EXPERIMENTAL INVESTIGATION OF THE SIZE EFFECT ON THE MECHANICAL PROPERTIES ON TWO NATURAL BUILDING STONES

Konstantinos N. Kaklis[1], Stelios P. Maurigiannakis[1], Zacharias G. Agioutantis[1,2] , Foteini K. Stathogianni[1] and Emmanouil K. Steiakakis[1]

[1]School of Mineral Resources Engineering
Technical University of Crete
Chania, GR-73100, Greece
[2] Department of Mining Engineering
University of Kentucky
Lexington Kentucky, 40506, USA

Keywords: Porolithos, Alfas, Building stones, Uniaxial compressive strength, Indirect tensile strength, Size effect.

Abstract. *This paper focuses on the experimental investigation of the mechanical properties of two natural building stones: Porolithos and Alfas. 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 of these materials. 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 which were appropriately attached on each specimen.*

1 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.

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 in his book 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. 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 test and the 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 should 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 machine axial loads and the localized concentrated stresses caused by improper gripping of specimens [3,4].

Because of these experimental difficulties, alternative techniques were developed to determine the tensile strength of rock. The Brazilian test uses a circular solid disc, which 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. 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].

The scale effect is well known for these tests and there are number of studies in the literature [11,12,13,14]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.

It should be noted that the so-called “scale effect” is split up into two categories: shape and size. The shape effect describes the impact of variation of 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., diameter) of the specimen where the height/diameter ratio remains constant [15].

This paper presents the effect of the size on UCS, indirect tensile strength, intact rock modulus and Poisson’s ratio for the Alfas and Porolithos building stones. The term “intact rock modulus” is used here instead of elastic modulus, in order to differentiate the modulus of intact rock to the deformation modulus of the rock mass.

2 TESTING MATERIALS

In order to experimentally examine the size effect on the uniaxial compressive and indirect tensile strength, specimens of Alfas and Porolithos building stones were tested. The Alphas 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 Porolithos stone is a bioclastic micritic limestone and it is composed by 99% of calcite ($CaCO_3$) and 1% of quartz (SiO_2).Horizons with different mechanical characteristics are evident within the Porolithos stone (Fig. 1).

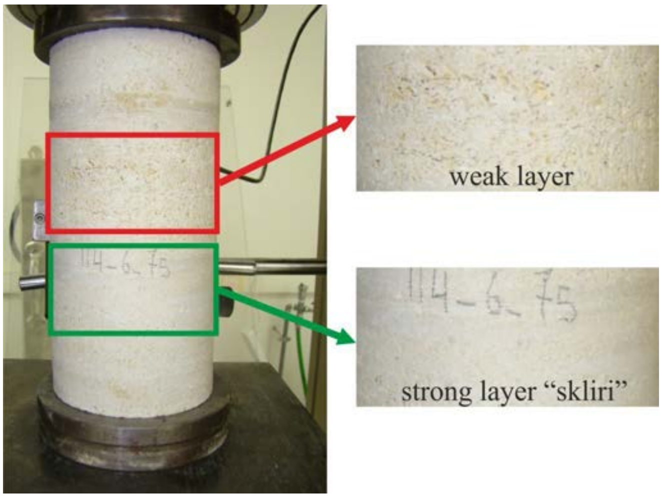


Figure 1. Horizons with different mechanical characteristics evident in a cylindrical specimen of the Porolithos stone.

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 apparent density is based on standard BS EN 1936 (2006)[18]. The average results of Alfas and Porolithos stones are shown in Table 1.

Building stone	Water Absorption (%)	Open Porosity (%)	Apparent Density (kg/m^3)
Alfas	12.19 (±0.61)	31.48 (±3.20)	2870 (±355)
Porolithos	3.97 (±1.09)	17.92 (±1.58)	2653 (±85)

Table 1. Physical properties of the Alfas and Porolithos stones.

3 EXPERIMENTAL TESTS

3.1 Uniaxial compression test

In uniaxial compression tests a cylindrical specimen of diameter *D* and height *h* is subjected to a uniformly applied load *P*, acting on the ends of the specimen (Fig. 2a), 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. 2b).

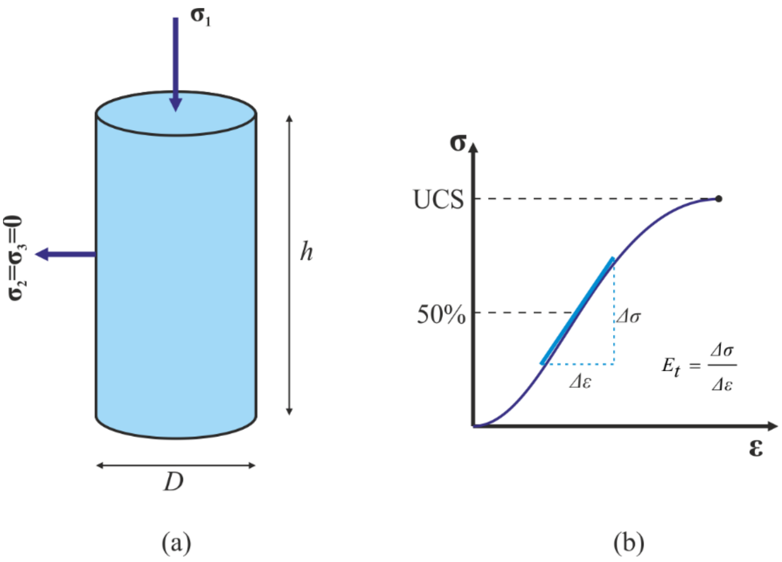


Figure 2. (a) Uniaxial compression test. (b) Stress-strain curve and the calculation of the tangent intact rock modulus.

3.2 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. 3a). The angle subtended at the center of the disc by the loaded section of the rim is equal to 2α. If the material behavior is assumed to be linear elastic, this geometry and loading ensures a nearly uniform tensile stress state in the center plane of the specimen (Fig. 3b). 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 at failure is a measure of the tensile strength:

$$\sigma_{\max} = \frac{2P}{\pi D t} \tag{1}$$

where P is the applied load.

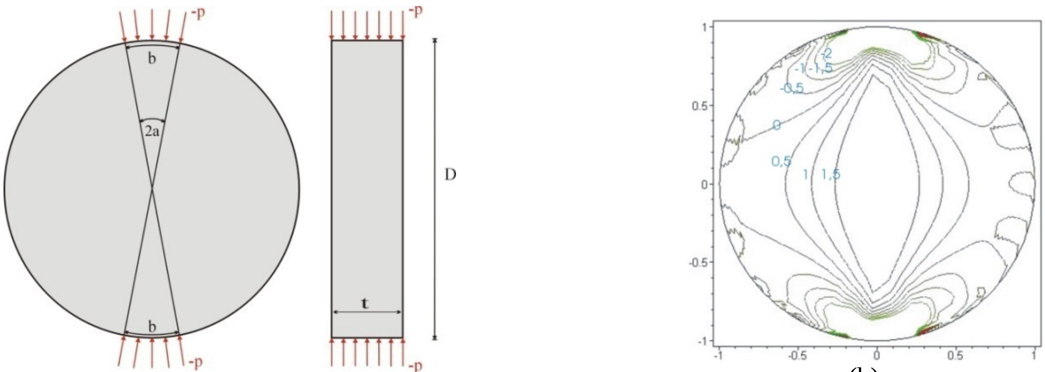
This maximum tensile stress at failure is a material property called splitting tensile strength f_{st}:

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

where P_f is the failure load.

Using measurements from electrical strain gages (ε_{xx}, ε_{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]:

$$E = \frac{16P}{\pi D t}\frac{1}{\varepsilon_{yy}\left(3+\dfrac{\varepsilon_{xx}}{\varepsilon_{yy}}\right)}, \quad \nu = -\frac{1+3\left(\dfrac{\varepsilon_{xx}}{\varepsilon_{yy}}\right)}{3+\left(\dfrac{\varepsilon_{xx}}{\varepsilon_{yy}}\right)} \tag{3}$$



(a) (b)

Figure 3. (a) Load configuration of the Brazilian test, (b) Distribution of the horizontal Stress Concentration factor $q_{xx}=\sigma_{xx}/(p\mathrm{a}/\pi)$ calculated from the theory of elasticity [21].

4 EXPERIMENTAL PROCEDURE

An appropriate number of block samples for Alfas and Porolithos stone were collected from the quarry near the Alfas village in Rethymnon, Crete, and subsequently carefully checked to ensure the homogeneity of the materials, the rift plane of Porolithos stone and the absence of visible weaknesses. The size of these blocks was 25x30x30 cm.

The Alfas stone is considered an isotropic material and, therefore, the orientation of the specimens is not taken into account. However, the specimens of the Porolithos stone were prepared by coring specimens out of Porolithos cubes normal to the plane of transverse isotropy (Fig. 4) in order to avoid variations in strength values which could result from testing specimens with different orientations of the transverse plane.

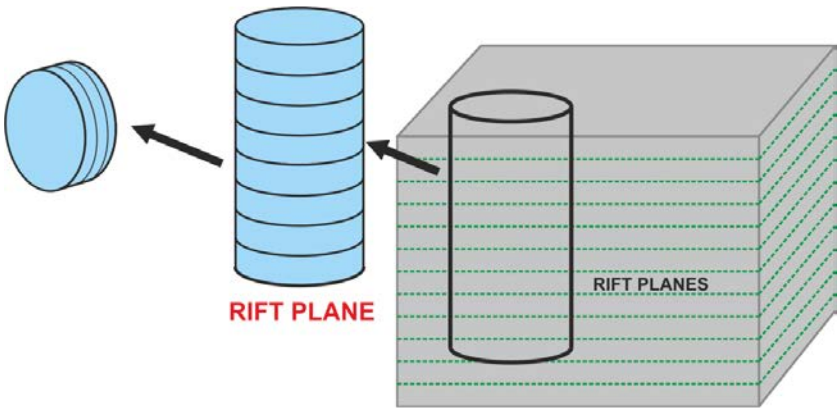
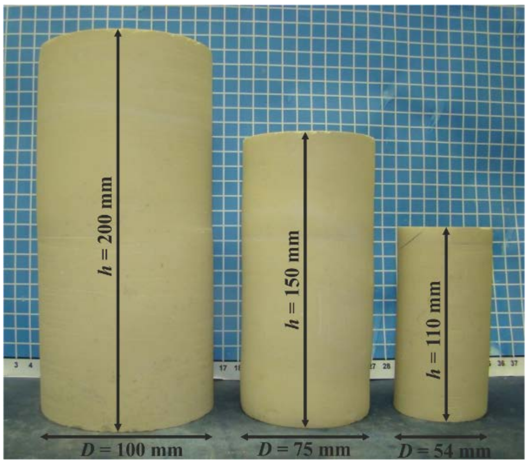


Figure 4.The orientation of the Porolithos specimens. The plane perpendicular to the symmetry axis of the cylindrical specimens is parallel to the plane of transverse isotropy (rift planes).

Three sets of cylindrical specimens and circular discs were prepared according to the ISRM specifications [19,22] for the uniaxial compression and Brazilian test respectively, both for Alfas and Porolithos stones (Fig. 5 and Fig. 6).The height *h* to diameter *D* ratio for the uniaxial compression test and 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 mm, *D*=75 mm and *D*=100 mm.

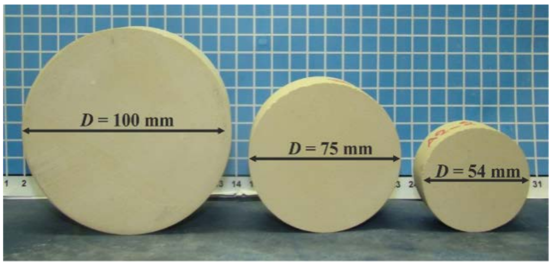
In order to measure the axial and lateral displacements, three biaxial 0/90 strain-gages were appropriately attached at 120^{o}to each other on the curved surface of the cylindrical specimens. The use of three strain gages was deemed appropriate in order to check the symmetry of the loading. On the circular discs for the Brazilian test, two strain-gages were attached at the center of each of the two flat surfaces of each disc.



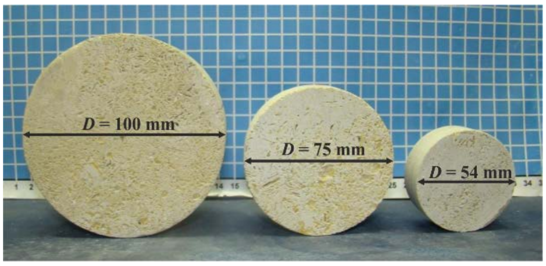
(a)

(b)

Figure 5. A series of cylindrical specimens with different diameters for (a) Alfas stone and (b) Porolithos stone.



(a)



(b)

Figure 6. A series of discs with different diameters for (a) Alfas stone and (b) Porolithos stone.

Load was applied using a stiff 1600 kN MTS hydraulic testing machine and a 500 kN load cell. The load was applied with a loading rate of 3 kN/s for the uniaxial compression tests and of 200 N/s for the Brazilian tests under load control mode for all experiments.

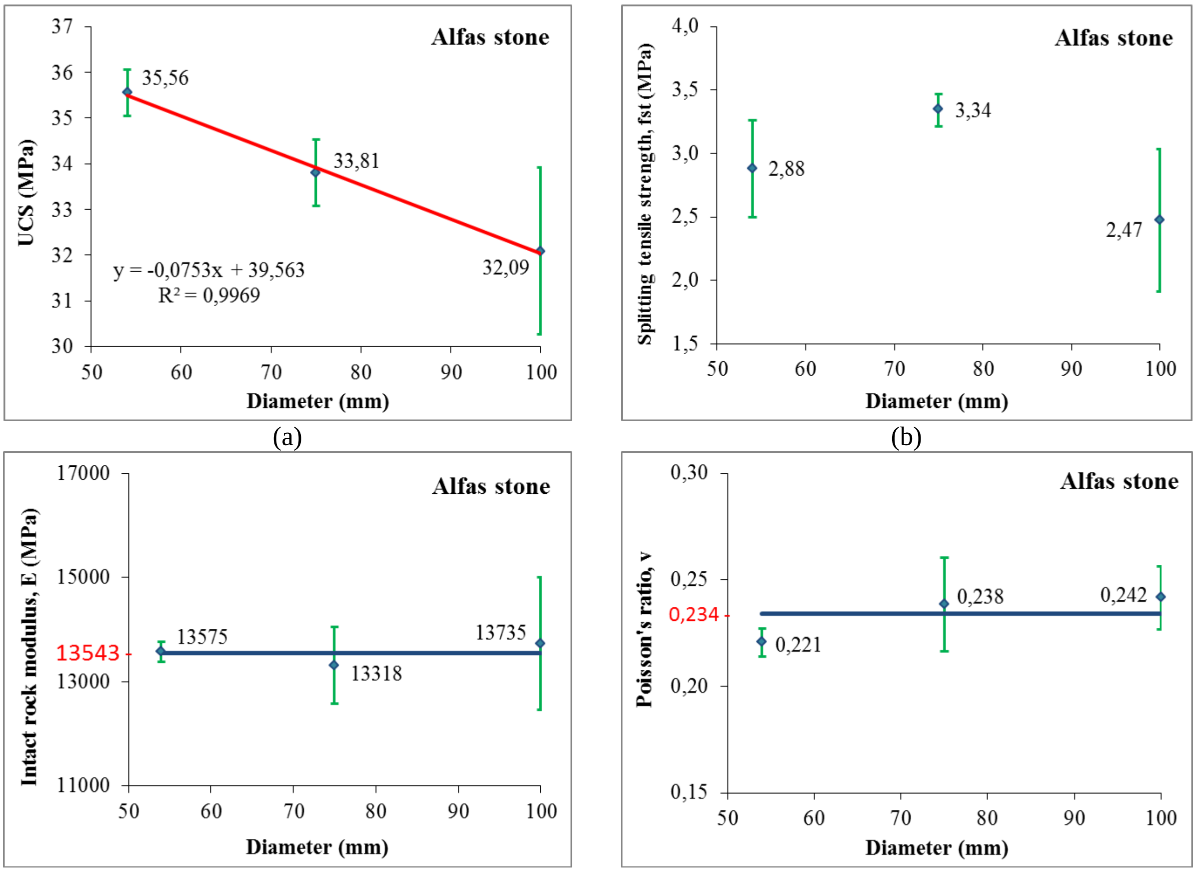
4 EXPERIMENTAL RESULTS

4.1 Size effect

In the present work a total of 35 uniaxial compression tests and 37 Brazilian tests were completed, including both Alfas and Porolithos building stones in order to investigate the size effect. Indicative results are presented in Fig. 7 and Fig. 8 for the Alfas and Porolithos stones respectively. Mean values of rock properties are plotted against the diameter together with their standard deviation values.

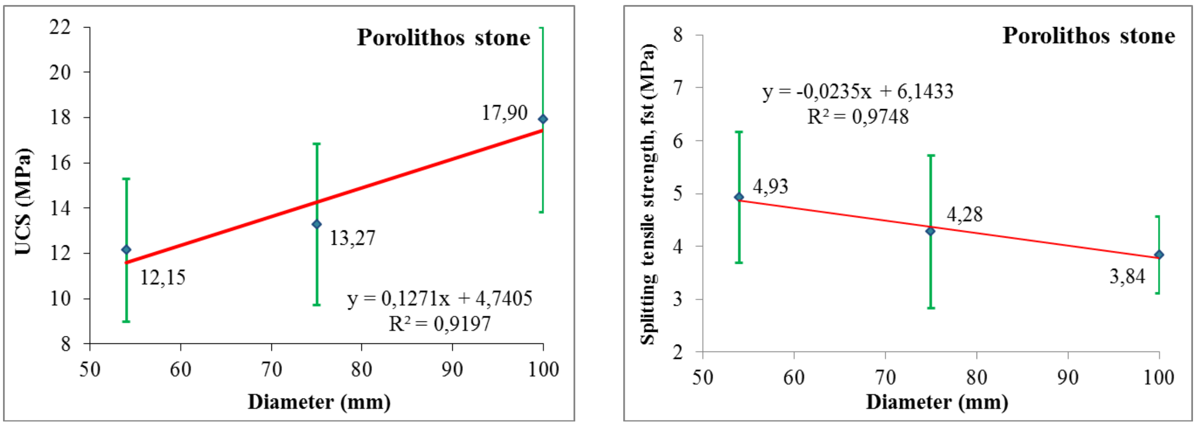
For the Alfas stone, Fig. 7a shows clearly that UCS decreases as the diameter increases. A difference between the UCS for the specimens with D=54 mm and D=100 mm is observed, which is up to 11%. The variation of the splitting tensile strength is not a monotonous function versus the diameter. A clear maximum exists and corresponds to the specimens with D=75 mm (Fig.7b).

Fig.7c and Fig.7d 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.



(c) (d)

Figure 7. (a) Uniaxial compression strength, (b) Splitting tensile strength, (c) Intact rock modulus and (d) Poisson's ratio of Alfas stone in correlation with the diameter.



(a) (b)

Figure 8. (a) Uniaxial compression strength and (b) Splitting tensile strength of Porolithos stone in correlation with the diameter.

On the other hand, Fig. 8a shows clearly that UCS increases as the diameter size of Porolithos stone specimens increases. A remarkable difference between the UCS for specimen size *D*=54 mm and *D*=100 mm is observed, which is up to 32%. The splitting tensile strength changes monotonously versus the diameter and decreases as the diameter increases. The difference in the calculated f_{st} is up to 22% (Fig.8b). Results for the intact rock modulus and Poisson's ratio for the Porolithos stone are not presented because they are very erratic due to the presence of the weak zones in the specimens.

4.2 Mode of fracture

Three different failure modes were observed during the uniaxial compression tests of Alfas stone. Some specimens failed along single shear planes (Fig. 9a), others failed in axial splitting (Fig. 9b) while a third group failed along conjugates shear planes (Fig. 9c).

As already discussed, the Porolithos stone specimens were banded with zones of different mechanical properties (although the mineralogical composition was the same between zones). As a result, failure of the cylindrical Porolithos stone specimens mainly occurred in the region of the weak zone (layer) as shown in Fig. 10.

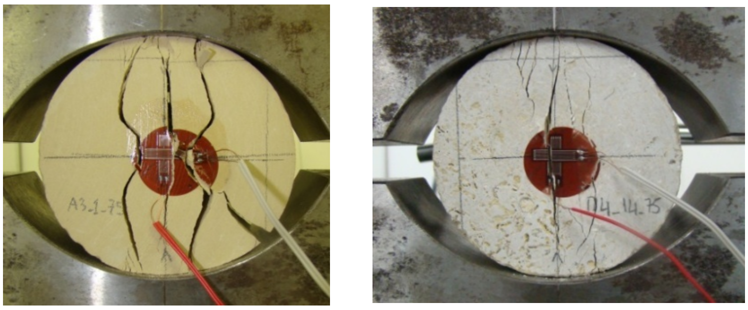
(a) (b) (c)

Figure 9.Typical crack patterns in Alfas cylindrical specimens. (a)Shear plane failure (b)Axial splitting failure (c)Failure on conjugates shear planes.

(a) (b)

Figure 10.Typical mode of fracture in Porolithos cylindrical specimens.

All specimens, for both the Alfas and Porolithos stones, 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. 11). Furthermore, in the case of Alfas circular discs it was observed that in addition to the central primary crack, two symmetrical secondary cracks were developed (Fig. 11a). This behavior is in full agreement with the ideal fracture propagation according to Colback [23].



(a) (b)

Figure 11.(a) Center primary fracture plane with typical secondary fractures in Alfas circular disc. (b) Center primary fracture plane in Porolithos circular disc.

5 CONCLUSIONS

The mechanical behavior and failure of the Alfas and Porolithos stone under uniaxial compression and indirect tension, as well as the dependence of their mechanical parameters on the size of the specimens were studied in the present work. It was concluded that almost all the mechanical parameters used to describe the behavior of the building stones 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.

Furthermore, experimental results indicate that the splitting tensile strength of Alfas stone is not a linear function of the diameters, but it exhibits a non-monotonous pattern. In addition, the UCS of the Porolithos stone is shown to increase as diameter increases. As the Porolithos stone specimens cannot be considered homogeneous and isotropic, experimental results illustrate that rock properties may be different than expected when materials substantially deviate from being homogeneous and isotropic.

For comparison, the obtained Alfas stone UCS data was plotted over the published diagram of Hoek and Brown [24] as shown in Fig. 12. Although the range of specimens tested during the experimental procedure described in this paper is not very wide, the selected core diameters represent typical core sizes for geotechnical testing practice.

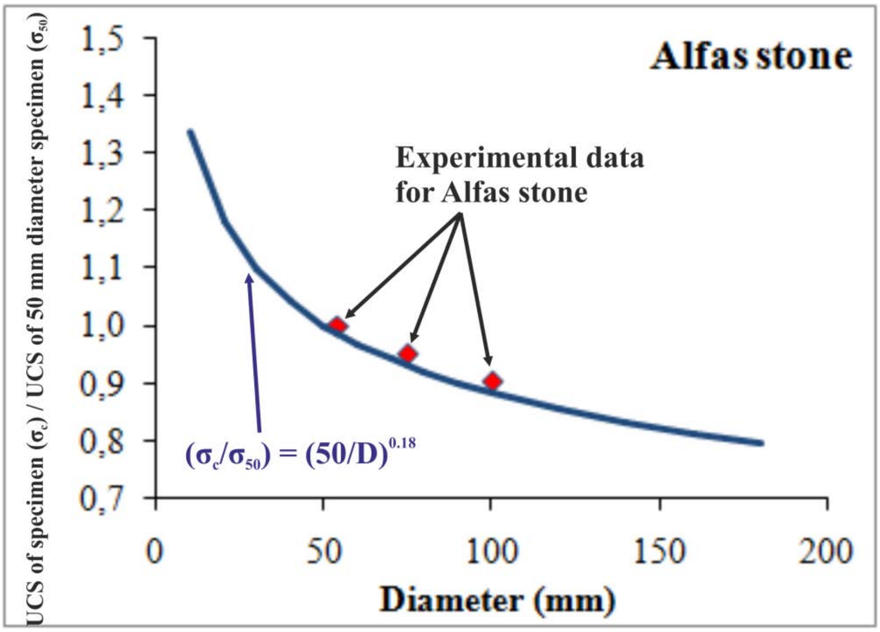


Figure 12. Relationship between UCS and specimen size plotted as dimensionless values [24].

The values of UCS for the Alfas stone that were experimentally determined are in full agreement with the following formula published by Hoek and Brown [24]:

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

where σ_c is the calculated UCS measured on the specimen and σ_{50} is the calculated UCS of a 50 mm diameter specimen.

Finally, more experimental work needs to be performed to reach definite conclusions regarding the size effect for the Alfas and Porolithos natural building stones.

ACKNOWLEDGEMENTS

This research has been co-financed by the European Union (European Social Fund-ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: THALES: Reinforcement of the interdisciplinary and/or inter-institutional research and innovation.

REFERENCES

[1] Dufour, F. (2007), "Size effect in geomaterials", *Revue Europénne de Génie Civil*. Vol. 11, Issue 7-8, pp. 963-975.

[2] Weibull, W. (1939), "A statistical theory of the strength of materials", *Royal Swedish Academy of Eng. Sci. Proc.*, No 151, pp. 1-45.

[3] Barla, G. and Goffi, L. (1974), "Direct tensile testing of anisotropic rocks",*Proceedings of the Third International Congress of Rock Mechanics*, Vol. **2**, Part A, Denver, pp.93-98.

[4] Nova, R. and Zaninetti, A. (1990), "An investigation into the tensile behavior of a schistose rock", *International Journal of Rock Mechanics and Mining Sciences &Geomechanics Abstracts*, Vol.**27**, pp. 231-242.

[5] Hondros, G. (1959), "The evaluation of Poisson's ratio and the modulus of materials of a low Tensile resistance by the Brazilian (indirect tensile) test with particular reference to concrete",*Australian Journal of Applied Science*, Vol. 10, pp. 243-264.

[6] Pinto, J.L. (1979), "Determination of the elastic constants of anisotropic bodies by diametral compression tests",*Proceedings of the Fourth ISRM Congress*, Montreux, Vol. 2, pp. 359-363.

[7] Amadei, B., Rogers, J.D. and Goodman, R.E. (1983), "Elastic constants and tensile strength of anisotropic rocks",*Proceedings of the Fifth ISRM Congress*, Melbourne, pp. A189-A196.

[8] Amadei, B. (1996), "Importance of anisotropy when estimating and measuring in situ stresses in rock",*International Journal of Rock Mechanics and Mining Sciences &Geomechanics Abstracts*, Vol. 33, pp. 293-325.

[9] Chen, C.S., Pan, E. and Amadei, B. (1998), "Determination of deformability and tensile strength of anisotropic rock using Brazilian tests",*International Journal of Rock Mechanics and Mining Sciences &Geomechanics Abstracts*, Vol. 35, pp.43-61.

[10] Exadaktylos, G.E. and Kaklis, K.N. (2001), "Applications of an explicit solution of the transversely isotropic circular disc compressed diametrically", *International Journal of Rock Mechanics and Mining Sciences*, Vol. 38, Issue 2, pp.227-243.

[11] Kourkoulis, S.K. (2011), "An experimental study of the mechanical behaviour of the 'Conchyliates' shell-stone: some irregularities of the size effects", *Strain, An International Journal for Experimental Mechanics*, Vol. 47, Issue 1, pp. e344-e356.

[12] Kourkoulis, S.K. and Ganniari-Papageorgiou E. (2010), "Experimental study of the size- and shape-effects of natural building stones", *Construction and Building Materials*, Vol. 24, Issue 5, pp. 803-810.

[13] Viso, J.R., Carmona, J.R. and Ruiz, G. (2008), "Shape and size effects on the compressive strength of high-strength concrete", *Cement and Concrete Research*, Vol. 38, pp. 386-395.

[14] Yi, S.T., Yang, E.I. and Choi, J.C. (2006), "Effect of specimen sizes, specimen shapes, and placement directions on compressive strength of concrete", *Nuclear Engineering and Design*, Vol. 236, pp. 115-127

[15] Thuro, K., Plinninger, R.J., Zah, S. and Schutz, S. (2001), "Scale effects in rock strength properties. Part 1: Unconfined compressive test and Brazilian test",*ISRM Regional Symposium, EUROCK 2001, Rock Mechanics - a Challenge for Society*, Espoo, Finland, 3-7 June 2001, pp. 169-174.

[16] Rietveld, H.M., (1969) "A profile refinement method for nuclear and magnetic structures", Journal of applied crystallography, Vol. 2, pp. 65-67.

[17] BS EN 13755 (2008) "Natural stone test methods. Determination of water absorption at atmospheric pressure", British Standards Institution.

[18] BS EN 1936 (2006) "Natural stone test methods. Determination of real density and apparent density, and of

total and open porosity", British Standards Institution.

[19] Bieniawski, Z.T. and Bernede, M.J. (1979), "Suggested methods for determining the uniaxial compressive strength and deformability of rock materials". *International Journal of Rock Mechanics and Mining Sciences &Geomechanics Abstracts*,Vol. 16, Issue 5, pp. 135-140.

[20] Kaklis, K.N. and Exadaktylos, G.E.(2006), "A strain gage method for the determination of the elastic parameters in a transversely isotropic disc on Dionysos marble", *5th Hellenic Conference on Geotechnical and Geoenviromental Engineering*, Xanthi, Greece, 31 May - 2 June 2006, Vol. 1, pp. 103-110.

[21] Kaklis, K.N. and Vardoulakis, I. (2004). "An experimental investigation of the size effect in indirect tensile test on Dionysos marble", *Proceedings of the 7th National Congress on Mechanics*, Chania, Greece, Vol. 2, pp. 151-157.

[22] Bieniawski, Z.T. and Hawkes, I. (1978), "Suggested methods for determining tensile strength of rock materials",*International Journal of Rock Mechanics and Mining Sciences &Geomechanics Abstracts*, Vol. 15, Issue 3, pp. 99-103.

[23] Colback P.S.B. (1967), "An Analysis of Brittle Fracture Initiation and Propagation in the Brazilian Test", *Proc. First Congress International Society of Rock Mechanics*, pp. 385-391.

[24] Hoek, E. and Brown, E.T. (1980), *Underground excavations in rock*, Inst. Min. Metall., Chapman & Hall, London.