Extended Abstract

Correlation between volumetric strain and porosity in saturated limestones

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Abstract

Porosity and permeability are two of the most important parameters regarding the knowledge about how rock masses are affected in terms of their geology and physical and mechanical behavior, whether in Mining or Petroleum Engineering. This matter is quite debated in both theoretical and practical studies. Laboratory analysis about the influence of different stress states in both porosity and permeability is a recurrent method to study, in a more profound way, what causes changes in these properties' behavior and what are the consequences it brings to rock masses.

The present study involves triaxial testing under drained and undrained conditions in saturated limestones from Serra de Aire e Candeeiros. The specimens were submitted to anisotropic stress states of 20-40 MPa of deviatory stress with confinement stresses of 10, 20 and 30 MPa. During the tests, pressurized water was introduced (about 33% of confinement stress). The properties measured during the laboratory tests were deviatory stresses, axial, horizontal and volumetric strains, pore pressure, changes in porosity and permeability.

It was concluded that the measured parameters show correlations between themselves which are worthy of being mentioned, namely with deviatory stress and volumetric strain.

Keywords: Porosity, Permeability, Triaxial tests under drained and undrained conditions, Anisotropic stresses, Volumetric strain, Porosity variation.

1. Introduction

The number of studies who persecute the influence of anisotropic stress in permeability, porosity and volumetric is greater every day because of its importance to many different areas of Science and Engineering, especially for Mining and Petroleum Engineering. In Mining Engineering, Guerreiro (2013) infatuates that the perception of how the poroelastic parameters are influenced by stress and strain is very important to understand how to operate in situations where it is important to build tunnels, cavities, holes, slope stability and other operations. Authors such as Zhu *&* Wong (1997), Holcomb *&* Olsson (2003) and Fortin *et al*. (2005) have studied the influence of stress and strain on porosity and permeability in a theoretical and laboratorial way. The purpose of the present work is to study the correlation between porosity and permeability and volumetric strain in high pressure triaxial tests on saturated limestones.

1.1. Triaxial tests

The most common triaxial test, and the one that matters the most in order to achieve the purpose of this work, is the compression or standard test, where an hydrostatic stress state is achieved in the first place and then the axial stress is raised to a deviatoric stress of interest or until failure occurs.

As Fjaer *et al*. (2008) and Rees (2013) state, the triaxial compression test presents the advantage, compared to other tests in Rock Mechanics, of controlling drainage conditions, alternating between drained and undrained conditions. The first authors reveal that drained triaxial tests suppose that it exists an opening between the interior and the exterior of the cell in order to limit pore pressure to a known value, being the most common the atmospheric pressure. On the other hand, undrained triaxial tests suppose that the fluid contained in the pores does not exit them, which generates a pressure that depends on the stress state and the fluid injection pressure.

1.2. Previous studies on rock properties

Rock mass behavior under various stress states is of the uttermost importance to different areas of Engineering, such as Mining, Civil and Petroleum Engineering.

1.2.1. Stress state influence on poroelastic and flow properties

The influence exerted on poroelastic and flow properties by different stress states is studied by various authors, although most of their studies focus only on the variation of porosity and permeability and lack the precise information on the mechanical properties behavior, mostly because the knowledge about Young Modulus and Poisson ratio and how they vary with the stress state is only important to obtain information about how will the rock behave when stress is applied to it. Santos (2017) establishes a relationship between the variation on Young Modulus, which translates stiffness, with pore compressibility, also stating that pore pressure and pressurized water introduced on his triaxial apparatus influence the mechanical properties of the saturated limestones tested.

Rocha (1985) tries to establish a relationship between mechanical parameters, volumetric strain and the applied stress state, presenting Figure 1, which translates the influence of the last on the other two parameters. Through Figure 1, Rocha (1985) observes that the volumetric strain increases with the increment of the axial stress, which means the total volume of the samples decreases. Upon relaxation, the volumetric strain and the total volume tend to return to the initial values. As for the Young Modulus and the Poisson ratio, the first has a similar tendencie to the volumetric strain, while the second tens to increase until the closure of the fractures occurs, after which it mantains constant until failure occurs and it stars to decrease.

Poroelastic properties include the mechanical parameters and porosity, so the influence of stress state on the three parameters is quite studied.

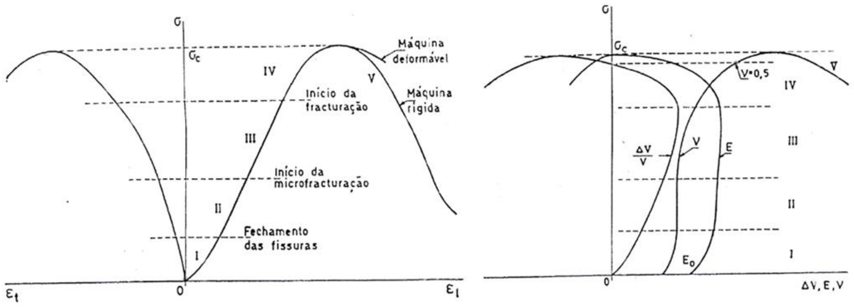

Figure 1 - Uniaxial compression curves with the relationship between stress, E, Poisson ratio and volumetric strain. Rocha (1985).

The variation of porosity with the stress state on itself is of interest to many scientific areas and to this work particularly.

Fjaer *et al*. (2008) refers that the study of how the porosity is influenced by the stress state depends on how pore compressibility is affected by the latter, describing that when pore pressure increases while the confining pressure remains constant, in triaxial tests, grain expansion occurs consequently increasing porosity.

Santos (2017) executed drained triaxial tests in hydrostatic conditions on saturated limestones and concluded that stress state tends to diminish pore compressibility, which leads to a decrease in rock stiffness that causes a decrease in porosity.

Not only pore compressibility can affect porosity. Walsh (1981), Zhu *&* Wong (1997), Al-Harty *et al*. (1999) and Holcomb *&* Olsson (2003) performed hydrostatic and non-hydrostatic triaxial tests in order to determine which one influenced porosity the most. The first three authors concluded that hydrostatic stress states where responsible for the greater amount of porosity variation, while the last authors determined that porosity evolution is independent of the chosen stress path.

On the other hand, Jia-Jyun *et al*. (2010) realized triaxial tests on sandstones and shales in order to study the influence of confining pressure on porosity changes. The authors concluded that porosity tends to decrease with the increment in confining pressure on both rocks.

Although the study about how the stress state influences porosity and permeability can be executed separately, most authors tend to group both parameters and study the influence of stress state on both of them.

Fortin *et al*. (2005) study the relationship between permeability, wave velocity and volumetric strain in *Bleurswiller* sandstones by the means of drained triaxial tests with confining pressures of 12, 30, 70, 90 and 110 MPa and pore pressure of 10 MPa. The way wave velocity is influenced by stress state will be ignored.

On the first set of tests, Fortin *et al*. (2005) performed under an hydrostatic stress state, dividing compaction in six domains, as it can be observed in Figure 2.

The region A_0 to A_1 corresponds to micro fracture closure, which translates in Figure 3 to a decrease in porosity while permeability remains constant. The elastic domain is represented in the section A_1 to P*, where porosity decreases with the increment in mean effective stress while permeability remains constant. P* represents the critical effective stress, where grains crush and pore collapse. After point P*, permeability and porosity tend to decrease at a high rate until the end of compaction, which is represented by point A_3. That point also represents the beginning of relaxation, where in the section A_3 to A_4 permeability remains somewhat constant and porosity decreases. The region A_4 to A_5 corresponds to axial stress discharge where the formerly closed micro fractures re-open and permeability increases.

The second set of triaxial tests consisted on executing compressive triaxial tests with confining pressures of 12 and 30 MPa, with the results present in Figure 3.

On the samples tested with 30 MPa of confining pressure, porosity tends to decrease at low rate with the increase in mean effective stress, while at lower confining pressures (12 MPa) that trend was more difficult to identify, as Fortin *et al*. (2005) stated. As for permeability, the authors concluded that dilatancy does not lead to great changes in permeability, which is in agreement with the low rate decrease identified in pore volume change.

In the third and last set of triaxial tests, Fortin *et al*. (2005) executed compressive triaxial tests with confining pressures between 50 and 100 MPa, as seen in Figure 4.

Observing Figure 4, Fortin *et al*. (2005) concluded that after the point C*, related to compaction, porosity and permeability tend to decrease, which lead to the conclusion that both parameters are correlated and are affected by stress the same way: when axial stress increases, porosity and permeability diminish.

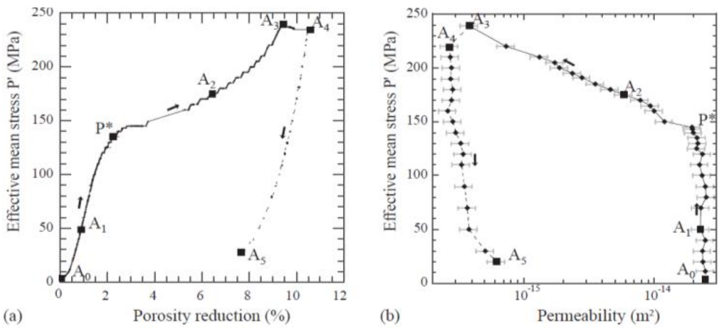

Figure 4 - Triaxial tests under hydrostatic condition that show the relationship between mean effective stress and: (a) porosity reduction and (b) permeability. Fortin et al. (2005).

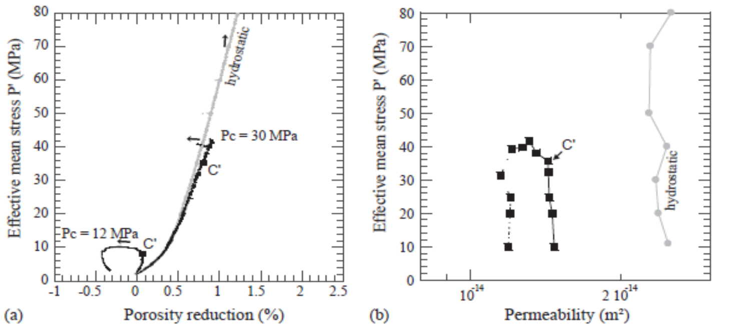

Figure 2 - Triaxial tests under non-hydrostatic stress states showing the relationship between mean effective stress and: (a) porosity reduction and (b) permeability. Fortin et al. (2005).

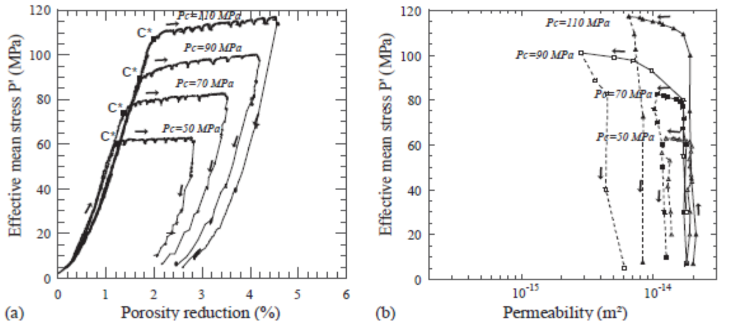

Figure 3 - Compressive triaxial tests under non-hydrostatic high stress states showing the relationship between mean effective stress and: (a) porosity reduction and (b) permeability. Fortin et al. (2005).

The effects of different stress states on permeability are contradicting according to the conclusions of authors such as Somerton *et al*. (1975) in coals, Morita *et al*. (1984) in sandstones and Holt (1990). The first authors concluded that permeability in coals depended essentially on the effective stress and that non-hydrostatic stress states and stress application direction did not influenced it greatly. On the other hand, Morita *et al*. (1984) stated that permeability had greater variations at lower confining pressures and that non-hydrostatic stress states were responsible for those variations. Finally, Holt (1990) agreed with the works of both authors by stating that permeability varies on both hydrostatic and non-hydrostatic stress states, although it variated greatly on the latter when compared to the hydrostatic stress state.

Holt (1990) also concluded that the increment in confining pressure generates an increase in the permeability of *Red Wildmoor* sandstones. By applying non-hydrostatic stress states on those sandstones, the author concluded that permeability decreases with the increment in axial stress. After attaining a certain value of axial stress, which was found to be between 60 and 80 MPa, the sandstones begin to deform non-elastically, which results in a high rate decrease in permeability for small increments in axial stress, as seen in Figure 5.

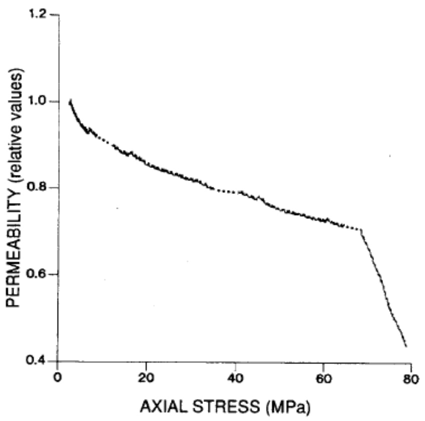

Figure 5 - Relationship between permeability and axial stress when non-hydrostatic stress states are applied to Red Wildmoor sandstones. Holt (1990).

After studying the relationship between permeability and axial stress, Holt (1990) studied the influence of axial strain on permeability, at non-hydrostatic stress states, utilizing three different confining pressures: 5, 10 and 30 MPa. Holt (1990) begins the tests by exercising an hydrostatic stress state, increasing the axial stress afterwards until the samples reach permanent deformation, which results in Figure 6.

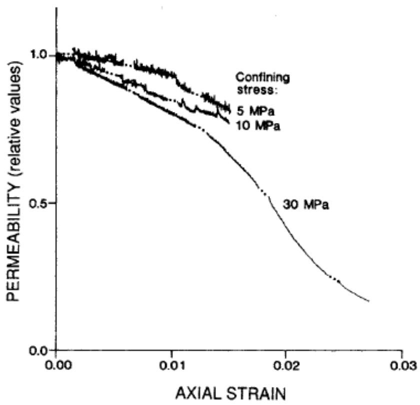

Figure 6 - Relationship between permeability and axial strain when non-hydrostatic stress states are applied to Red Wildmoor sandstones at three different confining pressures. Holt (1990).

Holt (1990) concluded that permeability decreases with the increment in axial strain and that the higher the confining pressure, the greater the decrease in permeability of *Red Wildmoor* sandstones.

Santos (2017) also studied the relationship between permeability and confining pressure, reaching results that matched the ones Holt (1990) achieved, although stating that permeability decreased polynomially with confining pressure, which corresponded to Ghabezloo *et al*. (2008) conclusions. Figure 7 shows the results obtained by Santos (2017) on saturated limestones.

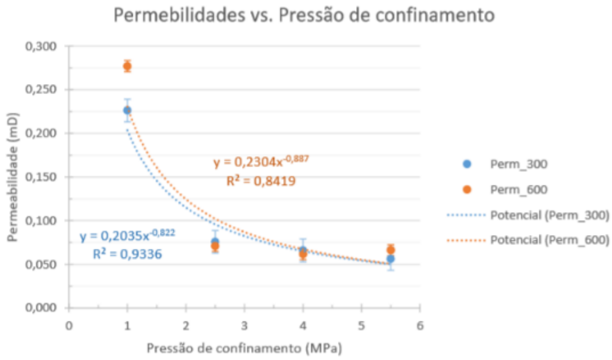

Figure 7 - Relationship between permeability and confining pressure in saturated limestones. Santos (2017).

1.2.2. *Porosity influence on mechanical and flow properties*

Porosity, as a poroelastic parameter, has influence on the other poroelastic parameters: Young Modulus and Poisson ratio.

As for the Poisson ratio, Yu *et al*. (2016) concluded that it increases with the increment in porosity, but only on rocks with initial Poisson ratio of 0,08 (Poisson ratio for quartz).

The relationship between permeability and porosity is studied by many authors such as Scheidegger (1974), DiGiovanni *et al*. (2000) and Fortin *et al*. (2005). The second author studies this relationship by executing triaxial compressive tests in *Castlegate* sandstones and concluding that grain crushing associated with pore rupture and collapse serve as fluid barriers, which means porosity reduction is associated with permeability reduction, which is in agreement with Morris *et al*. (2003) and Holcomb & Olsson (2003) conclusions on *Berea* and *Castlegate* sandstones, respectively.

1.2.3. *Geological influences on poroelastic and flow properties*

The influence of geological factors on mechanical parameters is due to the necessity of obtaining data that explained mechanical changes of rocks. Palchik (2013) concludes that Young Modulus and Poisson ratio depend on geological factors such as mineralogical compositions, types and form of grains and cementation. Guerreiro (2013) also states that natural cementation alters poroelastic properties, in agreement with Palchik (2013).

Scott *et al*. (1993) stated that porosity and Young Modulus are not directly correlated because of two competing geological factors: grain rupture associated with compaction; and micro fracture closure derived from mean stress action on the samples. Guerreiro (2013) states that the action that both geological factors have on the relationship between porosity and the mechanical parameters is not yet quantified, so the effects they have on this relationship is not well known.

Santos (2017) states that porosity and permeability evolution depends on intrinsic rock factors such as initial porosity and permeability, tortuosity, pore shape and sedimentary heterogeneities, which is supported by Walsh (1965), Zhu & Wong (1997), Davies & Davies (2001), Vajdova *et al*. (2004), Kwon *et al*. (2004), Jia-Jyun *et al*. (2010), which concluded these factors promoted a decrease in the permeability of granites, sandstones and shales.

Sulem & Ouffroukh (2005) also studied the influence of geological factors on permeability by executing undrained triaxial compressive tests. The authors stated that the rock deformation process, mainly the structural evolution of pores highly influences permeability, since the reduction of porosity is linked to a decrease in permeability. The authors also stated that, although no changes of fluid between the exterior and the interior of the triaxial cell occurred, pore pressure generated by stress state fluidized the material, which created voids where the fluid could flow, increasing permeability that way. Zhu & Wong (1996) and Vajdova *et al*. (2004) concluded that grain size influences uniformity and the arrangement of grains in rock structure, which influences initial porosity and consequently the porosity of rocks.

2. Samples and Procedure

2.1. Samples

The samples utilized in the present work came from an unique type of rock, which was limestone from Serra de Aire e Candeeiros, situated in the Centre Region of Portugal, between Rio Maior, Tomar and Leiria, in Maciço Calcário Estremenho. This region of Portugal is where the biggest limestone outcrop is situated (Carvalho *et al*., 2011). Most of them are from Superior and Middle Jurassic.

Throughout the triaxial tests, 11 samples of limestone, provided by MOCAPOR, were used. Its geometrical parameters are exposed in Table 1.

Table 1 - Geometric parameters of the limestones tested.

Geometric parameters	Values
Diameter	5,35 cm
Radius	2,675 cm
Length	11,115 cm
Section area	22,48 cm^2
Volume	249,87 cm^3

The ISRM standards about geometric parameters were respected, since the relationship between the samples length and diameter is comprehended between 2 and 3 and the general dimensions of the samples are 10 times the dimension of the biggest grain in the rock, which also verifies.

Considering MOCAPOR's website and all the data from the geometric parameters, the limestone provided by the company was Moleanos Beige type.

2.2. Procedure

In order to accomplish the objective of this work, two experimental procedures were done: determination of the initial porosity and triaxial testing.

2.2.1. Determination of the initial porosity

To determine the initial porosity of the samples, the Portuguese standard NP (2001) was followed. It was chosen the mentioned above because it fitted the type of equipment in GEOMEC laboratory in Instituto Superior Técnico.

From the 11 samples, 4 cylinders (representative of the 11 samples and originated from the coring process of them) were chosen to perform this test, which begins by measuring all the geometric properties of said cylinders. After the measurements, the cylinders were weighted in an electronic balance which calculates their density by measuring their weight inside and outside water. After obtaining its density at natural conditions, the cylinders were dried in an oven at 105ºC for 72 hours, repeating the process of weighting afterwards.

Upon measuring their dry density, the cylinders were put in a desiccator in order to withdraw air from their pores. In NP (2001) the depression created by the desiccator had to be 2±0,7 kPa for 24 hours. Because of the limitations of the laboratory equipment, the air depression created was 40 kPa, so the period of time was reduced from 24 to 3 hours, after which the measuring procedure done in the electronic balance was repeated.

Finally, this procedure ends by determining the density of the saturated cylinders by introducing them in containers of 800 and 600 mL, registering the initial level of water on them with and without the cylinders. After this measurements, the set container-cylinder is put on the desiccator and the process of saturation begins. The air depressions was maintained for 96 hours, after which the electronic balance procedure was repeated.

After this, NP (2001) provides Equation 1 for determining open porosity, which in this work corresponds to the initial porosity.

$$\phi = \frac{M_{sat} - M_{seca}}{M_{sat} - M_{secaimersaemágua}} \times 100 \qquad [1]$$

Where ϕ is the initial porosity, M_{sat} is the weight of the saturated cylinder, M_{seca} is the weight of the dry cylinder and $M_{secaimersaemágua}$ is the weight of the dry cylinder immersed in water, all of these in grams.

2.2.2. Triaxial testing

The triaxial tests were divided in two phases: undrained (where E, Poisson ratio, strains and pore pressure were taken) and drained (where the permeability was obtained).

Before the undrained triaxial testing started, it was important to check if everything was connected and working properly, such as: if the provider of compressed air was working, if the cable that connected the triaxial cell to the computer and the one who connected the triaxial cell to the accumulator were functional and if the strain gauges were reading values and if they were linked to the Wheatstone bridge.

After this checking, the hydraulic press is turned on and axial stresses are applied on the triaxial cell until a value of 1 kN is achieved, in order to maintain the piston in contact with the sample when the hydraulic oil began to fill the triaxial apparatus. After the cell is totally filled with the hydraulic oil, it is necessary to increase the axial stress and the confining pressure (regulated by an oil pump, which also had the capability to provide confining pressure to the sample) until an hydrostatic stress state is achieved. Then, pressurized water is put on the apparatus in order to measure pore pressure in the undrained test and permeability in the drained test.

After applying the pressurized water to the system, the axial stress is increased until a certain pre-established stress level was achieved. The applied stress had to respect the ISRM (1978) standard as for the rhythm of charge (1,1-2,5 kN or 0,5-1 MPa per second). After achieving the maximum established value for axial stress in the undrained triaxial test, the faucet for reading pore pressure is turned off and the faucet for allowing water to flow from the triaxial cell to the burette is opened, in order to begin the drained triaxial test. The level of water in the burette was read in a 20 minute time spread for 7 hours, after which the apparatus was left from one day to the next, where the burette readings are resumed until a 24 hour period is achieved.

3. Discussion

3.1. Porosity

After making all the necessary measurements described in 2.2.1., Equation 1 is utilized in order to determine the initial porosity of the limestones. For the Moleanos Beige limestones, the initial porosity measured was 3,44%, while the porosity for the Moleanos Beige limestones, provided by MOCAPOR's website is around 4,8%.

3.2. Triaxial testing

There were made 23 triaxial compression tests in the elastic regime combining multiple confining pressures and deviatoric stresses.

There were used 11 samples while the axial stresses applied ranged from 30 to 70 MPa Three different confining pressures were applied throughout 10 samples tested with 10 MPa of confining pressure, 5 with 20 MPa and 8 with 30 MPa.

Since the objective of the present work is to correlate porosity and permeability with volumetric strain at high stress states, it is important to start the present discussion by observing the relationship between the axial stress and the radial, axial and volumetric strains (Figure 8).

Figure 8 represents only the relationship between the axial stress and the different strains on non-hydrostatic stress states, since experimental data was not obtained for the hydrostatic stress state. In order to simulate the possible evolutions of stress-strain relationship on an hydrostatic stress state, the dotted lines were put on Figure 8.

Through Figure 8 it is possible to observe that axial and radial strain increase with the increment in axial stress, as observed for the regimes II, III and IV in Figure 1. On the other hand, volumetric and axial strains are more significant than radial strain, which is expected since the axial stress is the only one to increase after achieving the hydrostatic stress state.

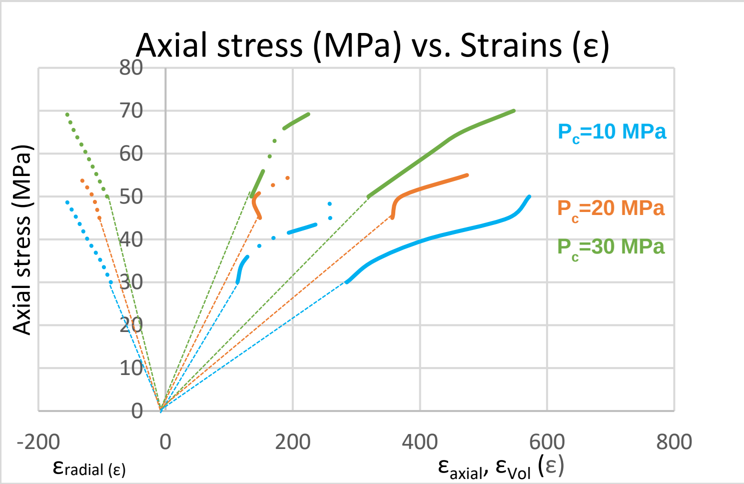

Figure 8 - Relationship between axial stress and axial, radial and volumetric strains.

3.2.1. Young Modulus

By observing Table 2, the Young Modulus lightly increases with the increment in axial stress and with the confining pressure, since axial strain decreases with the increase of the last one (Hooke's Law). This conclusion is in agreement with the ones obtained by Zhu & Wong (1997), Fortin *et al*. (2005) and Santos (2017) in sandstones and limestones, respectively. On the hand, the values for P_c=30 MPa do not follow the general trend of increasing with the confining pressure, which contradicts the other results obtained.

Young's Modulus evolves positively until a certain deviatoric stress is achieved ($\Delta\sigma_x$), decreasing afterwards. For P_c=10 MPa the Young Modulus increases until $\Delta\sigma_x$=25 MPa and from $\Delta\sigma_x$=35-40 MPa, decreasing between $\Delta\sigma_x$=25-35 MPa. For P_c=20 MPa, the Young Modulus increases until $\Delta\sigma_x$=30 MPa, decreasing afterwards, and for P_c=30 MPa, Young Modulus decreases from $\Delta\sigma_x$=20-30 MPa and from $\Delta\sigma_x$=35-40 MPa and increases between $\Delta\sigma_x$=30-35 MPa.

Table 2 - Relationship between Young's Modulus, Poisson's ratio and axial and volumetric strains.

Mean σ_x (MPa)	Mean test σ_x (MPa)	$\Delta\sigma_x$	Mean E (GPa)	Mean test E (GPa)	Mean ν	Mean test ν	Mean ε_{Vol}	Mean test ε_{Vol}	Mean ε_{axial}	Mean test ε_{axial}
Confining pressure P_c=10 MPa										
30		20	70,88		0,3		113		285	
35		25	75,95		0,32		123,5		327,5	
40	40,5	30	71,25	71,25	0,3	0,3	164,75	178,2	410,25	426,4
45		35	63,86		0,26		259		539	
50		40	70,42		0,27		252		572	
Confining pressure P_c=20 MPa										
45		25	69,52		0,29		148,5		356,5	
50	49	30	77,02	73,01	0,3	0,3	141,5	156	370,5	385,6
55		35	71,96		0,3		200		474	
Confining pressure P_c=30 MPa										
50		20	74,77		0,29		135		319	
60	62,5	30	70,26	70,42	0,3	0,3	165,6	182,25	415	448,75
65		35	71,28		0,31		179,5		465,5	
70		40	67,63		0,3		233,5		547,5	

As described before, Young Modulus essentially decreases between $\Delta\sigma_x$=25-35 MPa of deviatoric stress, which means that in that interval it may occur a phenomenon known as pore collapse, identified in high stress states in sandstones by Fortin *et al*. (2005). Observing Table 2, pore collapse for P_c=10 MPa does not occur immediately, since the deviatoric stress which causes it is only achieved near the maximum deviatoric stresses applied. For P_c=20 MPa, all the tests occur between that interval, which means that the Young Modulus determined is lower than what should have been if the pore collapse did not happened.

For P_c=30 MPa, although pore collapse happened at lower confining pressures, it may have occurred a secondary pore collapse for a smaller dimension family of pores, as identified by Lima *et al*. (2015) on his tests on saturated carbonates. Bearing that in mind, the primary pore collapse might have happened when the installed axial stress was 35-45 MPa and the secondary at 65-70 MPa.

Volumetric strain is also affected by pore pressure, which correlates to pore compressibility (Santos, 2017) (Table 3).

Santos (2017) concludes that volumetric strain is always superior in hydrostatic stress states at lower confining pressures when a greater pore collapse is measured. The results in this work show that an increment in pore pressure leads to an increase in volumetric strain when P_c= 10 MPa and P_c=30 MPa. When P_c=20 MPa, volumetric strain is lower when compared to the other confining pressures, which is due to the primary pore collapse.

Table 3 - Relationship between pore pressure (P_u) and volumetric strain.

Mean σ_x (MPa)	Mean test σ_x (MPa)	Mean P_u (kPa)	Mean test P_u (kPa)	Mean ε_{Vol}	Mean ε_{Vol}
Confining pressure P_c=10 MPa					
30	40,5	4	2,1	113	178,2
35		2,5		123,5	
40		1		164,75	
45		6		259	
50		1		252	
Confining pressure P_c=20 MPa					
45	49	3,5	3,8	148,5	156
50		1		141,5	
55		10		200	
Confining pressure P_c=30 MPa					
50	62,5	1	3,1	135	182,25
60		4,6		165,6	
65		0		179,5	
70		5		233,5	

Observing Tables 2 and 3, Young Modulus increases with the increment in pore pressure between P_c=10 MPa and P_c=20 MPa and decreases between the latter and P_c=30 MPa, which means that the conclusions obtained by Santos (2017) about the relationship between pore compressibility and pore pressure are in agreement with data of the present work.

Observing Table 3, pore pressure tends to increase with the increment in axial stress and confining pressure except in the interval 50-70 MPa, where primary pore collapse already occurred. The decrease in pore pressure after 50 MPa means that rock stiffness decreases.

3.2.2. Poisson's ratio

Observing Table 2, the Poisson ratio remains constant for an increase in axial stress, confining pressure and pore pressure. Pore collapse should have made the material expand laterally in an easier way because of the faster decrease in axial strain when compared to horizontal strain. However, the described phenomenon does not have sufficient magnitude for Poisson ratio to variate significantly with the increase in axial stress and confining pressure.

3.2.3. Porosity reduction

From the conclusions taken from Fortin *et al*. (2005), porosity variation is related to axial stress (Figure 9).

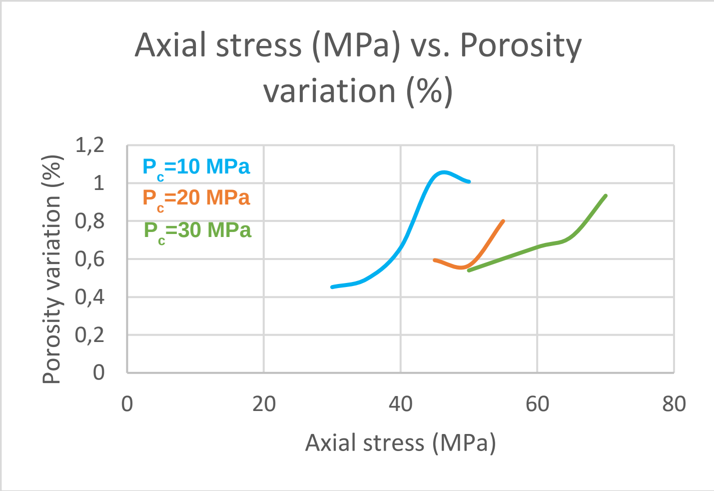

Figure 9 - Relationship between axial stress and porosity variation.

Since volumetric strains are positive, meaning compaction is occurring, the variation of porosity is, in fact, the reduction in initial porosity.

Figure 9 shows that porosity is reducing with increasing confining pressure, which is in agreement with Fortin *et al*. (2005) conclusions. Porosity reduction is greater at lower confining pressures, since for P_c=10 MPa porosity decreases 56,4% for a deviatoric axial stress of 15 MPa, while for P_c=30 MPa porosity decreases 42,2% for a deviatoric axial stress of 20 MPa.

As for the influence of axial stress in porosity reduction, the results are in agreement with the ones obtained by Bridgman (1949) and Matsushima for low porosity rocks, since porosity is decreasing with increasing axial stress.

On the other hand, by comparing Figures 8 and 9, it is possible to conclude that porosity and volumetric strain are correlated in high non-hydrostatic stress states because of the similarities between the data that shows the relationship between them and axial stress, which leads to the conclusion that when volumetric strain increases, porosity decreases.

Figure 9 also leads to the conclusion that primary pore collapse occurs at approximately 45 MPa of installed axial stress, because of the inflection point in P_c=10 MPa and P_c=20 MPa and the secondary pore collapse occurs at approximately 65 MPa because of the inflexion point in P_c=30 MPa.

3.2.4. *Permeability*

Permeability is determined by Darcy's Law and its relationship with axial stress is represented in Figure 10.

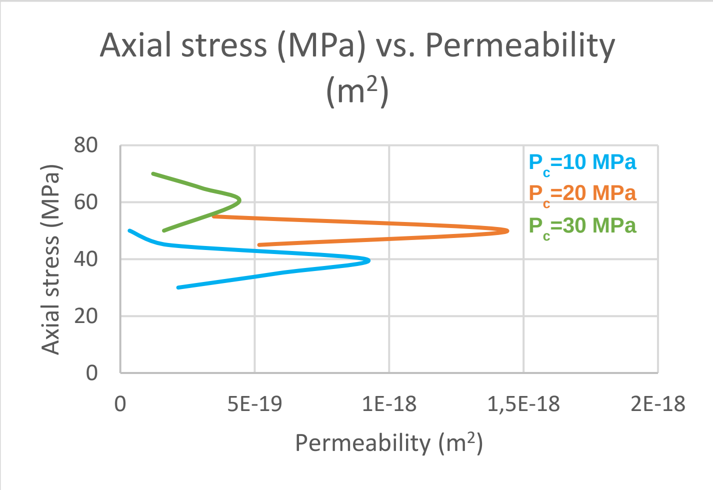

Figure 10 - Relationship between axial stress and permeability.

By observing Figure 10, permeability increases with the increment in axial stress until $\Delta\sigma_x$=30 MPa, after which it decreases rapidly with the increase in axial stress. On the other hand, permeability decreases with increasing confining stress, which can be related to a decrease in pore diameter (Santos, 2017).

Between $\Delta\sigma_x$=20-30 MPa permeability increases 76,4%, 64,09% and 63,09% for P_c=10, 20 and 30 MPa respectively. After $\Delta\sigma_x$=30 MPa permeability decreases 96,22%, 75,84% and 72,25% for P_c=10, 20 and 30 MPa respectively, which shows that, as Santos (2017) concluded, greater confining pressures leads to lesser variations in permeability.

Since volumetric strain and porosity reduction show similar behaviors when affected by axial stress, it is expected that both parameters show a correlation with permeability, which is the case, since volumetric strain and porosity reduction show similar behaviors to axial stress when correlated with permeability (the graphical correlation would be similar to that shown in Figure 10) leading to similar conclusions.

As for the relationship between permeability and pore pressure (Table 4), the first tends to increase with the increment of the second. Primary pore collapse leads to a decrease in pore pressure between P_c=20 MPa and P_c=30 MPa, which leads to a decrease in permeability that is in agreement with the conclusions of Zhu & Wong (1997), Vajdova *et al*. (2004) and Fortin *et al*. (2005) in sandstones.

Comparing the results obtained by Santos (2017) to the ones obtained in the present work (Table 4), it can be ensured that Santos (2017), for the same confining pressure (1MPa) and doubling pore pressure (from 300 to 600 kPa) obtained an increase of 18,77% in permeability. Observing Table 4, for a confining pressure 10 times higher than Santos (2017) and for a pore pressure difference of 5 kPa, the increment in permeability is 80%. However, due to pore pressure measurements problems (sometimes the software responsible for measuring pore pressure failed), results also point that for the same conditions referred earlier, permeability can decrease by 81%, which means that the results obtained in this work are merely indicative of the influence that pore pressure exerts on permeability.

Table 4 - Relationship between pore pressure and permeability.

Mean P_u (kPa)	Mean test P_u (kPa)	Mean k (m^2)	Mean test k (m^2)
Confining pressure P_c=10 MPa			
4	2,1	$2,15 \times 10^{-19}$	$5,35 \times 10^{-19}$
2,5		$5,85 \times 10^{-19}$	
1		$9,13 \times 10^{-19}$	
6		$1,77 \times 10^{-19}$	
1		$3,45 \times 10^{-20}$	
Confining pressure P_c=20 MPa			
3,5	3,8	$5,17 \times 10^{-19}$	$8,52 \times 10^{-19}$
1		$1,44 \times 10^{-18}$	
10		$3,48 \times 10^{-19}$	
Confining pressure P_c=30 MPa			
1	3,1	$1,62 \times 10^{-19}$	$2,91 \times 10^{-19}$
4,6		$4,4 \times 10^{-19}$	
0		$3,02 \times 10^{-19}$	
5		$1,22 \times 10^{-19}$	

4. Conclusions

The triaxial tests executed between axial stresses of 20 and 70 MPa and confining pressures of 10, 20 and 30 MPa lead to Young Modulus values between 70 and 72 GPa. Young Modulus increases lightly with the increment in axial stress and confining pressure, although that did not happened for P_c=30 MPa due to primary pore collapse between deviatoric axial stresses of 25 and 35 MPa and to secondary pore collapse between deviatoric axial stresses of 35 and 40 MPa. Outside of these intervals, Young Modulus is influenced by axial stress and confining pressure similarly to the works of Guerreiro (2013) and Santos (2017).

Poisson ratio did not change significantly with the increase in axial stress and confining pressure.

Volumetric strain and porosity are directly correlated in high non-hydrostatic stress states, which is in agreement with the conclusions obtained for the consulted bibliography. On the other hand, porosity reduction is greater for lower confining pressures, although porosity decreases with increasing axial stress and confining pressure.

Permeability and volumetric strain are correlated as well, which means that permeability is also correlated with porosity. Before the stage of pore collapse is achieved, permeability increases with the increment in porosity, after which it decreases rapidly with porosity reduction, in agreement with the conclusions obtained by Zhu & Wong (1997), Holcomb & Olsson (2003) and Fortin *et al*. (2005) in sandstones.

Finally, permeability variation with pore pressure is not as linear as Santos (2017) for low hydrostatic stress states, although the first increases with the increment of the second.

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