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Case study

Petrographic of limestone cultural heritage as the basis of a methodology to rock replacement and masonry assessment: Cartagena de indias case of study

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ABSTRACT

Cultural heritage assessment and restoration around the word is an issue of main interest, in which destructive and non-destructive tests are usually undertaken to make diagnosis and evaluate material mechanical properties. Since interventions are often limited due to high costs, lack of highly specialized staff and even excessive caution of the competent authorities, it is common to have a lack of information about the cultural heritage material mechanical properties, with a consequent uncertainty about the adequate rock replacement and their masonry mechanical strength.

In this perspective, the present research has taken as a case of study the defensive wall of Cartagena de Indias (UNESCO cultural heritage since 1984), introducing a petrographically based approach comparing fifteen limestones samples from five quarries and twelve structure samples. Firstly, is proposed a further step on improving the selecting rock criterion for replacement, identifying the main structure and quarry rock petrographical parameters, Bioclasts, Porosity, and Sparry Cement, and presenting a pyramidal scheme to be used in the replacement process. Subsequently, a new indicator was introduced for all rocks, and related to quarry rock uniaxial compressive strength (UCS_R), identifying thus the possible structure UCS_R range.

Finally, knowing UCS_R range, the uniaxial masonry mechanical strength range (UCS_M) for the study case is calculated by referring to the 2018 Italian Technical Standard (NTC, 2018 [1]).

1. Introduction

Historical constructions and heritage are a representation of the culture and history of a society. They are a very important part of the economy of the cities through tourism, therefore, preserving them should be a duty of the government, the civil society and the academic communities. Nevertheless, assessing the mechanical properties of the materials used in heritage constructions is often challenging because of the numerous construction processes or remodelling they are subjected along

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he centuries, which makes them heterogeneous, and because of the high costs and limitations of mechanical assessment of destructive (DT) and non-destructive (NDT) methods.

Among the different methods for limestone cultural heritage assessment, the application of petrographic techniques has been widely accepted in recent years [2–4]. Kock et al. [5], studied the Lede rock for replacement in Belgian historical monuments, which was used for building the Church of Our Lady at the Zavel in Brussels. They petrographically compared local Lede rock from a new quarry with a quarry French rock widely employed over the centuries. The replacement limestones showed a bioclast matrix, with Granular Spar and Ferroan Calcite, while Lede rock had a Cement Matrix with Micrite featuring different colour and texture. Furthermore, from a physic-mechanical characterization, the replacement rock showed a higher porosity and capillary absorption coefficient, and lower strength properties, leading to unpredictable consequences on the structural behaviour; nevertheless they do not propose a methodology for choosing the rock replacement material. Pappalardo et al., [6] Parent et al. [7], and Vasanelli et al. [8], recently studied the physical-mechanical parameters of limestone used in cultural heritage restoration processes, often showing criticalities in the selection process of the quarry rock, and more specifically the mechanical effect caused by rock substitution in the masonry system.

Columbu et al. [9], analyzed a Romanesque-style monument completed in 1116 BCE in Sardinia, Italy, to determine the petrographic and physical-mechanical features of sedimentary rocks on quarry and structure samples; Petrographic data allowed to determine the possible original quarry, nevertheless, the mechanical behavior of the replacement rocks has not been considered, neither the possible impact on structural behavior. On the other hand, Scrivano et al. [10] studied limestone from four different quarries, which has been commonly employed as structural or ornamental rock in historical buildings in Italy. Petrographic analysis and hygroscopic sorption analysis based on rock micro-porosimetry were coupled to uncover the liability of the relative humidity variation. The relationship between the mineralogical composition and the hygroscopicity was employed to assess the possible consequences of the weathering processes, however, consequences of using this material as a replacement have not yet been considered. Moreover, assessment of the mechanical properties of an existing masonry structure is a contemporary problem, often addressed using NDT, however, most of these methods have strong limitations [11–20].

Cartagena de Indias defensive walls, placed in the north of Colombia, declared UNESCO cultural heritage since 1984 [21], surround the historic city centre, and stand in front of the Caribbean Sea as the most ancient Latin-America fortification with a walled system of more than four km.

In the latest research directly assessing masonry mechanical parameters of the Cartagena walls [22], Masonry Uniaxial Compressive Strength (UCS_M) was evaluated by using ten rock cores extracted from a section of the structure (*Santa Catalina Bastion*) corresponding to a construction of a century after [23] the structure considered in this case of study (*Santo Domingo Bastion*), (Fig. 1). Rock cores where then subjected to uniaxial compressive strength test (UCS_R), and values ranging from 8.4 MPa to 12.0 MPa were found. Those values from the cores were directly taken as UCS_M to study the structural behaviour of the walls, considering their homogenous mechanical parameters, and neglecting the fact that UCS_R could be substantially higher than UCS_M [24,25]. Accordingly, extending the results found in a section to the whole structure can probably lead to overestimating or sub-estimating the mechanical parameters and the structural behaviour. Since the investigation of Covo Torres [22], the Culture Minister of Colombia limited the sample taking and in-situ analysis in order to protect the structure from excessive exploration, furthermore, DT and NDT were suspended. For this research the authors were exceptionally allowed to take samples from the structure to study the deterioration and possible restoration proposals.

Fig. 1. Historic City centre of Cartagena. In red the walled system, in Blue the part studied by Covo Torres, [22], and in Yellow the Santo Domingo Bastion, part studied in the present research. S. = Section studied in the present research. Adapted from Google Earth.

In a previous research, the authors [26] proposed a physical-mechanical characterization of five limestone from quarries surrounding the city, identifying their Uniaxial Compressive Strength (UCS_R) and proposing a methodology to select the replacement rocks of deteriorated blocks, based on Dry Sample Mass, Ultrasound P-wave Speed and rock Porosity. Nevertheless, the proposed methodology does not focus on the petrographical characteristics of replacement quarry rocks and structure rocks, which does not allow the authorities to select the most appropriate rock in mineralogical terms.

Therefore, according to the above, this research represents an additional step to establish a new selecting criterion for rock replacement, based on petrographical comparation between structure and quarry rocks; additionally, is presented a methodology to assess the mechanical parameters of a heritage limestone masonry structure, with limited access to take core samples and limited availability of non-destructive techniques. To illustrate the methodology proposed, it was applied to the defensive Walls of Cartagena de Indias in Colombia. The non-conventional methodology proposed, involving a petrographical comparison through the main parameters of the thin section analysed, between quarry and structure rock, allowed to identify a pyramidal scheme capable to categorizing the rocks, defining the most appropriate replacement. Furthermore, a petrographical indicator (I_p) was established to find a range of realistic rocks and masonry mechanical strength for the structure, based on the Italian Legislation for masonry structure constructions [1], (Table 1). This methodology could be applied to other cases of study with similar boundary conditions, and possibly corroborated with destructive and non-destructive techniques in further investigations.

2. Methodology

2.1. Structure sampling and thin section preparation

Three vertical sections in the external part of the Santo Domingo Bastion were chosen (Fig. 1), four points were also selected for each section at 0.3 m, 1.2 m, 2.5 m and 4.3 m from the ground level, and one sample for each point was taken for a total of 12 samples (named as 1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 2.4, 3.1, 3.2, 3.3, 3.4). Thin sections were prepared following the petrographic international standard [27], reaching a thickness lower than 30 μm. Thin sections were analysed using a petrographical *Olympus CX 31* microscope with magnifications ranging from x5 to x100 aimed at assessing the presence of bioclasts, terrigenous, algae, texture, distribution and quantification of primary and secondary porosity, presence of cracks, among others. Each thin section featured a dimension of 4.5 cm x 2.6 cm, and as for the characterization, a mesh of 300 equidistant points was used on the section to detect and count the attributes previously mentioned.

Limestone samples from five different quarries surrounding the city of Cartagena and traditionally used in the restoration process were also selected for petrographical characterization (named as rock type A, B, C, D, E). Additionally, as mentioned from a previous research [26] physical-mechanical characterization was carried out considering 40 5 × 5x5 cm samples for each limestone type for a total number of 200 samples, since it is usual in literature to find these sample dimensions [28–30]. Results of rock uniaxial compressive strength (UCS_R) on quarry samples varied from 1.5 MPa to 21.0 MPa in average.

The following 5-step methodology was implemented (Fig. 2), proposing firstly a new selecting criterion for replacement of structure deteriorated rocks, based on the main rock petrographical parameters; subsequently, correlating a new petrographical parameter (I_P) with rock UCS_R allowing to identify a range of structure UCS_R, currently unknown, from which was possible to determine the masonry UCS_M plausible range through the Italian Standard NTC [1] and the application circular released in 2019.

2.1.1. Rock selecting criteria for replacement, based on petrographical analysis

1) Analyse and compare thin sections from the structure (in this case 12 samples were analysed) and from the quarry material (in this case 15 samples were analysed), in order to find similarities in terms of limestone classification, matrix, porosity ratio and distribution, presence of cement, presence of bioclasts etc (as shown later in Fig. 3, Fig. 4 and Table 2)

Table 1
Determination of UCS_M knowing UCS_R and Type of Mortar (taken from Table 11.10.VII - [1]).

UCS_R (MPa)	Type of Mortar			
	M15	M10	M5	M2.5
2.0	1.0	1.0	1.0	1.0
3.0	2.2	2.2	2.2	2.0
5.0	3.5	3.4	3.3	3.0
7.5	5.0	4.5	4.1	3.5
10.0	6.2	5.3	4.7	4.1
15.0	8.2	6.7	6.0	5.1
20.0	9.7	8.0	7.0	6.1
30.0	12.0	10.0	8.6	7.2
≥40.0	14.3	12.0	10.4	–

Taken from NTC, [1], “Tabella 11.10.VII”.

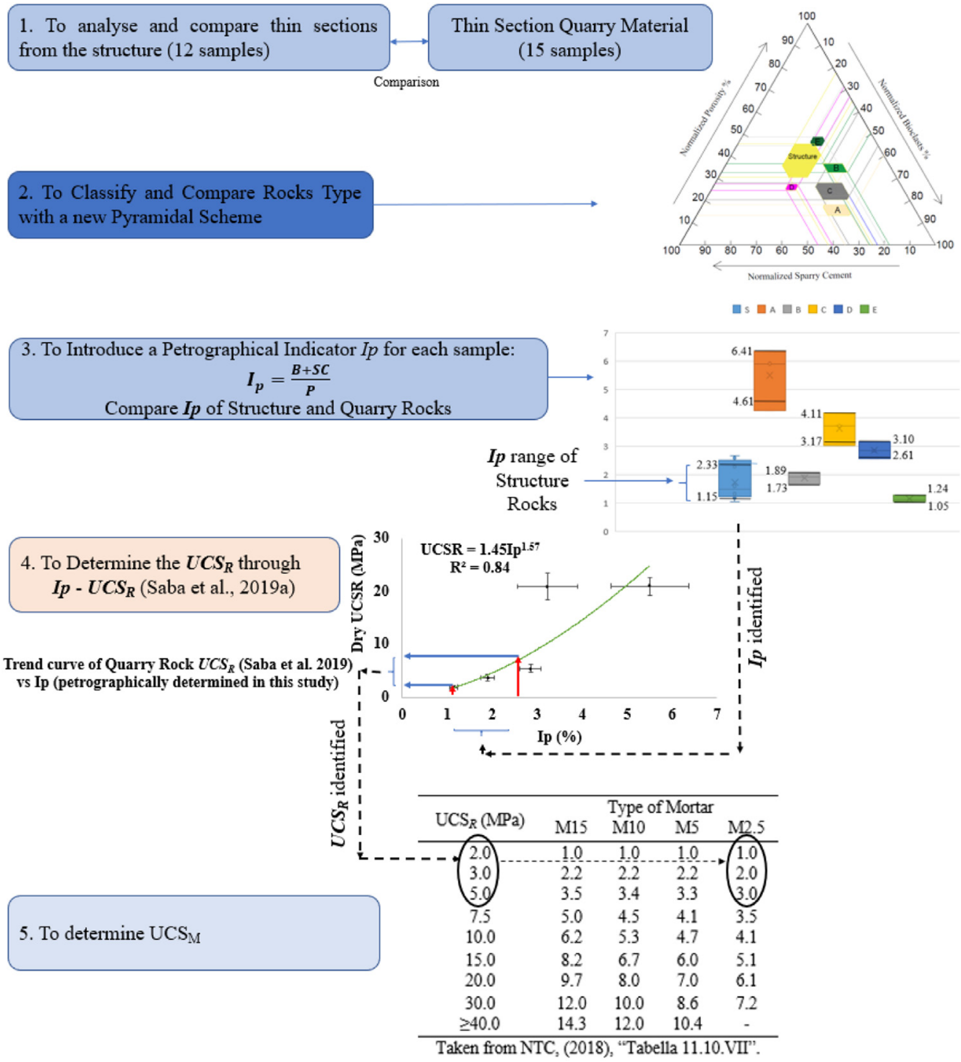


Fig. 2. Methodology scheme for rock selecting criteria and identification of UCS_M range.

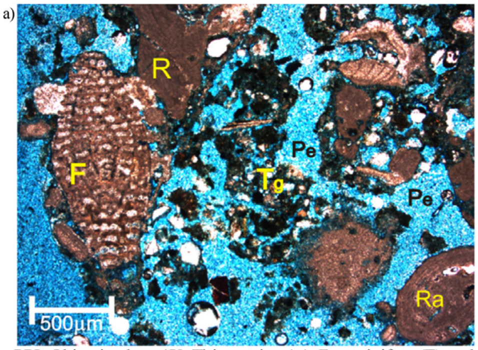
2) Classify and compare rocks by introducing a pyramidal scheme (as shown later in Fig. 5), based on the three main petrographical parameters, *P*, open porosity (%), *B*, bioclasts (%) and *SC*, Sparry Cement (%), found from the petrographical analysis of the rock's thin sections. The three parameters in this study case are representative of more than 88% of the total thin section samples (as shown later in Table 2), which were consequently normalized to the 100% total. The scheme proposed will be a tool for the competent authorities to choose the right replacement rock coming from different quarries.

Since limestone masonry mechanical strength is unknown, in absence of a direct mechanical characterization of the Cartagena walls masonry, the following purpose of this paper was to identify their possible range.

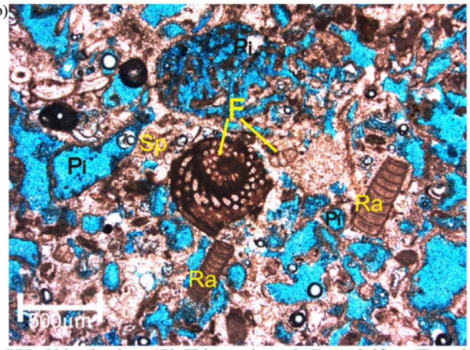
2.1.2. Rock mechanical-parameters definition based on petrographical analysis

After knowing the quarry rock mechanical behaviour [26] (Table 3), the goal was to find a petrographical parameter allowing to make an equivalence between the quarry rock mechanical behaviour (known UCS_R) and the structure rock mechanical behaviour (unknown). Furthermore, the methodology continues as follows:

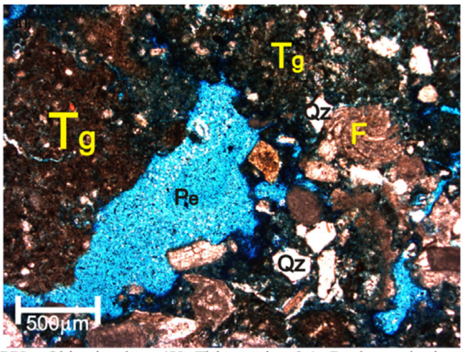
1) Introduce a new petrographical indicator (I_p), (Adim.), associated to each rock (1), and compare I_p range of the structure rocks to the I_p range of the quarry rock samples, in order to identify the sample with greater similarity (as shown later in Fig. 6). A range of shared I_p (minimum and maximum values) was found;

a)


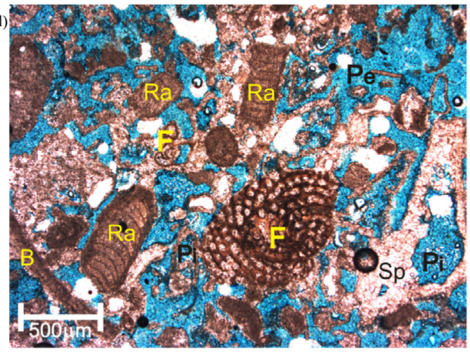
PPL Objective lens 4X. Thin section 1.1. Foraminifera **(F)**, red algae **(Ra)**, Rugosa fragments **(R)** and Terrigenous minerals: quartz and oxides **(Tg)**. Extraclast Porosity **(Pe)**

b)


PPL Objective lens 4X. Thin section 1.2. Foraminifera **(F)**, red algae **(Ra)**, Sparry cement **(Sp)**. Intraclast porosity **(Pi)**.

c)


PPL Objective lens 4X. Thin section 2.1. Rock weathering. Terrigenous minerals: Quartz **(Qz)** and Oxide crystals (Brown matrix). Foraminifera **(F).** Extraclast porosity **(Pe)**.

d)


PPL Objective lens 4X. Thin section 3.2. Foraminifera **(F)**, red algae **(Ra)**, Sparry cement **(Sp)** and Bivalvia fragments **(B)**. Extraclast porosity **(Pe)** and Intraclast porosity **(Pi)**

Fig. 3. Thin Section Structure Rocks.

$$I_p = \frac{B + SC}{P} \tag{1}$$

1) Estimate a curve-relationship between I_p and UCS_R [26] values (as shown later in Fig. 9. Ip – P curve; average values with associated curves (confidence interval 90%)), since they have a physical relationship due to the fact that UCS_R behaviour is related to presence and distribution of *P*, *SC* and *B*; furthermore, apply the equation found using the minimum and maximum I_p values established in *Step 3*, selecting a UCS_R (MPa) range;

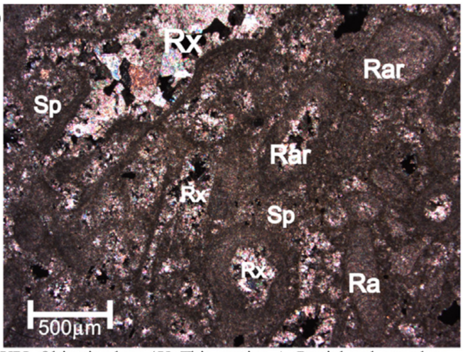
Instead of finding the equivalence between the structure rock and the quarry rock by referring to Porosity as the only parameter, it was considered appropriate to set a new petrographic I_p parameter that also included two more predominant factors in rock petrography and in rock behaviour, such as Bioclasts and Cement, which affect the mechanical capacity of the rock.

2.1.3. Masonry mechanical-parameters calculation based on italian standard

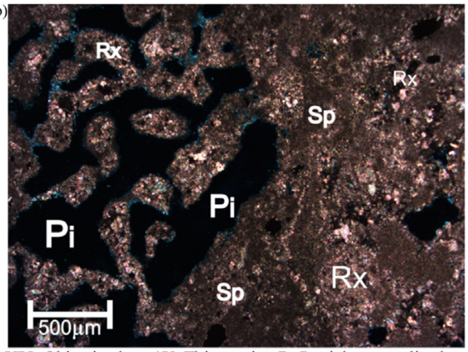
1) Determine the Masonry Uniaxial Compressive Strength (UCS_M), by using the Italian standard [1], implementing the UCS_R range found in *Step 4*, (see Section 2.2. of the present document), (as shown later in Table 4).

2.2. Definition of masonry mechanical parameters and scenarios

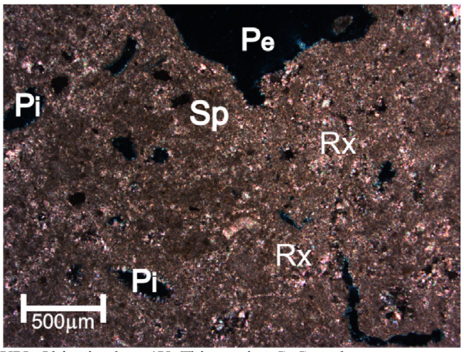
UCS_R could be significantly different from UCS_M masonry, due to mortar presence between joints and possible activation of different global and local collapse mechanisms [31,32]. However, local legislation does not provide specific guidance on it, therefore, in the absence of experimental data, and in absence of in situ non-destructive tests (NDT), the Italian standard [1] was taken as a matter-reference to determine UCS_M.

a)


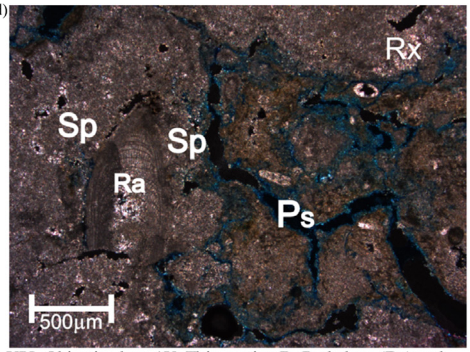
XPL Objective lens 4X. Thin section A. Partial and complete recrystalized bioclasts **(Rx)**, sparry cement **(Sp)**, Red algae **(Ra)**, red algae partially recristalized **(Rar)**.

b)


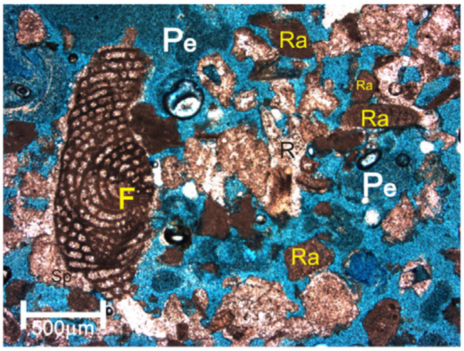
XPL Objective lens 4X. Thin section B. Partial recrystalized bioclasts **(Rx)**. Sparry cement **(Sp).** Intraclast porosity of a Coral **(Pi)**.

c)


XPL Objective lens 4X. Thin section C. Complete recrystalized bioclasts **(Rx)**. Sparry cement **(Sp)**. Intra **(Pi)** and extraclast porosity **(Pe)**.

d)


XPL Objective lens 4X. Thin section D. Red algae **(Ra)** and recristalyzed Foraminifera **(Rx)**. Sparry cement **(Sp)**. Secundary porosity: micro cracks **(Ps)**.

e)


PPL Objective lens 4X. Thin section E. Several Red algae **(Ra)**, Foraminifera **(F)** and Rugosa fragments **(R)**. Extraclast porosity **(Pe)**.

Fig. 4. Thin Section Quarry rocks.

It is worth to mention that the Italian Standard [1] provides a methodology for new masonry mechanical strength assessment, knowing UCS_R and mortar type (Table 11.10.VII of [1], reported in this document as Table 1); on the other hand, the Circular application to the NTC, [1], called Circolare NTC [33], provides a table (Table C.8.5.1, reported in this document as Tables 5 and 6) for existing masonry mechanical strength assessment, categorizing the types of masonry and the connection joints. These data could be taken without further analysis on the existing masonry.

Nevertheless, in the appendix of the Table C8.5.I of Circolare NTC [33], reference is made to the fact that even in the case of existing masonry, Table 11.10.VII of NTC [1], for new masonry is still valid, considering UCS_R and mortar type, if strength data are directly measured on rock and masonry mortar on the structure studied. In our case of study, as mentioned, no direct measures are available, therefore, an indirect method is offered, based on petrographic characteristics, to determine the rock uniaxial compressive strength - UCS_R. Moreover, from previous research [34,35] is known that Cartagena walls mortars are mechanically weak, made of beach sand and poorly assembled lime, the latest agrees with the literature findings about lime based mortars in historical buildings [36–40], therefore, mortar is assumed by the authors within the lowest resistance class (M2.5, corresponding to Uniaxial compressive strength of 2.5 MPa), according to the Italian standard NTC [1].