# Effect of porosity and water saturation on the mechanical properties and P-wave velocity of calcarenite rocks used in the construction of historical monuments of Rabat (Morocco)

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## Abstract

The objective of this paper is to study the effect of porosity and water saturation on the mechanical and acoustical behavior of isotropic porous materials of a solid matrix containing dry, saturated and partially saturated spherical pores, using a homogenization technique based on the Mori-Tanaka model. The mechanical properties of calcarenite rocks are determined from P-wave velocity measurements. The comparisons between the predictions of Mori-Tanaka model and experimental results are discussed and analyzed.

**Keywords:** *Calcarenite rock, porous media, homogenization, Mori-Tanaka, mechanical properties, P-wave velocity, porosity, water saturation.*

## 1. Introduction

The study of the role of porosity and fluid flow in the mechanical and acoustical behavior of porous media is fundamental to understanding phenomena in different fields (geophysical subsurface, seismology, engineering, monuments, and construction). Indeed, the presence of porosity and water saturation results in a modification of mechanical and acoustic properties which can be modelled by homogenization techniques.

Some authors have applied the models of homogenization to describe the behavior of porous media. Thus Guéguen et al. [1] used the differential self-consistent model to determine the elastic moduli of porous media. Xu [2] applied changing scale methods for modeling the behavior of unsaturated porous media whose solid phase consists of a linear elastic material. Miled et al. [3] studied the prediction of elastic moduli of isotropic porous materials constituted of a solid matrix based on well-known Mean-Field Eshelby-based homogenization schemes.

Many studies have been devoted to the modeling of effective mechanical and acoustic properties of partially saturated porous media [4, 5]. Gassmann's equations [6] provide the effective elastic moduli of saturated rock for low frequency, provided you know in advance the effective elastic moduli of dry rock. The bulk modulus of fluid $K_f$ is then written:

$$\frac{1}{K_f} = \frac{S}{K_w} + \frac{1-S}{K_g} \tag{1}$$

where $k_w$ and $k_g$ are the bulk modulus for the liquid and gas. S is the degree of water saturation.

In a homogeneous isotropic elastic medium, the velocity of wave propagation plane compressive-type (P-wave) is given by:

$$V_p = \sqrt{\frac{k + \frac{4}{3}\mu}{\rho}} \tag{2}$$

## 2. Materials and methods

### 2.1. Materials

The rock used in this work is the calcarenite. It is mainly used in various sectors: construction, renovation of historical monuments, stones, sculptures. This sedimentary rock colored yellow ocher is found mainly in the Rabat- Salé region, it was used for the construction and restoration of various historical monuments of Rabat. It is characterized by high porosity (18–47%) and elevated permeability [7, 8]. Its chemical composition is very rich in calcium carbonates [9].

### 2.2. Mechanical properties and P-wave velocity of a dry and saturated rocks

The estimate of the macroscopic elastic tensor of a dry and saturated porous media corresponding to the Mori-Tanaka scheme, are respectively [10]:

$$C_{dry}^{MT} = C_m + \phi_{inc}\left[\phi_m S^E : C_m^{-1} + (C_{inc} - C_m)^{-1}\right]^{-1}$$

$$C_{sat}^{MT} = C_f - (1-\phi_p)\,(C_f - C_m)\,\Big[\,(1-\phi_p) I + \phi_p \left[I + S^E : C_m^{-1} : (C_f - C_m)\right]^{-1}\,\Big]^{-1}$$

The elastic properties and P-wave velocity in the dry porous media containing spherical pores are respectively:

$$k_{dry} = k_m\,(1-\phi)\,(1+a\phi)^{-1} \tag{3}$$

$$\mu_{dry} = \mu_m\,(1-\phi)\,(1+b\phi)^{-1} \tag{4}$$

$$E_{dry} = E_0\,(1-\phi)\,(1+c\phi)^{-1} \tag{5}$$

$$V_{p\,dry}^2 = V_{p\,m}^2 \frac{(1+d\,\phi)}{(1+a\phi)\,(1+b\phi)} \tag{6}$$

where $k_m$ and $\mu_m$ are the elastic bulk and shear modulus of matrix, $E_0$ is Young's modulus of the matrix, $\phi$ is the porosity.

The elastic properties and P-wave velocity in the saturated porous media containing spherical pores are respectively:

$$k_{sat} = k_m \ (1-a\phi) \ (1+e\phi)^{-1} \quad (7)$$

$$\mu_{sat} = \mu_{dry} = \mu_m \ (1-\phi) \ (1+d\phi)^{-1} \quad (8)$$

$$E_{sat} = E_0 \ \frac{(1-\phi)(1-a\phi)}{1+b\phi-c\phi^2} \quad (9)$$

$$V_{P\ sat}^2 = V_{P\,m}^2 \ \frac{1+f\phi-g\phi^2}{(1+e\phi)\ (1+d\phi)\ (1-\phi)} \quad (10)$$

## 2.3. Mechanical properties and P-wave velocity of a partially saturated rocks

From equations (3), (4), (7) and equation (8) and using equation (1), we derive the elastic moduli ($k_{unsat}$ and $E_{unsat}$) depending on the degree of water saturation S for a porous media:

$$k_{unsat} = k_{dry} \times \frac{1+a\,k_f}{1+b\,k_f} \quad (11)$$

$$E_{unsat} = \frac{E_{dry}}{1-\alpha \dfrac{k_f}{1+\beta\,k_f}} \quad (12)$$

The variation of P-wave velocity of a porous media according to the degree of water saturation S is given by:

$$V_p^{unsat} = \sqrt{\frac{k_{unsat}+\frac{4}{3}\mu}{\rho_{unsat}}} \quad (13)$$

## 3. Results and discussions

## 3.1. Effect of porosity

From measurements of different sample weights, the water total porosity of all samples varies between 25.69 and 35.83 % [8]. The results of measurement of P-wave velocities of dry samples range from 3.56 to 3.8 km/s and those of water saturated samples vary between 3.59 and 3.9 km/s [11].

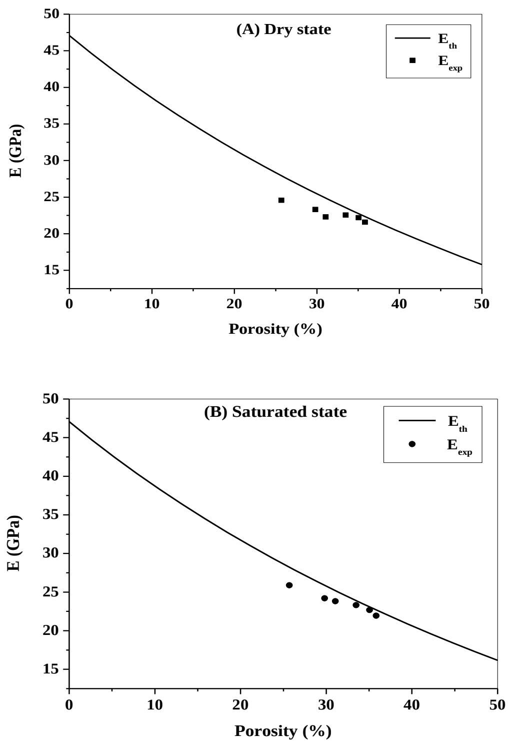


Fig.1. Comparison of measurements of Young's modulus E as a function of porosity for calcarenite rocks with the predictions of Mori-Tanaka model: (A) dry state, (B) saturated state.

The Young's modulus E in the saturated porous media is more important than those in dry porous media. This result is consistent with experimental results obtained on calcarenite rocks (Fig. 1).

From Fig. 1, we can seen that this theoretical model fits well with the experiments data in dry and saturated calcarenite rocks containing spherical pores.

The bulk modulus k is greater in saturated porous media, the shear modulus μ remains unchanged and P-wave velocity $V_P$ is more important in dry porous media. This result is interpreted by the fact that the density is higher in saturated porous media.

The comparison between Eq. (6) and Eq. (10) and experimental results is plotted in Fig. 2. This figure showed a good agreement between Mori-Tanaka model and experimental results for dry and saturated calcarenite sedimentary rocks, which can be used to predict the acoustic behavior of calcarenite rocks.

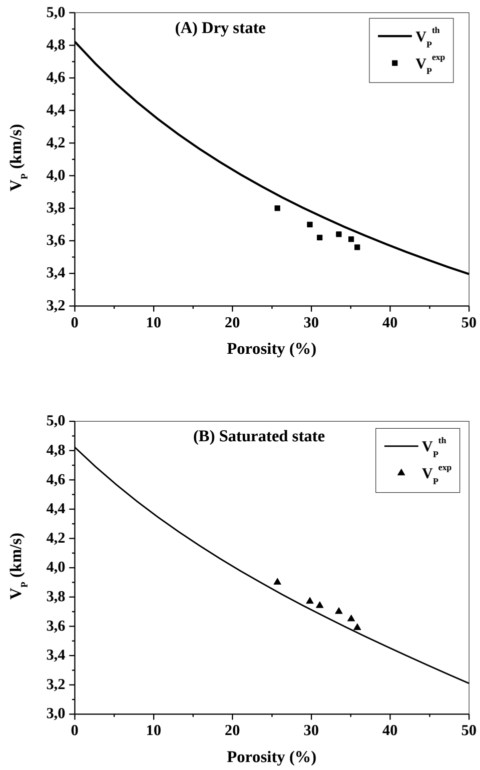


Fig.2. Comparison of P-wave velocity data as a function of porosity for saturated calcarenite rocks with the predictions of Mori-Tanaka model: (A) dry state, (B) saturated state.

## 3.2. Effect of degree of water saturation

The results of the modeling of a partially saturated porous media using the Mori-Tanaka model, show that the bulk modulus k and Young's modulus E increases with the degree of water saturation S (Figs. 3 and 4). From the curves, we see a slow increase of elastic moduli up to 80 % of saturation, then for strong saturation, the bulk modulus k and Young's modulus E are increasing rapidly, which is in the same sense as the work of Gregory [4].

Theoretically, using the Mori-Tanaka model for a partially saturated porous media constituted by a solid matrix containing spherical pores, and when the porosity is important, which is the case, and for low or medium saturation, the effect of density is dominant: the P-wave velocity decreases as the density increases. By approaching a strong saturation, the effect of bulk modulus becomes preponderant: P- wave increases with density. The result is that the curve of variation of P-wave velocity with the degree of saturation S presents a minimum (Fig. 5).

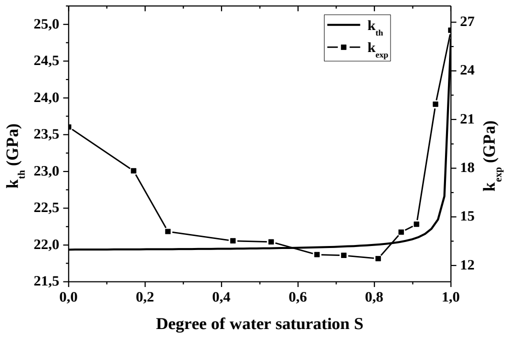


Fig.3. Bulk modulus k versus degree of water saturation S for a calcarenite sample of porosity 33.5%.

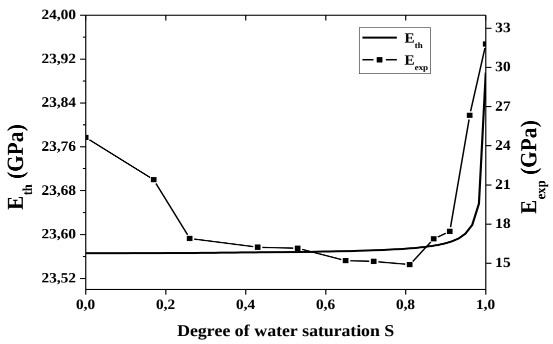


Fig.4. Young's modulus E versus degree of water saturation S for a calcarenite sample of porosity 33.5%.

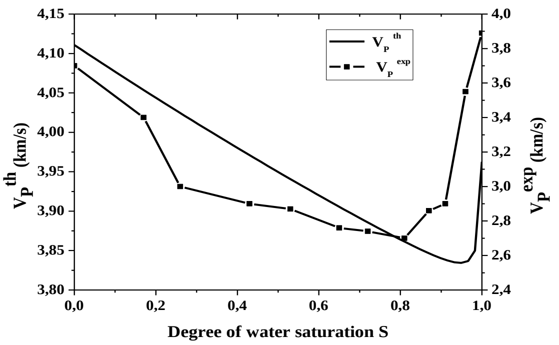


Fig.5. P-wave velocity versus degree of water saturation S for a calcarenite sample of porosity 33.5%.

This minimum, degree of saturation limit, often corresponds to a fairly high degree of saturation, greater than 80%.

We carried out measurements of P-wave velocity to different degrees of saturation on two samples of different porosities. The curves shown in Fig. 5, shows the variation of P-wave velocities measured with the degree of saturation for a calcarenite sample. We find we find the general shape of the curve found in the literature [1] and the theoretical model, with minima corresponding to degrees of saturation situated between 80% and 90%.

## 4. Conclusion

This work is to predict the elastic and acoustic behavior of calcarenite sedimentary rocks used in the construction of historical monuments of Rabat, Morocco.

The elastic properties in saturated state are more important than those in dry state. A good agreement is shown between the Mori-Tanaka model and experimental results for dry and saturated calcarenite sedimentary rocks, which can be used to predict the elastic behavior of calcarenite rocks.

Furthermore, we have established two new equations that describe the variation of bulk modulus k and Young's modulus E as a function of degree of water saturation by using the Mori-Tanaka model.

## Références

[1] Guéguen Y, Chelidze T, Le Ravalec M. Microstructures, percolation thresholds, and rock physical properties. Tectonophysics, 279:23-35. 1997

[2] Xu Y. Approches multi-échelle pour l'étude du comportement des systèmes polyphasiques - application aux milieux poreux non saturés, Thèse Ecole National des Ponts et chausses 2004.

[3] Miled K, Sab K, Le Roy, R. Effective elastic properties of porous materials: Homogenization schemes vs experimental data. Mechanics Research Communications; 38: 131–135. 2011

[4] Gregory A R. Fluid saturation effects on dynamic elastic properties of sedimentary rocks. Geophysics; 41: 895-921,1976.

[5] Mavko G, Hoeksema R N. Estimating seismic velocities at ultrasonic frequencies in partially saturated rocks. Geophysics; 59: 252-258,1994.

[6] Gassmann F. Uber die Elastizitatporosen Medien (Elasticity of porous media); 96, 1-23, 1951.

[7] Zaouia N, ELwartiti M, Baghdad B. Superficial alteration and soluble salts in the calcarenite weathering. Case study of Almohade monuments in Rabat: Morocco, Environ Geol; 48: 742–747, 2005.

[8] Rahmouni A, Boulanouar A, Boukalouch M, Géraud Y, Samaouali A, Harnafi M, Sebbani J. Relationships between porosity and permeability of calcarenite rocks based on laboratory measurements. Journal of Materials and Environmental Science; 5: 931-936, 2014.

[9] Samaouali A, Laanab L, Boukalouch M, Géraud Y. Porosity and mineralogy evolution during the decay process involved in the Chellah monument stones. Environ Earth Sci; 59: 1171–1181, 2010.

[10] Huynh Q V. Estimation des propriétés poromécaniques effectives des argilites: apport des méthodes d'homogénéisation. Thèse de Doctorat, Institut National Polytechnique de Lorraine , 2006.

[11] Rahmouni A, Boulanouar A, Boukalouch M, Géraud Y, Samaouali A, Harnafi M, Sebbani J. Prediction of Porosity and Density of Calcarenite Rocks from P-wave Velocity Measurements, International Journal of Geosciences, 4, 1292-1299, 2013.