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Estimating porosity and density of calcarenite rocks from P-wave velocity

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Abstract. Petrophysical proprieties such as porosity, density, saturation have a marked impact on acoustic proprieties of rocks. Hence, there has been recently a strong incentive to use new geophysical techniques to invert such properties from seismic or sonic measurements for rocks characterization. The P-wave velocity, is non-destructive and easy method to apply in both field and laboratory conditions, has increasingly been conducted to determine the geotechnical properties of rock materials. The P-wave velocity of a rock is closely related to the intact rock properties and measuring the velocity in rock masses describes the rock structure and texture. The present work deals with the use of simple and non destructive technique, ultrasonic velocity to predict the porosity and density of calcarenite rocks that is characteristic in historical monument. The ultrasonic test is based on measuring the propagation time of a P-wave in the longitudinal direction. Good correlations between P-wave velocity, porosity and density were found, which indicate them as appropriate technique for estimating the porosity and density.

1 Introduction

Characterization of rock materials by ultrasonic methods is widely used. Since 1972, ultrasonic velocity measurements are applied to determine the quality of natural stones, in order to demonstrate homogeneity and degree of alteration [1]. Mamillan [2] applied ultrasonic velocity measurements to stone conservation and diagnostic state of alteration on marble sculptures introducing a new non destructive methodology to stone conservation.

Ultrasonic pulse velocity has been used for many years in geotechnical practice and mining science. They are widely used to determine properties and states of materials, in the case of engineering solids measurements of ultrasonic wave propagation velocities are routinely used to determine elastic constants [3, 4]. There has been an Increasing use of ultrasonic velocity measurements for non destructive characterization of material microstructures and mechanical properties [5, 6]. Therefore, it is Important to have appropriate practical methods for making velocity measurements on a variety of material samples.

Various researchers [7, 8] demonstrated that the prediction of petrophysical properties in rocks is often difficult due to possession of complex textures and petrophysical properties, porosity and permeability, which are dependable and influenced by the diagenetic processes they may have undergone right from the time of deposition to the late diagenesis set in. Certain studies that combined seismic, petrophysical and petrological data to established useful relationship between velocity and petrophysical of rocks were carried out by [5, 9].

The study of compressional and shear wave propagation a material to dry and saturated evaluates the physical properties of materials such as porosity, cracking state and its elastic properties in modeling of the wave propagation. For rocks, it is often interested in the compressional waves propagation (P-wave) and shear waves (S-wave). For a P-wave, the vibration occurs in the direction of propagation and affects the volume of the rock. For S-wave, the vibration propagates in a plane normal to the direction of propagation; it is slower than the P-wave and does not propagate in water. The P wave and S-wave are characterized by their velocities V_P and V_S respectively and their attenuation.

The relationship between velocity and density in rocks is usually considered as linear [10]. The transit time of the waves depends on the density of the minerals forming the rocks [11]. It depends too on porosity (voids proportion and pore size distribution), and on the possibly anisotropic arrangement of the material forming particles [12].

Physical properties, such as porosity and density, are important parameters for the quality of building stones hence if good correlations are established between P-wave velocity and the physical properties of calcarenite rocks, this would be helpful for those working in stone processing plants. In this study, the possibility of estimating the physical properties of calcarenite rocks from P-wave velocity obtained from laboratory measurements was investigated.

2 Materials and methods

The materials used in this study are sedimentary rocks calcarenite, collected in a quarry near the town of Rabat, Morocco. The monuments of Rabat are all constructed by the plioquaternary calcarenite that constitutes the basement of the whole region. A few kilometers to the north of the city, quarries still provide this ornamental rock widely used by stone craftsmen. It is characterized by variable and high porosity (18–47%) and thus an elevated permeability [13]. Its chemical composition is very rich in calcium carbonates and its rough surface allows a high receptivity to the atmospheric gaseous pollutants and to hydrous marine sprays charged with various salts.

Measurements of P-wave velocity, porosity and density were performed on samples $7\times7\times7$ cm^3. These measures will help to better understand and identify the characteristics of the porous network of materials used in the construction of the monument of Rabat.

2.1 Porosity

Many techniques are used to estimate the porosity [14, 15], and highlight some geometric properties of the porous network. The technique used for this work is the total saturation with water.

The evaluation of the porosity of a material can not be done directly. Indeed, the estimation of void volume in the connected content material requires the injection of a fluid whose properties are known. The total saturation by a wetting fluid (usually water) is the easiest method to access the value of porosity. According to a suitable protocol, after degassing, the sample is fully saturated with water, and after different weighed, a value of the total porosity is calculated.

The method of measuring the water total porosity is that defined by the standard RILEM [16], which provides that the samples are soaked in the absence of air, ie in monophasic regime.

Initially, the samples were dried in an oven at 105 °C to constant mass. Then they were weighed once dry (Ws), then placed in a vacuum chamber, where they are subjected to a primary vacuum of 2 × 10-2 mmHg (2.6 Pa) for 24 hours. Meanwhile, in another crystallizer, water distilled and degassed under high vacuum.

After 24 hours of degassing, the samples were soaked vacuum by capillary: the water level is readjusted regularly as and when the progress of the fringe capillary in the material [17]. When the samples are totally immersed, the vacuum is broken, and they are held for 24 hours. Finally, a weighing of samples saturated (W_1) and a hydrostatic weighing (W_2 = weight of saturated samples subjected to Archimedes) complete measures the value of porosity is given by:

$$N_t(\%) = \frac{W_1 - W_s}{W_1 - W_2}\times 100 \qquad (1)$$

with W_1 the weight of the sample saturated with water, W_2 weight saturated obtained by hydrostatic weighing, W_s is the dry weight of the sample.

2.2 Density

Bulk density is determined either by measuring precisely sample dimensions and sample weight, after drying in an oven at 105 ℃ during 24 h, or by hydrostatic weighing method which is based on the Archimedes principle on a sample saturated and submerged in a wetting fluid: water. In this test, samples are dried in an oven at 105 ℃ until constant weight (W_s). Then, the samples are saturated by imbibition in a cell under vacuum during 24 h, by complete immersion during a day in outgassed water. Then a hydrostatic weighing of the saturated samples immersed in water (W_2) and a weighing in air of the saturated samples wiped with a wet rag (W_1) are carried out. Dry (ρ_{dry}) and saturated (ρ_{sat}) bulk density can then be calculated from:

$$\rho_{dry} = \frac{W_s}{W_1 - W_2} \qquad (1)$$

$$\rho_{sat} = \frac{W_1}{W_1 - W_2} \qquad (2)$$

The results of density are given in Table 1.

2.3 P-wave velocity

Measuring propagation velocity of ultrasonic waves in a material such as stones is ways to further investigation of the mechanical tests have the advantage of being non-destructive testing [9]. Wave propagation in solids is based on the theories of elasticity that link efforts and low strains. These elastic waves are polarized in two perpendicular directions in the two plane waves: longitudinal compression wave called the primary wave (P-wave) representing the vibration of particles parallel to the direction of wave propagation, and transverse wave called shear secondary wave (S-wave), representing the vibration of particles perpendicular to the direction of propagation.

The principle of ultrasonic pulse velocity measurement involves sending a wave pulse into specimen by an electro-acoustical transducer and measuring the travel time for the pulse to propagate through the specimen. The pulse is generated by a transmitter and received by a similar type of receiver in contact with the other surface. In the experimental studies, the transmitter and receiver were placed at the opposite ends of specimens.

As a result, the traveling length of the ultrasonic pulse was the length of the specimen. The specimen surface must be prepared in advance for a proper acoustic coupling by applying grease. Light pressure is needed to ensure firm contact of the transducers against the specimen surface.

Knowing the path length (L), the measured travel time between the transducers (t) can be used to calculate the pulse velocity (V) using the formula:

$$V = \frac{L}{t} \qquad (2)$$

where V is pulse velocity (km/s), L is path length (cm) and t is transit time (μs).

3 Results and discussions

Porosity controls all other physical parameters of the rock (density, permeability, thermal conductivity ...). It corresponds to the ratio of the total pore volume and the total volume of the rock and is expressed as a percentage. In practice, only the open porosity of a rock is measurable. The space created between the grains and microcracks is often recorded with the volume of porosity. In this work, we used the water total porosity.

Table 1 show that these samples have a difference of porosity. The total porosity of the samples varies between 25.69 and 35.83%. The average porosity is 31.83%.

Table 1. Physical properties of calcarenite rocks.

Sample	P-wave velocity (Km/s)		Density (g/cm^3)		Porosity (%)
	Dry	Saturated	Dry	Saturated	
1	3,8	3,83	1,75	2	25,69
2	3,7	3,74	1,68	1,97	29,82
3	3,62	3,69	1,64	1,95	31,07
4	3,64	3,62	1,59	1,92	33,50
5	3,61	3,65	1,6	1,95	35,07
6	3,56	3,59	1,6	1,94	35,83

The P-wave velocity is dependent of several parameters: mineral composition, porosity, presence of cracks and water content. The measured velocity in a macroscopic sample is a balanced average of the velocity in the minerals (e.g. 6,06km/s in quartz, 6,65km/s in calcite) and in the fluid present in the porous network (e.g. 1,5km/s in water, 0,34km/s in air), altered by the crossing of solid-solid, fluid-fluid or solid-fluid interfaces. The measurements have been performed on dry and water saturated samples.

The results obtained for the 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 3.83 km/s. These results are consistent with literature results [18, 19]. In general, we observe that the high value of the P-wave velocity is obtained for the samples saturated and the low value is obtained for dry samples. The authors Boulanouar et al [18] and Guéguen et al. [20] compared the velocities P-wave in dry and saturated with water, they observed generally V_P (sec) <V_P (saturated). Beck [21] observed that the P-wave velocity is higher in the saturated state for the Tuffeau (white) and the stone of Sebastopol.

In order to describe the relationships between P-wave velocity, porosity and density of the tested rock samples, a regression analysis was carried out. The equation of the best fit line and the coefficient of determination (R^2) were determined for each test result.

The best fit line and its regression analysis for each data set is illustrated in Figures 1–4. It can be seen from the Figures that, in all cases, the best fit relationships were found to be best represented by linear regression curves.

The values of P-wave velocity of rocks were correlated with the porosity of the rocks.

The graphs between P-wave velocity and porosity are shown in Figures 1 and 2.

There is linear relation between P-wave velocity (V_P) and porosity (N) for calcarenite rocks. A strong correlation (R^2=0.8899 (dry), R^2=0.9356 (saturated)) was found between P-wave velocity and porosity for rocks (Figures 1 and 2). The equations of this relation are given below:

$V_P = -0{,}021 * N + 4{,}3239$ (Dry samples)

$V_P = 0{,}0224 * N + 4{,}4008$ (Saturated samples)

The plot of P-wave velocity as a function of density (ρ) is shown in Figures 3 and 4. There is a linear relationship between P-wave velocity and density for calcarenite rocks. A strong correlation (R^2=0.8451 (dry), R^2=0.8681 (saturated)) was also found between P-wave velocity and the density for rock. Gaviglio [12] and Yasar [9] reported a relation between P-wave velocity and density in carbonate rocks only with a regression coefficient of 0.78 and 0.81, respectively.

The equations of relation are as given below:

$V_P = 1{,}2466 * \rho + 1{,}6085$ (Dry samples)

$V_P = 2{,}9867 * \rho - 2{,}1523$ (Saturated samples)

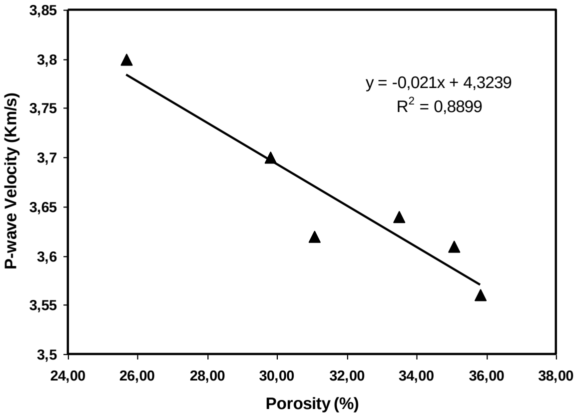

Fig.1. P-wave velocity versus porosity for dry rock samples

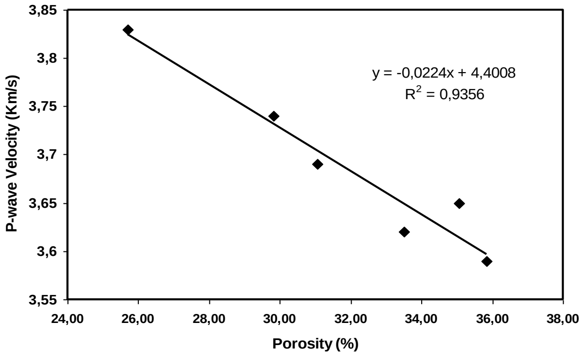

Fig.2. P-wave velocity versus porosity for saturated rock samples.

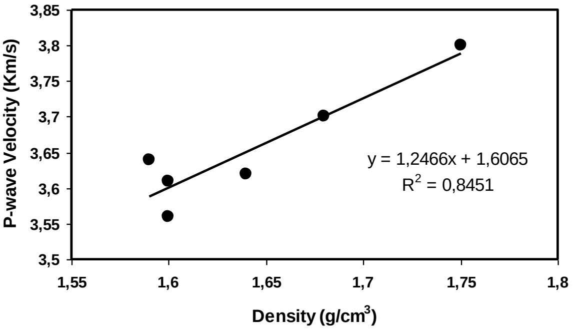

Fig.3. P-wave velocity versus density for dry rock samples.

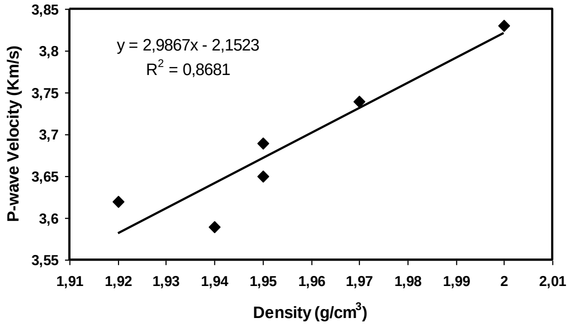

Fig.4. P-wave velocity versus density for saturated rock samples.

The empirical methods used in this study were evaluated by comparing their results with each other. Data from each test were used in the respective empirical equation to calculate other properties. The predicted values of porosity and density values were then plotted against the measured values for all tested rocks, respectively, on 1:1 line (Figures 5, 6, 7, and 8). Point lying on the slope line indicates an exact estimation. It is clear from the Figures. 5, 6, 7 and 8 that P-wave velocity is one of the reliable methods for estimating porosity and density and to avoid cumbersome and time-consuming laboratory test methods.

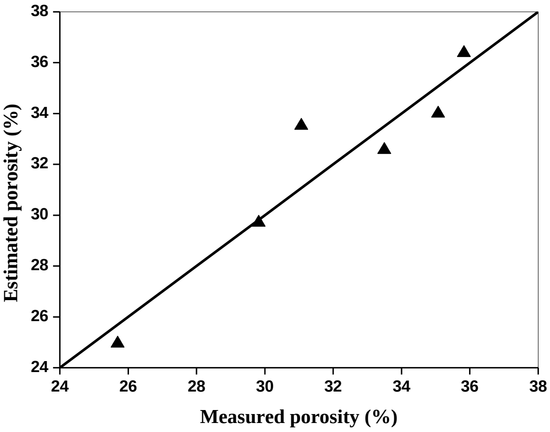

Fig.5. Estimated porosity and measured porosity from P-wave velocity for dry samples.

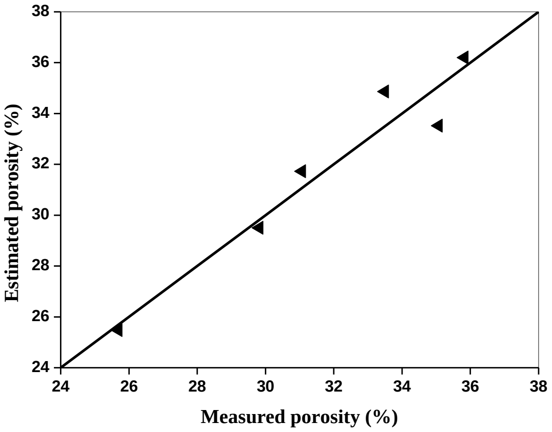

Fig.6. Estimated porosity and measured porosity from P-wave velocity for saturated samples.

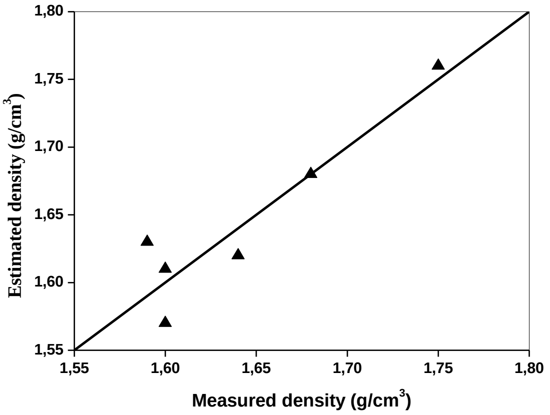

Fig.7. Estimated density and measured density from P-wave velocity for dry samples

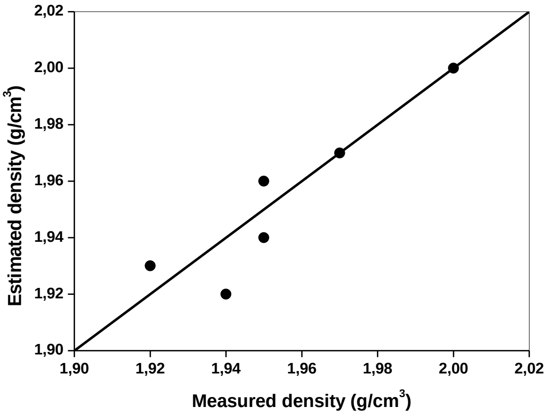

Fig.6. Estimated density and measured density from P-wave velocity for saturated samples

To determine the empirical relationships between P-wave velocity, thermal conductivity and porosity of the tested rock, the t-tests have been performed using the so-called Student t-test. The t-test is performed to test the null hypothesis. According to the t-test, when computed t-value is greater than tabulated t-value, the null hypothesis is rejected and the obtained correlation coefficient (R-value) is acceptable. In the present study the t value is computed and compared with the tabulated value. Since, a 95% confidence level was chosen in this test, a corresponding critical t-value 2.92 is obtained. Table 2 shows the calculated and tabulated values of t test.

In all the above cases for rocks, calculated value of t-test is much higher than the tabulated value and hence they all have significantly strong correlation among themselves and this may be used for prediction of the porosity and density using P-wave velocity.

Table 2. Tabulated results of the t-test.

Rock tests	R^2	t-test	
		Calculated value	Tabulated value
P wave velocity and Porosity for dry rock samples	0,8899	5,68	2,92
P wave velocity and Porosity for saturated rock samples	0,9356	7,61	2,92
P wave velocity and density for dry rock samples	0,8451	4,67	2,92
P wave velocity and density for saturated rock samples	0,8681	5,13	2,92

4 Conclusions

In this study, basic physical properties of 6 rocks samples have been measured and analyzed in an integrated manner. Laboratory measurements have been carried out on the following physical parameters: porosity, density and P-wave velocity.

A strong coefficient of determination was found between P-wave velocity with porosity and density of the tested calcarenite rocks. This was also verified by Student’s t test, which showed higher calculated values for each relation, rather than tabulated values. Hence, they all have significantly strong correlation among themselves and the proposed correlation equations can be used for determination of porosity and density by P-wave velocity.

The study has shown that porosity and density can be estimated by the use of P-wave velocity with the given empirical equations for calcarenite rocks that are characteristic in historical monument. Such a correlation can provide a good estimation of such properties as porosity and density, which in many cases can avoid time-consuming and tedious test methods.

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