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Experimental studies on the mechanical behavior of Mayan archeological rocks

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Abstract
Mayan buildings have been the subject of significant archaeological and architectural research; however, so far there have been no relevant references concerning structural or mechanical behavior. Ancient Mayan constructors used calcareous rocks to build temples and housing that were placed systematically to withstand mechanical loads in the structures. This paper studies the mineralogical and mechanical characteristics of calcareous stony material that formed part of Mayan archeological vestiges in Yucatan area. The orientation of the rocks´ geological strata was taken into account to study mechanical behavior from cylindrical cores in compressing test. On the other hand, bars were also manufactured to simulate lintel or architrave structural performance. Compression and bending tests confirmed a high influence of the geological layer orientation, since the mechanical properties of such rocks were found to vary with direction. Acoustic emission was used to provide information referring to onset and propagation of damage in cylinder and bar samples.

Keywords: mechanical properties; rocks; failure mechanisms; acoustic emission technique.

Estudios experimentales del comportamiento mecánico de rocas arqueológicas Mayas

Resumen
Las edificaciones mayas han sido tema de importantes investigaciones arqueológicas y arquitectónicas; sin embargo, no existen referencias relevantes concernientes a comportamientos estructurales o mecánicos. Los constructores Mayas utilizaron rocas calcáreas para construir templos y viviendas que fueron colocadas sistemáticamente para resistir carga mecánica estructural. Este artículo estudia las características mineralógicas y mecánicas de rocas que formaban parte de vestigios arqueológicos mayas en el área de Yucatán. La orientación del estrato geológico fue tomada en cuenta para el estudio del comportamiento mecánico de núcleos cilíndricos en pruebas a compresión. Así mismo, barras fueron manufacturadas para simular el desempeño estructural de linteles y arquitrabes. Pruebas de compresión y flexión demostraron alta influencia de la orientación de la capa geológica, ya que las propiedades mecánicas de tales rocas varían con la dirección. La técnica de emisión acústica proporcionó información acerca del inicio y la propagación del daño en las muestras cilíndricas y las barras.

Palabras clave: propiedades mecánicas; rocas; mecanismos de fractura; técnica de emisión acústica.

1. Introduction

Manuscript It is well known that rock mechanics plays an important role in the design, erection and performance assessment of various constructions applications and that, the stone placement in the structure, is based in its mechanical capabilities. Mayan archaeological sites are numerous in the Yucatan peninsula of Mexico; such vestiges were built up by using local calcareous stones that exhibits different properties depending on the geographical area where they were taken.

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Calcareous stone is highly abundant in Yucatan peninsula and it is strongly believed that it was chosen by Mayan Prehispanic Civilization to be part of edifications depending on its location on them (i.e. foundations, walls, and roof) considering physical and mechanical characteristics of the used stone. Many rocks exposed near the Earth's surface show well defined fabric elements in the form of bedding, stratification, layering, foliation, fissuring or jointing, such geological formation can influence the mechanical properties of stones. Commonly, anisotropy is one of the factors that affect the behavior of rocks. The properties of such rocks vary with direction. In general, rocks have some degree of anisotropy, and isotropic rocks are rarely found in nature [1]. Limited studies have been carried out on experimental and theoretical work to determine and explain the mechanical behavior of anisotropic rocks that possess cleavage, bedding, or schistosity planes. Some of those investigations are focused in determine the strength parameter as well as the deformation characteristics of rocks identifying a high dependence on the orientation of the anisotropy with respect to the principal stress directions [2,3]; others have studied the effect of stones' physical properties in uniaxial compression resistance [4]. Anisotropy is also the characteristic of intact laminated, stratified or bedded sedimentary rocks such as shales, sandstones, siltstones, limestones, coal, etc. Here, the anisotropy results from complex physical and chemical processes associated with transportation, deposition, compaction, cementation, etc. It is noteworthy that rocks which have undergone several formation processes may present more than one direction of planar anisotropy such as foliation and bedding planes in slates. These directions are not necessarily parallel to each other. In addition, linear features such as lineations can be superposed on the planar features [5]. McLamore and Gray [6] stated three basic failure theories for anisotropic rocks: firstly, the Walsh-Brace theory [7] that indicates that the stony materials are composed by long, non-randomly oriented cracks that are superposed on an isotropic array of randomly distributed smaller cracks in such distribution that the cracks close at relatively low values of applied stress. Secondly, the Single Plane of Weakness Theory, that assumes failure to occur due to tensile stresses and by consequence, the rock fails in shear mode and finally, the variable cohesive strength theory that describes a failing in shear by action of variables such as cohesive strength and a constant value of internal friction [8]. They also [6] identify three types of failure in the anisotropic rocks studied which includes shear faulting, both across and along the bedding or cleavage planes; "plastic" flow or slip along the bedding plane; and failure due to the formation of kink bands. Goshtasbi et al. [9], carried out experimentation on orientation angles, β (the angle between the major principal stress direction and schistose plane), of 0°, 30°, 45°, 60° and 90° submitted to uniaxial compression test and found significant differences related to the onset and progression of cracks in rocks. Hence, the determination of anisotropic strength behavior of slates in this zone is essential for design purposes. Mayan constructors shaped the rocks and placed them in strategic position depending of the mechanical support within the structure. Small rectangular stones were mainly used in walls and part of the roofs and arches. Larger stones were placed in façades with a pronounced slope (or talud) on platforms and a combination of the talud and apron moldings with the long axis of the stones parallel with the wall. Straight enclosures (lintels) are important part of the structural system in Mayan architecture and are central points for relevant studies on faults and fractures due to environmental degradation processes. This paper focuses on the characterization of archeological stones in compressive and bending test simulating the real position of rocks in antique Mayan structures. The examination of these elements allowed the understanding of their mechanical behavior regarding compression and bending efforts to get results on its resistance capacity with respect to load axis. Cylindrical compression samples and bars for bending tests were monitored in real time by acoustic emission technique (AE) which is a non-destructive test (NDT) that enables the identification of the damage sequence and failure mode in many kinds of materials. This method has been qualified as a very reliable characterization among rocks [10-14].

2. Experimental

2.1. Archeological site

Archeological sites are classified from I to IV depending on architectonic-constructive characteristics, dimensions, specialty, etc. [15]. Sites from this work belong to range IV being the analyzed stones part of structures of monumental architecture and from housing. Stones from two archeological Mayan sites, Caucel and Dzunum, located Northwest of Merida (Preclassic Late/ Early Classic 300 B.C. - 600 A.C.) were collected to be characterized physical and mechanically (Fig. 1). Stones correspond to Prehispanic structures and belong to housing buildings.

2.2. Photogrammetry

Photogrammetry is a valuable technique used to study and define as precise as possible, the form, dimensions and position in space of an object, employing essentially measurements over an image (draw, photography, etc) of the

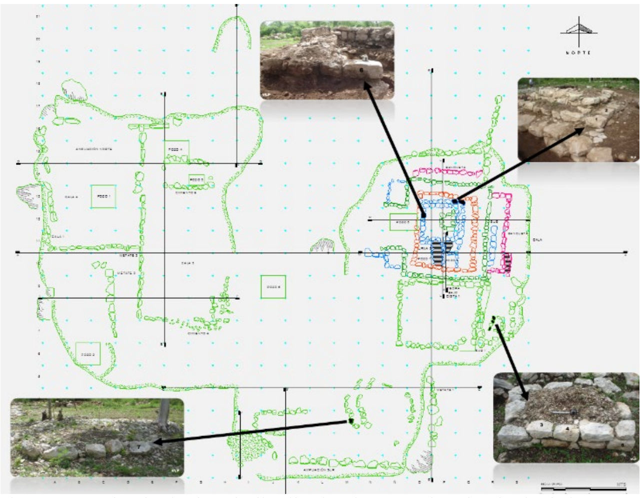


Figure 1. Archeological rock distribution in Caucel archeological site.
Source: Adapted from authors own information

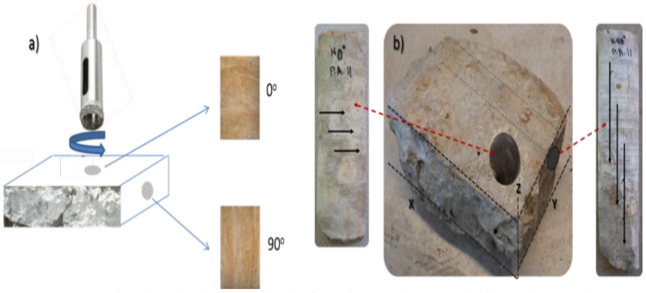


Figure 2. Archeological stony cylindrical samples, a) drill and sample orientation, b) rock strata direction (black arrows).
Source: Adapted from authors own information

cited object. This metric and graphic registration methodology was carried out by CAD software in order to dimension the rocks strata. Mechanisms and measurement criteria as well as the cylinder evaluation were based on data obtained from geological information. Cylinder samples (rock cores) were photographed and such images overlapped to have a full appearance of the area. Strata were identified and each subarea contoured with a specific color to quantify the layers.

2.3. Compression test

The archeological calcareous stones were drilled with diamond core barrel in order to extract cylindrical petrous samples (stone´s core) with normalized drills (2”) based in ASTM D4543, and D2938. Stone´s nucleus were obtained taking in account the anisotropy in correlation with the rock´s layers at 0° and 90° with respect to the rock position (Fig. 2). Several archeological rock samples from different site locations were used to be nucleus extracted. Each individual archeological stone provided two nucleus (at 0° and 90°) to be tested and mechanical and fracture behavior comparisons be made in relation to the stony cylindrical sample stratus orientation. Cylindrical specimens cut parallel to strata (90°) were designated by either X or Y assuming that these orientations are the rock´s orthotropic axes.

Stone cylinders were aligned with a diamond disk obtaining samples with a minimum of natural defects such as cavities, porous, etc. and then, photographs were taken to record the geometry of the running layers. Mechanical tests in compression mode were undertaken in a Shimadzu AG-I universal machine using a 100 kN load cell and a crosshead velocity of 0.2 mm/min. Acoustic Emission MICRO II PCI-2 equipment with two piezoelectric sensors was attached to the stone cylinders samples surface and a thermoplastic adhesive was used as acoustic coupling (Fig. 3a). Threshold was fixed at 37 dB to observe acoustic signals derived from the failure mechanisms of the stones.

2.4. Bending test

Bending tests were conducted according to standard ASTM C1161-13. This method covers the determination of the flexural strength of ceramic materials at ambient temperature. The test used was three bending points coupled with a device fitted with vulcanized rubber for a better distribution of load (Fig. 3b).

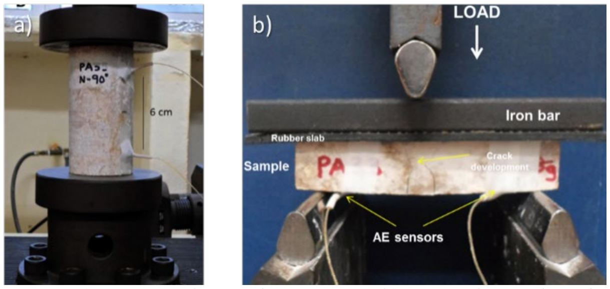


Figure 3. a) Compression rock core test, b) Stony bars taken from archeological rocks for bending test.
Source: Adapted from authors own information

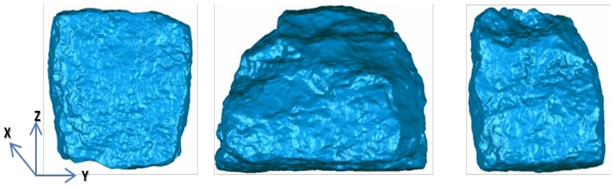


Figure 4. Archeological rock 3D surface scheme.
Source: Adapted from authors own information

The mechanical tests were carried out on a universal testing machine AG-I Shimadzu with a load cell of 100 kN and at a crosshead speed of 0.1 mm/min assisted by AE MICRO II PCI-2. Piezoelectric sensors were attached to the specimen at a distance of 20 mm at each end of the bar being such sensors 60 mm apart in order to locate the sources of initiation of failures and monitor in real time the onset and development of damage. The threshold was set to 35 dB to observe acoustic signals derived from the mechanisms of stone fracture.

3. Results

3.1. Photogrammetry

A topographic surface study was initially carried out to archeological rocks in order to observe the local deviations of its surface from the perfectly flat plane. 3D technique was used to appreciate the nanoscale nature of surface irregularities that might substantially affect the bulk properties influencing its macroscopic mechanical behavior (Fig. 4).

Surface topography, also known as surface texture, surface finish or surface profile, indicates transfer layer formation during sliding therefore it is important identify its position since surface topography can be either isotropic or anisotropic. Such orientations are related to internal petrous layers known as strata; consequently they have a vital role in transferring mechanical load under external compression stresses. Fig. 5 exhibits the stratigraphy of a transversal cut (0º) of an archeological rock where it is possible to distinguish the distribution of geological strata (parallel layers that lie one upon another). It can be appreciated that individual bands vary in thickness from a few millimeters to centimeters where each band represents a specific mode of deposition. The calcareous rocks of the Yucatan peninsula have a very heterogeneous distribution due to the various diagenetic environments involved in their formation therefore they present high variation in strata conformation [16].

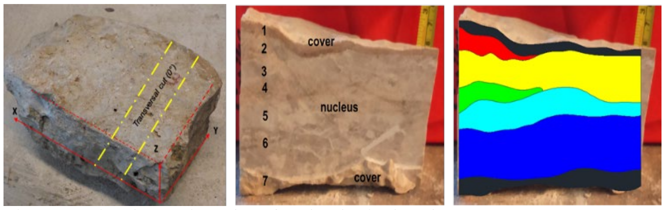


Figure 5. Simple stratigraphy of archeological rock.
Source: Adapted from authors own information

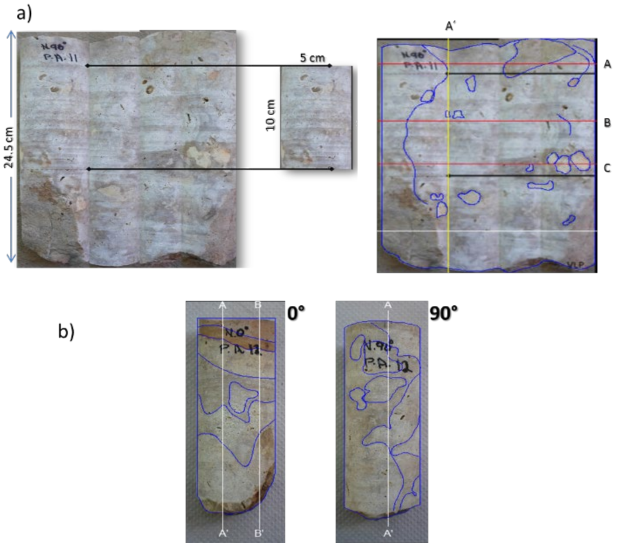


Figure 6. Stratigraphy of Archeological rock, a) Sample 11 oriented at 90°, b) Sample 12 oriented at 0° and 90°.
Source: Adapted from authors own information

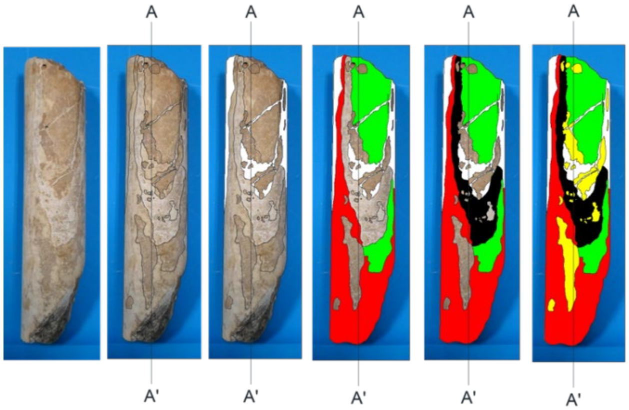


Figure 7. Stratigraphication of archeological rock oriented at 90°.
Source: Adapted from authors own information

Fig. 6 presents strata distribution from an archeological rock nucleus obtained to elaborate cylinders for compression test. Images were taken to the cylinder and overlapped to have a “map” in order to be able to observe the geological layers clearly. It is well known that mechanical behavior of rocks is dependent on the anisotropy degree.

Layering, cleavage, schistosity, and other foliation constitute types of planar anisotropy that can have a pronounced effect on the strength and deformation behavior of rocks. Such effect in stratum orientation on stones mechanical behavior can be explained by photometric studies by analyzing the conformation of geological layers. Fig. 7 presents a sequence of images where layers can be differenced. By geological reasons, these layers are not the same in each sample; therefore, this conformation influences the final mechanical behavior. Another important fact to point out is that, in this calcareous stones dissimilar types of aggregates (solid marine sediments) can be found in different amount (represented in yellow in the last graphic) such as shells.

3.2. *Compression test*

In anisotropic rocks the angle of faulting varies considerably [17], therefore stones exhibit variations in its mechanical behavior depending on the geological layers orientation. Results obtained during the experimental compression mechanical tests determined that mechanical parameters are influenced by the stratum orientation with respect to the compression load direction where certain degree of anisotropy was observed. The compressive strength as a function of sample orientation was determined for archeological calcareous anisotropic rocks. The orientation of the plane of anisotropy (bedding or cleavage plane) was varied between 0° and 90° regarding the axial load. The test results indicate that anisotropic sedimentary stony materials fail or deform by shear along the bedding plane. Table 1

Table 1.
Physical parameters of compression test samples

Archaeological Cylindrical Stones Nucleus					
Archaeological site	**Sample**	**Dimension**			**Density**
		Length (cm)	**Diameter (cm)**	**Mass (g)**	**g/cm^3**
Caucel	*PA11-N-0°*	9.8	5	503	2.61
Caucel	*PA11-N-90°*	10	5	513.6	2.61
Caucel	*PA12-N-0°*	10	5	518	2.63
Caucel	*PA12-N-90°*	10	5	519	2.64

Archaeological Cilindrical Stones Nucleus					
Archaeological site	**Sample**	**Dimension**			**Density**
		Length (cm)	**Diameter (cm)**	**Mass (gr)**	**g/cm^3**
Dzunum	*SA32-N-0°*	5	5	243.8	2.48
Dzunum	*SA32-N-90°*	5	5	240.2	2.44
Dzunum	*SA33-N-0°*	10	5	462.8	2.35
Dzunum	*SA33-N-90°*	10	5	458.2	2.33

Source: Adapted from authors own information

Table 2.
Mechanical parameters of compression test samples

Site Caucel South, Yucatán, México				
	PA11-N-0°	***PA11-N-90°***	***PA12-N-0°***	***PA12-N-90°***
Max. Strength σc (MPa)	16.84	25.89	11.88	30.7
Max. Strain (%)	1.32	2.41	1.99	2.22
Modulus *E* (MPa)	12.68	10.71	14.97	13.78

Site Dzunum, Yucatán, México				
	SA32-N-0°	***SA32-N-90°***	***SA33-N-0°***	***SA33-N-90°***
Max. Strength σc (MPa)	17.65	19.61	15.13	17.01
Max. Strain (%)	4.33	3.44	1.4	2.37
Modulus E (MPa)	4.07	5.07	10.8	7.17

Source: Adapted from authors own information.

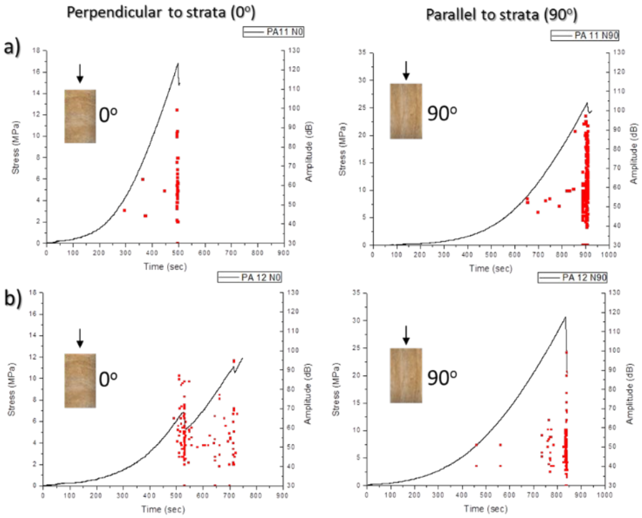


Figure 8. Stress-strain-AE amplitude curves of rocks from Caucel archeological site, a) sample PA11 and b) sample PA12.
Source: Adapted from authors own information

displays the physical properties for archeological rocks cylindrical samples obtained to be tested in uniaxial compression while Table 2 shows the mechanical parameters. Such considerations establish that stones tested modulus (*E*) compared to stones with geological layers at 0°. calcareous stones in Yucatan peninsula are found between 13 to 39 MPa (about 140 to 400 kg/cm^2) [18].

Typical stress-strain-AE amplitude curves are presented in Fig. 8 for two pairs of samples taken from both, Caucel and Dzunum, archeological sites. Acoustic emission signals detected during compressive load application the evolution of damage degree identifying cracking onset and failure progression until samples fracture. Examining both samples tested perpendicular to strata (0°), the arrival of AE elastic waves energy upon the expansion of internal primary microcracks and defects exhibited high amplitude at around 500s indicating total fracture for sample PA11 and the appearing of a significant crack that lowered the applied stress for PA12. On the other hand, for samples tested parallel to rock geological strata (90°), first signals developed around microcracks after 460s for PA12 and 600s for PA11 indicating that, at this orientation, discontinuities appeared generating microflaws (low amplitude) that eventually grow until fracture emitting signals with higher amplitude. Stresses and in particular compressive stresses tend to close microcracks or discontinuities thus making rock behavior non-linear and rock anisotropy pressure dependent.

Fig. 9 shows typical specimen failures, which were quite brittle under atmospheric conditions, yet flowed plastically at high confining pressures. Typical “cones of fracture” were experienced. As stated by Meng et al. [10], in terms of microperspective, strain deformation that lead to fracture in rocks, mainly results from sliding among crystal particle interfaces and lattices. Additionally, natural geological conformation in calcareous stones such as strata alignment, internal voids or cavities, different petrous bodies (shells, gravel, etc) governs mechanisms of fracture. Therefore, the crack patterns in anisotropic rocks under compression loads are more complex than those observed in a homogenous specimen. Fig. 9 exhibits mechanical damage in archeological cylindrical samples experimented after compression tests. The direction of cracks can be initialized along the circumferential or perpendicular to the bedding plane. As stress increases, more microcracks initiate and propagate coalescing along the stone nucleus specimens. When the number of significant cracks in the material exceeds the threshold, the flaws start to connect with each other, and the whole sample would break into pieces. This corresponds to the collapse failure point in stress-strain-AE amplitude curves displayed in Fig. 8. For rocks with well-developed planar anisotropy, the mode of deformation is strongly dependent on the anisotropy as well as on ductility.

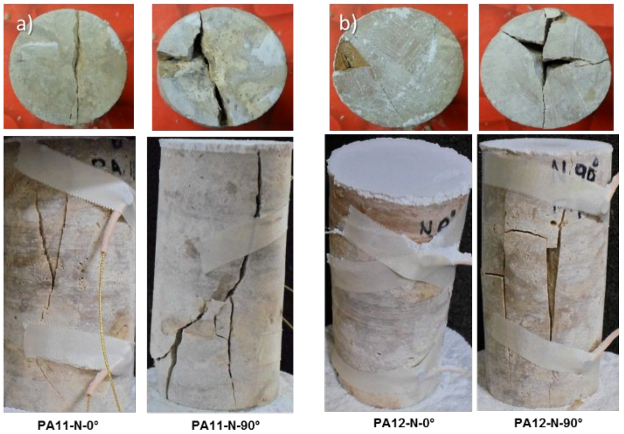


Figure 9. Compression tested samples fractography, a) sample PA11 and b) sample PA12.
Source: Adapted from authors own information

3.3. *Bending test*

Stony bars were obtained from archeological rocks in order to evaluate mechanical properties by three point bending test adapted to acquire uniform stress distribution along the bar. The purpose is to simulate a real load distribution in a lintel positioned in an architectural structure (Fig. 10). Archeological calcareous rocks from Dzunum site were used for this examination.

Fig. 11 shows the stress-strain-time-AE amplitude curve for a representative stony bar sample under bending test. First AE signals indicating onset of damage are found around 0.1% strain (after 40s), stress is increased with time generating low amplitude signals related to microcracking progression until total fracture occurs around 0.6% strain (300s).

Figure 10. Schematics of archeological lintel as a horizontal structural part that is placed above across the opening.
Source: Adapted from authors own information

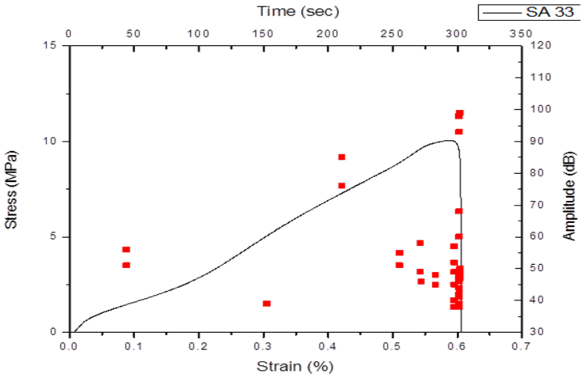


Figure 11. Stress-strain-Time-AE amplitude curves of bars tested in bending.
Source: Adapted from authors own information

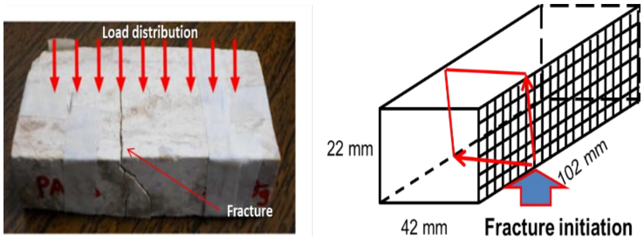
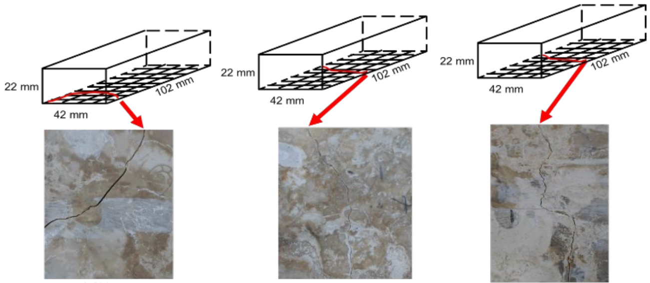


Figure 12. Fractured bar showing cracks progression.
Source: Adapted from authors own information



a) Sidecut b) Shear - tensil. c) Shear - tensil.

Figure 13. Surface crack development on bending test stony samples.
Source: Adapted from authors own information

It is noticeable to mention that bars experimented a reliable load distribution since AE continuous events were acquired in low amount meaning that the stone behaved mostly in elastic deformation. Higher amount of signals were only detected until total fracture.

Significant crack runs randomly when starting damage process, later, it turns transversally along the stony bar provoking a catastrophically fracture (Fig. 12). Visualization of fractured surface indicated that crack progression is highly dependent of irregularities in the rock such as internal voids, small stones, seashell, etc. Mechanical behavior is greatly controlled by the dominant cracking surface that develops affecting completely the stony bar sample.

Damage development and fracture approach are represented in Fig. 13. In these images is clearly observed that the surface morphology is a key factor to dictate the evolution of cracking. The phenomenon was observed when samples fractured according the shear load direction that determined that the stone internal structural arrangement influences failure progression and fracture mode.

4. Conclusions

Based on the data obtained experimentally measured in the laboratory by mechanical compression and flexural tests, it was determined that archaeological stone damage development vary in their mechanical behavior; that is, due to the strata system in which they are geologically formed, the damage initiation and progression is significantly affected by the anisotropy and the geoformation of the rocks. Therefore, rocks compression and flexural strength are in function of the orientation of the geological strata regarding to the load axis.

Archeological stones belonging to Mayan Civilization housing were characterized physical and mechanically by extracting the core (nucleus) and varying the geological layers orientation (0° and 90°). Stones mechanical behavior stability was improved when samples were oriented at 90° than at 0° and such results are highly related to the geological layers compaction during compression test. It was also identified that geological stratum directly affects the fractography in the crack initiation, propagation and development until fracture.

Bars samples in bending mode, manufactured to recreate the lintels or architraves that are part of the structural system of Pre-Hispanic Mayan buildings, were more susceptive to formation of superficial cracking damage affecting the failure mode. Results were consistent to that superficial damage observed in archeological lintels in Mayan structures.

It has been documented that these elements are fractured along the architrave either in the sides or in the middle due to overweight and, consequently, weakened section causes the collapse. Acoustic Emission technique demonstrated to be an essential characterization tool in order to identify the signals and correlate them to the crack initiation and propagation.

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References

[1] Kwasniewski, M.A., Mechanical behavior of anistropic rocks, in: Hudson, J.A. ed., Comprehensive Rock Engineering, Pergamon Press, Oxford, 1, 1993.

[2] Donath, F.A., Experimental study of shear failure in anisotropic rocks, the geologic. ll Society of America, Bulletin 72, pp. 985-989, 1961. DOI: 10.1130/0016-7606(1961)72[985:ESOSFI]2.0.CO;2

[3] Donath, F.A., Strength variation and deformational behavior in anisotropic rocks, in: Judd W.R. (ed), State of stress in the earth's crust, American Elsevier Publishing Company, New York, N. Y., 1964, pp. 281- 298.

[4] Galván-Ceballos. and, Restrepo, I.A., Resistance correlation with compression uniaxial effective humidity and porous rocks, DYNA, 83(198), pp. 9-15, 2016. DOI: 10.15446/dyna.v83n198.53151

[5] Amadei, B., Importance of anisotropy when estimating and measuring in situ stresses in rock, International Journal of Rock Mechanics and

Mining Sciences & Geomechanics Abstracts, 33(3), pp. 293-325. 1996. DOI: 10.1016/0148-9062(95)00062-3

[6] McLamore, R. and Gray, K.E., The mechanical behavior of anisotropic sedimentary rocks, Journal of Engineering for Industry, 89(1), pp. 62-73, 1967. DOI: 10.1115/1.3610013

[7] Walsh, J.B. and Brace, W.F., A fracture criterion for brittle anisotropic rocks, Journal of Geophysical Research, 69, pp. 3449-3456, 1964. DOI: 10.1029/JZ069i016p03449

[8] Jaeger, J.C., Shear failure of anisotropic rocks, Geologic Magazine, 97, pp. 65-72, 1960. DOI: 10.1017/S0016756800061100

[9] Goshtasbi, K., Ahmadi, M, and Seyedi, J., Anisotropic strength behavior of slates in the Sirjan-Sanandaj zone, The Journal of the South African Institute of Mining and Metallurgy, [online]. 106, pp. 71-76, 2006. Available at: https://www.saimm.co.za/Journal/v106n01p071.pdf

[10] Meng, Q., Zhang, M., Han, L., Pu, H. and Chen, Y., Acoustic emission characteristics of red sandstone specimens under uniaxial cyclic loading and unloading compression, Rock Mechanics and Rock Engineering, 51(4), pp 969-988, 2018. DOI: 10.1007/s00603-017-1389-6

[11] Lei, X., Masuda, K., Nishizawa, L., Liu, L., Ma, W., Satoh, T. and Kusunose, K., Detailed analysis of acoustic emission activity during catastrophic fracture of faults in rock. Journal of Structural Geology 26, pp. 247-258, 2004. DOI: 10.1016/S0191-8141(03)00095-6

[12] Rudajev, V., Vilhelm, J. and Lokajicek, T., Laboratory studies of acoustic emission prior to uniaxial compressive rock failure, International Journal of Rock Mechanics and Mining Sciences 37, pp. 699-704, 2000. DOI: 10.1016/S1365-1609(99)00126-4

[13] Meglis, I.L., Chow, T.T. and Young, R.P., Progressive microcrack development in tests on Lac du Bonnet granite-I. Acoustic emission source location and velocity measurements, Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. 32(8), pp. 741-750, 1995. DOI: 10.1016/0148-9062(95)00014-8

[14] Fonseka, G.M., Murrelli, S.A.F. and Barnes, P., Scanning electron microscope and acoustic emission studies of crack development in rocks, Int. J. Rock Mech. Min. Sci. & Geomech. Ahstr. 22(5), pp. 273-289, 1985. DOI: 10.1016/0148-9062(85)92060-1

[15] Garza-Tarazona, S. and Kurjac-Bacso, E.B., Atlas Arqueológico del Estado de Yucatán, SEP-INAH, México, 1980.

[16] Espinosa, L., Ceron, M. and Sulub, Y., Limestone rocks of the Yucatan peninsula. Description of the lithology and physical properties based on the results of exploration, investigation and laboratory tests. International Journal of Rock Mechanics and Mining Sciences 35, pp. 410-411, 1998.

[17] Tavallali, A. and Vervoot, A., Effect of layer orientation on the failure of layered sandstone under brazzilian test condition, International Journal of Rocks Mechanics & Mining Sciencies, 47, pp. 313-322, 2010. DOI: 10.1016/j.ijrmms.2010.01.001

[18] Ordaz, M., El conocimiento técnico-constructivo de la cultura maya en la arquitectura religiosa virreinal de Yucatán, México, in Salazar-Gonzalez, G., (Ed.), Modernidad, Tecnología y Diseño., México, pp. 340-353, 2009.

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