Study of the Effect of Stratum Orientation on Damage Initiation and Propagation on Mayan Archeological Limestone by Using Acoustic Emission Technique

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***Abstract*—It is well known that rock mechanics plays an important role in the design, construction and performance assessment of various constructions applications and that its position in the structure is based in its mechanical capabilities. Several Mayan stones that once were located in different places in an archeological building were taken to laboratory to extract its nucleus by a drill. Cylindrical samples were obtained considering the direction of geological stratum line formation in the rock to evaluate mechanical behavior with stone anisotropy. Detailed analysis of AE parameters was used to monitor progressive changes in crack development and mechanical parameters were obtained allowing identifying the load transfer and stressing distribution. Acoustic Emission (AE) technique is a powerful nondestructive testing tool for examining the behavior of materials deforming under stress. When rocks or structures are subjected to stress, elastic waves are spontaneously generated, these being called "acoustic emission". Therefore, it can be also used to monitor fracture or damage in a rock mass by listening to AE events during failure progression under compressive loads. Acoustic Emission (AE) technique under laboratory testing conditions was used to understand the mechanical behavior and fracture processes of Mayan archeological rocks under compression tests. AE analysis combined with compression tests yielded information on the damage process (micromechanics) up to macroscopic failure.**

***Index Terms*—acoustic emission, mayan civilization, stone characterization, mechanical properties**

I. Introduction

Mayan archaeological sites are numerous in the Yucatan Peninsula of Mexico [1]. Most of the surviving buildings date from around Late Preclasic to Late Post Classic (300 B.C-1500 A.C.) [2]. Most sites are surrounded by relatively undeveloped countryside. The Classic Maya built environment encompasses all the known "built forms" of Maya centers: temples, palaces, ballcourts, patios, reservoirs, roads, and causeways as well as the tombs, monuments, the formal and informal embellishments associated with them, and their ambient spaces. All these forms constitute the database for understanding how the Maya used and conceived of the places they built and inhabited. Such vestiges sit solidly and reassuringly where they are precisely because ancient Prehispanic Civilization chose to build them in particular places. Archaeological sites and historical monuments in the Mayan area were constructed with different limestones [3] that offer different resistances to degradation by the various types of contamination. Limestones from the Yucatan peninsula contain basically two types of rocks: red and white limestone, both consisting of calcium carbonate according to X-ray diffraction analyses. A major difference is their porosity: white rocks are 2.48 times more porous than red rocks. Classic Maya buildings stand as mute monuments attesting to the use of limestone in construction in the past. Construction materials used for Mayan housing are diverse; however due to its color, specific weight, resistance and maneuverability calcareous stone has been

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one of the most employed materials for edification [4]. The Yucatán Peninsula, in Mexico, is a partially emergent carbonate platform with an extensive continental shelf so the geology consists of almost pure carbonate rocks [5], [6]. 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 the position on it i.e foundations, walls, roof depending on the physical and mechanical characteristics of the used stone. The stones, having rough rectangular shape, weighed more than 100 kg, requiring at least two or three individuals to move them. These stones consisted of relatively uniform, roughly hewn, flat stones stacked vertically in walls. The large stones were also 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. The increasing sizes of stones and greater labor needed to transport and place them indicate an expanding investment in the architectural landscape. Numerous archeological structures were built with structural walls of stone masonry and mortar. Many have not survived the test of time. Some have had obvious signs of distress such as bowing, bulging, and cracking. Others have had catastrophic failures occur without warning. Therefore, it is important, due to the lack of information, to characterize archeological calcareous stone that have different function in an archeological edification to understand its characteristics and failure mechanisms by using different available methods. Description of rock failure process using only conventional stress and strain measurements is not sufficient. The rock failure process is associated with Acoustic Emission (AE). AE can be defined as the transient elastic waves generated by the rapid release of energy from a source within a material [7]. The Acoustic Emission (AE) method of detecting the nucleation and growth of microscopic cracks in rocks is widely used in studies of pre-failure damage accumulation under external loading. AE technique can be used to monitor the production of the micro-cracks development and the failure process in the rock test sample continuously and in-real-time, which makes it better than other methods [8], [9]. This research focuses in the mechanical behavior characterization of Maya stones obtained from archeological sites in Yucatan, very near to Merida, the Capital City. All rock fracture studies were performed with Maya archeological stones. AE pulses served as indicators of latent rock damage as the rock is brought to failure at applied stress. The data collection from the samples was performed under compression load, which is typical for natural tectonic processes.

II. Experimental Procedure

A. Archeological Sites

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

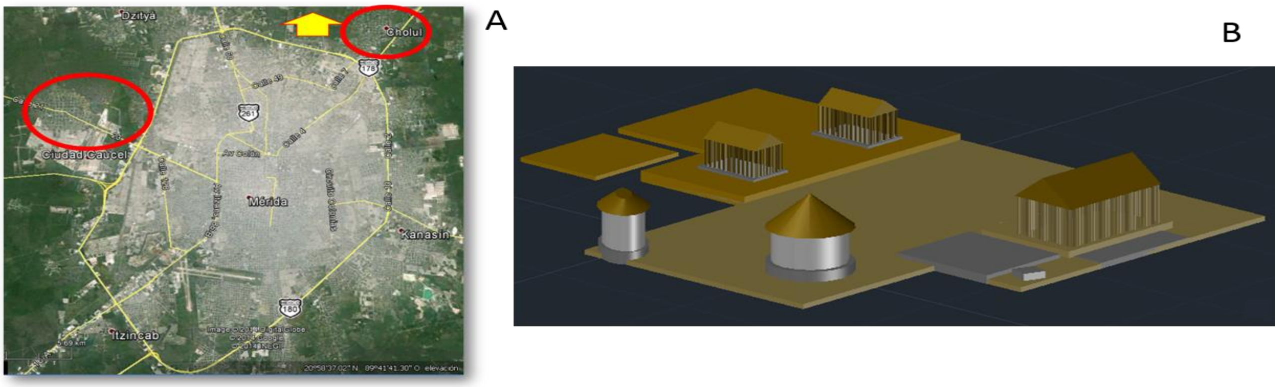

Figure 1. Archeological sites location in Merida City and a hypothetical reconstruction.

B. Experimental

Archeological calcareous stones were taken to laboratory to be tested with a sclerometer to determine its hardness and resistance by obtaining the weight of each sample. The stones were drilled in order to extract cylindrical petrous samples (stone´s heart) with normalized drills (2”) based in ASTM D4543 [10], and D2938 [11]. 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). 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 100Kn load cell and a crosshead velocity of 0.2 mm/min. Acoustic Emission MICRO II PCI-2 equipment with piezoelectric sensors were attached to the stone cylinders samples surface and a thermoplastic adhesive were used as acoustic coupling (Fig. 3). Threshold was fixed at 37 dB to observe acoustic signals derived from the failure mechanisms of the stones.

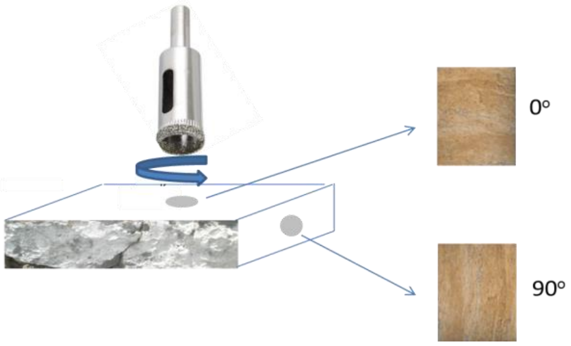

Figure. 2. Stone cylinder samples at 0 ° and 90 °.

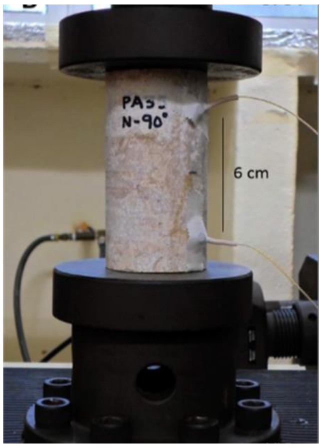

Figure 3. Nucleus stone under compression test with AE sensors.

III. Results and Discussions

Results obtained during the experimental mechanical tests determined that archeological stones exhibited variations in its mechanical behavior and that it is depending on the anisotropy degree (geological layers orientation) [12] as shown in Table I. Volumetric weight test for all stone cylindrical samples provided density values between 2.03 to 2.64 g/cm^3 with data dispersion (SD) of 0.19.

TABLE I. Mechanical Parameters Obtained from Archeological Maya Stones

MECHANICAL PROPERTIES				
SITE	SAMPLE	MAXIMUM STRESS (MPa)	MAXIMUM STRAIN (%)	ELASTIC MODULUS (MPa)
Chan chen	STONE 1-0°	13.92	1.8	823.52
Chan chen	STONE 1-90°	29.06	0.7	4000
Chan chen	STONE 2-0°	13.28	1.2	717.39
Chan chen	STONE 2-90°	16.34	0.3	4166.6
Xaman-susulá	STONE 1-0°	16.84	1.32	12.68
Xaman-susulá	STONE 1-90°	25.89	2.41	10.71
Xaman-susulá	STONE 2-0°	11.88	1.99	5.97
Xaman-susulá	STONE 2-90°	30.7	2.22	13.78
Dzunum	STONE 1-0°	17.65	4.33	620.34
Dzunum	STONE 1-90°	19.61	3.44	709.01
Dzunum	STONE 2-0°	15.13	1.4	1219.76
Dzunum	STONE 2-90°	17.01	2.37	1124.89

Mechanical parameters exhibited the effect of stratum orientation respect the compression stress direction where certain degree of anisotropy was observed. Stones tested at 90 ° displayed higher values in maximum load compared to stones with geological layers at 0 °. However, elastic modulus (E) was perceived to be higher at 90 °. It has been reported [13] that compression stress values for calcareous stones in Yucatan peninsula are found between 13 to 39 MPa (about 140 to 400 kg/cm^2).

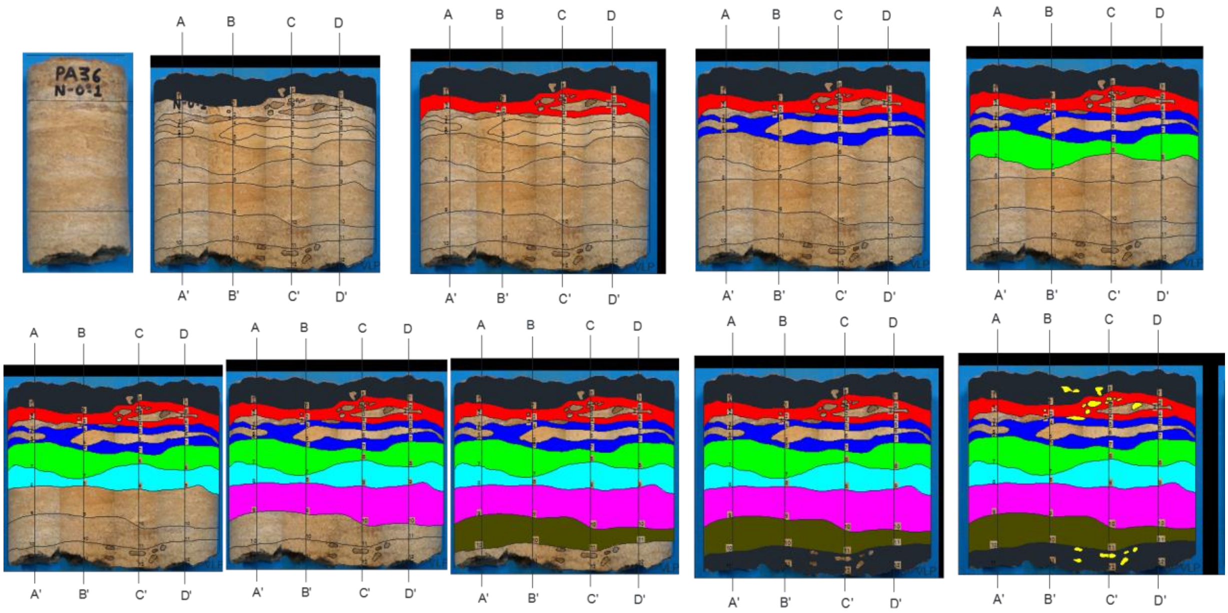

Figure 4. Archeological stone photometry, stratum oriented at 0°.

Such effect in stratum orientation on stones mechanical behavior can be explained by photometric studies by analyzing the conformation of geological layers. Fig. 4 presents a sequence of photos 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 different types of aggregates (solid marine sediments) can be found in different amount (represented in yellow in the last graphic) such as shells.

Stone sequence with stratum at 90 ° is represented in Fig. 5. As noticed, a lower amount of layers can be confined in the cylindrical nucleus. Some stones exhibited geological voids that can act as stress concentrators affecting as well the mechanical behavior.

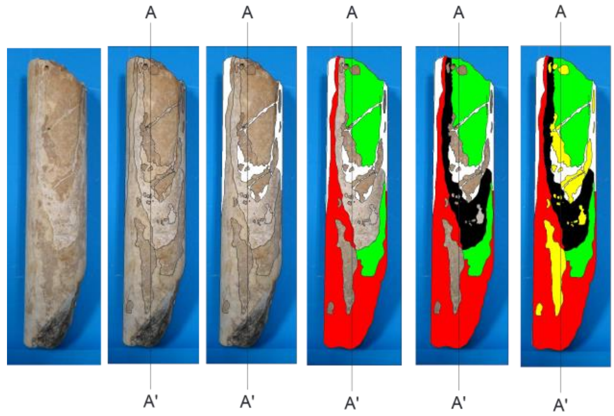

Figure 5. Archeological stone photometry, stratum oriented at 90 °

Acoustic emission characterization on mechanical properties is shown in Fig. 6 for stones from each archeological Maya site.

All nucleus stone samples exhibited a lineal elastic behavior at low deformations where no AE signals are detected since no damage is occurring in this interval of time. After this point, the curve is stepped up and, at 0 °, it can be correlated to the compaction of geological layers of the stone. Higher stresses originate the intensification of acoustic emission indicating significant internal failure in the stone structure. Stone samples oriented at 90 ° showed higher resistance (stress and deformation) that are supported by the latter detection of acoustic signals. Amplitude appears to be higher since more energy is needed to fracture de rock at this direction. Archeological stones from Chan chen displayed a major amount of AE waves which can be correlated to the higher amount of significant damage found in this stone. First signals are detected by sensor after about 160 s with low amplitude waves indicating that minimal damage such as microcracks due to stress concentrators (probably in cavities or void inside the rock) are appearing. Stone samples from Xaman-susulá and Dzunum exhibited lower amount of AE signal detected, such signals incremented intensity when internal cracks were developed and progressively coalesced until total fracture.

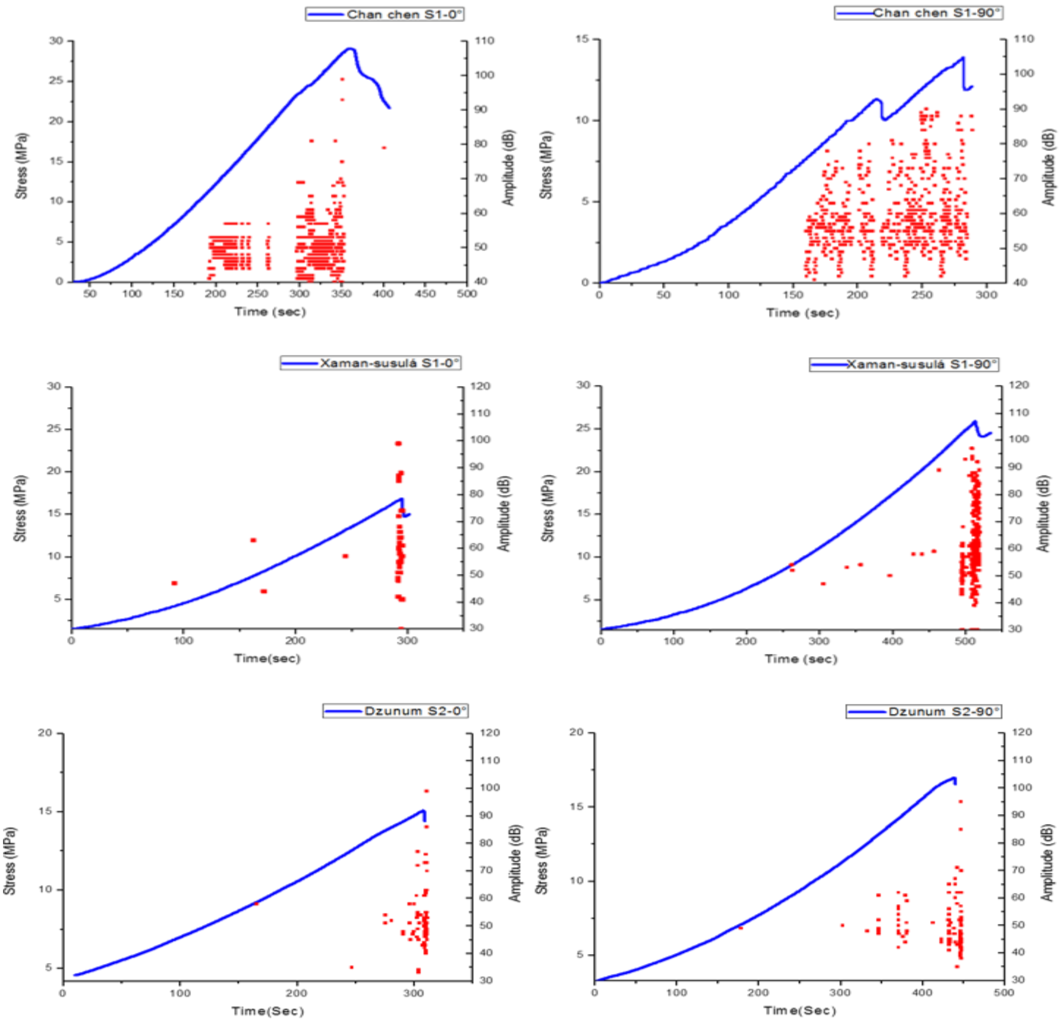

Figure 6. Stress-Time-Amplitude, acoustic emission signals

Fractography of cylinder stone samples in compression can be seen in Fig. 7. Cracks in samples at 0° direction appear to follow the horizontal lines of geological layers until they converge in a stress concentration point to develop vertically until material displacement originated by crushing until fracture. Cracks at 90° direction developed parallel to compression load direction following the line of geological layers. By analyzing AE data (events, energy and amplitude) it is possible to state that microcracks with low AE signals amplitude initiate at low strain un voids or cavities that act as stress concentrators. Friction and filling cavities follow the damage sequence until compaction when stress is augmented, therefore higher density of events are detected. Those microcracks finally join together to create significant damage that, at the end, fracture the stone cylinder producing last higher release of energy.

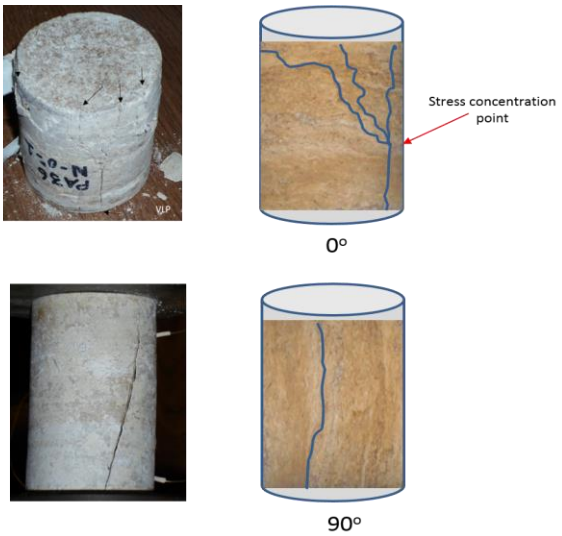

Figure 7. Archeological stones fractured samples, stratum oriented at 0° and 90°.

IV. Conclusions

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°). Mechanical behavior was higher when samples were oriented at 90° than at 0° and these 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. Acoustic Emission technique demonstrated to be an essential characterization tool in order to identify the signals and correlate them to de crack initiation and propagation. By analyzing the location of different stones (depending on its stratum orientation) in an ancient Mayan construction, it is possible to assume that Mayan constructers had enough acknowledgements to understand the mechanical behavior of calcareous stones and the load distribution and resistance.

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