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Physico-mechanical characterization of the limestone used in Cartagena walls and a proposal for their restoration process

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HIGHLIGHTS

- Physico-mechanical limestone characterization.
- Selecting criterion for structure rock replacement.
- Identification of restoration materials in a fortified structure.

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ABSTRACT

The defensive walls of Cartagena de Indias, UNESCO cultural heritage since 1984, surround the historic centre of the Colombian City. Nowadays, the walled city represents the main tourist attraction of the Colombian Caribbean Sea and is also a world destination. Despite this importance, due to anthropogenic and environmental factors, the walĺs structure is highly deteriorated, with widely damaged sections at distinct risk of collapse, where replacement of deteriorated stone blocks is carried out without a technical criterion. The main purpose of this paper was to determine some criteria for selecting the most appropriate limestone to be used in the restoration process, based on empirical relations among ultrasound wave speed, mechanical strength, porosity, bulk density and elastic modulus of different limestones taken from five quarries located around the city. Analyzed physical properties showed that the current wall's stone open porosity ranges between 18% and 25%, while the quarry stone range is between 7% and 44%. As for the quarry stone, the uniaxial compressive strength (UCS) variation varied from 1.88 MPa to 21 MPa. Results showed that in order to select the best stone to be used as a replacement, samples should have an ultrasound P-wave speed between 3844 and 4195 ms^{-1}, and a dry mass between 223 and 251 g in a 5 cm cubic sample. A valid tool is proposed to the relevant authorities in the subject-matter to identify the right range of porosity and mass of the quarry stone to be employed in substitution of the deteriorated wall blocks, thus facilitating the restoration practices.

1. Introduction

Historical monuments throughout the world are one of the most important heritages left by our ancestors, as they have the privilege of showing human roots and identity, therefore, their protection and preservation from deterioration should be a must for every country [1].

Numerous symbolic and well known monuments can be mentioned; the Coliseum and Sant'Angelo Castel of Rome in Italy [2,3], the Parthenon in Athens, Greece, symbols of power and testament of civilization [4]. Furthermore, Chichén Itzá in Mexico [5], and Machu Picchu in Peru [6] as an emblem of the massiveness of the pre-Hispanic civilizations in South America, among many others around the word [7,8]. All of them tackle with surrounding aggressive climate conditions that accelerate their deterioration, and as a matter of fact, 54 of those sites are currently classified as in imminent danger due to anthropogenic and natural factors [9]. Cultural heritage integrity is endangered by anthropogenic and environmental factors, day and seasonal cycles of temperature and humidity, sea spray, rising damp as well as rainwater, wind and vehicular traffic [10–14], which are all responsible for overstressing and damaging the cultural heritage and monuments. The previous condition becomes more severe because of the lack of maintenance and restoration process management to be accomplished in most monuments and heritage cities [15–19]. Restora-

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tion processes are normally complex and articulated in several steps: 1) diagnosis of the deterioration degree and its main causes; 2) cleaning process of crusts, patinas, dirt, biodeterioration, etc.; 3); pre-consolidation and consolidation of the stone; 4) reintegration of faults and heavily damaged sections with specific restoration mortars and replacement stones possibly from the original quarry; 5) surface protection, by applying hydrophobic products that prevent or hinder the passage of moisture into the stone; 6) determination of ordinary and extraordinary maintenance plans.

Due to fund limitation and lack of expert research teams, not all the aforementioned steps always take place, furthermore, procedures are often by-passed depending on the case of study [20,21], . There has been a particular engineering interest in Step *4* during the last years [22–25]. Pappalardo et al., (2016) [22], studied the geotechnical characterization of the limestones employed for the reconstruction of a UNESCO world heritage Baroque monument in southeastern Sicily (Italy). They found a wide range of physico-mechanical parameters, leading to further possible damage if implemented without a replacement criterion. Forestieri et al., (2015), [26], studied the hydric and physico-mechanical behavior of the four quarry stone materials, to provide recommendations for possible restoration interventions in the built heritage in Calabria (Italy). Kock et al. (2013), [27], when studying the historic building stone used in the NW of Belgium for restauration processes, showed that replacement stones have a higher porosity and capillary absorption coefficient, and lower strength properties, with unpredictable repercussions in structural behavior and deterioration of the original structure [28,29].

The defensive Walls of Cartagena de Indias, located in the north of Colombia in a tropical area, facing the Caribbean Sea, are a typical example of Spanish colony architecture. They were built between XVII and XIX centuries, and declared in 1984 by the UNESCO as a significant heritage of the world, being the most extensive fortification in South America [30]. It stretches over more than four km, consisting of an external escarpment and an internal counter-escarpment six meters high on average, among which there is an embankment featuring a variable width between 10 m and 50 m. The stone masonry structure is heterogeneous due to different phases of accomplishment, different stone characteristics and the construction technique as shown from previous research [11,31–36]. Currently, the structure is partially covered by black crusts, biodeterioration and clear signs of aging (Fig. 1-a). Due to lack of ordinary and extraordinary maintenance plans, materials are usually replaced without previous analysis, employing hydraulic mortars and stones from the surrounding quarries (Fig. 1-b). The lack of characterization of the restoration materials, and comparison with the structure materials, is often a problem that can lead to a wrong selection, thus accentuating the deterioration of the structure.

The purpose of this paper is to show a proposed technical criterion for selecting the most appropriate stones to be used in the restoration process (step 4), based on an experimental work, aimed to characterize the physico-mechanical properties of the limestone available near the city. From the obtained data, relationships between ultrasound wave speed, mechanical strength, porosity, bulk density and elastic modulus of five different types of quarry limestone were analysed, pointing out the consequences from using this material in the restoration process without discrimination. On the other hand, structure thin sections from previous studies were analysed, identifying a porosity range of the structure stone and using it as a comparison parameter between structure and quarry stone. A valid methodology developed to guide the competent authorities to choose the right replacement limestone was proposed to avoid further damage to the structure. Although the methodology proposed was developed initially for Cartagena walls, it is believed that it could be applied to any cultural heritage structure.

2. Methodology

2.1. Quarry material characterization

Limestones from five different quarries surrounding the City were analyzed, showing visible differences among each other in terms of color, weight and porosity, as shown in Fig. 2, which are the stones normally used in the restauration process.

25 cm^3 cubic blocks were extracted and reduced to around 40 cubes of $5.0 \times 5.0 \times 5.0$ cm for each stone type, with a total number of around 200 samples for the physical-mechanical characterization. Specimens were dried in an oven at 70.0 ± 5.0 °C up to a constant weight, each labeled uniquely and taking their three dimensions, that are, height h (mm), length l (mm) and width w (mm) with a digital caliper, and moreover, following the Natural Stone Test Methods summarized in the UNI EN 1936 [37]. The Dry m_d (g), Saturated m_s (g) and water immersion m_h (g) weights were measured in order to calculate the Real Volume V_R (m^3), (1), Open Porosity P_o (%), (2), and Apparent Density ρ_b (kg m^{-3}), (3).

$$V_R = hlw \quad (1)$$

$$P_o = \frac{m_s - m_d}{m_s - m_h} 100 \quad (2)$$

$$\rho_b = \frac{m_d}{m_s - m_h} \rho_{rh} \quad (3)$$

where ρ_{rh} is the water density at 20 °C, 998 kg m^{-3}.

Non-destructive tests were also carried out using a *Proceq Pundit* Lab Ultrasound with 500 kHz Transducers [38], to measure the

a) b)

Fig. 1. a) Widespread deterioration in a Structure section; b) Stone replacement process on the Cartagena walls.

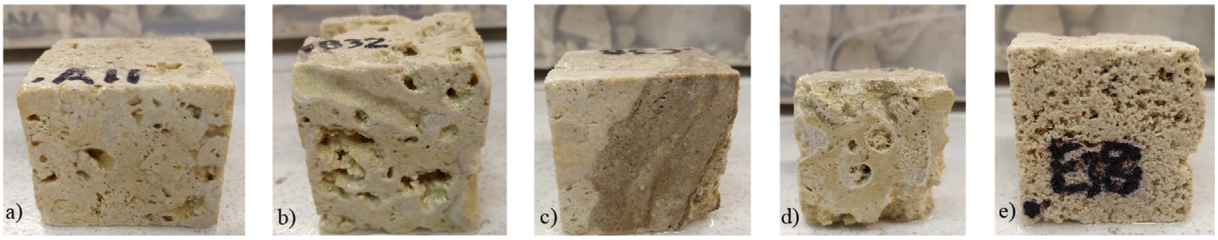


Fig. 2. Quarry Limestone selected. a) Stone type A; b) Stone type B; c) Stone type C; d) Stone type D; e) Stone type E.

P wave Speed (*Vp*) (m s^{-1}) in the three axial directions (*x*, *y*, *z*) of each sample in saturated conditions and expressed as the average of three readings. In order to assess the anisotropy of each sample, the rates proposed by Guydader and Denis, (1986), [39], were applied (4).

$$dM = \left[1 - \left(\frac{2V_{Pmin}}{V_{Pmean} + V_{Pmax}}\right)\right]100 \quad (4)$$

where *dM* (%) is the total anisotropy index, considering the three axial directions, where V_{Pmin} is the minimum *P* wave speed (m s^{-1}), V_{Pmean} is the average *P* wave speed (m s^{-1}), and V_{Pmax} is the maximum *P* wave speed (m s^{-1}).

Hydraulic conductivity K (m s^{-1}) was experimentally determined by following the same principles of the ASTM D2434-68 Standard Test Method for Permeability of Granular Soils (Constant Head method) [40]. The setup of the experiment carried out is shown in Fig. 3.

When stable flow conditions were reached, *K* was measured as follows (5):

$$K = \frac{QL}{Ah\Delta t}100 \quad (5)$$

where *L* (m) is the sample height, *A* (m^2) is the sample cross section, *h* (m) is the hydraulic head, *Q* (m^3) is the volume of passing water, and Δt (s) is the time interval. Finally, the quarry material was subjected to Uniaxial Compressive Strength (UCS) test, by using a *Shimadzu AGX Plus 300 kN* machine and applying a loading rate equal to 1 mm min^{-1}. Samples were separated in two groups, 100 were kept dry, the other 100 were saturated in distilled water, ensuring that average porosity and standard deviation of the two groups were as similar as possible.

Eight of the 100 dry samples during the *UCS* test were equipped with Kyowa KFGS120Ω Triaxial, 0°/45°/90° stacked rosette for Stress Analysis, commonly known as Strain Gages, to calculate the elastic modulus by measuring the deformation (Fig. 4).

In a previous research [36], reported by Saba et al., (2019), [11] thin sections were produced by submerging a stone sample from the Cartagena wall into an epoxydic resin, and once it was hardened, slices of few millimeters were cut and pasted in a glass support and slightly smoothed up to a thickness of less than 30 µm. Then they were impregnated with a blue colorant to highlight the pores and conduct an analysis with an *Olympus CX 31* petrographical microscope with magnifications from ×5 to ×100. Particularly, from the thin section analysis, the porosity ratio range of the structure stone was identified in order to determine the quarry samples more similar to those measured directly from the structure.

3. Results and discussion

3.1. Quarry material characterization

Quarry materials were characterized, and the results were summarized and reported in Table 1.

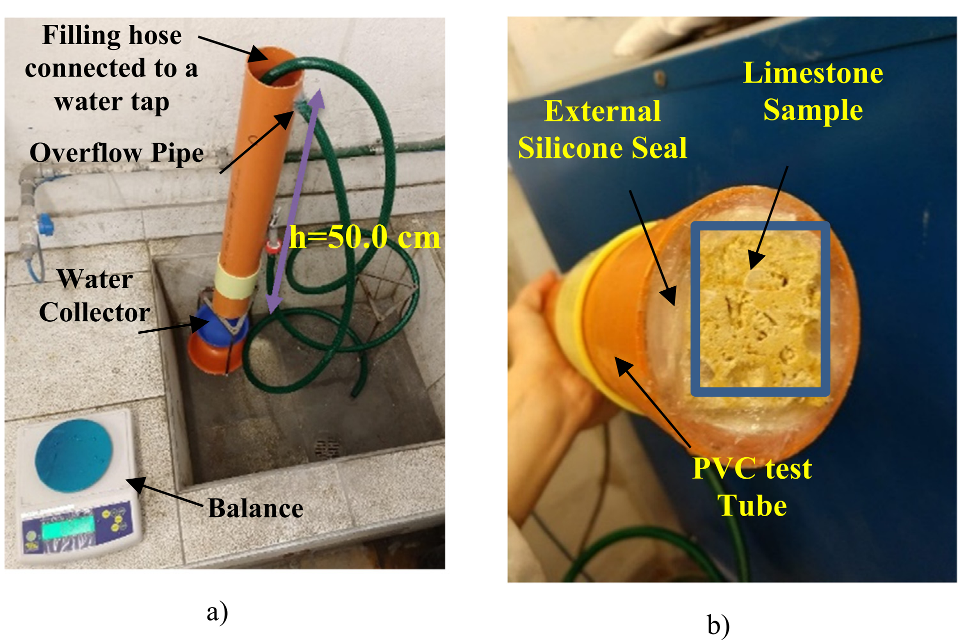
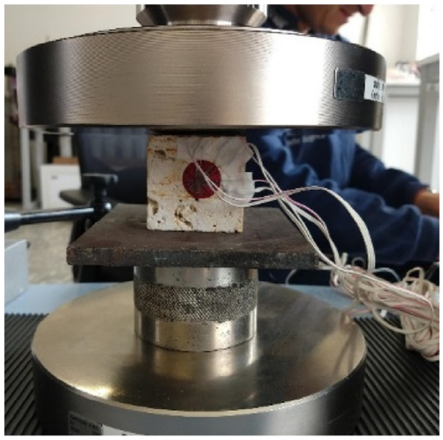


Fig. 3. Ad Hoc Hydraulic Conductivity test. a) System developed; b) Sample fixing.



a)

b)

Fig. 4. a) Sample during UCS Test; b) Strain Gages installed in the sample.

Results confirmed a wide average range of the main parameters, P_0 from 9.38% to 41.26%, and *UCS* from 1.45 MPa to 21.00 MPa. Fig. 5-a) show that total porosity almost holds the absolute control of the Apparent Density (known as well as Bulk Density) of the stone. Such parameters are strictly linked by a linear relation, with a negative trend and a coefficient of determination ($R^2 = 0.98$). This is because the presence of voids is involved in the computation of Bulk Density, leading to higher values in lower-porosity stones, as reported by Pappalardo et al., (2016), [22], which have similar limestone results. *Vp* and P_0 (Fig. 5-b) show a potential correlation curve with a $R^2 = 0.78$, showing that a lower P_0 is linked to a higher *Vp*, due to the fact that the P-wave passes through the solid material and is not transmitted through the voids. Fig. 6 shows the relationship between P_0 and Dry UCS, with R^2 above 0.70 in both dry and wet conditions, which follow the same trend pattern approximated to a potential equation. Type-*B* stone despite featuring less porosity than type-*D* stone, is shown to have less *UCS* in average (Table 1), probably due to the fact that it is characterized by macro porosity (Fig. 2-b), which makes it difficult to keep the water inside the pores during the saturated mass weighting. The superficial macro-pores release water more easily, thus influencing the porosity values of the type-*B* stone and causing a fake-effect, whereas this apparently does not occur with the other types of stones.

Parent et al., (2015), [24], by means of a state of the art analysis about the relation between *Vp* and the Mechanical Parameters of Limestones, including works from 1958 to 2014, remarked a strong relationship also confirmed in this research as shown in Fig. 7. *Vp* measures were not accomplished in dry samples because the 500 kHz transducers did not provide any appropriate signal, despite the matter guidelines suggest to use transducers from 75 kHz to 3 MHz [38], and in any way, only fully available transducers were used.

Following the classification of ultrasonic velocities [41], reported in Table 2, it can be noted that a wide *Vp* range is embraced, from low to very high velocities, and particularly type *A* and *C* stones fall within the class 4 and 5 limits.

Furthermore, for *Vp* a statistical analysis was performed from the data measured. The main purpose of this analysis was to fit each rock data set to a probability distribution model. This analysis was performed using MATLAB R2013a (The MathWorks Inc., Natick, Massachusetts, US), in which all statistical inferences assumed a confidence level of 95% ($\alpha = 0.05$). The goodness of normal fitted distributions for each rock type was assessed using a procedure based on the log likelihood ratio test, which results showed values between −244 and −314, meaning that the normal distribution is a good estimator of the data. Fig. 8 a) and b) shows the normal and the cumulative distributions of the data.

Considering that stone is a natural material, whose features present irregularities, unintended distribution of pores and cracks, crystal orientation, grains, stratification, and lamination structures, the relationship between the parameters measured sometimes could be difficult to identify. However, the results summarized in Table 3, show R^2 with curves that seems to be able to describe the correlation between the parameters considered. The mutual correlation between physical and mechanical properties, has been recently discussed by many authors [22,24,42] and the results

Table 1
Summarized results of the quarry stone characterization.

Characteristic	Stone Type A	B	C	D	E
V_R ($mm^3 \times 10^5$)	1.45 ± 0.08	1.55 ± 0.16	1.51 ± 0.11	1.51 ± 0.10	1.42 ± 0.08
M_s ($g \times 10^2$)	3.22 ± 0.18	2.57 ± 0.30	3.34 ± 0.23	2.97 ± 0.28	2.32 ± 0.15
M_h ($g \times 10^2$)	1.82 ± 0.11	1.42 ± 0.16	1.86 ± 0.14	1.56 ± 0.19	1.03 ± 0.07
M_d ($g \times 10^2$)	3.09 ± 0.18	2.39 ± 0.27	3.16 ± 0.23	2.71 ± 0.29	1.79 ± 0.12
P_0 (%)	9.38 ± 1.26	14.86 ± 2.73	11.78 ± 2.39	18.43 ± 3.11	41.26 ± 1.55
ρ_b ($kg\ m^{-3}$)	2192. ± 37	2064. ± 106	2135. ± 70	1922 ± 110	1380 ± 35
Average Vp ($m\ s^{-1}$)	5000. ± 147	4616. ± 168	4978. ± 231	3793 ± 366	3406 ± 133
dM (Unit)	0.96 ± 0.2	0.95 ± 0.02	0.95 ± 0.04	0.91 ± 0.06	0.9 ± 0.05
Dry UCS (MPa)	21.00 ± 4.7	3.56 ± 1.27	20.93 ± 6.91	5.39 ± 2.02	1.88 ± 0.36
Wet UCS (MPa)	13.48 ± 4.4	2.2 ± 0.60	13.69 ± 5.00	2.99 ± 1.50	1.45 ± 0.28
Wet UCS/Dry UCS	0.35 – 1.09	0.33 – 1.22	0.31 – 1.33	0.31 – 1.33	0.52 – 1.13

Vp = Ultrasound *P* wave Speed, 500 kHz transducers.

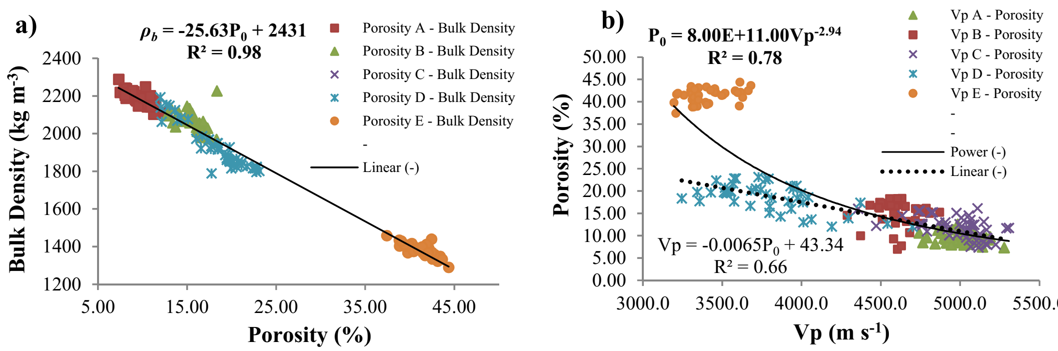


Fig. 5. a) Open Porosity – Bulk Density correlation; b) Vp (in saturated samples) – Open Porosity Relation Average.

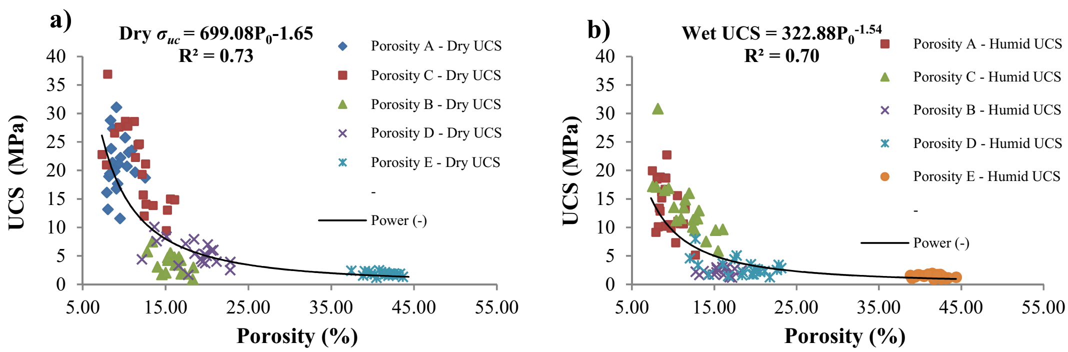


Fig. 6. a) Porosity – Dry UCS separated for Stone Type; d) Porosity – Wet UCS separated for Stone Type.

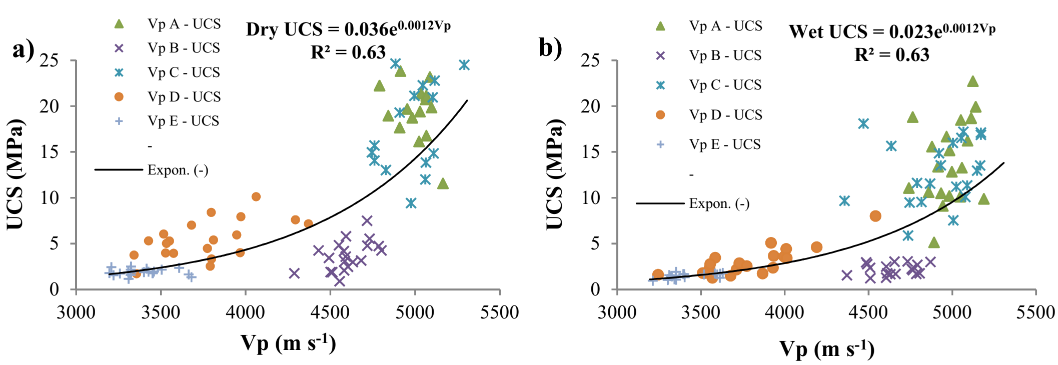


Fig. 7. a) Vp – Dry UCS Relation; b) Vp – Wet UCS Relation.

Table 2
Classification of ultrasonic velocities [41].

Class	*Vp* (m s^{-1})	Definition	Stone Type of the Present Study
1	<2500	Very Low Velocity	
2	2500–3500	Low Velocity	E
3	3500–4000	Middle Velocity	D
4	4000–5000	High Velocity	B-(A-C)
5	>5000	Very High Velocity	A-C

achieved in the present research are in good agreement with literature findings, even with the trend curves shape, which most of the time are exponential or potential.

Stone Elastic Modulus (*E*) were calculated using Stain Gages, and results are reported in Table 4.

In Fig. 9 a) and b) can be observed the correlation between P_0 vs *E* and *UCS* vs *E*, though, due to only eight strain gages used and six usable data obtained (for samples *A39* and *D1* Strain Gages broke off during the test, consequently the data are not available), the correlation is not sufficiently reliable, given the difference in behavior between the stone types examined. However, could be noted that omitting the sample *A1*, P_0 vs E_S are perfectly correlated with a linear equation ($R^2 = 1$) (Fig. 9a).

However, Table 3 highlights that almost all correlation curves are exponential or potential, which indicates that they follow a similar law between them, as mentioned in accordance with the results achieved in literature [22,24,42,43].

3.1.1. Stone hydraulic conductivity (K)

Stone hydraulic conductivity results are shown in Table 5. Fig. 10 shows a tendency of *K* to increase as P_0 increases as well, apart from sample *B32*, confirming that the real P_0 value of the type-B stone is much higher than the one measured, being characterized for its macro-porosity, hardly detectable with traditional methods. Wu et al., (2018), [43], studied the *K* – P_0 relation of