*Focussed on Recent advances in "Experimental Mechanics of Materials" in Greece*

# Experimental investigation of the mechanical properties of Alfas stone

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**ABSTRACT.** This paper focuses on the experimental investigation of the mechanical properties of the Alfas natural building stone. Two series of uniaxial compression tests and indirect tensile tests (Brazilian tests) were performed in order to determine the uniaxial compressive strength and the indirect tensile strength respectively. Different sets of cylindrical specimens and circular discs were prepared by varying their geometry in order to examine the size effect on the respective strength values. Also, the size effect was investigated with respect to the calculated intact rock modulus and Poisson's ratio. All specimens were prepared by following the ISRM suggested methods and the load was applied using a stiff 1600 kN MTS hydraulic testing machine and a 500 kN load cell. Strain was measured using biaxial 0/90 stacked rosettes appropriately attached on each specimen.

**KEYWORDS.** Alfas; Building stones; Uniaxial compressive strength; Indirect tensile strength; Size effect.



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## INTRODUCTION

Scaling is a major issue for the analysis of large structures made of geomaterials (including rock and soil masses) studied and tested at a smaller scale. In laboratories the researchers are capable to measure the strength of a small specimen and need a scaling law to deduce the strength of a large structure.

The size effect analysis can be dated back to the 15th century when Leonardo da Vinci stated that *among cords of equal thickness, the longest is the least strong* and that a cord *is so much stronger … as it is shorter*. That is the first statement of size effect even though the proportionality between structural size and strength was a bit exaggerated.

In 1638, Galileo when founding the material strength theory rejected da Vinci's rule, but pointed out that large animals have relatively bulkier bones than small ones. He called this statement the weakness of giants.

In 1686, Mariotte conducted several experiments with ropes and deduced that a long rope and a short one always support the same weight unless a long rope happens to have a fault, whereas it will break sooner than in a shorter one. He proposed that this is a consequence of the principle of the inequality of the matter whose absolute resistance may be less in one place than another [1]. At that time, mathematics were not developed enough to properly state the statistical explanation of size effect. This was accomplished two centuries later by Weibull [2].

In rock mechanics and engineering geology, the uniaxial compression and the indirect tension test (Brazilian test) are considered to be the most widely spread methods to obtain rock strength properties and parameters such as the intact rock modulus and Poisson's ratio.

Tensile strength may be measured using the direct tension test. However, this test presents experimental difficulties and is not commonly conducted in rock mechanics laboratories. This is due to both the bending stresses and/or torsion moment caused by the eccentricity of imposed axial loads and the localized concentrated stresses caused by improper gripping of specimens [3,4].

Because of these experimental difficulties, alternative techniques have been developed to determine the tensile strength of rock. In the Brazilian test, a circular solid disc is compressed to failure across the loading diameter. Hondros [5] has analytically solved the Brazilian test configuration in the case of isotropic rocks, while Pinto [6] extended Hondros' method to anisotropic rocks and checked the validity of his methodology on schisteous rock formation. Recent investigations have led to a closed form solution for an anisotropic disc [7,8], a series of charts for the determination of the stress concentration factors at the center of an anisotropic disc [9], and explicit representations of stresses and strains at any point of an anisotropic circular disc compressed diametrically [10].

It should be noted that the so-called "scale effect" is split up into two categories: shape and size effect. The shape effect describes the impact of the height/diameter ratio of a cylindrical specimen on rock strength properties. The size effect is defined by the influence of the absolute size (i.e., volume) of geometrically self-similar specimens. In case of cylindrical specimens this reduces the changes in diameter where the height/diameter ratio remains constant [11].

The scale effect is well known for both the compressive and tensile tests as there are numerous studies in the literature [12,13,14,15] that have investigated the effect of various factors such as size, shape, porosity, density on the uniaxial compressive strength (UCS) and the indirect tensile strength.

This paper presents the effect of the size on UCS, indirect tensile strength, intact rock modulus and Poisson's ratio for the Alfas building stone. The term "intact rock modulus" is used here instead of elastic modulus, in order to differentiate the modulus of intact rock with respect to the deformation modulus of the rock mass.

## TESTING MATERIAL

In order to experimentally examine the size effect on the uniaxial compressive and indirect tensile strength, specimens of Alfas building stone were tested. The Alfas stone is a micritic (microcrystalline) homogeneous limestone. X-ray diffraction (XRD) and Rietveld quantitative method [16] results, indicate that it is composed by 91% of calcite ($CaCO_3$), 2% of quartz ($SiO_2$) and 7% aragonite ($CaCO_3$).

The determination of water absorption at atmospheric pressure is based on standard BS EN 13755 (2008) [17], while the determination of open (effective) porosity and bulk (apparent) density is based on standard BS EN 1936 (2006) [18]. The average results for Alfas stone are shown in Tab. 1.

| Water Absorption (%) | Open Porosity (%) | Bulk Density (kg/m$^3$) |
|---|---|---|
| 12.19 (±0.61) | 31.48 (±3.20) | 2870 (±355) |

Table 1: Physical properties of the Alfas stone.

## THEORETICAL CONSIDERATIONS

### *Uniaxial compression test*

In uniaxial compression test a cylindrical specimen of diameter *D* and height *h* is subjected to a uniformly applied stress $\sigma_y$, acting on the ends of the specimen (Fig. 1a), following the ISRM suggested method [19]. In addition to the peak stress value, the complete stress-strain curve is recorded in order to calculate the tangent intact rock modulus $E_{50}$ (Fig. 1b).

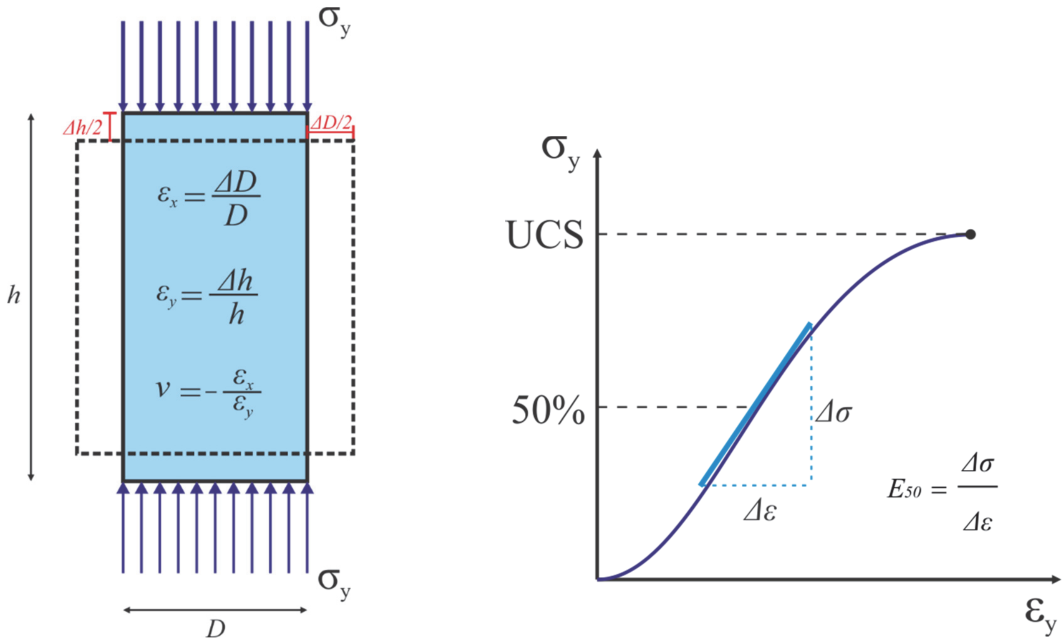



Figure 1: (a) Uniaxial compression test and calculation of axial and lateral strains and Poisson's ratio. (b) Stress-strain curve and the calculation of the tangent intact rock modulus.

### *Indirect tensile test (Brazilian test)*

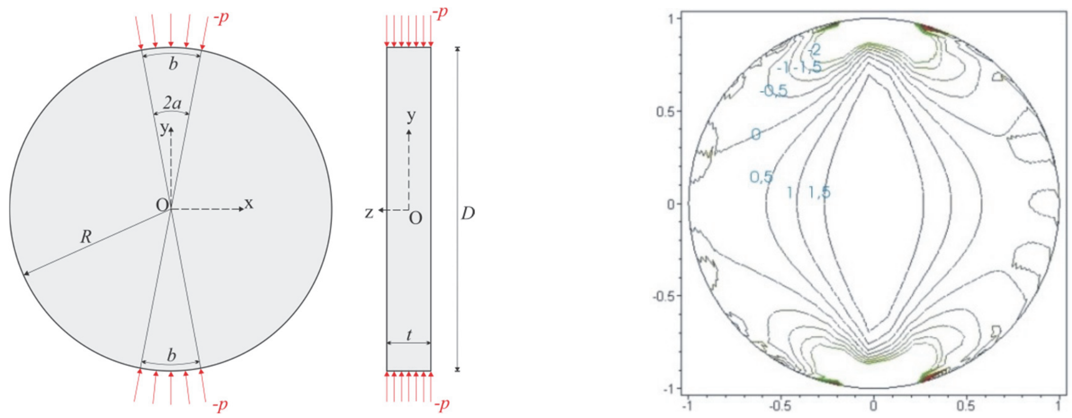
In the Brazilian test a cylindrical specimen of diameter *D* and thickness *t* is subjected to a uniform radial pressure *-p*, acting along an arc of length *b* at each end of the diameter (Fig. 2a). The angle subtended at the center of the disc by the loaded section of the rim is equal to *2a*. If the material behavior is assumed to be linear elastic, this geometry and loading procedure ensures a nearly uniform tensile stress state in the center plane of the specimen (Fig. 2b). According to this distribution, the expected failure mode is the splitting of the specimen in two halves across the plane of loading. For brittle elastic materials, the maximum tensile stress ($f_{st}$) is a material property called splitting tensile strength and is linearly related to the failure load ($P_f$):

$$f_{st} = \frac{2P_f}{\pi D t} \tag{1}$$

Using measurements from electrical strain gages ($\varepsilon_{xx}$, $\varepsilon_{yy}$) that are attached to the center of a specimen, the elastic parameters can be calculated for an isotropic material using the following relationships [20]:

$$E = \frac{16P}{\pi D t} \frac{1}{\varepsilon_{yy}\left(3 + \frac{\varepsilon_{xx}}{\varepsilon_{yy}}\right)} \tag{2}$$

$$\nu = \frac{1+3\left(\frac{\varepsilon_{xx}}{\varepsilon_{yy}}\right)}{3+\left(\frac{\varepsilon_{xx}}{\varepsilon_{yy}}\right)} \quad (3)$$




(a) (b)

Figure 2: (a) Load configuration of the Brazilian test, (b) Distribution of the horizontal Stress Concentration factor $q_{xx}=\sigma_{xx}/(p\alpha/\pi)$ calculated according to the theory of elasticity [21].

## EXPERIMENTAL PROCEDURE

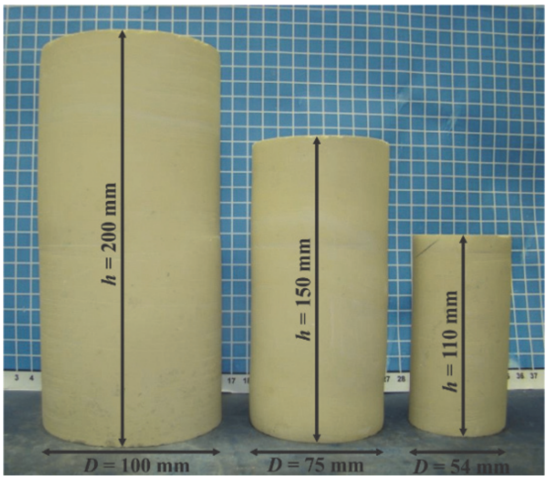
A sufficient number of block samples for the Alfas stone was collected from the quarry near the Alfas village in Rethymnon, Crete, Greece, and subsequently carefully checked to ensure the homogeneity of the materials. The size of these blocks was 25x30x30 cm. Specimens were prepared for uniaxial compression and indirect tension testing as detailed below. In all testing, load was applied by a stiff 1600 kN MTS-815 hydraulic testing frame and a 500 kN load cell using a load control mode.

### *Uniaxial compression test*

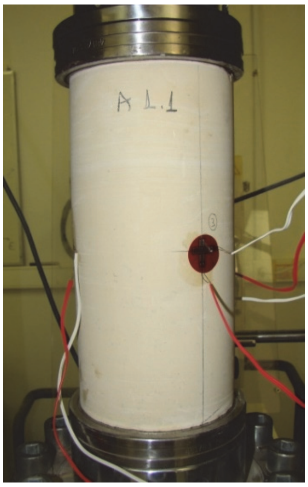
Using the freshly quarried Alfas stone, three sets of cylindrical specimens were prepared according to the ISRM specifications [19] for the uniaxial compression test (Fig. 3a). In order to investigate the size effect, specimens were prepared with diameters $D$=54, 75 and 100 mm. The height $h$ to diameter $D$ ratio for the uniaxial compression test remained constant and equal to 2. Special care was taken to ensure that the two bases of the cylinders were parallel to each other and perpendicular to the longitudinal axis of the specimens. All experiments were carried out using a very thin film of vaseline jelly as lubrication between the bases of the specimens and the loading platens. The loading rate was 3 kN/s.
In order to measure the axial and lateral strain during the UCS test, three biaxial 0/90 strain gages were appropriately attached at 120$^{o}$ to each other on the curved surface of the cylindrical specimens, midway between the cylinder bases (Fig. 3b). The use of three strain gages per specimen was deemed appropriate (especially for the larger specimens) in order to check the symmetry of the generated surface strains on the specimen during loading.

### *Indirect tensile test*

Three sets of circular discs were prepared according to the ISRM specifications [22] for the Brazilian test (Fig. 4a). The ratio of the diameter $D$ to thickness $t$ for the Brazilian test remained constant and equal to 2. In order to investigate the size effect, specimens were prepared with diameters $D$=54, 75 and 100 mm. Subsequently, two strain gages were attached on the center of each flat surface of the circular discs used for the Brazilian tests (Fig. 4b).
The specimens were placed between two steel loading jaws designed to contact diametrically opposed surfaces over an arc of approximately 0.1 radians, (as suggested by ISRM [22]), and the test was conducted with a loading rate of 200 N/s.

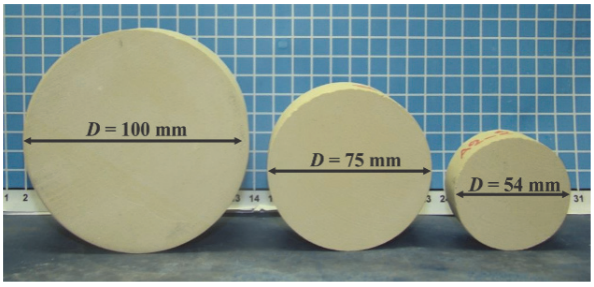



(a)

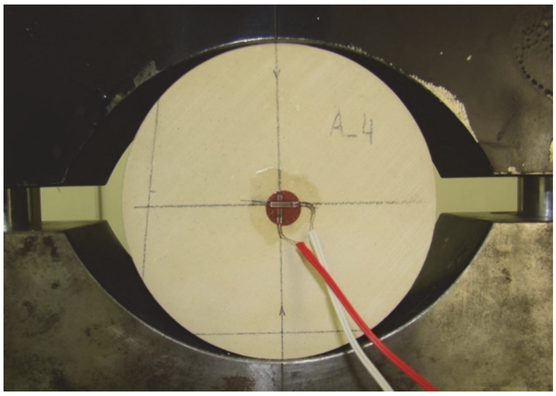



(b)

Figure 3: (a) A series of cylindrical specimens with different diameters and constant ratio $h/D = 2$ for Alfas stone. (b) The position of the strain gages for cylindrical specimens.




(a)




(b)

Figure 4: (a) A series of circular discs with different diameters and constant ratio $D/t = 2$ for Alfas stone. (b) The position of the strain gages attached to the circular discs.

## EXPERIMENTAL RESULTS AND DISCUSSION

### *Uniaxial compression tests*

By processing the experimental data, the basic mechanical properties of the material were determined. The uniaxial compressive strength, intact rock modulus and Poisson's ratio are presented in Tab. 2 for the three different sizes of the cylindrical specimens. Note that the intact rock modulus and Poisson's ratio for each specimen was calculated at 50% of the UCS of that specimen. Furthermore, the lateral and axial peak strains and the strain energy density up to the peak load were calculated.

Results from a typical cylindrical specimen with diameter $D$=100 mm are presented in Fig. 5a, b. It is observed that the strain values measured by the three strain gages are similar (Fig. 5a). It can also be observed that for small strains the constitutive law is almost linearly elastic.

Fig. 5c, d present the variation with the uniaxial stress of the intact rock modulus and Poisson's ratio respectively, for three specimens with diameter $D$=54 mm. The similarity of these results with respect to the trend and repeatability of the intact rock modulus is evident, at a region where stresses are about 50% of the strength. The variation of Poisson's ratio with stress is consistent along the full stress path for all three specimens.

| *b* [mm] | *D* [mm] | *Number of tests* | *Number of specimens with strain gages* | *Uniaxial compressive strength* [MPa] | | *Intact rock modulus* *E* [MPa] | | *Poisson's ratio* *v* | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | *Average* [MPa] | *St. Dev.* [MPa] | *Average* [MPa] | *St. Dev.* [MPa] | *Average* | *St. Dev.* |
| 110 | 54 | 6 | 6 | 35.56 | 0.51 | 13575 | 193 | 0.221 | 0.007 |
| 150 | 75 | 6 | 6 | 33.81 | 0.73 | 13318 | 733 | 0.238 | 0.022 |
| 200 | 100 | 6 | 6 | 32.09 | 1.82 | 13735 | 1272 | 0.242 | 0.015 |

Table 2: The experimental results of the uniaxial compression tests for Alfas stone.

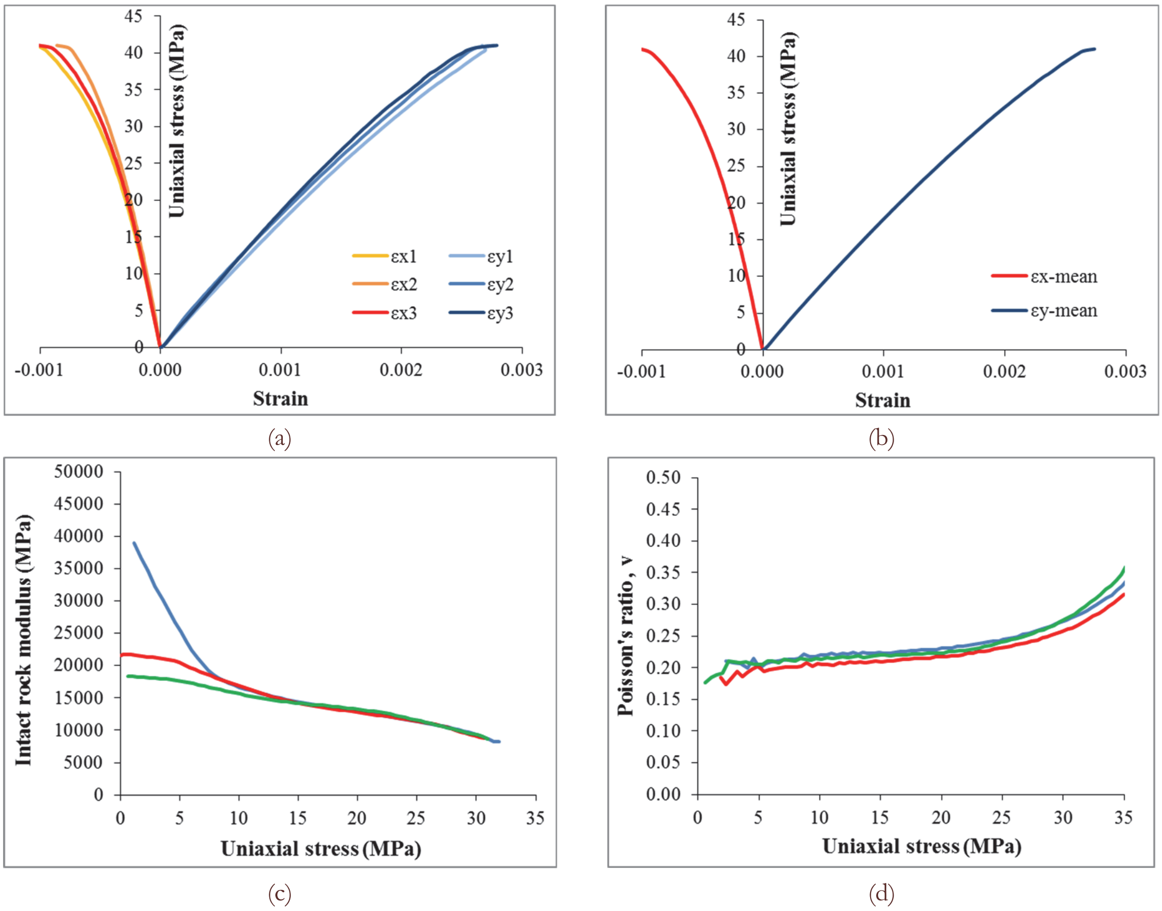



Figure 5: Typical diagrams for uniaxial compression tests. (a) Stress-strain curves from the three biaxial strain-gages, (b) Mean value stress-strain curves, (c) Intact rock modulus and (d) Poisson's ratio in correlation with the uniaxial stress.

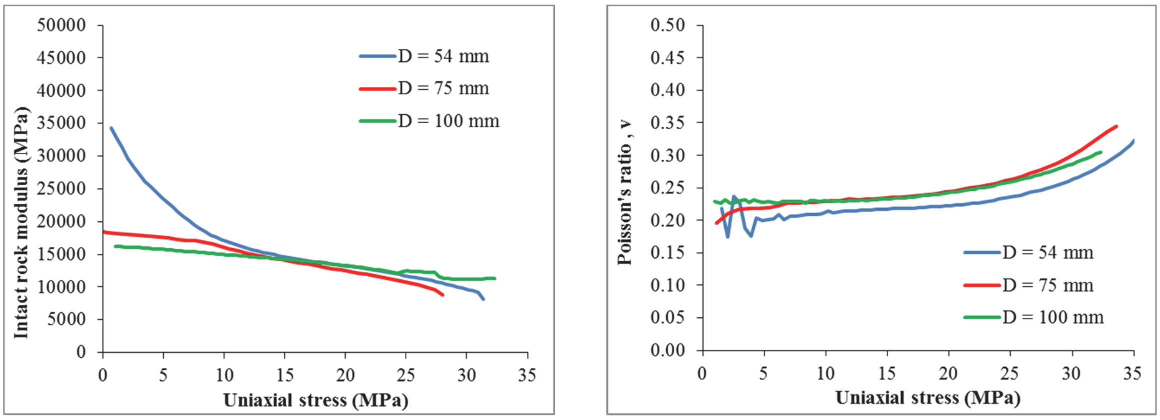
Three different failure modes were observed during the uniaxial compression tests of Alfas stone. Some specimens failed along single shear planes (Fig. 6a), others failed in axial splitting (Fig. 6b) and a third group failed along conjugate shear planes (Fig. 6c). It should be noted that in all cases specimens exhibit extensive spalling before failure.

### *Size effect for uniaxial compression tests*

A total of 18 uniaxial compression tests were completed in order to investigate the size effect for the Alfas natural building stone under uniaxial compression. Initially, the mean curves of intact rock modulus and Poisson's ratio, for each set of cylindrical specimens, are plotted in correlation with the uniaxial stress (Fig. 7). For the case of Poisson's ratio (Fig.7b) the trend of these curves is similar for all diameters, while for the intact rock modulus (Fig.7a) this similarity is only observed for stresses greater than 50% of specimen strength.

(a) (b) (c)

Figure 6: Typical crack patterns in Alfas cylindrical specimens. (a) Shear plane failure ($D$=75 mm); (b) Axial splitting failure ($D$=100 mm); (c) Failure on conjugates shear planes ($D$=54 mm).




(a) (b)

Figure 7: The mean curves of (a) Intact rock modulus and (b) Poisson's ratio of Alfas stone for each of the three diameters in correlation with the uniaxial stress.

Mean values of rock properties are plotted against the diameter together with their standard deviation values (Fig. 8). Fig. 8a clearly shows that UCS decreases as the diameter increases for a constant height to diameter ratio. A difference between the UCS for specimens with $D$=54 mm and $D$=100 mm is observed, which is up to 11%. Also, the same trend is observed for the strain energy density (Fig. 8d). Fig. 8b and Fig. 8c present the variation of the intact rock modulus and Poisson's ratio, as derived from the uniaxial compression test using strain gages. Experimental results show that these parameters remain almost constant for different specimen diameters, with mean values of E=13543 MPa and ν=0.234, respectively. The dependence of the lateral and axial peak strains on the diameter of specimens is presented in Fig. 8e and Fig. 8f respectively. The variation of the peak strains is not a monotonic function versus the diameter. A clear maximum exists and corresponds to the specimens with $D$=75 mm. The high standard deviation values calculated for some experiments series can be attributed to the small number of specimens used for this analysis.

*Indirect tensile tests*

The results obtained from the diametral compression tests for the three different circular disc specimen sizes are presented in Tab. 3. Results include values for the splitting tensile strength, the intact rock modulus, Poisson's ratio and the shear modulus. Note that the intact rock modulus, Poisson's ratio and shear modulus for each specimen was calculated at 50% of the indirect tensile strength of that specimen. Furthermore, the lateral and axial peak strains up to the peak load were calculated. Note that the intact rock modulus, Poisson's ratio and shear modulus values calculated for the circular discs with $D$=54 mm, correspond to only one specimen, because strain gage measurements failed in other specimens of this series.

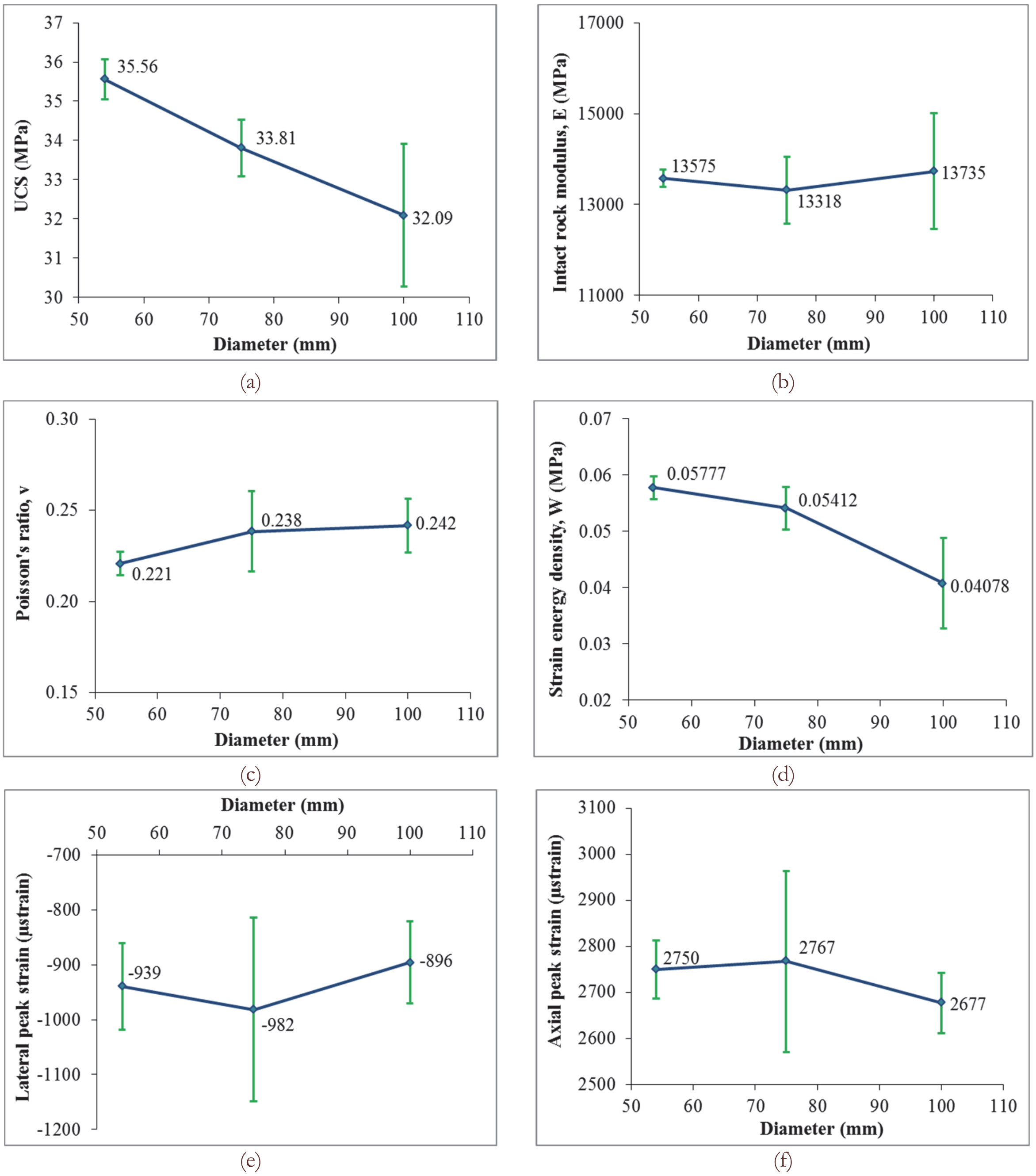



Figure 8: (a) Uniaxial compression strength, (b) Intact rock modulus, (c) Poisson's ratio, (d) Strain energy density, (e) Lateral peak strain and (f) Axial peak strain with respect to the diameters of the specimens.

Results from a typical circular disc specimen with diameter $D$=100 mm are presented in Fig. 9a-e. The difference between the strain values measured by the strain rosettes on opposite sides of the specimen is shown in Fig. 9b. This has also been observed in other experimental unpublished data by the authors and, currently, it is attributed to a number of experimental difficulties such as: material inhomogeneity, imperfections in the geometry of the disc specimens, which may result in eccentric loading of the discs through the steel jaws, as well as minute differences in the orientation and location of the strain gages with respect to the vertical axis and the center of the specimen respectively. Fig. 9c presents the curves constructed by averaging the respective curves in Fig. 9a; these are the values used in subsequent calculations. Fig. 9 d, e present the variation of the intact rock modulus and Poisson's ratio respectively (as calculated by eq. 2 and 3) with respect to the indirect tensile stress for the same specimen. Experimental values represented by these curves remain almost constant at about 50% of the indirect tensile strength.

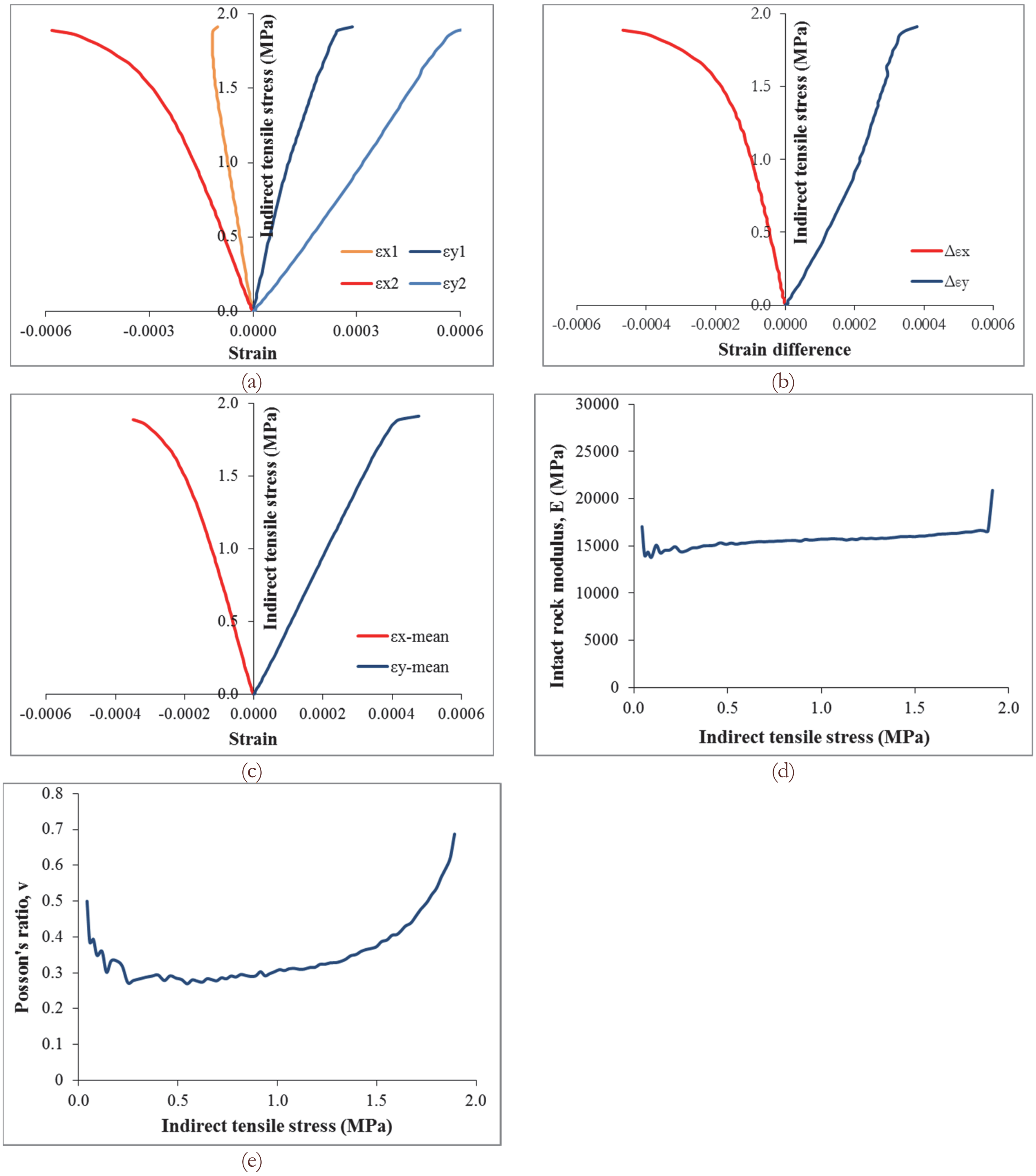


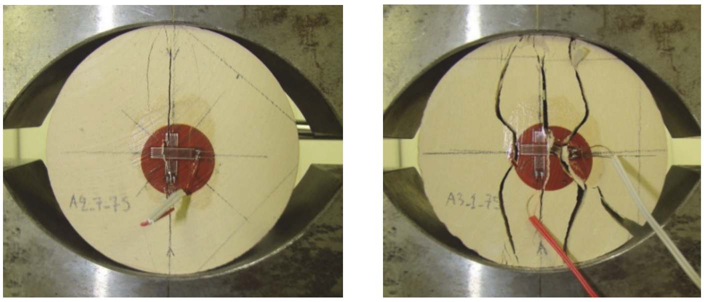

Figure 9: Typical diagrams for Brazilian tests. (a) Stress-strain curves from the two biaxial strain-gages, (b) Stress-difference strain curves from the two biaxial strain-gages, (c) Mean values stress-strain curves, (d) Intact rock modulus and (e) Poisson's ratio in correlation with the indirect tensile stress.

The issue of the different strain values measured on the opposite sides of the disc specimens is intriguing and a number of experimental options are currently being studied / explored by the authors in order to investigation this discrepancy. One way to reduce experimental errors due to utilization of strain gages is to use optical techniques such as the procedure of Digital Image Correlation (DIC) [23, 24] which does not depend on the accurate placement of measuring devices on each specimen. In order to investigate this issue, both sides of a specimen need to be monitored at the same time. An approach that would reduce specimen seating errors would be to conduct Brazilian tests where the disc specimens will be directly loaded by the loading platens of the compression testing frame (as specified by ASTM – D3967) where eccentric loading can be directly alleviated by the spherical seating of the upper compression platen.

| *D* [mm] | *t* [mm] | *Number of tests* | *Number of specimens with strain gages* | *Splitting tensile strength* $f_{st}$ [MPa] | | *Intact rock modulus* $E$ [MPa] | | *Poisson's ratio* $\nu$ | | *Shear modulus* $G$ [MPa] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *Average* [MPa] | *St. Dev.* [MPa] | *Average* [MPa] | *St. Dev.* [MPa] | *Average* | *St. Dev.* | *Average* [MPa] | *St. Dev.* [MPa] |
| 54 | 27 | 8 | 1 | 2.88 | 0.38 | 19100 | - | 0.333 | - | 7163 | - |
| 75 | 37.5 | 7 | 3 | 3.34 | 0.13 | 21300 | 7938 | 0.293 | 0.019 | 8269 | 3179 |
| 100 | 50 | 6 | 3 | 2.28 | 0.35 | 14422 | 713 | 0.290 | 0.033 | 5588 | 245 |

Table 3: The experimental results of the Brazilian tests for Alfas stone specimens loaded diametrically.

All specimens, for the Alfas stone, subjected to the Brazilian test, failed as expected by the underlying theory, i.e. by developing an extension fracture along the loaded diametral plane which is assumed to be the result of the induced tensile stress normal to the loaded plane (Fig. 10a). Furthermore, it was observed that in addition to the central primary crack, two symmetrical secondary cracks were developed (Fig. 10b). This behavior is in full agreement with the ideal fracture propagation according to Colback [25].



(a) (b)

Figure 10: (a) Center primary fracture plane. (b) Center primary fracture plane with typical secondary fractures.

### *Size effect for indirect tensile tests*

A total of 21 Brazilian tests were completed in order to investigate the size effect for the Alfas natural building stone under diametral compression. The mean values of rock properties are plotted against the diameter together with their standard deviation values (Fig. 11).

The variation of the splitting tensile strength with respect to specimen diameter is not a monotonic function. A clear maximum exists and corresponds to the specimens with $D$=75 mm (Fig.11a). A similar non-monotonic behavior has been observed by Kourkoulis [12] for the UCS of "Conchyliates" shell-stone, where the maximum value appears for the specimens with diameter $D$=100 mm. The author attributed this anomaly to the fact that "the specimen starts behaving as a structure rather than as a homogeneous material, since the size of the conches becomes well comparable to the characteristic size of the specimen". This non monotonic dependence of the UCS and the splitting tensile strength with respect to the diameter of the specimens is also mentioned by Vardoulakis et al. [26, 27] and Kaklis and Vardoulakis [21] for a more homogeneous stone, the Dionysos marble.

Although, both the Alfas building stone (investigated in this study) and Dionysos marble (investigated in previous studies) can be considered almost homogeneous materials and their typical grain size cannot be compared to the size of the specimens, nevertheless, they present this non-monotonic behavior. It is clear that additional research needs to be performed to reach definite conclusions regarding this non-monotonic behavior.

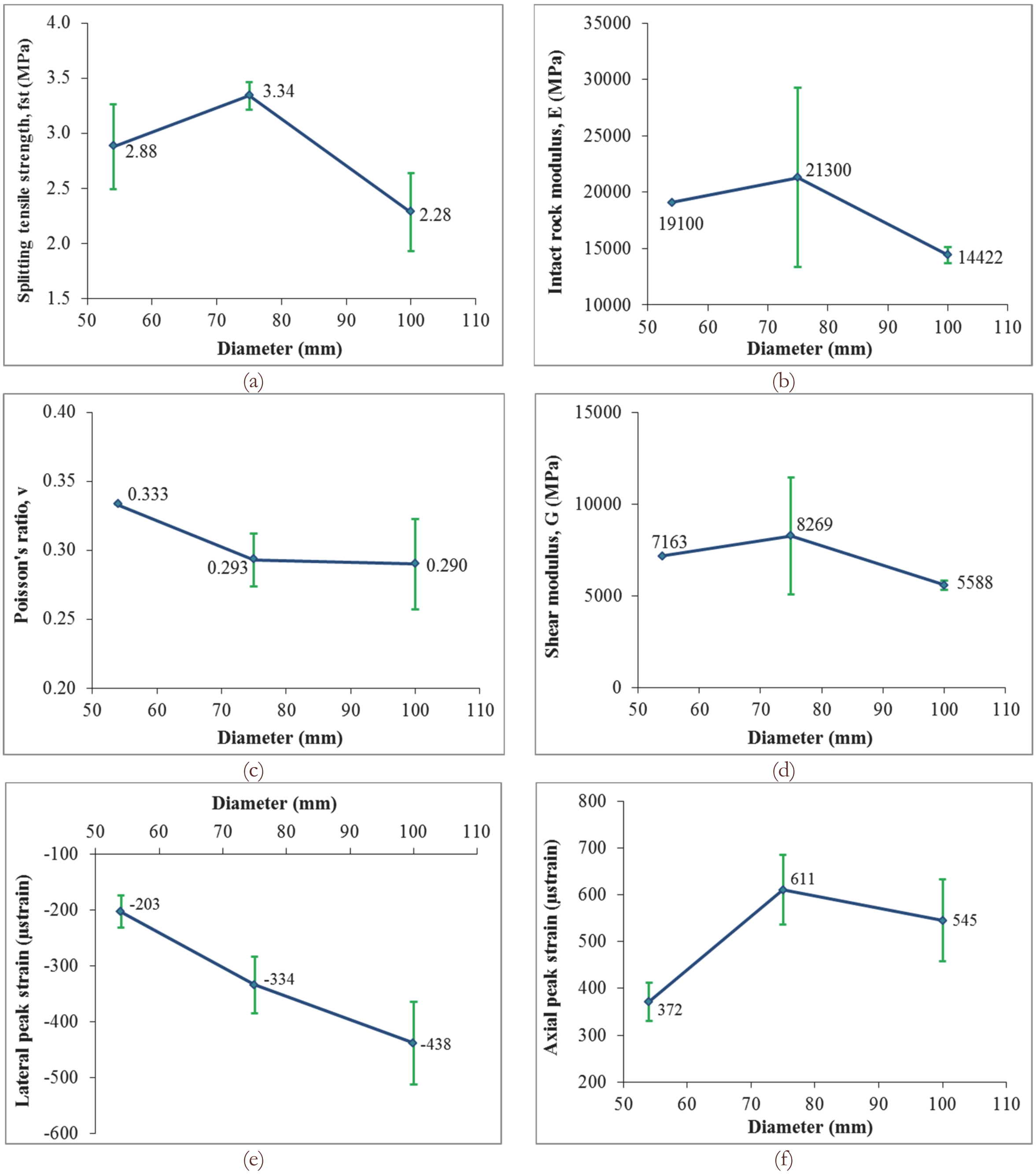



Figure 11: The dependence of (a) the splitting tensile strength, (b) the intact rock modulus, (c) Poisson's ratio, (d) the shear modulus, (e) the lateral peak strain and (f) the axial peak strain on the diameter of the specimens.

## *Discussion and Additional Considerations*

As previously mentioned the so called "size effect" must depend on the bulk material (volume) of the specimen and its limits (external surface) that are exposed to different stress/strain states (plane-stress, plane-strain or triaxial) as well as other factors such as environmental, specimen machining factors, etc. It implies that comparisons must be performed in classes of geometrically self-similar specimens. Consequently, different "shapes" of specimens cannot be compared. This is demonstrated from Fig. 8a and 11a where a qualitatively different behavior of strength is obtained. At the same time, it seems that the size effect may not a material property, but a specimen characteristic and the "law of 3/2", i.e. the ratio (volume)/(external surface), which in the present case reduces to specimen diameter *D*, may be an over-simplification.

This issue requires a long discussion which is outside the scope of this paper.
For comparison, the obtained Alfas stone UCS data were plotted on the diagram published by Hoek and Brown [28] as shown in Fig. 12. Although the range of specimen diameters does not cover a very wide range, the selected core diameters represent typical core sizes using in geotechnical testing practice.

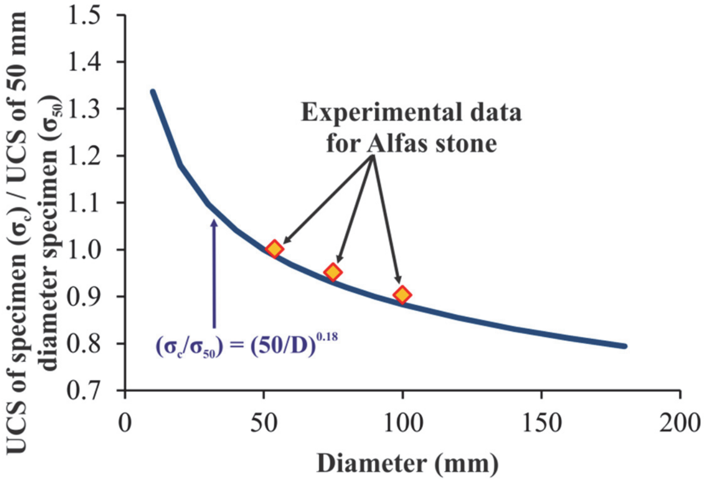


Figure 12: Relationship between UCS and specimen size plotted as dimensionless values [28].

The values of UCS for the Alfas stone that were determined experimentally, are in full agreement with the following formula published by Hoek and Brown [28]:

$$\frac{\sigma_c}{\sigma_{50}} = \left(\frac{50}{D}\right)^{0.18} \tag{4}$$

where $\sigma_c$ is the calculated UCS measured on the specimen and $\sigma_{50}$ is the calculated UCS of a 50 mm diameter specimen.
Furthermore, Kaklis and Vardoulakis [21] suggest that for Dionysos marble the dependence of the splitting tensile strength to specimen size, seems to follow Carpinteri's fractal law [29] which advocates the formation of a fractal fracture manifold.
By observing typical crack patterns generated during specimen failure in the current investigation (see examples in Fig. 6) it is evident that specimen spalling and axial splitting rather than specimen shearing may be the predominant failure modes for the Alfas stone. Both axial splitting and spalling failure modes are related to indirect tensile failure. Fig. 13 presents the variation of the uniaxial compressive strength with the specimen diameter of Alfas stone in a double logarithmic plot. The correlation coefficient of the trend line presented in Fig. 13 is almost 100% which suggests that a similar fractal law may apply for uniaxial compression, when splitting can be considered a predominant failure mechanism. The exponent $n$ in the scaling law for the case of Alfas stone is $n = 2.668$, based on the procedure detailed in [21]. A similar correlation for the Brazilian tests is not attempted since the variation of the indirect tensile strength with specimen diameter exhibits a non-monotonic behavior.

## CONCLUSIONS

This paper presents experimental results and correlations on the mechanical behavior of the Alfas stone for a range of uniaxial compression and indirect tension tests. A total of 18 cylindrical specimens and 21 Brazilian disc specimens were tested for three different diameters ($D$=54, 75 and 100 mm). Many specimens where fully instrumented with strain gages to fully capture the deformational characteristics of each test. In addition, the dependence of the mechanical parameters on the size of the specimens was investigated.

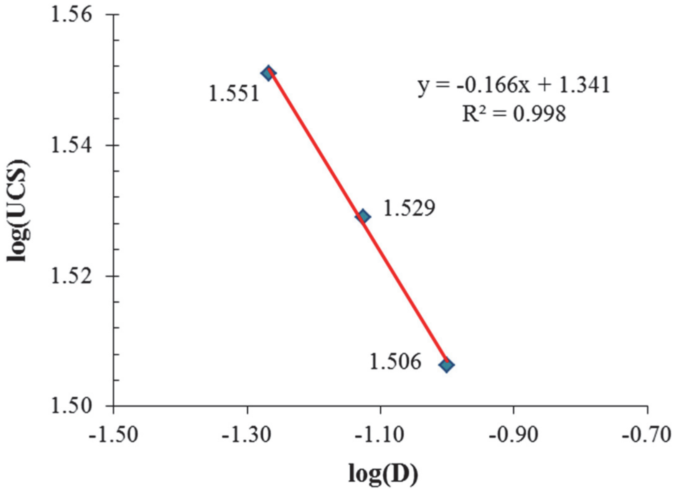



Figure 13: Variation of the UCS with the specimen diameter.

Results show that almost all the mechanical parameters used to describe the behavior of the building stone depend on the size of the specimens, with the exception of the intact rock modulus and Poisson's ratio which appear to be constant with varying specimen diameters. The values of UCS for the Alfas stone that were experimentally determined are in full agreement with the formula published by Hoek and Brown [28]. In addition, an almost perfect linear correlation between UCS and diameters in a double logarithmic chart was developed, which indicates that when specimen spalling and axial splitting rather than specimen shearing is the predominant failure mode, the dependence of UCS to specimen size may follow Carpinteri's fractal law [29].
Furthermore, experimental results indicate that the splitting tensile strength of Alfas stone is not a linear function of the specimen diameter, but it exhibits a non-monotonic pattern. Although this non-monotonic behavior has also been previously presented in the literature [12], it is clear that additional research needs to be performed to reach definite conclusions regarding the dependence of the splitting tensile strength to specimen diameter.

## ACKNOWLEDGEMENTS

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