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

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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 schistose 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 (CaCO₃), 2% of quartz (SiO₂) and 7% aragonite (CaCO₃). The Porolithos stone is a bioclastic micritic limestone and it is composed by 99% of calcite (CaCO₃) and 1% of quartz (SiO₂). 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.](image)

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.

<table>
<thead>
<tr>
<th>Building stone</th>
<th>Water Absorption (%)</th>
<th>Open Porosity (%)</th>
<th>Apparent Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfas</td>
<td>12.19 (±0.61)</td>
<td>31.48 (±3.20)</td>
<td>2870 (±355)</td>
</tr>
<tr>
<td>Porolithos</td>
<td>3.97 (±1.09)</td>
<td>17.92 (±1.58)</td>
<td>2653 (±85)</td>
</tr>
</tbody>
</table>

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 $2\alpha$. 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:

$$\sigma_{\text{max}} = \frac{2P}{\pi Dt}$$

where $P$ is the applied load.

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

$$f_{st} = \frac{2P_f}{\pi Dt}$$

where $P_f$ is the failure load.

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]:

$$E = \frac{16P}{\pi Dt} \frac{1}{\varepsilon_{yy}} \left( 3 + \frac{\varepsilon_{xx}}{\varepsilon_{yy}} \right), \quad \nu = -\frac{1 + 3 \left( \frac{\varepsilon_{xx}}{\varepsilon_{yy}} \right)}{3 + \left( \frac{\varepsilon_{xx}}{\varepsilon_{yy}} \right)}$$
4 EXPERIMENTAL PROCEDURE

An appropriate number of block samples for Alfas and Porolithos stone were collected from the quarry near the Alfαs 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.

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°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.
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 $\nu=0.234$, respectively.
Konstantinos N. Kaklis, Stelios P. Maurigiannakis, Zacharias G. Agioutantis, Foteini K. Stathogianni and Emmanouil K. Steiakakis

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.

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.

![Figure 9](image1.jpg)
**Figure 9.** Typical crack patterns in Alfas cylindrical specimens. (a) Shear plane failure (b) Axial splitting failure (c) Failure on conjugates shear planes.

![Figure 10](image2.jpg)
**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].
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.

![Alfas stone diagram](image)

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]:

\[ \frac{\sigma}{\sigma_{30}} = (50/D)^{0.18} \]
\[
\frac{\sigma_c}{\sigma_{50}} = \left( \frac{50}{D} \right)^{0.18}
\]

where \(\sigma_c\) is the calculated UCS measured on the specimen and \(\sigma_{50}\) 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.

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total and open porosity”, British Standards Institution.


