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Experimental study of the size- and shape-effects of natural building stones

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Dedicated to the memory of the late
Professor Ioannis Vardoulakis

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ABSTRACT

The dependence of the mechanical properties of natural building stones on the size and the shape of the specimens is studied experimentally. Attention is focused to the Kefalonia porous stone, a candidate substitute of the Kenchreae porous stone used by ancient Greeks for the erection of the Epidaurean Asklepieion. Series of uniaxial compression tests were carried out using both cubic and cylindrical specimens of various sizes. A number of mechanical properties were determined including the peak stress, the modulus of elasticity, the stress drop after the peak stress, the peak strain and the strain energy density up to the peak load. A strong dependence of the above properties on both the dimensions and the shape of the specimens was concluded. In addition, it was indicated that the dependence of some of the above properties on the size of the specimens is not monotonous. The conclusions drawn are in good agreement with similar ones obtained for Dionysos marble, the material used today for the restoration of the Parthenon temple of Athens as well as for the "Conchyliates" shell-stone the material that has been used for the construction of the Zeus Temple at Olympia.

1. Introduction

Restoring a monument is a complicated multidisciplinary scientific task. Series of problems, varying from elementary ones (strength and deformability of the materials) to rather complex ones (preservation of the structural system, determination of the minimum interventions, their reversibility and of course their durability) are to be considered and solved before decisions are reached. Archaeologists, architects and civil engineers collaborate in order to meet the final target, the extension of the life of the monument. The final decisions are usually a compromise between various, and often contradictory, points of view.

The structural stability of the monument is, of course, the most important among the problems of the experts working for the restoration (although sometimes it is outweighed in public perception by the aesthetics of the surface of the stone Fig. 1 [1]). The problem is exacerbated in case large fragments of structural elements, or whole elements of the structure, are missing and have to be replaced. The ideal solution is to have access to the source of the authentic material. Unfortunately this is the exception rather than the rule. In most cases there are no known functioning quarries of the desired material or the areas of the ancient quarries have been built over. In such a case, a new stone has to be chosen as a substitution material. The substitution stone and the authentic one should react similarly to environmental influences, natural wear and weathering and mechanical loads.

This paper focuses on some aspects of the mechanical behaviour of such a stone, the porous stone of Kefalonia, which is considered as a candidate substitute for the Kenchreae porous stone, the material used by ancient Greeks for building the Epidaurean Asklepieion, the most celebrated healing centre of the ancient world [2]. The authority and radiance of Asklepios, the healer god of antiquity, brought to the sanctuary financial prosperity, which in the 4th and the 3rd centuries BC enabled the implementation of an ambitious program aimed at housing the worship in monumental buildings. The extensive remains of the site have been brought to light during excavations conducted since the late 19th century to the present day. The study of the Kefalonia stone is associated with the restoration project in progress of three monuments of the Asklepieion, namely the circular building of Tholos (the healing god's assumed subterranean dwelling place), the Avaton or Enkoimeterion (a large stoa used for the incubation and cure of the sick) and the Propylon of the Gymnasium (a building complex used for the sacred meals). All three follow the same construction principles regarding the choice of material. Their foundations are built of the locally available weak calcareous conglomerate, known as "*foundation porous stone*".

The comparative study of the original material of the monuments and the substitute one dictates the size of the specimens:

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Fig. 1. An overview of a restored pillar from Avaton of the Epidauros Archaeological site, exhibiting the coexistence of ancient (Kenchreae porous stone) and new material [1].

They must be as small as possible since for obvious reasons it is not permitted to prepare large specimens from the original stones. Unfortunately it is common knowledge that the mechanical properties and the values of the mechanical constants of most building materials depend on the size and the shape of the specimens and this dependence is not yet fully understood. In this direction an experimental study was undertaken to enlighten some aspects of these phenomena for the Kefalonia porous stone and draw some conclusions that could be of help for the engineers involved in the restoration project of the Epidauros monuments, who are dealing with structural elements the dimensions of which are at least one order of magnitude larger than those of the laboratory specimens.

2. The size- and the shape-effects

The geometry and the shape of the specimens proposed by standards for the determination of the compressive strength of brittle geomaterials differ concerning both their shape and size. The specimens most often used are either cylindrical or cubic. The dependence of the compressive strength on the shape of the specimens has been widely studied and various empirical formulae have been proposed for the relation between the strength obtained from specimens of these geometries. In addition it is known that the nominal strength of structures changes by scaling their size. This phenomenon was already observed by Leonardo da Vinci who concluded that "*if two ropes have the same thickness the longest is the weaker*" [3]. However, it was only at the beginning of the 20th century when quantitative results for the dependence of the nominal strength of glass fibers on their diameter were published by Griffith [4]. This dependence is caused by the dimensional inhomogeneity between the stress ($[F][L]^{-2}$) and the stress intensity factor ($[F][L]^{-3/2}$), which leads to a $-1/2$ constant slope of the graph of the nominal strength versus the structural size in a bilogarithmic diagram [5].

From this point on and for half a century the size effect was attributed to the statistical nature of the distribution of flaws within a structure and it was described by the "weakest-link" concept introduced by Fisher and Tippett [6] and developed by Weibull [7]. A non-statistical approach did not appear until early 1970s when Walsh [8] published results that could not be described by purely statistical approaches. This discrepancy and similar ones observed experimentally for other materials placed limitations to the use of the statistical approach. The main scepticism was that the power law of the Weibull theory for the nominal strength implies the absence of any characteristic length. Such a conclusion is unacceptable for the materials characterized as quasi-brittle which exhibit a finite fracture process zone.

Today two approaches are identified: The first one (deterministic-energetic) has been introduced by Bažant [9,10] and is based on the observation that the failure of quasi-brittle materials is characterized by both energy and stress quantities, i.e. the fracture energy, G_f, and the tensile strength, f_t. From dimensional analysis it is concluded that such a material possess a characteristic length, l_o, depending on the size of the fracture process zone. The second approach, introduced by Carpinteri [11,12], relates the size effect to the fractal nature of the crack surfaces. Both theories were introduced for tensile loading of structures with preexisting cracks or notches, for which the failure is caused by the localization of the strain, which in turn results in a finite size fracture process zone. However, it is believed today that the strain localization is the cause of failure also for structures under uniaxial compression, the difference being that the damage zone is larger. For the case of concrete under uniaxial compression Kim and Yi [13] proposed a modification of Bažant's law for the dependence of the compressive strength, f_o, on the dimensions of the specimen, assuming a ratio of height-to-diameter equal to 2:

$$f_o = \frac{Bf'_c}{\left[1 + \frac{d}{\lambda_1 (f'_c) d_a^m}\right]^{1/2}} + \alpha(f'_c) f'_c \tag{3}$$

B, m, λ_1 are constants, d_a stands for the maximum aggregate size, f'_c is the compressive strength of the standard cylinder, d is the specimen's diameter and α is the crack band length.

Understanding the size effect is of paramount importance since the majority of laboratory tests are carried out using specimens with dimensions of the order of 10–40 cm. These results are then extrapolated in order for conclusions to be drawn for structures with dimensions of much larger size, of the order of a few meters. Unfortunately up to now definite conclusions concerning the laws governing the transition region from the size of the laboratory specimens to the size of the real structures have not been reached and as a result the design codes are still based on empirical or semi-empirical formulas obtained from curve fitting to the experimental results [10].