we can mention Harmuth which reports the effect of the size of a crack on the energy of rupture (Harmuth 1997):

$$\gamma_{app} = \gamma_o \left(1 - 2n \frac{a_o}{b}\right) \qquad (6)$$

These relationships suggest a decay of the fracture energy as porosity increases. In addition to the scarcity of work on the subject, we note that these equations are neither empirical nor theoretical. They have been advanced, probably, by analogy with the Young's modulus.

Indeed, Recent experimental work (Dorey et al 2001) contradicts this result. Dorey et al. find the following curve:

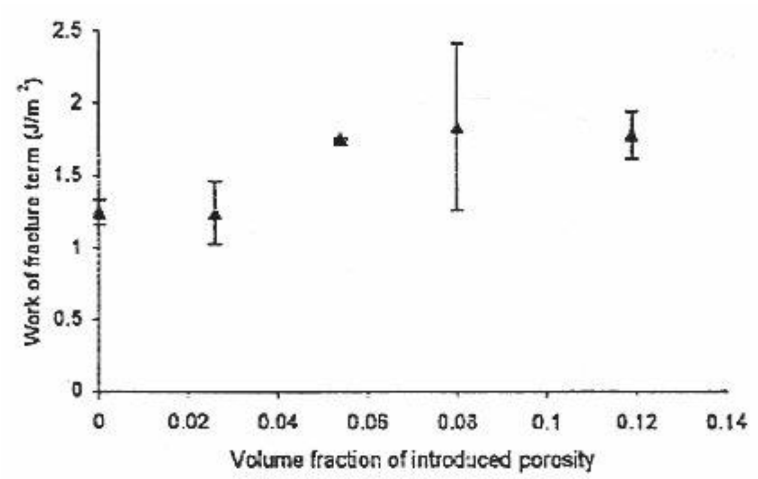

Fig. 1: Rupture porosity function de % porosity

While Sebbani (2001) has shown the influence of porosity on the breaking energy in the following form:

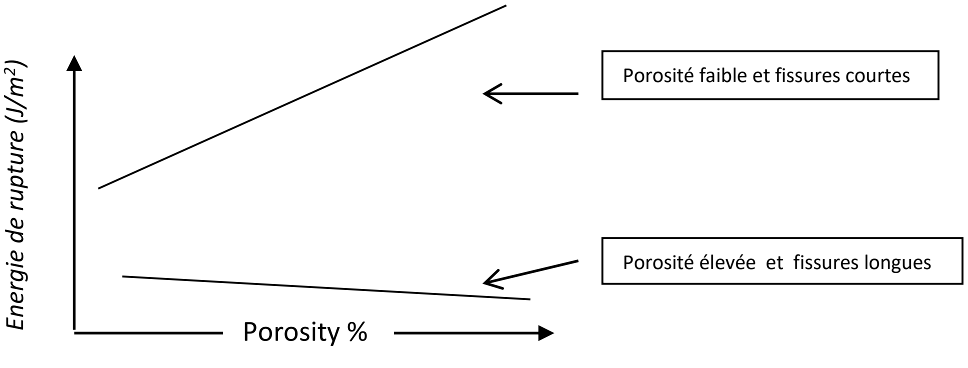

Fig. 2: Worl :ion volume fraction of introduced porosity

Micromechanical analysis of damage through meso cracks

When considering deterioration processes, the general classification of materials between porous and nonporous is very useful for identifying where the harmful effect may occur.

We present a study that consists of a 3D generalization to provide macroscopic modeling elements derived from micromechanical analysis, so we follow a scaling process to choose the internal variable of damage and establish the law of behavior according to the porosity of these materials.

Construction modeling elements

The modeling developed is inspired by the works of Pensée V and Kondo D (2001).

This micromechanical analysis involves the following two steps: the choice of the meso cracking related to its internal parameters and the evaluation of the effective Young's modulus.
The central idea is to consider a matrix (ν_0 ,μ_0 ,λ_0 and tensor of elasticity C°) containing many meso fissures, supposed planar, and then we focus on those belonging to the same family, and which do not interact between them. They are small compared to the elemental volume Ω which contains only one meso crack and which is considered large enough to be representative of the microstructure of the material.

The ith meso fissure considered is circular of radius a, and noted ωi of normal $\vec{n}_i$ such as $(\vec{n}_i, \vec{t}_i, \vec{s}_i)$ is orthonormed direct and ω+ and ω- both sides of the meso crack.

We note $\vec{u}$ the displacement at a point $\vec{x}$ of ωi
We define the parameters β (of opening of the meso crack), α and γ (sliding of the meso crack):

$$\alpha = \frac{1}{|\Omega|} \iint_{\omega^+} [u_t] \vec{x} ds \qquad \beta = \frac{1}{|\Omega|} \iint_{\omega^+} [u_n] \vec{x} ds \qquad \gamma = \frac{1}{|\Omega|} \iint_{\omega^+} [u_s] \vec{x} ds \tag{7}$$

With $[u]$: displacement along a given axis.
The total deformation of the matrix is: $E = E^m + E^d$

E^m : Deformation of the homogeneous matrix.

E^d : Deformation due to discontinuity of displacement of the following meso crack $(\vec{n}, \vec{t}, \vec{s})$, it is expressed by:

$$E^d = \alpha(\vec{n} \overset{s}{\otimes} \vec{t}) + \beta(\vec{n} \otimes \vec{n}) + \gamma(\vec{n} \otimes \vec{s}) \tag{8}$$

With $(\vec{n} \overset{s}{\otimes} \vec{t})$: symmetrical part of the tensor product.

Expression of stiffness tensor

The material being isotropic, this allows us to write its effective Young's modulus as follows:

$$E_{eff} = E_s \left[1 - P(1 - S_{11})^{-1} \right] \tag{9}$$

In the case of pore in the form of Penny Shape , S_{11} is of the form:

$$S_{11} = \frac{\pi(13 - 8\nu)a_3}{32(1-\nu)a_1} \tag{10}$$

This allows us to write the effective Young's module:

$$E_{eff} = E_s \left[1 - P\left(\frac{32(1-\nu)a_1}{32(1-\nu)a_1 - \pi(13-8\nu)a_3} \right) \right] \tag{11}$$

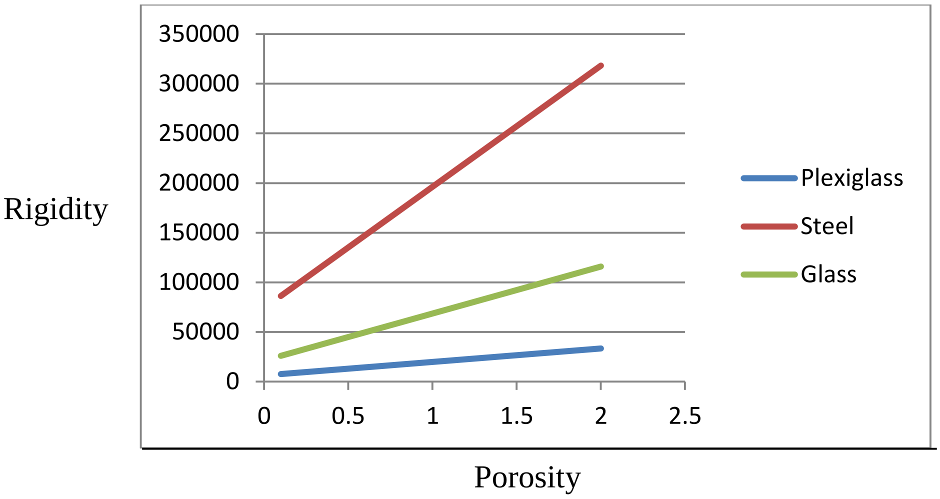

Fig. 3: Variation of rigidity with porosity for various materials

Conclusion

In our studies, the homogenization in saturated porous media seems effective for the determination of the homogenized tensor, indeed this method is interested in the macroscopic behavior of a saturated porous medium. This method is can be used in the macroscopic behavior of a saturated porous medium comprising N classes of pores characterized by a shape and an orientation.

Thus, the effect of porosity is shown for various mechanical materials.

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