

PHYSICAL AND MECHANICAL CHARACTERISTICS OF THE GRAVINA CALCARENITE (SOUTHERN ITALY)

MICHELE LUPO^(*), RINALDO GENEVOIS^(**) & PIA ROSELLA TECCA^(***)

^(*) Engineering Geologist, Pomarico-Matera (Italy)

^(**) Engineering Geologist - Padova (Italy)

^(***) CNR-IRPI - Corso Stati Uniti, 4 - 35127 Padova (Italy)

Corresponding author: pia.tecca@irpi.cnr.it

EXTENDED ABSTRACT

Un ruolo importante nel controllo delle proprietà fisiche e meccaniche delle rocce è dato dalla porosità e dalla presenza dell'acqua. Allo scopo di indagare questi aspetti sono state analizzate le caratteristiche della "Calcarenite di Gravina", una tipica formazione Plio-Pleistocenica affiorante nei dintorni della città di Matera macroscopicamente caratterizzata da elevate porosità e da basse resistenze. Dal punto di vista geologico la città di Matera sorge su un rilievo costituito, dal basso verso l'alto, dai "Calcari di Altamura", dalla "Calcarenite di Gravina" e dalla "Argille Sub-appennine". Le caratteristiche geologiche, strutturali e geomorfologiche dell'area sono riportate in numerosi articoli (es.: AZZAROLI, 1968; GRASSI, 1974). Si tratta di una roccia classificabile come "tenera", utilizzata come pietra da costruzione o da taglio e considerata sufficientemente resistente sebbene i processi di alterazione possano ridurre sensibilmente le proprietà meccaniche determinando intensi fenomeni erosivi e collassi repentini.

Il presente lavoro riporta i risultati delle prove effettuate su campioni secchi e saturi utilizzando campioni di roccia intatta raccolti in sette differenti siti nell'intorno di Matera, tenendo così conto della variabilità spaziale e temporale della porosità e delle strutture sedimentarie di questa formazione.

Le caratteristiche fisiche e meccaniche della calcarenite, classificata nella III Classe di BIENAWSKI (1989), sono state investigate determinando: contenuto in acqua (w) e densità (ρ), naturali ed allo stato saturo, porosità (n), resistenza a compressione uniassiale (σ_c) ed a trazione indiretta (σ_t) e modulo di Young (E) sia allo stato secco che saturo.

Le analisi chimiche e mineralogiche hanno mostrato l'uniformità composizionale della calcarenite, mentre sono state notate anche visivamente importanti variazioni nelle dimensioni, geometria e connettività dei pori. I valori statistici ottenuti per le proprietà fisiche indagate sono riportati in tabella e le relative distribuzioni nella figura. In generale, si può notare una notevole dispersione nei valori di porosità con i valori più elevati propri dei campioni prelevati alla sommità delle pareti di campionamento. La distribuzione della porosità in funzione del contenuto naturale in acqua indica, quasi sempre, un basso grado di saturazione. La relazione tra densità secca e saturata e valori di porosità risulta lineare, indicando che tutti i pori risultano saturi per semplice immersione in acqua e, quindi, che tutti i pori sono interconnessi.

La resistenza a compressione ed a trazione e la deformabilità sono proprie di rocce deboli porose, con valori medi delle distribuzioni log-normali nelle differenti condizioni di saturazione simili. Considerando i risultati ottenuti in condizioni naturali e secche i valori di resistenza a compressione uniassiale, che classificano la calcarenite al limite tra "rocce a resistenza bassa e molto bassa", sono linearmente correlati. I valori di deformazione a rottura oscillano tra 0.5% e 4.0% e le curve tensione-deformazione indicano un comportamento generalmente del tipo plastico-elastico-plastico, più elastico nel caso di porosità molto basse. Le tensioni di chiusura delle microfratture risultano molto basse indicando l'alta deformabilità della matrice carbonatica. Il modulo elastico risulta sempre alquanto disperso con valori relativamente bassi, più elevati in condizioni sature.

In conclusione, la Calcarenite di Gravina risulta avere una struttura costituita da microfratture e micro- o macropori inclusi in un mezzo carbonatico sostanzialmente elastico, il cui comportamento meccanico è controllato dall'evoluzione dei processi di danneggiamento indotti dalla propagazione delle microfratture e/o dal collasso dei macro-pori. Le correlazioni tra proprietà fisiche e meccaniche indicano che si può osservare una variazione di comportamento per valori della porosità pari al 25-30%: a bassi valori di porosità la matrice della roccia è spazialmente più continua e, quindi, le proprietà della roccia integra saranno prevalenti; a più alte porosità le proprietà meccaniche dipenderanno principalmente dalle dimensioni, geometria e distribuzione dei pori. Un ulteriore sviluppo di questa ricerca sull'effetto delle caratteristiche geometriche e della distribuzione dei pori e della loro saturazione è ancora in corso.

ABSTRACT

One of the most important problems in designing engineering works is the knowledge of the strength parameters of the rock masses. Beside the soil-structure interaction, a satisfactory performance of structures requires that rock mass properties such as deformation modulus, intact rock and global rock mass strengths and shear strength parameters are reliably defined.

The studied Calcarene of Gravina, is a calcarenitic rock outcropping in the area of the town of Matera (Southern Italy). It is a natural soft rock, mainly used since prehistoric times as building and dimension stone, considered durable although air pollution and water weathering markedly reduce the mechanical properties both at short and long term. Consequently, locally existing cliffs may be affected by erosive phenomena and, even, by unexpected collapses resulting from complex hydro-chemo-mechanical processes.

This paper presents the evaluation of the Calcarene of Gravina physical and mechanical properties, using laboratory tests on intact rock samples collected in seven different locations. From a macroscopic point of view, calcarenites are highly porous materials showing the presence of three main components: calcareous grains, micrite matrix and sparite cement. Dry and saturated calcarenite samples have been tested according to the ISRM suggested methods at room temperature ($\sim 20^\circ$). As the studied Calcarene cannot be considered homogenous rocks, being characterized by largely scattered pore sizes, further research on the effect of porosity on mechanical properties, mainly strength and deformability is needed and still ongoing.

KEYWORDS: porous rocks, geomechanics, calcarenite, Matera

INTRODUCTION

One of the most important problems in designing engineering works is the knowledge of the strength and elastic parameters of the rock masses. Beside the soil-structure interaction, a satisfactory performance of structures requires that rock mass properties such as deformation modulus, intact rock and global rock mass strengths and shear strength parameters are reliably defined.

As rock mass structure is generally very complex, mainly due to the existence of discontinuities and heterogeneity, different parameters control the properties of rock masses including, besides intact rock properties, characteristics and mechanical properties of joints. Physical and mechanical parameters of intact rock specimens are commonly determined in laboratory, while properties of rock mass are ideally found by conducting specific field tests (e.g. BIENIAWSKI, 1978; BARTON & BANDIS, 1980; BARTON, 1983; SERAFIM & PEREIRA, 1983; PALMSTRÖM & SINGH, 2001; EDELBRO *et alii*, 2006; HOEK & DIEDERICHS, 2006; ZHANG, 2010).

The determination of the global mechanical properties of a jointed rock masses remains a rather difficult task because many parameters affect their deformability and strength (HOEK & BROWN, 1997; CAI *et alii*, 2004). Consequently, it is nearly impossible to develop a universal law able to predict, in a practical way, their global strength. Moreover, because of the discontinuous nature of rock masses, their behavior is dependent on the relative scale between the problem domain and the rock blocks formed by existing discontinuities.

Besides rock masses discontinuities, porosity plays an important role controlling the mechanical properties as well as the fluid flow and transport through the rocks. The aim of this paper is to determine, besides basic physical properties, the values of uniaxial compressive strength, point load strength, and indirect tensile (Brazilian) strength of a very porous rock in order to analyze how they will influence the magnitude of and relationship between the mechanical properties.

For this purpose, it has been considered a soft and macroscopically very porous geological formation corresponding to the Calcarene of Gravina, locally called “Matera Tuffs”, a typical Plio-Pleistocene formation outcropping in southeastern Italy (CIARANFI *et alii*, 1988). The studied Calcarene of Gravina outcrops in the area of the town of Matera (Southern Italy) where existing natural cliffs are locally affected by erosive phenomena or, even, by unexpected collapses due to complex hydro-chemo-mechanical processes and, supposedly, by evident strong variation of porosity. This natural soft rock, mainly used since prehistoric times as building and dimension stone, is considered durable although air pollution and water weathering markedly reduce their mechanical properties both at short and long term.

These rocks (in the following simply ‘calcarene’) are formed by carbonate particles, from microscopic to visible to naked eye, mainly consisting of fragments of corals, shell and calcareous rocks and algae. Loose grains were successively bonded to each other by precipitated calcium carbonate that formed calcite bonds at the inter-grain contacts.

The physical and mechanical data of these rocks available in the scientific literature do not characterize as a whole the Calcarene di Gravina Fm as these rocks are rather heterogeneous, due to the significant spatial variations of their porosity and sedimentary structures.

The paper will present the assessment of calcarenite properties, using laboratory tests on intact rock samples collected in seven different locations. Samples, in natural, dry and saturated state, have been tested under unconfined conditions, at room temperature ($\sim 20^\circ$). Specimen preparation and testing were performed according to ULUSAY (2015) suggested methods.

Sampled rocks consist of medium to fine grained, white to yellow bioclastic carbonate rocks, with a micritic calcareous matrix. Grains, largely in contact with each other, are generally

smaller than 0.5 mm on average. Mean chemical composition of examined calcarenite is 95-98% calcium carbonate with a few traces of aluminum and magnesium. According to the Folk classification of carbonate rocks, the calcarenite is an allochemical rock, where calcareous grains are embedded in a matrix of microcrystalline carbonate.

The analysis of thin sections detected a highly porous microstructure of calcite crystals grains and pores of a great size variability, with a spatial irregular distributed predominance of macropores with respect to micropores. Connections between grains appear to be originated by diagenetic processes or by some chemical precipitation phenomena. The former may be considered as persistent bonds, while the latter, made up by microscopic calcite crystals, should be considered unstable since they can be demolished by the pores saturating waters and, then, again deposited during pore drying.

The extremely variable values of the physical and mechanical properties may be considered indicative of variations found in any “typical” calcarenite. Since porosity strongly controls the mechanical behaviour of these rocks (e.g. PALCHIK & HATZOR, 2002), further research on the effect of porosity on mechanical properties, mainly strength and deformability is still ongoing.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The city of Matera, located in the Lucania Region (Southern Italy), rises at the eastern side of the Bradanic Plio-Pleistocene sedimentary Basin, over a calcareous relief belonging to the Matera’s Murgia. The calcareous outcrops, in contact with the more erodible argillaceous sediments of the Bradanic foredeep, can be directly observed in natural or artificial cliffs.

The bedrock of this area is formed by the Altamura Limestones (“Calcri di Altamura”) Formation, an Apulia Platform Unit made up by alternating compact limestones, dolomitic limestones and dolomites late Cretaceous aged, overlaid by the Plio-Pleistocene Bradanic succession (AZZAROLI, 1968) consisting, from bottom to top, by:

- Gravina Calcarenite (“Calcarenite di Gravina”, Upper Pliocene-Lower Pleistocene): porous organogenic calcarenite, locally called “tufi” (tuffs), with a typical “grainstone” texture, high porosity and medium size particles, exhibiting a massive structure, irregular hints of sub-horizontal layering and a maximum thickness of 55-60 m. This formation is transgressive on the underlying “Calcri di Altamura”, locally through a conglomeratic layer.
- Terrigenous deposits consisting of two sub-units: the Sub-Appennine Clays (“Argille Sub-Appennine” Formation, Lower Pleistocene), and the sandy-conglomeratic deposits forming the marine terraces (Lower-Middle Pleistocene). The Argille Sub-Appennine Fm. are represented by blue

marly silty clays with thin sandy layers, at times heteropic with the “Calcareniti di Gravina”; layering is generally indistinct and the maximum outcropping thickness is in the order of 1000 m. Upwards, the frequency of sands layers strongly increases and the formation gradually passes to the overlying sandy-conglomeratic deposits.

The stratigraphic sequence ends with terraced alluvial deposits (Pleistocene-Holocene), mainly gravelly or sandy, with limited thickness. The structural setting of the area is characterized by a flat-topped morpho-structural element (the Matera Horst) constituted by cretaceous limestones weakly dipping to SSE and bordered by buried high-angle NNW-SSE faults; the monoclinial setting is locally complicated by some small undulations. The geological sketch map of the study area is shown in Figure 1.

In response to the Quaternary tectonic uplift, marine terraces formed and a drainage system of wide valleys and deep gorges developed. These last ones represent the main morphological elements of the area locally known as “gravina”: the most spectacular one is the Gravina di Matera, a 70-80 m deep canyon characterized by almost vertical walls, hanging valleys and meanders (GRASSI, 1974; BOENZI, 1988).

SAMPLING AND METHODS

The calcarenite was sampled from the cliffs and quarries situated along the Gravina di Matera canyon. The samples have been obtained by means of a manual electrical drilling machine (about 40 mm external and 33 mm internal diameter and 220 mm length); in case of very porous and low cemented calcarenite, cubic samples (about 30x30x30 cm) were taken.

The evaluation of physical and mechanical properties was carried out according to the methods indicated by ULUSAY (2015). Due to the rock high crumbliness, from the cubic blocks it has been possible to obtain cylindrical specimens of about 51 mm in diameter. All samples were prepared with a height-to-diameter ratio of 2.5, obtaining in all 216 cylindrical samples for physical and mechanical testing.

Chemical and mineralogical characteristics were determined by carbonate content and X-Ray diffraction tests with the aim to control the uniformity of the composition.

Because of the extreme porosity of any calcarenite (ANON, 1979), these rocks cannot be considered as a continuum material and the total porosity will, then, govern their physical properties and mechanical behavior.

Apparent density, calculated by mass/volume ratio, was determined on all samples both in dry and water saturated conditions. No water pressure was applied during the saturation phase (water immersion technique). Absolute or total porosity was obtained by the expression:

$$[1 - \rho_d / (G_s \rho_w) * 100\%] \quad (1)$$

using measured values of dry bulk density ρ_d (kg/m³), assuming

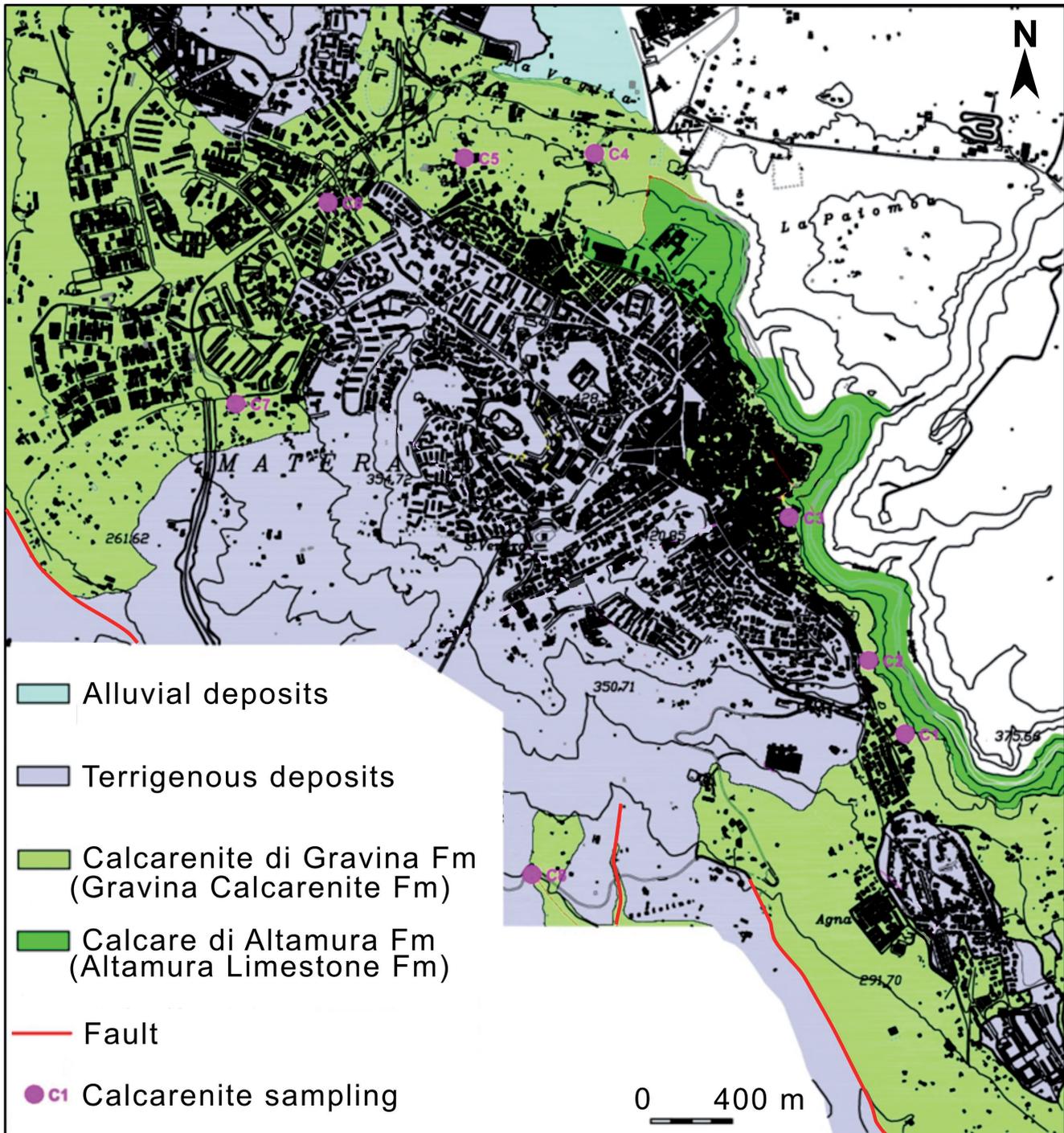


Fig. 1 - Geological map of the Matera town area

a specific gravity of $G_s = 2.71$, typical of the calcite, and a water density ρ_w equal to 1000 kg/m^3 .

Mechanical properties have been determined through 108 uniaxial compressive tests on dry and saturated samples,

because triaxial tests were deemed less reliable due to the strong heterogeneity of examined rock and the spatial variability of size and shape of voids. Uniaxial compressive strength (UCS or σ_c) and tangent and secant moduli (E), in dry and saturated

conditions, were obtained on samples cored from the same block and visually similar as for the porosity. Dry conditions were obtained by oven-dried samples at a temperature of 110 C° for 24 h. Tests were performed according to the standard procedures; their bases were smoothed to a roughness smaller than about 0.01 mm, and perpendicularity was kept within about 0.05 radians. An initial vertical stress of 0.01 MPa has been applied to ensure a uniform contact of the specimen base with the loading platens. Specimens were tested with a strain rate of about 10⁻⁵/s, corresponding to a test duration of approximately 10 minutes.

The tensile strength was determined performing 20 Brazilian tests in which a disc shaped specimen of the rock is compressed to failure, at a constant strain rate, by two opposing normal strip loads at the disc periphery (ULUSAY, 2015). At failure, occurring at the point of maximum tensile stress, the tensile strength of the rock (Pa) is calculated as:

$$\sigma_t = *2P/\pi DL = 0.636 P/DL \quad (2)$$

where *P* is the load at failure (N), *D* is the diameter of the sample (mm), and *L* is the thickness measured at the sample center (mm).

FIELD AND LABORATORY RESULTS

Field surveys were preliminarily conducted to define the geomechanical setting of the rock mass (ULUSAY, 2015). Actual discontinuity sets are characterized by a low frequency, so that the rock mass could be locally considered almost as a continuum. The geomechanical field survey indicated two main discontinuity sets, almost sub-vertical, roughly oriented N-S and E-W; a joints spacing from moderate (0.6÷2.0 m) to wide (2÷6 m); a medium value of the joints persistence (3÷10 m); an open “gapped” joints aperture (0.5-2.5 mm), and the presence of joints filled by calcite.

Overall, the rock mass may be classified as a fair quality rock (III Class of the Bieniawski classification, 1989). However,

field surveys highlighted the great variability of lithological characteristics, especially in the vertical direction: from the bottom to the top, the rock mass mostly shows a decrease of both the grainsize, from coarser to finer particles, and the lithification process, from medium to poorly compacted rock more similar to a cemented sand.

Physical and mechanical parameters were investigated by assessing: volumetric mass density (ρ), both in dry and saturated state; porosity (*n*); unconfined compressive (σ_c) and indirect tensile strength (σ_t); Young modulus (*E*) in dry and saturated states.

Table 1 summarizes the obtained results indicating the statistical values of properties and statistical parameters of normal distributions. Besides the normal distribution, log-normal distribution for the water content has been considered.

PHYSICAL PROPERTIES

Chemical and mineralogical analyses performed on 17 samples have shown the compositional uniformity of the calcarenite with a CaCO₃ content from 93% to 97%. Important variations in pore size distribution and geometry pore connectivity and, in some cases, microfracture density can also be visually observed. It can be consequently believed that physical and mechanical properties can assume values broadly scattered. The density and water content histograms and the distribution probability density functions, that best-fit to the data, are shown in Figure 2.

Natural, dry and saturated bulk density values are rather scattered, generally somewhat low for rock materials. Mean bulk density values are rather low indicating high porosity values, while the great difference of dry and saturated bulk densities indicates a high interconnectivity of pores. Natural water content values are mostly low, showing a general poor condition of pore saturation (Fig. 2d), depending also on the shallow sampling.

	ρ_n (kg/m ³)	ρ_d (kg/m ³)	ρ_s (kg/m ³)	n (%)	w (%)
<i>No</i>	106	101	101	101	99
<i>max</i>	2450	2590	2540	60.1	30.1
<i>min</i>	1400	250	1780	5.9	0.15
<i>Normal distribution</i>					
\bar{x}	1759.9	1879.9	2091.4	25.5	
<i>s</i>	248.8	309.9	179.1	11.8	
<i>Log-normal distribution</i>					
μ		1.21			
σ		1.63			

Tab. 1 - Physical properties of calcarenite (Gs=2.71). Legend: No: number of samples; Max, Min: maximum and minimum value; ρ_n , ρ_d , ρ_s : natural, dry and saturated densities, respectively; n: porosity; w: water content. \bar{x} , *s*: mean and standard deviation of the normal distribution; μ , σ mean and standard deviation of the log-normal distribution

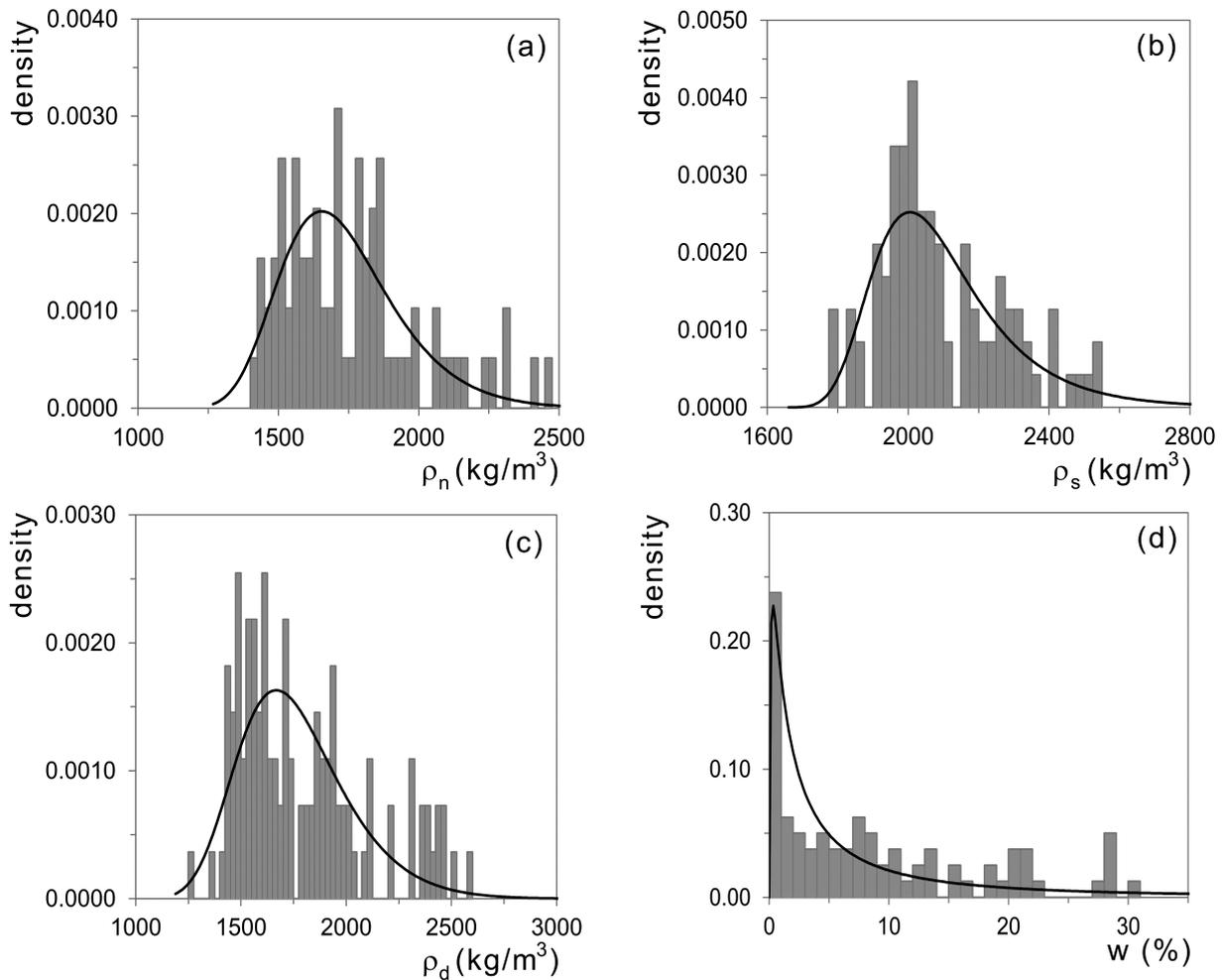


Fig. 2 - Density histograms of (a) natural, (b) saturated and (c) dry bulk densities with GEV functions and (d) of water content with log-normal function

Calcarenite exhibits a large scatter in porosity values (Fig. 3a), higher natural values being observed in samples located at the top of the outcropping formation. The distribution of the porosity values as function of the natural water content confirms the under-saturation of the collected samples: measured values spread consistently below the theoretical line of complete saturation values (Fig. 3b), showing that saturation in natural conditions is not complete.

Thin sections observations confirm the great variability of porosity: shape, sizes and distribution of pores widely scatter (Fig. 4). The fabric is typical of relatively loosely packed calcarenite, with a framework of skeletal grains consisting of shell fragments and sub-rounded limestone particles cemented by calcite crystals at the contacts. A significant part of the pore volume is represented by macro-pores with size up to 6-8 mm, formed by particles either in close contact or connected through finer particles, thereby influencing physical and mechanical behaviour.

MECHANICAL PROPERTIES

The rock strength is a basic parameter for many characterization systems, strength criteria and engineering calculation methods. A relatively large number of laboratory tests were conducted on calcarenite samples to stress the influence of physical properties on its strength and deformability.

Uniaxial compressive and Brazilian tests

Uniaxial compression and Brazilian tests were carried out on natural, dried and saturated rock samples determining the uniaxial compressive (σ_c) and tensile (σ_t) strengths, the stress-strain relationships at failure and the Young's modulus (E).

Mean value of the uniaxial compressive strength in natural condition (σ_{nat}) corresponds to "low strength rocks" as in BIENIAWSKI (1989) classification. Results obtained on dried specimens show a significant reduction in the mean values, bringing the calcarenite to the limit between "low and very low

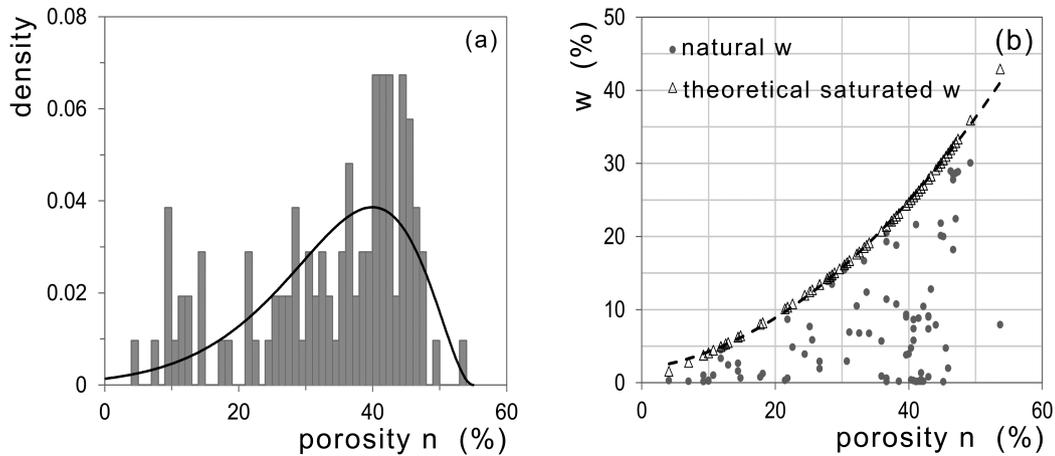


Fig. 3 - Density histogram and Beta4 function of porosity values (a); relationship between measured natural water content and porosity (b). Δ : theoretical upper bound of water content values

strength rocks” of the same classification. Statistical values are displayed in Table 2.

The obtained strength values in natural (\bar{x} : 8.13 MPa; s : 7.82 MPa) and dry (\bar{x} : 6.40 MPa; s : 3.90 MPa) conditions have been processed all together ($\sigma_{j,nat-dry}$) because a small number of tests was performed in dry conditions and the differences between the two datasets are not statistically significant.

In the two considered saturation conditions, peak strength values are mostly represented by left skewed histograms with log-normal distributions best fitting to the data sets (Fig. 5a and b). Mean and standard deviation parameters of the log-normal distributions are quite similar (Tab. 2), and the two data sets, compared using the WILCOXON test (1945) (TILL, 1974), show that the hypothesis that they follow the same distribution cannot be rejected: the risk to reject this hypothesis while it is true is 100.

Considering the scarce pore saturation condition of natural samples and the small number of analysed dried samples, the obtained values of axial strain at failure of tested specimens

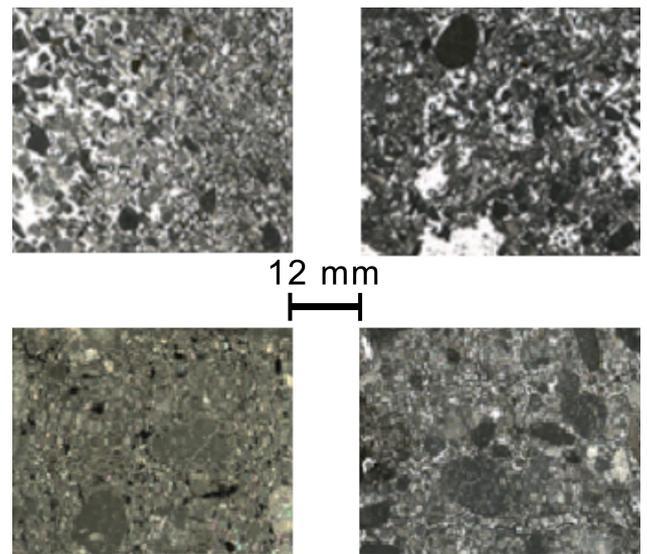


Fig. 4 - Examples of calcarenite microstructures observed in thin section

	σ_c nat-dry (MPa)	σ_c sat (MPa)	ϵ_r nat-dry %	ϵ_r sat %	ϵ_r nat-dry-sat %	σ_c (MPa)	σ_t nat-dry (MPa)	σ_t sat (MPa)
No	86	33	33	15	48	40	18	18
max	52.51	27.71	3.81	2.45	3.81	7.8	3.18	2.46
min	0.42	0.62	0.59	0.54	0.54	0.03	0.96	0.57
\bar{x}	7.83	5.78	1.54	1.27	1.45	1.3	1.65	1.16
s	9.18	6.30	0.82	0.49	0.74	1.7	0.64	0.47
Log-normal distribution parameters								
μ	1.48	1.24	---	---	0.26	---	0.44	0.08
σ	1.10	1.01	---	---	0.47	---	0.34	0.36

Tab. 2 - Calcarenite statistical values of strength (compressive and tensile) and failure axial strain. σ_c nat-dry, σ_c sat: natural/ dry and saturated states unconfined compression strengths; ϵ_r nat-dry, ϵ_r sat: natural/ dry and saturated states strains at failure; σ_c : closure stress; σ_t nat-dry, σ_t sat: natural/ dry and saturated states tensile strengths. Other symbols as in Table 1

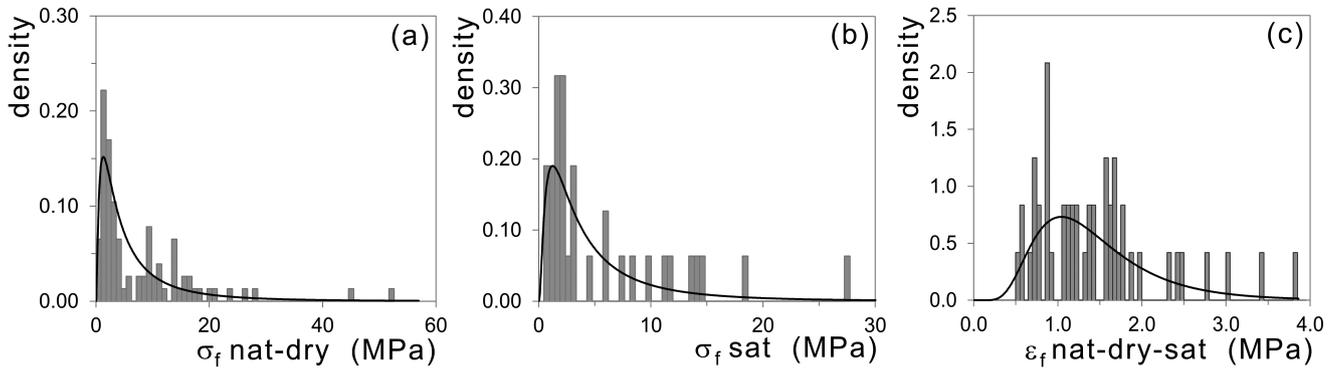


Fig. 5 - Density histogram and Beta4 function of porosity values (a); relationship between measured natural water content and porosity (b). Δ : theoretical upper bound of water content values

in natural, dry and saturated conditions have been analysed all together. Values of strain at failure (ϵ_f), ranging between about 0.5% and 4.0% are rather common in weak to medium strong rocks. Strains result quite scattered and are represented by a slightly left skewed histogram (Fig. 5c).

The relevance of water content on the uniaxial compressive strength has been outlined performing 34 tests in both natural/dry and saturated conditions. Natural/dry and saturated strengths result to be linearly related with a good determination coefficient (Fig. 6).

The decrease of the peak strength in saturated calcarenite is in the order of 50% (Fig. 6).

The crack closure stress has been, then, calculated locating the first inflection point on the axial strain-axial stress curve by the moving point regression technique (EBERHARDT *et alii*, 1998); only about the 35% of samples showed stress-strain curves suitable for closure stress determination, especially those with high strength values. These curves (Fig. 7a) generally display a plastic-elastic-plastic behaviour and only in a few cases, especially for low porosity samples, a more elastic behaviour. The closure stress values are quite scattered (Fig. 7b) as they depend, besides the factors previously described (orientation, shape, source and proximity of other fractures) on the fact that almost all cracks have intersections whose closure may require shear motions along some others.

Closure stresses show a very low mean value (Tab. 2) indicating either a high deformability of the matrix or the presence of relatively long, narrow cracks (low aspect ratio).

The relationship of crack closure stress with porosity and peak stress at failure seems to confirm the dependence of failure mode on the porosity: closure stresses are, indeed, practically insignificant at porosity values equal or greater than 40% (Fig. 8a). On the other hand, closure stresses are rather low (less than 0.5 kPa) at failure stresses lower than 2-3 kPa, seemingly pointing out in this way the prevalence of the cataclastic failure on the brittle one (Fig. 8b).

Since axial strain measurements provide the most insight

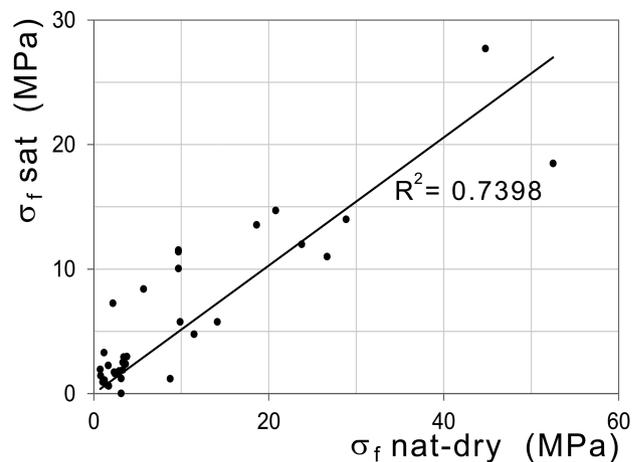


Fig. 6 - Natural/dry ($\sigma_{f, nat-dry}$) vs. saturated strengths ($\sigma_{f, sat}$)

into delineating the stages of crack development, the calcarenite elastic properties, primarily described by Young's modulus (E), were determined for both the initial closure stress phase and the following near-linear elastic one (Tab. 3).

In the closure phase, the Young modulus (E_0) has been calculated as slope between the origin of the stress-strain curve and the observed inflection point. Since we did not observe any evident differences between moduli calculated for different saturation conditions, the E values have been represented all together, showing data widely spread and a very low mean value. Data are well represented by a normal probability density distribution function (Fig. 9a). Following the stress closure phase, the stress-strain quasi-linear phase is characterized by higher elastic moduli. In natural/dry state, tangent moduli ($E_{nat-dry}$) tend to concentrate on values smaller than about 500 MPa and are properly represented by a log-normal probability density distribution function, as the elastic moduli in saturated E_{sat} conditions (Fig. 9c).

Statistical values of elastic moduli, calculated on natural/dry and saturated conditions, are reported in Table 3. Test results show that in saturated conditions mean elastic moduli (E_{sat}) are slightly

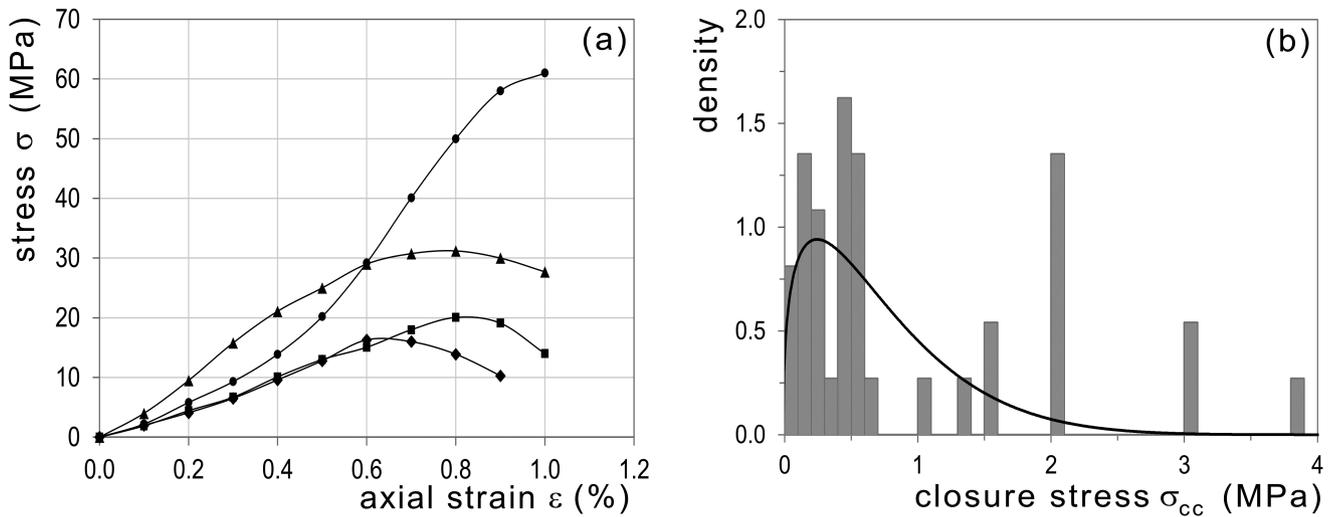


Fig. 7 - Examples of stress-strain curves (a). Histogram and GEV function of closure stress (b)

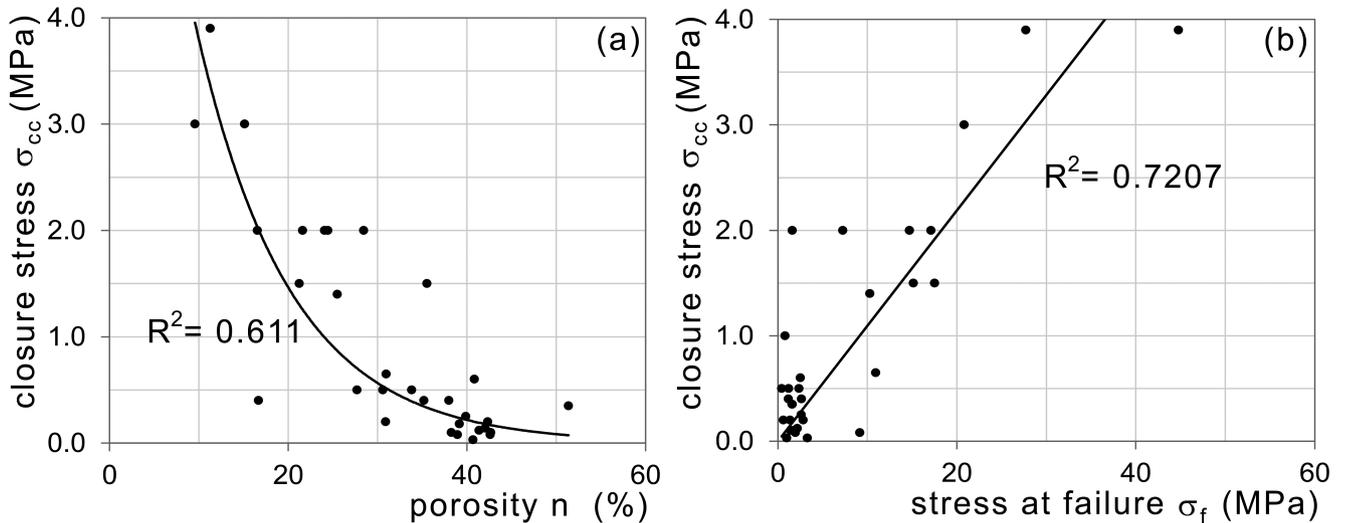


Fig. 8 - Closure stress as a function of (a) porosity and (b) axial stress at failure in natural/dry and saturated conditions

smaller than the natural/dry moduli ($E_{nat-dry}$) and no statistically significant difference exists between the two values distributions.

Brazilian tests

Many researchers have highlighted the relevance of tensile strength in controlling failure processes in brittle materials, but its determination is often neglected mainly due to difficulties in preparing test specimens and obtaining reliable results. Furthermore, considering that tensile strength can be related to the crack initiation threshold, various correlations have been drawn to obtain tensile strength directly from unconfined compressive strength tests. In order to solve these difficulties, the ISRM suggested the Brazilian test for indirectly determining the tensile strength of rocks.

	E0 (MPa)	E nat-dry (MPa)	E sat (MPa)
No	36	66	20
max	683	2989	2478
min	11	40	29
x	184.3	758.6	730.3
s	199.1	813.8	330.4
<i>Log-normal distribution parameters</i>			
μ	184.3	80.5	5.87
σ	196.3	116	1.37

Tab. 3 - Values of the calcarenite elastic moduli Secant modulus of closure phase (E0); tangent moduli of the linear phase in natural/dry (Enat-dry) and saturated (E sat) conditions. Other symbols as in Table 1

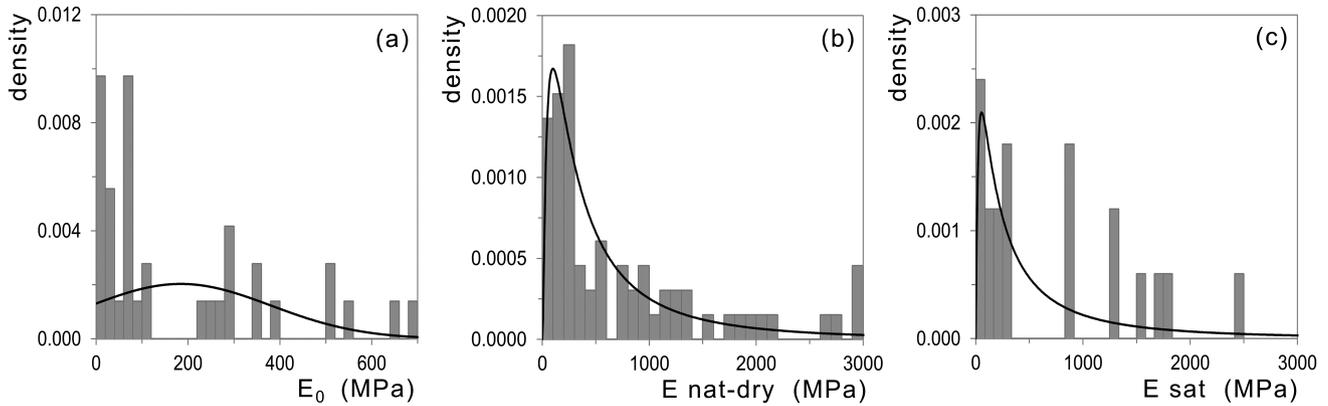


Fig. 9 - Density histograms and log-normal functions of elastic modulus: (a) closure phase (E_0); (b) quasi linear phase natural/dry ($E_{nat-dry}$) and (c) saturated (E_{sat})

Due to the characteristics of the tested calcarenite, we had the opportunity to perform in dry and saturated states only 18 Brazilian Tensile Strength (BTS) tests bearing in mind, however, that this testing method is generally more appropriate for homogeneous and isotropic rocks since calculation are based on the assumption of the classical theory of elasticity. Statistical values of results are shown in Table 2 and the density histograms with the best-fit probability density distribution functions are reported in Figure 10.

The obtained test data are widely scattered almost in a roughly similar range, but the Wilcoxon test indicated that hypothesis of having the same distribution should be rejected and that the risk of rejecting the hypothesis while it is true is only 0.02%.

DISCUSSION OF RESULTS

The behavior of rocks is affected, among other things, by the

total porosity value and particularly by the pore structure that plays a critical role in rocks physical and mechanical properties. The studied calcarenite is homogeneous from the point of view of the composition, but highly heterogeneous at the pore-scale level. Its microstructure, observed under the optical microscope, can be represented by a model that include both linear cracks and micro or macro-pores, embedded in an essentially elastic continuum. As a whole, the pore size distribution can be considered approximately as bimodal: a macro-porosity, forming the essential of the porosity value, and a microporosity, corresponding to inter and intra-particle pores (Fig. 11 and Fig. 4). However, while total porosity can be easily determined, conversion from volume to pore distributions is problematic and requires some assumptions about the size and shape of real pores.

Calcarenite exhibits a large scatter in porosity values (Fig. 3a) and an incomplete saturation in natural state (Fig. 3b). The

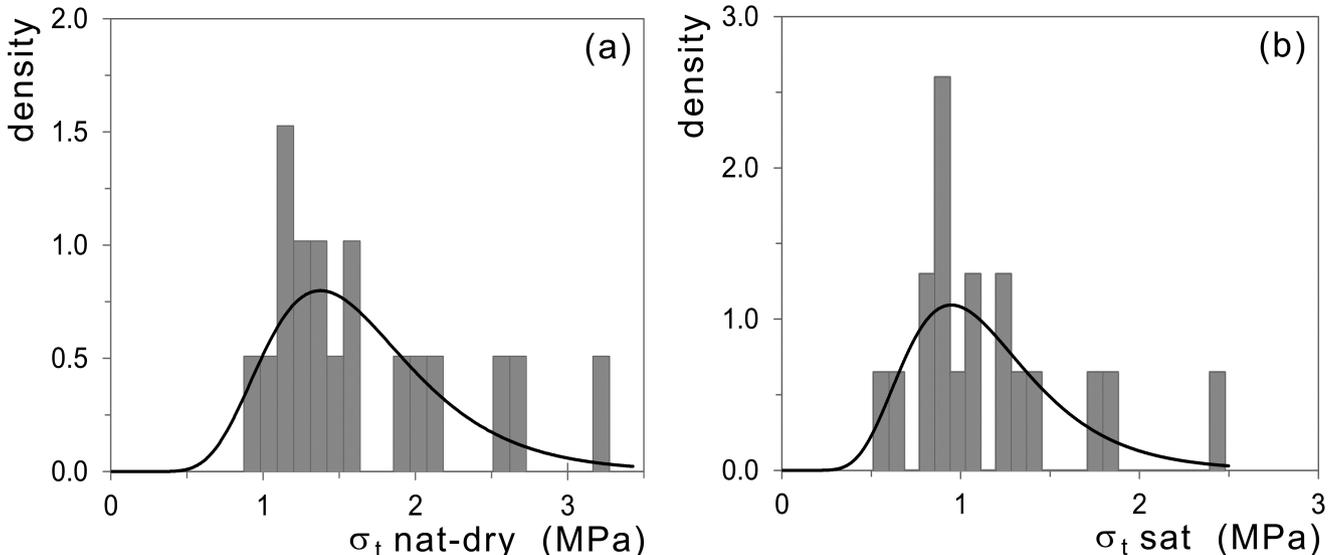


Fig. 10 - Density histograms and log-normal functions of tensile strength σ_t in (a) natural/dry and (b) saturated states

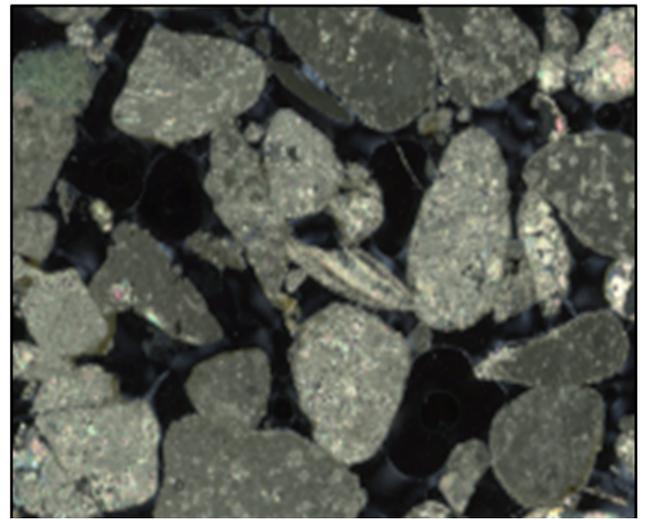
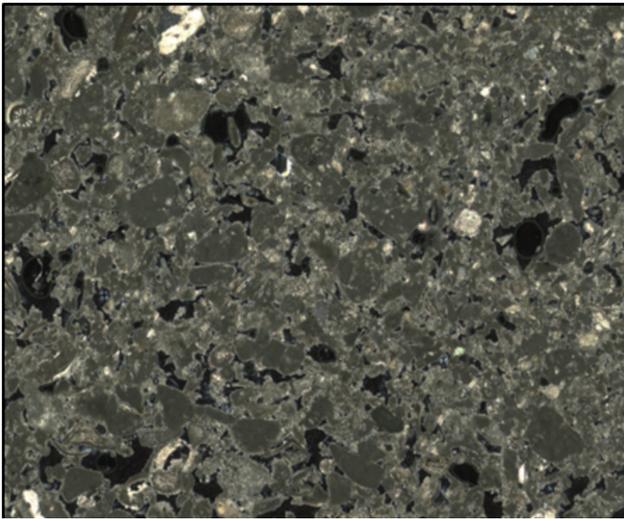


Fig. 11 - Calcarenite thin sections showing different pore size, shape and distribution. Horizontal field view 10 mm

pores connectivity has been, then, investigated examining the obtained values of dry and saturated densities with reference to the corresponding water content. Linear relationship between porosity and saturated density with a high determination coefficient ensures that experimental data are correct (Fig. 12), while relationship between saturated water content and porosity indicates that almost all the pores have been saturated (Fig. 3b). Considering that no water pressure was applied during the saturation stage, experimental data point out that almost all existing pores are interconnected and the effective porosity may be considered equal to the total one.

Compressive strengths are closely related to sample density, and then to its porosity (Fig. 13), but the large variability of results obtained in performed mechanical tests (Tables 2 and 3) indicates that the porosity has to be considered relevant in failure process as regards both its magnitude and its influence on deformations development.

As displayed in Figure 7a, stress-strain curves show mostly a behavior corresponding to plastic-elastic-plastic or plastic-elastic type and only in a few cases, especially for low porosity samples, a more elastic behavior. However, no acceptable relationship can be found between compressive strength and strain at failure (Fig. 14): axial strain values are largely scattered for peak stress values approximately lower than 5 MPa, but they seem to concentrate in the range 1.5-2.0% for peak stresses higher than about 20 MPa. It should be observed, however, that some differences can be noticed between natural/dry and saturated states: in saturated state, probably as a result of the water effect, strains at failure show lower strain values.

Different causes can contribute to the variability of rock strength values (e.g. DYKE & DOBEREINER, 1991) and mainly: i) the inherent microstructural features, such as the geometry of

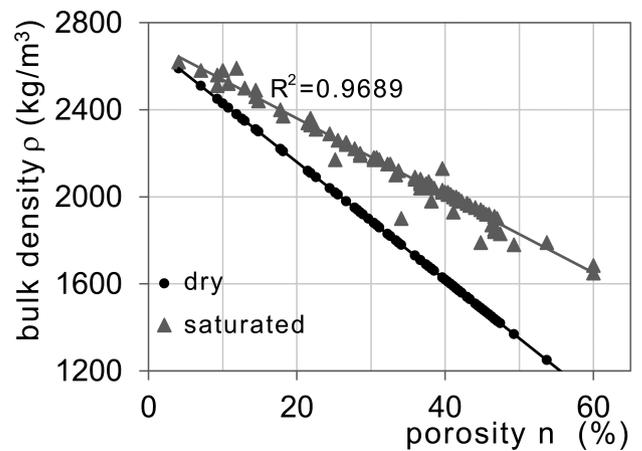


Fig. 12 - Theoretical dry and measured saturated bulk densities as a function of porosity

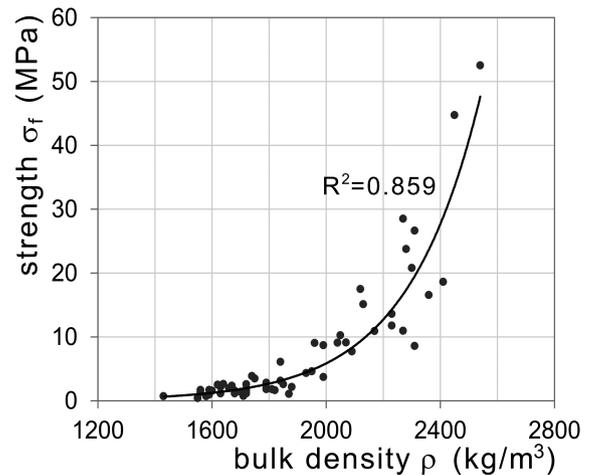


Fig. 13 - Uniaxial compressive strength as a function of natural bulk density

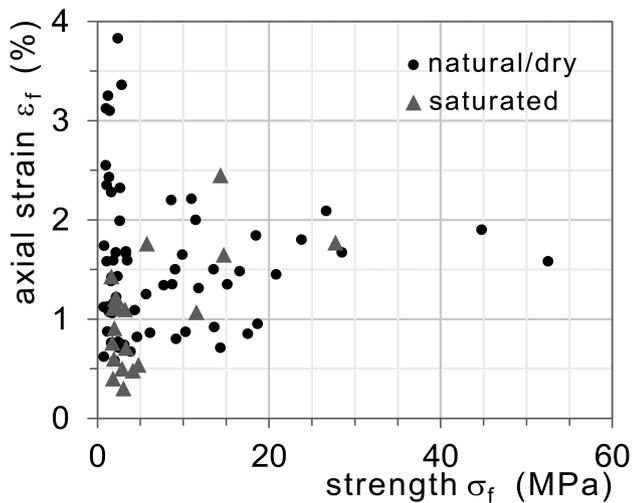


Fig. 14 - Axial strains at failure as a function of natural/dry and saturated peak stresses

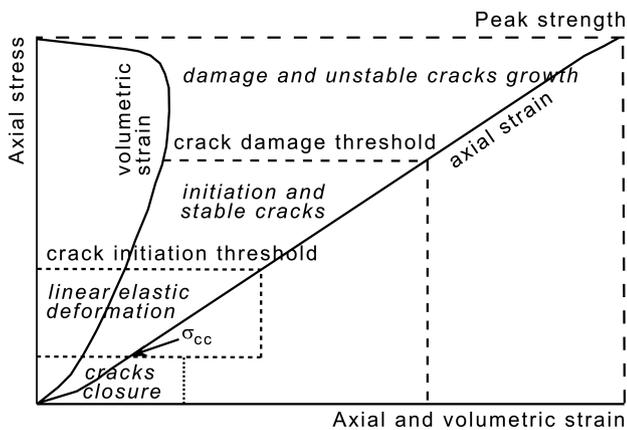


Fig. 15 - General scheme of the evolution of rock deformation and significant threshold stresses occurring in axial loading. σ_{cc} : closure stress

grain boundaries and pores; ii) the total porosity; iii) the grain contact area; iv) the presence of water, especially in weaker rocks (e.g. HAWKINS & MCCONNELL, 1992). Because the development of failure, especially in carbonate rocks, is highly influenced by porosity, a particular attention has been paid to this parameter, also due to the large values that it can reach, and to its effect on both axial strain and strength values.

In rock materials, failure is commonly considered to be preceded by a cracks growth, stable as it requires progressive increases in deviatoric stress. Their coalescence leads, eventually, to the failure in the brittle regime (ASHBY & SAMMIS, 1990). Recently ZHU *et alii* (2010) have shown that at least two different porosity types should be considered conducting to rather distinct failure mechanisms both strongly influenced by cracks nucleation and propagation: the wing cracks brittle failure and the cataclastic pores collapse failure.

In unconfined stress state, macroscopic failure is expected to be brittle, but failure modes are mechanically different: the former is brittle and essentially dilatant (wing cracks model); the latter (cataclastic pores collapse) is ductile and compactant and develops in rocks with high porosities (WONG *et alii*, 2001). It should be noted that the two failure modes are not necessarily simultaneous: both obey to the Mohr/Coulomb criterion, but with failure parameters strictly depending on pore sizes and shapes. In the brittle failure regime, once the closure of the crack has occurred, failure is originated at pre-existing flaws when the tensile stress at the tips exceeds the cohesive strength of the material and when closure of the crack has occurred (BRACE, 1960). Two different scenarios may be envisaged in cataclastic pores collapse failure. In one case, the stress concentration in the proximity of a macropore will induce a halo of localized damage leading to the development of the cataclastic collapse. In the other scenario, in highly porous rocks bonds between grains around macro-pores can be easily broken causing the pore collapse.

In compression tests, failure of rock specimen involves several different stages recognizable in the stress- strain curve (Fig. 15).

In the present experimental work, due to the lack of radial strain measurements, only three stages have been recognized: 1) a crack closure phase; 2) a linear elastic deformation and stable crack propagation phase; 3) a final failure phase. The influence of porosity on strength values has been, then, analyzed separately considering the stresses required for cracks closure and for failure.

It has been already shown that stresses at crack closure are moderately correlated to porosity values: the considered power regression, with a determination coefficient of 0.611, indicates that crack closure stresses drop below a value of approximately 0.5 MPa at porosity value lower than about 30% (Fig. 8a). The correlation of crack closure stresses with axial stresses at failure (Fig. 8b) indicates that porosity will affect in a similar way both the closure stress and the stress at failure.

Due to the presence of water, sedimentary rocks generally experience higher uniaxial compressive strength losses, largely varying from 10% to 80% (VÁSÁRHELYI, 2003; HAWKINS & MCCONNELL, 1992; WONG *et alii*, 2016). For medium strength cemented rocks, ROMANA & VÁSÁRHELYI (2007) indicated a ratio saturated/dry uniaxial compressive strengths of 0.6-0.7. In travertine, a high porosity carbonate rock, TÖRÖK & VÁSÁRHELYI (2010) found a linear relation with a ratio equal to 0.888 and a coefficient of determination $R_2=0.95$. Overall, the degree of sensitivity of rocks to water content seems to be controlled by the rock microfabric and by their mineralogical composition as well. Actually, the presence of water has a strong influence in the crack opening, due to the decrease in surface energy of the opposing crack surfaces. This process facilitates the crack propagation by decreasing both the elastic limit and the peak strength and

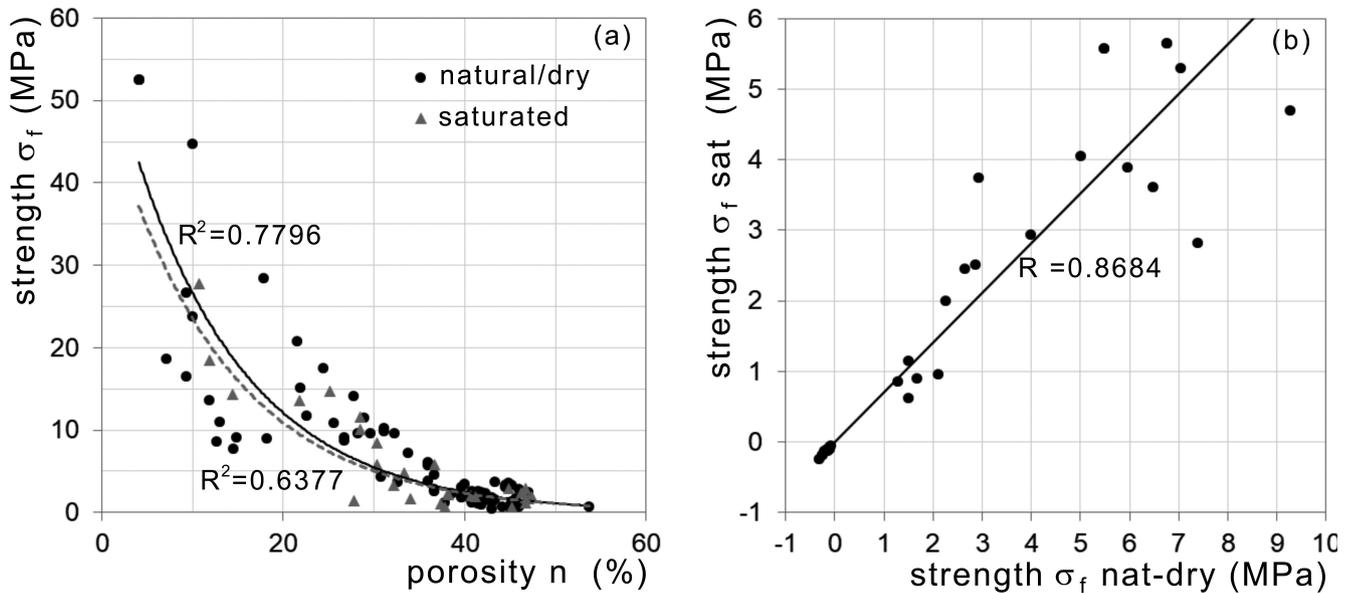


Fig. 16 - Relationship of compressive strength (σ) in dry and saturated conditions as a function of (a) porosity; and (b) natural/dry and saturated strengths (both compressive and tensile)

increasing, in case, water pressures within pores. Furthermore, in poorly cemented rocks, the presence of water affects also existing cementation and bond strength between grains.

The uniaxial compressive strength results are, as usual, inversely related to porosity (Fig 16a), following a negative exponential law for both dry and saturated conditions, confirming that all types of pores behave as significant stress concentrators. The determination coefficient indicates an enough good relationship for both dry specimen ($R_2=0.78$) and saturated ($R_2=0.64$) conditions; the inflection point for both curves correspond to porosity values of about 25%. The stress difference between the two regression curves is, however, rather little and it becomes insignificant (less than 1 MPa) when porosity is higher than about 30%. At higher porosity values, mean peak strengths are lower than 5 MPa and are characteristic of very weak rocks (MARINOS & HOEK, 2001).

Dry and saturated strengths, in compression and tension, are linearly correlated (Fig. 16b) with a quite good determination coefficient ($R_2=0.87$), that indicates a mean strength reduction factor $(\sigma_{dry})/(\sigma_{sat}) \approx 0.6$. The strength decrease could be caused to a debonding or a dissolution process of pre-existing diagenetic bonds, a process that, however, cannot be considered uniform all over the tested samples due to the irregular distribution of both pore sizes and type of bonds. On the other hand, as the peak strength depends on which failure mechanism is active or prevailing (wing cracks failure or pore collapse), the presence of water will have different effects.

The relation between water weakening and failure mode is consistently explained by micromechanical models (e.g. BAUD *et alii*, 2000). In a dry brittle elastic medium, the propagation of a

crack (wing cracks model) occurs until the specific surface energy attains its critical value that corresponds to the fracture energy. In saturated conditions, the strength loss depends on the solid-fluid interface energy and the strength will be lower due to reductions of both the specific surface energy and, partly, the friction coefficient.

Unlike the brittle failure regime, a few data exist as regards the water effect in case of pores collapse (cataclastic failure regime). Here, besides the reduction of the specific surface energy, the initial yield stress scales with both the mineral particle and grain contacts strengths, showing water weakening effects pretty variable but seemingly equal to the double of that observed in the brittle failure regime (ZHU & WONG, 1997; BAUD *et alii*, 2000).

During the initial phase of loading in wing cracks failure and due to the normal stress component, pre-existing linear cracks progressively close up from their edges to the centre, with a gradual increase in axial stiffness until the applied compressive stress reaches a level said “crack-closure stress”. The cracks behaviour during axial loading is even more complicated if non-linear cracks are considered. The closure of arched cracks, defined as the condition under which the normal displacement somewhere along the crack goes to zero, has been recently studied by RITZ & POLLARD (2011). In their analysis, each part of the crack will close almost independently for specific orientations and magnitudes of the applied stress, depending on the mechanical properties of the material forming the concave side of the crack that moves toward the outer crack surface.

In conclusion, the stress-strain response in wing cracks failure mode will not be linear and its value range depends basically on initial crack density and geometry, and deformability of the

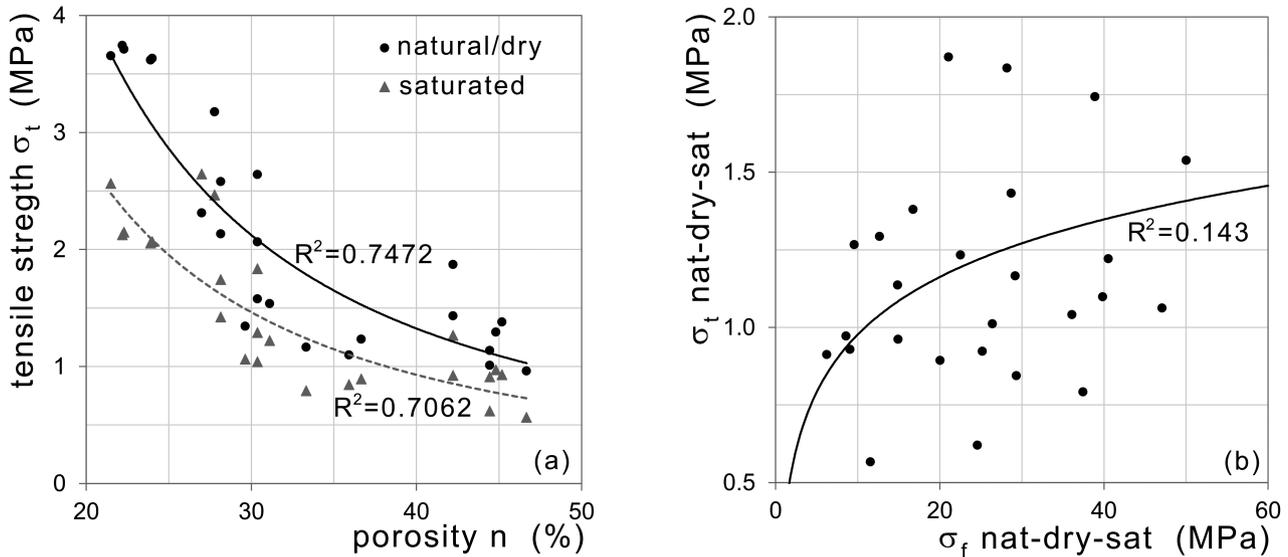


Fig. 17 - Relationship of (a) dry and saturated tensile strengths to porosity; (b) tensile strengths as a function of axial compressive strength, in dry and saturated conditions

rock matrix. After closure, cracks will remain in contact even if external stresses are still acting: they will displace and then open only at a certain stress level, that depends on the friction coefficient of crack sides and on the presence of fluids.

Tensile strength, a parameter controlling rock failure processes, has been examined considering its relationships with both porosity and unconfined compressive strength. A power regression best fits tensile strength values (σ_t) to porosity in dry and saturated conditions (Fig. 17a) and in both cases the determination coefficients are higher than 0.70. The ratio of dry to saturated tensile strengths slightly decreases with porosity value increase, approximately from 2.5 to 2.3, indicating that the water presence effect is only weakly dependent on porosity value.

Considering both natural/dry and saturated conditions (Fig. 17b), tensile and axial compressive strengths are very poorly correlated ($R_2=0.14$) showing, however, an inflection point at a strength value of about 10 kPa that corresponds to a porosity of about 20-22 % (Fig. 16a).

The trend of elastic modulus in relation to compressive strength has been assessed considering separately the cracks closure phase and the following linearly elastic one.

Because the rock deformability is affected, besides the matrix modulus, by the aspect ratios of existing pores, as longer cracks are more easily closed, higher $E0$ values can be connected to smaller aspect ratios and lower values to larger ones and/or to macropores collapse. The experimental calcarenite's initial modulus ($E0$) results rather low, having a mean value of 184 MPa and strongly correlated to the value of cracks closure stress (Fig. 18a). Higher values are linked to porosities lower than

about 30%, a value corresponding to the inflection point of the best-fitting polynomial probability density function (Fig. 18b). It could be concluded, then, that cracks of smaller aspect ratio should be prevailing in low porosity calcarenites.

Because the presence of pore fluid affects both the elastic parameters and the inelastic deformation processes, in the linear elastic phase the relationships between tangent elastic modulus E and corresponding unconfined compressive strength result different if natural/dry and saturated conditions are considered. Primarily, it is meaningful to note that the E values are much lower than those generally quoted for carbonate rocks with analogous porosity values, likely as a consequence of the weakness of the particles bonds (e.g. PALCHIK, 2011). $E \text{ nat-dry}$ values are linearly correlated to the compressive strengths, with a moderate determination coefficient (Fig. 19a). In saturated conditions the best fit distribution of $E \text{ sat}$ corresponds to a power probability density function with a moderate to weak determination coefficient. The comparison between the two regressions shows that $E \text{ sat}$ values are higher than the values in natural/dry conditions both for a compressive strength lower than about 12 kPa (Fig. 19a), and for porosity values higher than about 20% (Fig. 19b). These results have to be critically considered in the light of existent theoretical considerations on rocks behaviour (MAKHNEKO & LABUZ, 2016).

As matter of facts, the effect of water on rocks deformability is known to be rather complex, mostly because, in porous rocks, elastic modulus values are the result of different, and in some way interdependent, properties basically depending on rock and pores characteristics, on the saturation conditions and pore water pressure dissipation.

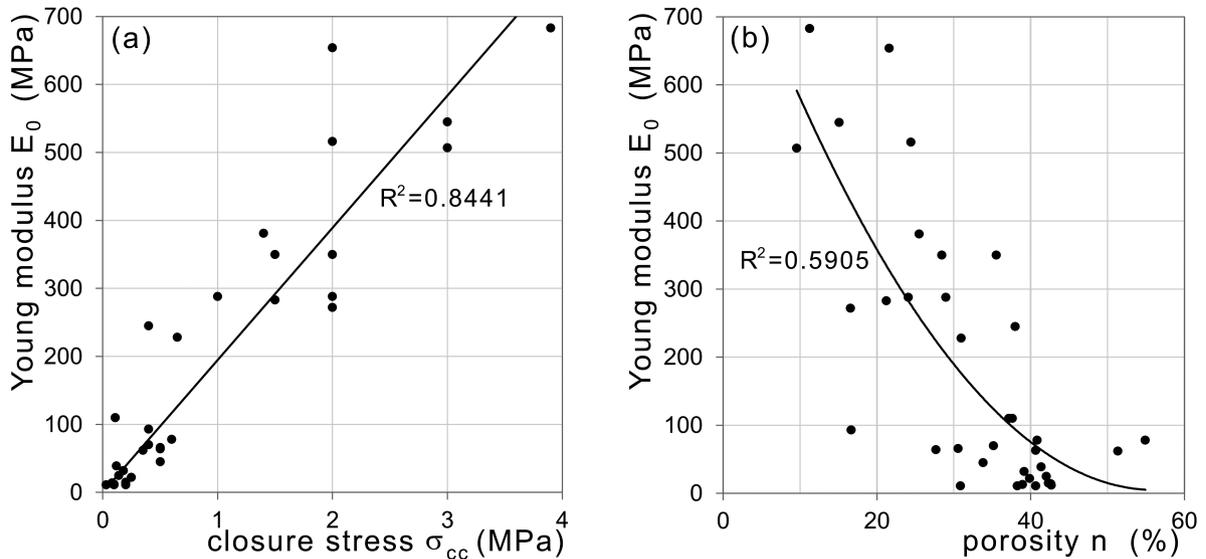


Fig. 18 - Relationship of the initial elastic modulus E_0 as a function of (a) closure stress and (b) porosity

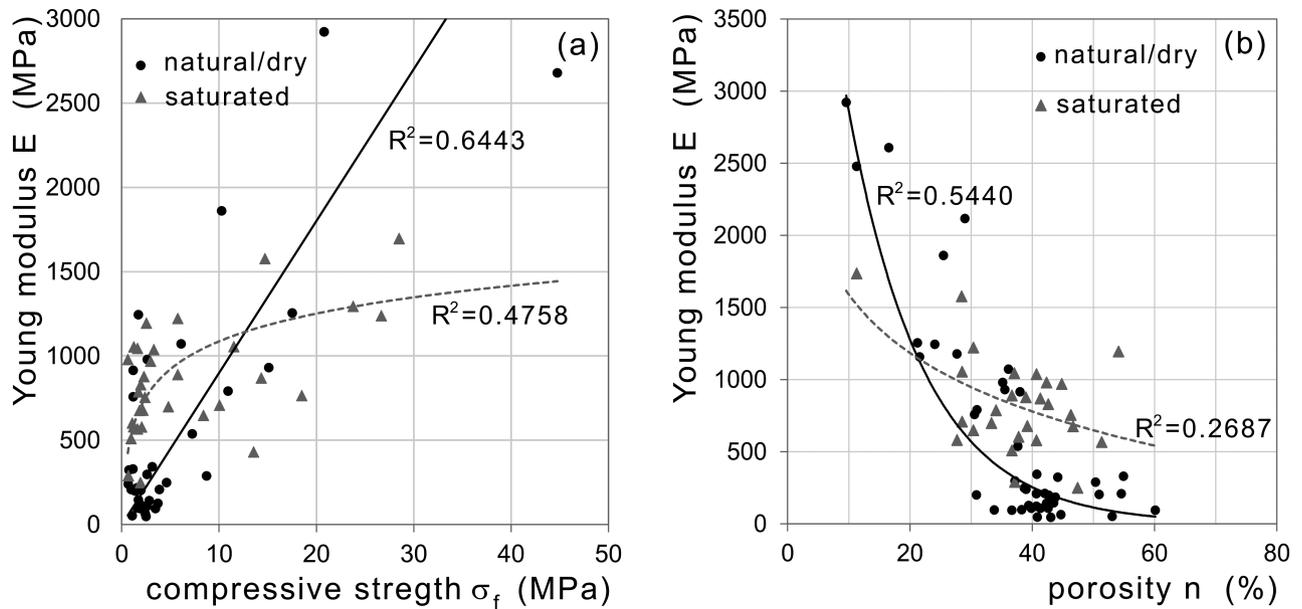


Fig. 19 - Relationship of Young modulus E , in natural/dry and saturated conditions, as a function of (a) uniaxial compressive strength and (b) porosity

In particular, the rock bulk modulus (in the order of GPa) is comparable to that of the saturating water (2.24 GPa), with the consequence that the rock’s framework bears the applied stress at least as much as the saturating pore fluid. In saturated conditions, we have then to consider both the undrained compressibility of the solid phase that is, as a first approximation, the compressibility of solid grains (K_s), and the drained compressibility of the porous material (K).

For the drained condition, pore pressure in the specimen

is constant and its excess equal to zero. In this case, since the water is free to flow, the axial load increase is taken only by the rock matrix. The specimen then deforms more than if the test were performed under undrained condition, where the pore fluid takes, instead, part of the loading in addition to deform itself. Hence, the drained modulus K will be lower than the undrained one K_u .

In undrained conditions, the rate of loading is too fast to allow the water pressure dissipation and the stiffness of the

filling fluid (water and air) will be taken into account: the sample loading will cause deformations as if all the pores were filled with solid material, and the bulk modulus will be greater than the drained ones.

The porous rock bulk modulus can be, then, related to the total volume change or only to the pore volume change. Generally, these moduli are different but, under conditions of fully connected pores and elastically isotropic solid phase, they both can be identified with the bulk modulus of the solid constituent K_s . However, this assumption could not be valid for tested calcarenite, where intergranular cement may have different elastic properties and pore spaces may be not fully connected.

In conclusion, the following inequality may be assumed as a first approximation:

$$0 \leq K \leq K_u \leq K_s$$

Even if, due to a relevant heterogeneity of tested samples, inconsistent results may be obtained, the undrained moduli (K_u) are mostly larger than the drained counterparts.

Theoretical considerations on bulk modulus K of porous rocks can be transferred to the elastic modulus E , since K and E are correlated by the Poisson coefficient, both drained and undrained.

The result that the elastic moduli of calcarenite in saturated conditions are greater than those in natural or dry conditions, can be explained considering that, for porosity higher than about 20%, they have been obtained in undrained conditions, because the presence of not fully connected pores and/or a non-isotropic solid phase. For lower values of the porosity (Fig. 19b) and higher values of the compressive strength (Fig. 19a), elastic moduli E_{sat} display lower values than those in natural/dry conditions, but it should be considered that the number of available data is very limited.

Concluding, in natural/dry conditions, the elastic modulus can be considered as corresponding to the drained value for high porosities and low value of compressive strength while, in saturated conditions, it can be drained or undrained, depending on the rate of dissipation of pore water pressure during loading. As the undrained modulus should be greater than the drained one, our results seem to indicate an undrained condition for porosity higher than about 20%.

Elastic moduli in natural/dry conditions and porosity are exponentially correlated with a moderate determination coefficient and an inflection point of the non-linear regression located at a porosity value of about 25%. No reliable relationship with the porosity appears as regards the saturated elastic moduli (Fig. 19b). However, it is remarkable to note that, for porosity higher than about 20%, saturated moduli are higher than the corresponding natural/dry moduli.

REFERENCES

- ANDRIANI G.F., LOLLINO P., PERROTTI M. & FAZIO N.L. (2019) - *Incidence of saturation and fabric on the physical and mechanical behaviour of soft carbonate rocks*. In: Proceedings of 53rd U.S. Rock Mechanics/Geomechanics Symposium, Brooklyn, New York, USA, 9-23-26 June 2019, 5 pp.

CONCLUSIONS

Physical and mechanical test results lead to the conclusion that the Gravina Calcarenite may be considered as moderately cohesive, with a microstructure that could be represented by a model including voids with different aspect ratios (cracks and micro- macropores) embedded in an elastic medium. Considering the observed distribution of pores and their millimetric sizes, tested samples may be classified as “vesicular specimens with millimetric to centimetric voids” (MINEO & PAPPALARDO, 2016).

Many Authors (e.g. HAWKINS & McCONNELL, 1992) have examined the influence of physical characteristics on strength and deformability of sedimentary rocks, but only a few concerned very porous rocks (PALCHIK & HATZOR, 2004; VAJDOVA *et alii*, 2004) and fewer the Gravina Calcarenite (LAGIOIA, 1996; CIANTIA & HUECKI, 2012; CIANTIA *et alii*, 2015). In particular, ANDRIANI *et alii* (2019) have developed this topic on the same lithotype (Calcarenite of Gravina Formation).

Results of laboratory tests on natural/dry and saturated samples indicate that the mechanical properties might be controlled by the evolution of damage induced by both pore-manated and/or sliding wing cracks and macro-pores collapse. The behaviour of Gravina Calcarenite should be examined, then, considering it as a system made up of a rock matrix and distributed pores with different sizes, aspect ratios and shapes, filled or not by water.

All the examined correlations between physical and mechanical properties and porosity show that, at porosity values approximately between 25% and 30%, a change in the examined parameter trend may be observed. For lower porosities, strength and stiffness seem to be mainly determined by the framework of cemented particles. In the higher porosity domain, coarser particles can be in contact directly or through finer grains: the strength and stiffness are determined, therefore, by the extent and type of the existing bonds. We might attribute to this range of the porosity a threshold meaning: if porosity is smaller than 25-30%, rock matrix is more spatially continuous and the rock matrix properties will dominate, whereas for higher porosity values pore geometry and distribution will mainly influence the mechanical properties. The particular microstructure of the calcarenite seems to generate also a reduction of the permeability, responsible of the undrained condition in saturated tests.

The effect of porosity on strength and deformability has to be analysed in depth, separately analysing the mechanical behaviour of low and high porosity samples, as well as the presence of fluid in the pores, that lowers the energy required for the activation of pore collapse.

ARMA, Alexandria, Virginia, USA.

- ANON O.H. (1979) - *Classification of rocks and soils for engineering geological mapping: part 1-rock and soil materials*. Bulletin of Engineering Geology and the Environment, **19** (1): 364-371.
- ASHBY M. F. & SAMMIS C. (1990) - *The damage mechanics of brittle solids in compression*. Pure and Applied Geophysics, **133**: 489-521. Doi: 10.1007/BF00878002.
- AZZAROLI A. (1968) - *Calcarenite di Gravina. Studi illustrativi sulla Carta Geologica d'Italia. Formazioni geologiche*. Servizio Geologico d'Italia, I: 183-185.
- BARTON N. & BANDIS S. (1980) - *Some effects of scale on the shear strength of joints*. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., **17** (1): 69-73. Doi: 10.1016/0148-9062(80)90009-1.
- BARTON N. (1983) - *Application of Q-system and index tests to estimate shear strength and deformability of rock masses*. In: Proceedings of International Symposium on Engineering Geology and Underground Construction, Lisbon, Portugal, 1(II): 51-70. Elsevier, Amsterdam, The Netherlands. Doi: 10.1016/0148-9062(84)90104-9.
- BAUD P., ZHU W. & WONG T. (2000) - *Failure mode and weakening effect of water on sandstone*. Journal of Geophysical Research, **105** (B7): 16371-16389. doi: 10.1029/2000JB900087.
- BIENIAWSKI Z.T. (1978) - *Determining rock mass deformability: experience from case histories*. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., **15**: 237-248.
- BIENIAWSKI Z.T. (1989, ED.) - *Engineering rock mass classification*. 251 pp. John Wiley & Sons, New York.
- BOENZI F. (1988) - *Nuove osservazioni geomorfologiche sulla Murgia materana: dati e problemi*. Rivista Geografica Italiana, **95**: 337-344.
- BRACE W.F. (1960) - *An extension of the Griffith theory of fracture to rock*. Journal of Geophysical Research, **65** (10): 3477-3480.
- CAI M., KAISER P.K., UNO H., TASAKA Y. & MINAMI M. (2004) - *Estimation of rock mass deformation modulus and strength of jointed hard rock masses using the GSI system*. Int. J. Rock Mech. Min. Sci., **41**: 3-19. Doi:10.1016/S1365-1609(03)00025-X.
- CIANTIA M.O., CASTELLANZA R. & CROSTA G.B. (2015) - *Effects of mineral suspension and dissolution on strength and compressibility of soft carbonate rocks*. Engineering Geology, **184**: 1-18. Doi: 10.1016/j.enggeo.2014.10.024.
- CIANTIA M.O. & HUECKEL T. (2012) - *Weathering of submerged stressed calcarenites: chemo-mechanical coupling mechanisms*. Geotechnique, **63** (9): 768-785. <http://dx.doi.org/10.1680/geot.SIP13.P.024>.
- CIARANFI N., PIERI P. & RICCHETTI G. (1988) - *Note alla carta geologica delle Murge e del Salento (Puglia centromeridionale)*. Mem. Soc. Geol. It., **41**: 449-460.
- DYKE C.G. & DOBEREINER L. (1991) - *Evaluating the strength and deformability of sandstones*. Quarterly Journal of Engineering Geology and Hydrogeology, **24** (1), 123-134. Doi: 10.1144/GSL.QJEG.1991.024.01.13.
- EBERHARDT E., STEAD D., STIMPSON B. & READ R.S. (1998) - *Identifying crack initiation and propagation thresholds in brittle rock*. Can. Geotech. J., **35** (2): 222-233. Doi: 10.1139/cgj-35-2-222.
- EDELBRÖ C. (2003) - *Rock mass strength: a review*. Technical report, 2003 (16), pp. 92. Lulea University of Technology, Sweden.
- EDELBRÖ C., SJÖBERG J. & NORDLUND E. (2006) - *A quantitative comparison of strength criteria for hard rock masses*. Tunn. Underground Space Technol., **22** (1): 57-68. <https://doi.org/10.1016/j.tust.2006.02.003>.
- GRASSI D. (1974) - *Evoluzione morfologica dei depositi calcarenitici quaternari in corrispondenza dei versanti vallivi della Puglia e della Lucania, con particolare riferimento alla Gravina di Matera*. Geol. Appl. Idrogeol., **9**: 95-117.
- HAWKINS A.B. & McCONNELL B.J. (1992) - *Sensitivity of sandstone strength and deformability to changes in moisture content*. Quarterly Journal of Engineering Geology and Hydrogeology, **25** (2): 115-130. <https://doi.org/10.1144/GSL.QJEG.1992.025.02.05>.
- HOEK E. & BROWN E.T. (1997) - *Practical estimates of rock mass strength*. Int. J. Rock Mech. Min. Sci., **34** (8): 1165-1186. [https://doi.org/10.1016/S1365-1609\(97\)80069-X](https://doi.org/10.1016/S1365-1609(97)80069-X).
- HOEK E. & DIEDERICHS M.S. (2006) - *Empirical estimation of rock mass modulus*. Int J Rock Mech. Min. Sci., **43**: 203-215. <https://doi.org/10.1016/j.ijrmms.2005.06.005>.
- LAGIOIA R. (1996) - *Comportamento meccanico di una calcarenite di Gravina di Puglia*. Rivista Italiana di Geotecnica, **4**: 69-84.
- MAKHNEKO R.Y. & LABUZ J.F. (2016) - *Elastic and inelastic deformation of fluid-saturated rock*. Phil. Trans. R. Soc., A 374 (20150422), 1-22. <http://dx.doi.org/10.1098/rsta.2015.0422>
- MARINOS P. & HOEK E. (2001) - *Estimating the geotechnical properties of heterogeneous rock masses such as flysch*. Bull. Eng. Geol. Env., **60**: 85-92. Doi: 10.1007/s100640000090.
- MINEO S. & PAPPALARDO G. (2016) - *The use of infrared thermography for porosity assessment of intact rock*. Rock Mech. Rock Eng., **49** (8): 3027-3039. Doi: 10.1007/s00603-016-0992-2.
- PALCHIK V. (2011) - *On the ratios between elastic modulus and uniaxial compressive strength of heterogeneous carbonate rocks*. Rock Mech. Rock Eng., **44** (1): 121-128. Doi: 10.1007/s00603-010-0112-7.
- PALCHIK V. & HATZOR Y. H. (2002) - *Crack damage stress as a composite function of porosity and elastic matrix stiffness in dolomites and limestones*.

- Engineering Geology, **63** (3-4): 233-245. [https://doi.org/10.1016/S0013-7952\(01\)00084-9](https://doi.org/10.1016/S0013-7952(01)00084-9).
- PALCHIK V. & HATZOR Y. H. (2004) - *The influence of porosity on tensile and compressive strength of porous chalks*. Rock Mech. Rock Eng., **37** (4): 331-341. DOI: 10.1007/s00603-003-0020-1.
- PALMSTRÖM A. & SINGH R. (2001) - *The deformation modulus of rock masses - Comparisons between in situ tests and indirect estimates*. Tunn. Underground Space Technol., **16** (2): 115-131. DOI: 10.1016/S0886-7798(01)00038-4.
- RITZ E. & POLLARD D. (2011) - *Closure of circular arc cracks under general loading: effects on stress intensity factors*. Int. J. Fract., **167** (1): 3-14. <https://doi.org/10.1007/s10704-010-9511-8>.
- ROMANA M. & VASARHELYI B. (2007) - *A discussion on the decrease of unconfined compressive strength between saturated and dry rock samples*. In: RIBEIRO E SOUSA, OLLALA & GROSSMANN (EDS.), Proc. 11th ISRM Cong. The Second Half Century of Rock Mechanics, Lisboa, 9-13 July 2007, I, 139-142. Taylor & Francis, London.
- SAMMIS C. & ASHBY M.F. (1986) - *The failure of brittle porous solids under compressive stress states*. Acta Metallurgica, **34** (3): 511-526. DOI: 10.1016/0001-6160(86)90087-8.
- SERAFIM J.L. & PEREIRA J.P. (1983) - *Consideration of the geomechanical classification of Bieniawski*. In: Proc. Int. Symp. on Engineering Geology and Underground Construction, LNEC, Lisbon, I (II), 1133-1144.
- TILL R. (1974) - *Statistical Methods for the earth Scientist*. 154 pp. The Macmillan Press LTD, London. <https://doi.org/10.1007/978-1-349-15536-1>.
- TÖRÖK Á. & VÁSÁRHELYI B. (2010) - *The influence of fabric and water content on selected rock mechanical parameters of travertine, examples from Hungary*. Eng. Geol., **115** (3-4): 237-245. DOI: 10.1016/j.enggeo.2010.01.005.
- ULUSAY R. (2015, ED.) - *The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014*, 293 pp. Springer, Switzerland. doi: 10.1007/978-3-319-007713-0.
- VAJDOVA V., BAUD P., WU L. & WONG T. (2004) - *Compaction, dilatancy, and failure in porous carbonate rocks*. Journal of Geophysical Research, **109** (B05204), 16 pp. DOI:10.1029/2003JB002508.
- VAJDOVA V., BAUD P., WU L. & WONG T. (2012) - *Micromechanics of inelastic compaction in two allochemical limestones*. Journal of Structural Geology, **43**: 100-117. <https://doi.org/10.1016/j.jsg.2012.07.006>.
- VÁSÁRHELYI B. (2003) - *Some observation regarding the strength and deformability of sandstones in case of dry and saturated conditions*. Bull. Eng. Geol. & Env., **62** (3): 245-249. DOI: 10.1007/s10064-002-0186-x.
- WILCOXON F. (1945) - *Individual comparison by ranking methods*. Biometrics Bulletin, **1** (6): 80-83. <https://doi.org/10.2307/3001968>.
- WONG T., BAUD P. & KLEIN E. (2001) - *Localized failure modes in a compactant porous rock*. Geophysical Research Letters, **28** (13): 2521-2524. <https://doi.org/10.1029/2001GL012960>.
- WONG L., MARUVANCHERY V. & LIU G. (2016) - *Water effects on rock strength and stiffness degradation*. Acta Geotechnica, **11** (4): 713-737. DOI: 10.1007/s11440-015-0407-7.
- ZHANG L. (2010) - *Estimating the strength of jointed rock masses*. Rock Mech. Rock Eng., **43** (4): 391-402. DOI: 10.1007/s00603-009-0065-x.
- ZHANG J. & BENTLEY L.R. (2003) - *Pore geometry and elastic moduli in sandstones*. CREWES Research Report, (15), 20 pp., University of Calgary.
- ZHU W. & WONG T. (1997) - *The transition from brittle faulting to cataclastic flow: permeability evolution*. Journal of Geophysical Research, **102** (B2): 3027-3041. <https://doi.org/10.1029/96JB03282>.
- ZHU W., BAUD P. & WONG T. (2010) - *Micromechanics of cataclastic pore collapse in limestone*. Journal of Geophysical Research, **115** (B04405), 17 pp. <https://doi.org/10.1029/2009JB006610>.

Received February 2019 - Accepted December 2019