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# Preserving the Great Mosque of Cordoba (Spain): Characterization of Natural Stone Based on Rebound Hammer and Ultrasonic Tests †

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**Abstract:** The preservation of The Great Mosque of Cordoba (Spain) as a carrier of Andalusian collective memory requires innovative approaches to assess and maintain its structural health. This research centers on two non-destructive methods: direct ultrasound testing and rebound hammer. Laboratory tests were performed on natural stone provided by the primary material supplier for the Mosque's restoration and rehabilitation works. Non-destructive and destructive tests were carried out over 10 ashlars and 100 cubic and prismatic specimens, which were cut from the ashlars. Tests were conducted in multiple directions to investigate stone anisotropy. Destructive testing indicated isotropy, but ultrasound test results disagreed. Sensitivity analysis of specimen dimensions affected result dispersion, but not average properties.

**Keywords** mosque of cordoba; natural stone; ultrasonic tests; rebound hammer; anisotropy

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## 1. Introduction

The Great Mosque of Córdoba is an architectural masterpiece dating back to the 8th to the 10th century, stands as a symbol of Islamic cultural heritage in the Iberian Peninsula. In 1984, UNESCO designated it as a World Heritage Site [1]. Natural stone, present in its construction, requires meticulous evaluation and characterization to ensure its structural integrity and longevity.

Due to the impracticality of extracting specimens from the building, non-destructive testing (NDT) emerges as a viable alternative for material characterization. However, the existing literature lacks the strong correlations necessary to interpret the non-destructive testing results for this specific material. This research centers on two commonly used non-destructive methods: direct ultrasound test (UST) and rebound hammer test (RHT).

The primary goal is to validate UST and the RHT as reliable tools for comprehending the mechanical attributes of natural stone presents in the Great Mosque. The former assesses elastic ultrasonic wave propagation velocity, while the latter reflects the stone's superficial strength through a rebound index, both of which can be potentially correlated with the stone's compressive properties [2].

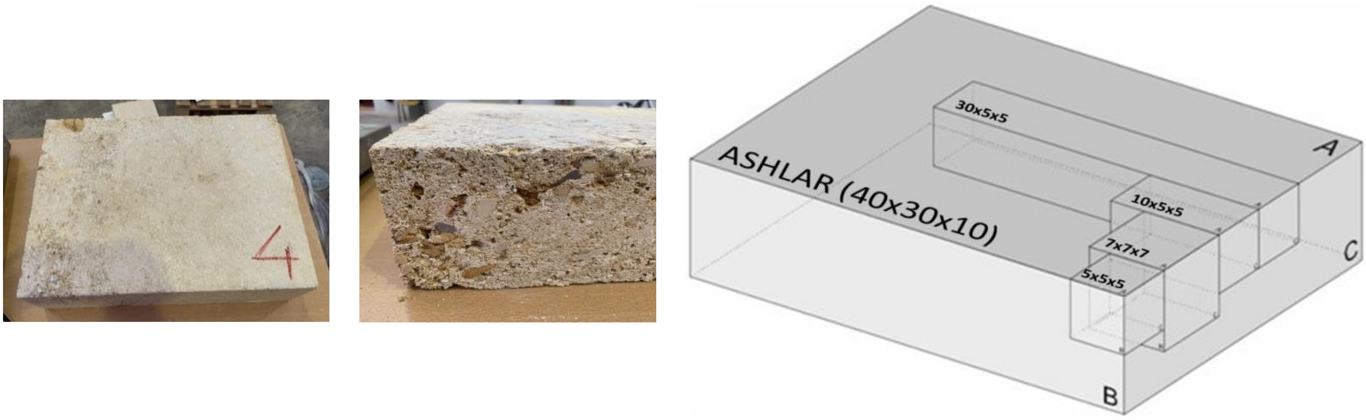
In this study, the natural stone present in the monument is characterized using NDT and the resulting values are correlated with the compressive strength obtained through destructive testing (DT) on the same material [3].

## 2. Materials and Methods

The construction of the Mosque was accomplished by repurposing architectural elements from other notable structures, including Roman marble columns and Byzantine capitals. However, the predominant material used in the majority of the mosque's structure is Cordoba's freestone, sourced from nearby quarries. This particular stone, known as bio-calcarenitae, has a rich historical utilization in the Cordoba region. Several varieties of biocalcarenites, such as biomicrite, biosparite, and biorudite [4], can be identified, originating from the Tortonian marine marginal facies within the Guadalquivir Depression. These varieties consist of amalgamated carbonate deposits with a sandy matrix, notable for their abundance of fossils and sedimentary microfauna.

Due to the impracticality of procuring samples directly from the Mosque of Córdoba, 10 ashlars of 40 × 30 × 10 cm were provided from one of the region's quarries, Mármoles y Piedra Gutierrez [5], Figure 1a,b, a primary supplier of natural stone for restoration projects within the Mosque. These ashlars were quarried with the grain orientation intact. As a result, a hypothesis was formulated suggesting that the stone could display anisotropic mechanical properties related to the direction of natural compression, specifically, the direction perpendicular to plane A as shown in Figure 1c. To simplify, 'direction A' will be the reference henceforth. The perpendicular directions to planes B and C, denoted as 'directions B and C', also named as '⊥ to A', are initially considered to present an isotropic behavior.

The experimental campaign utilizing non-destructive tests comprised two sub-campaigns. The first sub-campaign involved conducting ultrasonic and rebound hammer tests directly on the ashlars themselves. In the second sub-campaign, various specimens were obtained by a cutting process, and they were tested by UST and three different destructive tests: uniaxial compression, three points bending and split or indirect tensile test. These specimens included both cubic and prismatic shapes with varying dimensions, as depicted in Figure 1c.




(**a**) (**b**) (**c**)

**Figure 1.** Ashlars provided by the quarry: (**a**) an ashlar sample; (**b**) detail of natural stone surface and (**c**) nominal dimensions of ashlar and specimens (units in cm).

Dry density is a parameter closely linked to porosity, as both metrics assess the quantity of voids within a given volume. The real and apparent densities have been determined in accordance with the specified technical standard [6]. In the present study, a range from 1800 kg/m$^3$ to 1850 kg/m$^3$ of dry density was observed for ashlar samples.

Three different destructive tests: uniaxial compression, three points bending and split or indirect tensile test, were carried out. A monoaxial testing machine was used and the tests were conducted following the appropriate technical produce in each particular test. A summary of the results from the destructive tests is presented in Table 1.

Furthermore, flexural strength ($f_f$) and tensile strength ($f_t$) exhibit a noteworthy correlation with compressive strength ($f_c$). Statistical analyses were conducted to determine the significance of these correlations, resulting in linear relations (Equations (1) and (2)).

$$f_f = 0.32\, f_c \quad (1)$$

$$f_t = 0.11\, f_c \quad (2)$$

**Table 1.** Results from the destructive tests for each test type.

| Mech. Prop. | Dim. [mm] | Direction | Mean Value [MPa] | STD [MPa] |
|---|---|---|---|---|
| Compressive strength ($f_c$) | 50 × 50 × 50 | A | 6.06 | 0.66 |
| | | ⊥ to A | 5.61 | 1.09 |
| | 70 × 70 × 70 | A | 6.33 | 0.85 |
| | | ⊥ to A | 6.00 | 1.48 |
| Flexural strength ($f_f$) | 50 × 50 × 300 | A | 1.9 | 0.30 |
| | | ⊥ to A | 2.0 | 0.20 |
| Tensile strength ($f_t$) | 50 × 50 × 100 | A | 0.70 | 0.08 |
| | | ⊥ to A | 0.70 | 0.08 |

For the UST, the determination of the propagation velocity of volumetric type P elastic waves involves initiating an excitation at one point on one side of the specimen and measuring the time it takes for the elastic wave to reach the opposite side, where a sensor is placed to detect its arrival. This testing method, commonly referred to as a direct test, has been carried out following the technical recommendation [7]. The velocity is calculated by dividing the distance between the source and the receiver by the time-of-flight. It's important to note that in the presence of voids, cracks, defects, etc., the wave may not travel in a straight path between the source and the receiver. Consequently, the velocity determined in such cases is considered an 'apparent' velocity rather than the actual velocity value [8]. The equipment provides the receiver signal after the excitation pulse is generated (Figure 2).

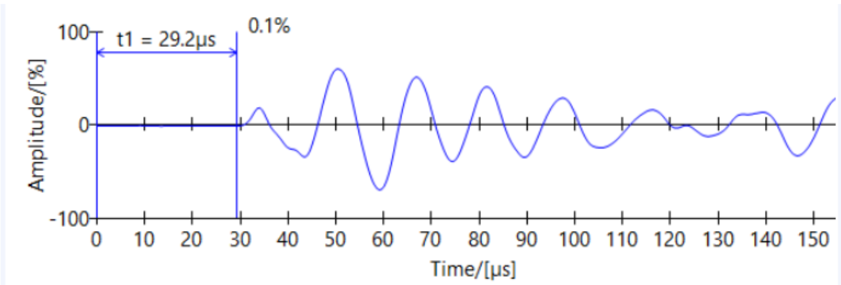
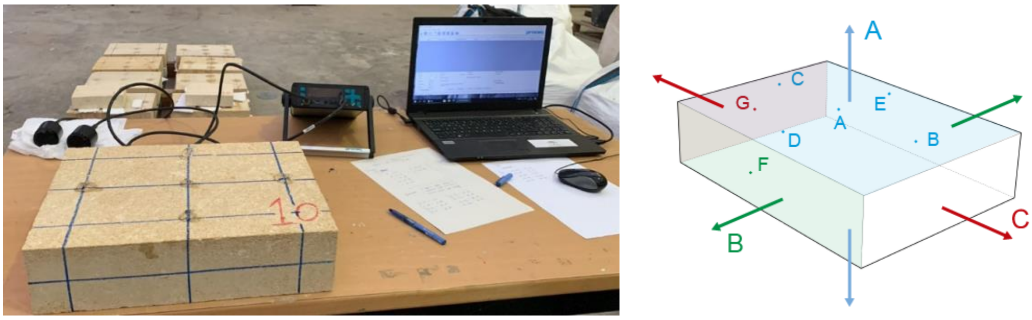



**Figure 2.** Ilustration of the receiver signal from ultrasonic equipment.

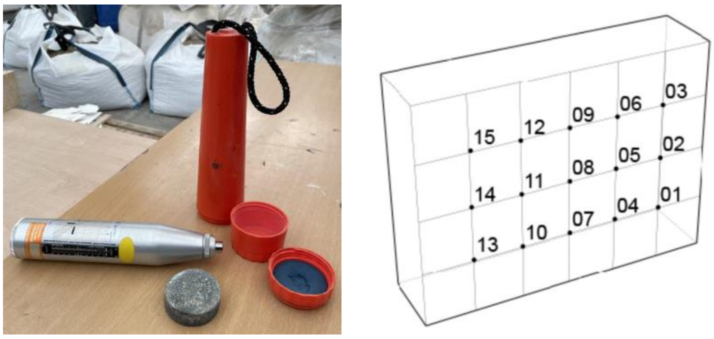
A Pundit Lab system by Proceq was used. Two 54 kHz piezoelectric sensors were employed, capable of functioning as either the excitation or the receiver probe. These sensors were chosen to enable inspection over the possible distances. For the ashlar samples, the direct propagation velocities were determined in three directions 'direction A' and 'direction B and C' ('⊥ to A'), Figure 3. Due to practical considerations, and notably the larger surface area in direction A compared to B and C, it allowed for a more extensive distribution of measurement points: points A, B, C, D, and E in 'direction A'; point F in 'direction B'; and point G in 'direction C', Figure 3b. After the cutting process, the UST were conducted on all cubic and prismatic specimens in the three designated directions.

The RHT, often referred to as the Schmidt hammer test, is utilized for assessing the compressive strength of ashlar surfaces. The tests were conducted in compliance with the concrete technical standard [9]. This method involves impacting the surface under examination with a spring-loaded hammer, and then measuring the rebound value or rebound index (RI) of the hammer to determine the surface's hardness [10]. The RI is correlated with the compressive strength of the material. The RI were determined at 15 points distributed on two opposite faces of ashlar samples (Figure 4), and from these, compressive strength of the material was computed.




(**a**) (**b**)

**Figure 3.** (**a**) UST equipment and (**b**) testing directions of the ashlars and measuring points.




(**a**) (**b**)

**Figure 4.** (**a**) Rebound hammer and (**b**) measuring points grid.

## 3. Results and Discussion

The results of the Non-Destructive Testing (NDT) performed are presented below. Initially, an evaluation of ultrasonic velocities for both ashlar samples and cubic and prismatic specimens extracted from ashlar origin is provided. Subsequently, a statistical analysis of propagation velocities is conducted for cubic and prismatic specimens, considering each measurement direction. Finally, an analysis of rebound values is carried out to establish a correlation between a reference value and the material's compressive strength.

Table 2 shows the mean values and standard deviations of ultrasonic velocities for the 10 ashlars, organized by measurement direction. These values collectively indicate an isotropic or low-anisotropy behaviour, as observed from both the mean and standard deviation values. However, the standard deviations indicate that this observation must be considered with caution.

**Table 2.** Mean values and standard deviations of direct UST for each measurement direction.

| Direction | Mean Velocity (m/s) | Standard Deviation |
|---|---|---|
| A | 2393.2 | 198.4 |
| B | 2312.9 | 123.8 |
| C | 2245.0 | 121.3 |

For 100 cubic and prismatic specimens, the velocities of UST have been categorized based on specimen dimensions and the testing direction, as shown in Table 3. Some notable phenomena are discernible. Firstly, these velocities exhibit higher mean values when compared to the ashlar samples. This can be attributed to a greater concentration of internal heterogeneity, resulting in increased resistance for the elastic wave pulse to traverse from the initial point to the final destination. Secondly, the variations in velocities across different directions raise questions about isotropic behaviour. However, it is evident that no predominant direction exists.

**Table 3.** Mean values and standard deviations of direct UST for each measurement direction and for each size of specimen.

| Ashlar | Dim. [mm] | Direction A | Direction B | Direction C |
|---|---|---|---|---|
| 1 | 50 × 50 × 50 | 2730.1 (64.6) | 2610.4 (103.6) | 2506.9 (88.4) |
| | 70 × 70 × 70 | 2501.4 (80.6) | 2766.7 (56.9) | 2739.2 (59.8) |
| | 50 × 50 × 300 | 2617.6 (57.0) | 2521.2 (37.9) | 2590.2 (108.8) |
| 2 | 50 × 50 × 50 | 2482.0 (100.1) | 2426.0 (101.3) | 2490.6 (108.4) |
| | 70 × 70 × 70 | 2400.7 (59.1) | 2544.6 (53.0) | 2567.2 (81.7) |
| | 50 × 50 × 300 | 2586.5 (109.0) | 2596.3 (31.9) | 2506.38 (36.8) |
| 3 | 50 × 50 × 50 | 2453.5 (41.7) | 2542.5 (69.7) | 2540.8 (85.6) |
| | 70 × 70 × 70 | 2384.0 (63.6) | 2558.7 (96.2) | 2558.1 (78.4) |
| | 50 × 50 × 300 | 2470.4 (65.0) | 2547.6 (73.0) | 2511.8 (94.6) |

In order to compare different measurement directions, Figure 4 shows a statistical analysis of the results for all specimens. The diagram includes key statistical measures, such as the median value (indicated by the red line), the 25th and 75th percentiles (represented by the lower and upper edges of the box, respectively), the extreme values (illustrated as whiskers), and any outliers (denoted by red crosses). Notably, the dispersion of median values is significantly lower when contrasted with the range of extreme values for each measurement direction.

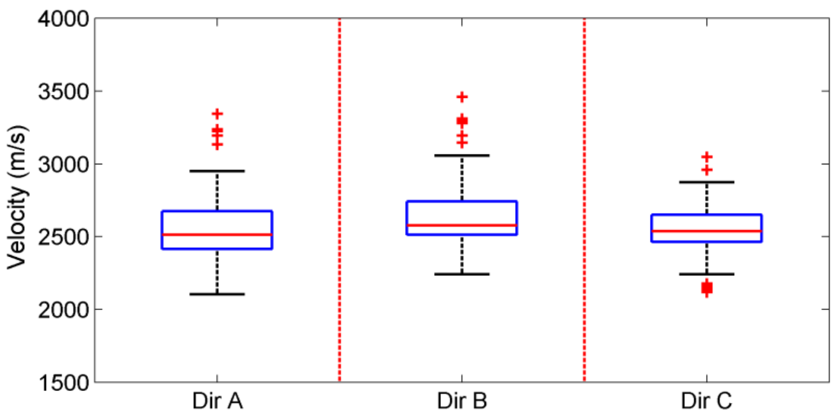



**Figure 4.** Statistical analysis of ultrasonic velocities for each measurement directions. The red line indicates the median value, the lower and upper edges of the box indicates the 25th and 75th percentiles, whiskers illustrated the extreme values, and the outliers are denoted by red crosses.

On the other hand, the results of the RHT exhibit a degree of consistency in terms of the compressive strength, even though fact that the RHT were carried out on different ashlars than those employed in compression tests of cubic specimens, Table 4. Due to limitations in the measurement range of the rebound hammer, to determine the compressive strength, the linear correlation $f_c = 0.8 \cdot RI - 5.017$, with $R^2$ value of 0.76, provided by [11] was employed, which was developed for a natural stone with similar characteristics.

**Table 4.** Results of rebound hammer test and compression strength values.

| | Mean Value | Standard Deviation |
|---|---|---|
| Rebound Index (RI) | 12.19 | 1.96 |
| $f_c$ from [50 × 50 × 50] mm³ specimens (DirA) | 6.06 MPa | 0.66 |
| $f_c$ from [70 × 70 × 70] mm³ specimens (DirA) | 6.33 MPa | 0.85 |
| Compression strength from correlation [11] | 4.73 MPa | 1.57 |

## 4. Conclusions

A mechanical characterization based on non-destructive test of the natural stone used for the construction of the Córdoba's Mosque (biocalcarenite) has been performed, including ultrasonic test and rebound hammer test.

The results presented here can be regarded as a preliminary step toward developing valid correlations for material inspection and damage detection in The Great Mosque of Cordoba. These results indicate a consistent mechanical behaviour for different specimen dimensions (ashlars, cubic, and prismatic specimens) and a lack of determined anisotropic behaviour in the tested directions, according to [12,13].

As future work, the authors suggest assessing mechanical properties associated with material rigidity, such as Young's Modulus or G Modulus, and establishing correlations with wave propagation velocity. Additionally, investigating the impact of surface roughness and moisture on external surfaces is an interesting aspect to be explored in forthcoming non-destructive experimental campaigns.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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