THE ANNALS OF “DUNAREA DE JOS” UNIVERSITY OF GALATI
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
Nº. 2 - 2023, ISSN 2668-4748; e-ISSN 2668-4756
Article DOI: https://doi.org/10.35219/mms.2023.2.03

ADVANCED METHODS TO CHARACTERIZE THE STRUCTURAL MATERIALS OF RELIGIOUS BUILDINGS CONSTRUCTION

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ABSTRACT

The paper aims to present a bibliographic study of works on the characterization of materials, for mosques and historical minarets, using destructive methods (uniaxial compression, tension direct and indirect), and non-destructive testing (Schmidt rebound hardness, ultrasonic pulse velocity (UPV), scanning electron microscope (SEM) and X-ray diffraction (XRD) and their usefulness in the field of protection built cultural heritage. These religious buildings usually are constructed of brick masonry, stone, or/and reinforced cement concrete. Further, the form and amount of a structural defect is a function of the environment to which the structure is subjected. The different techniques used, for various construction materials, have determined the following parameters: the surface hardness, pulse velocity, structural composition, compressive strength, tensile strength and chemical composition. In general, these parameters govern the behavior under the different actions, and contribute to the strengthening and protection of the structure.

KEYWORDS: characterization, historical masonry, religious buildings, non-destructive tests, destructive tests

1. Introduction

Minarets hold great cultural significance as a part of humanity's heritage for coming generations, due to their historical and architectural value. However, over time, historical masonry minarets may experience damage from factors such as material degradation, seismic activity, differential settlement, and environmental effects [1]. The damages that masonry minarets suffer can lead to structural instabilities that can ultimately result in the destruction of the entire structure. Therefore, the safety of these religiously significant buildings must be thoroughly investigated, and a voluminous body of academic literature has been published, elucidating the intricacies of structural assessment procedures. Indeed! Destructive and non-destructive investigations are invaluable tools used to characterize the materials of these historical structures. By conducting these tests, engineers and architects can determine the necessary parameters for finite element modeling, which enables them to simulate the dynamic behavior of the structure under various conditions. Finally, this information can be used to reinforce and protect the structure, ensuring its longevity for generations to come [2]. To concretize the study, we have taken the example of several minarets which have been the subject of previous studies, which are:

1. Hacı Mahmut Mosque, which is situated in the charming town of Bolvadin, which is a part of the Afyon province in Turkey. The minaret stands independently on the north-east corner of the mosque, and boasts of an octagonal base that is almost as tall as the outer wall of the mosque itself. The minaret stands tall at an impressive height of 24.5 meters. The transition from the pulpit to the shaft is achieved through the skilful use of moldings with circular surfaces. The shaft itself is circular and extends all the way up to the balcony, which is supported by a base made up of similar moldings with circular surfaces. The balcony, in turn, is fashioned in the form of a parapet. The cylindrical comb, with a diameter smaller than the shaft, culminates in a metallic spire that adds to the allure of the minaret. Constructed using brick and stone masonry, the minaret has a total of 76 concrete boarding steps at its center, Fig. 1.

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Fig. 1. *General view of hacı mahmut mosque* [1]

2. The Urla Kamanli Mosque, located in Urla, Izmir, Turkey, is an architectural masterpiece that has stood the test of time. Although there is no written record of the building date or the constructors, using comparative methods of architectural components in light of art history, it has been determined that this structure dates back to an era of early 14th century to mid-15th century (Erim 1995). The mosque is a member of a group of structures named Yahsi Bey Complex, which comprises a tomb, a Turkish bath, a primary school, and two fountains.

The structure has a square plan of 10 x 10 m, a wall thickness of 110 cm, and a height of 12.66 m. The dome and the window arches are brick masonry with thick mortar joints, while the walls of the structure are stone masonry with thick mortar joints and limestone. Utilizing squinches, which are brick masonry elements depicted in Figure 2, is a technique employed to achieve the seamless transition from walls to dome on the corners of historical structures.

Fig. 2. *South elevation view of the mosque* [3]

3. The Al-Omariya mosque, situated in the ancient city of Mosul on the western bank of the Tigris River, stands as a testament to the enduring legacy of Islamic architecture. Built in 1563 AD, three years after the arrival of Hajj Qassim bin Ali Al-Omari in Mosul, by order of the Ottoman Sultan Suleiman Al-Qanuni, the mosque remains one of the most esteemed places of worship in the region. The mosque's architectural splendour is further elevated by the addition of its minaret, which is located in the western wing of the courtyard. Comprised of three distinct parts, the prismatic base, with a width of 2.5 m and a height of 1.5 m, the cylindrical trunk, with a diameter of 2 m and a height of approximately 11 m, and the dome, which rises to approximately 2.5 m in height, as exemplified in Figure 3, the minaret stands tall, exceeding 23 m in height above the mosque's roof.

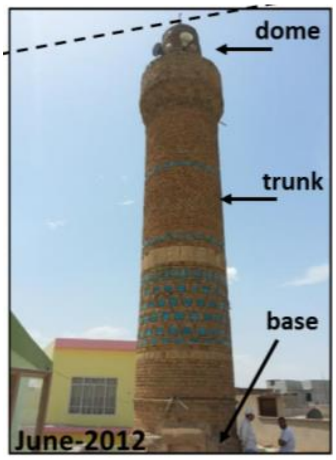

Fig. 3. *General view of Al-Omariya mosque* [4]

4. The Sütlü Minaret Mosque is an exquisite example of Ottoman architecture, characterized by a singular dome that adorns its silhouette (as depicted in Fig. 4). Situated beyond the city walls of the Battalgazi District in the City of Malatya, this mosque is steeped in historical significance. The edifice derives its name from its striking appearance, which evokes the imagery of "milky" hues. The mosque's pristine white facade, crafted from stones that retain their lustrous colour, is a testament to its enduring elegance and aesthetic appeal. The mosque is quadruple fronted and has an elevation in the west-east direction. The entry to the mosque is located on the west side facing the road.

In the initial survey, it was detected that two different types of stones were used in the construction, and the walls inside the building were completely covered with plaster. The wall is built with coursed rubble stones approximately 180 cm from the ground. The minaret of the mosque is approximately 21 m tall, and the body of the minaret has a diameter of 162 cm. The pulpit has a stone

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coating, while the body section of the minaret was built with bricks.

Despite the absence of explicit details regarding the construction date of the Sütlü Minaret Mosque, experts have deduced that it was erected in the 16th century. This conclusion is based on the mosque's striking resemblance to the Ak Minaret Mosque, a similarly-styled edifice in the Malatya region. Over the centuries, the mosque has undergone various restorations, including a significant one in 2005 by The Directorate General of Foundations. Furthermore, an inscription on the mosque's walls bears witness to a repair work conducted in 1808.

Fig. 4. *The overall perspective of the Historical Sütlü Mosque* [5]

To accurately characterize the materials that comprise the structures, both destructive and non-destructive tests were carried out on samples of mortar, stones, and bricks that were obtained from the structures.

2. Non-destructive methods

2.1. Hardness test

To determine the surface hardness values (rebound value) of the clay brick and stone samples, for Hacı Mahmut Mosque, L and LB type Proceq Schmidt Hammers were applied. Furthermore, the Schmidt Hammer test was employed on both the stones and clay bricks that make up the intact minaret. The test results are outlined in Table 1.

The Urla Kamanli Mosque underwent a rigorous testing process to determine the strength of its stone cylinder core samples. Schmidt rebound hardness test, as per the guidelines set by the International Society for Rock Mechanics (ISRM) (1981) [6], was carried out. A steel cradle that had a cylindrical slot of the same radius as the core held the sample. A Type L Schmidt hammer, possessing an impact energy of 0.74 Nm, was utilized. A total of 37 core samples were tested, and the average results for each stone are presented in Table 1.

To assess the surface hardness of the Historical Sutlu Minaret Mosque, a Schmidt hammer was used to measure the hardness at 10 different points. The hardness measurements were carried out in accordance with ISRM 1978 [7]. A total of 20 values obtained per sample, as per ASTM D5873-14 [8], and the average value of hardness on the surface was calculated. The hardness measurement results for the walls of the historical mosque are presented in Table 1 for easy reference and analysis.

Table 1. *Schmidt hammer test results*

The mosque	Location	Schmidt hammer (R)
Hacı Mahmut Mosque	Stone	49
	Inner Brick	30.801
	Outer Brick	41.915
	Concrete boarding steps	50
Urla Kamanli Mosque	Stone south 1	30.8
	Stone south 2	31.7
	Stone west 1	39.7
	Stone west 2	38
The Historical Sütlü Minaret Mosque	1	31
	2	36
	3	34
	4	35
	5	51
	6	45
	7	43
	8	45
	9	45
	10	41

2.2. The ultrasonic pulse velocity (UPV)

For Hacı Mahmut Mosque, ultrasonic wave velocity tests were conducted on the materials of the structures using Pundit type equipment. These tests helped to determine the velocity of sound waves passing through the materials, which can provide valuable information about their composition and properties. Furthermore, the stone samples' modulus of elasticity values was determined as per the ASTM (1969) standards [14], which helped to further characterize the mechanical properties of the materials. Table 2 presents the results of the test.

To determine the quality of the brick and stone core samples used in the construction of Urla Kamanli Mosque, an ultrasonic pulse velocity test was conducted. This was accomplished through the use of CNS Farnell Electronic's Pundit type equipment on brick samples (D = 25.6 mm) and stone core (D = 54 mm). The digital unit recorded the time duration for the ultrasonic pulse waves to pass through the sample, and the velocity of the wave was calculated based on the distance between the probes. The results of the ultrasonic pulse velocity test are presented in Table 2 for easy reference and analysis.

Table 2. *The ultrasonic pulse velocity test results of stone and bricks*

The mosque	Sample	Pulse velocity (m/s)	
Hacı Mahmut Mosque	Stone	4030	
	Inner Brick	2170	
	Outer Brick	2304	
	Concrete boarding steps	-	
Urla Kamanli Mosque	Stone south 1	3291	
	Stone south 2	3456	
	Stone west 1	5187	
	Stone west 2	5536	
	Brick	1398	
Al-Omariya mosque		Dry	Saturated
	Brick	1963	2613
The Historical Sütlü Minaret Mosque	Restoration Stone	Vp	Vs
		2773	1642
	Original Stone	3612	2669

To evaluate the quality of the cylindrical brick samples used in the building of Al-Omariya mosque, an ultrasonic pulse velocity (UPV) test was performed. The test was conducted on both dry and saturated (fully vacuum-pressure saturated) cylindrical brick samples (Ø 40 mm x 50 mm) using a pundit pulse apparatus. During the test, a direct pulse was sent from the source electrode through the sample's body, and the pulse was received by the receiver transducer. UPV was calculated by dividing the sample's length by the transmission time of the wave. The test values are presented in Table 2 for easy reference and analysis.

Ultrasound methods were employed to evaluate the quality of the masonry building elements used in The Historical Sütlü

Minaret Mosque. The dynamic elasticity modulus was determined in accordance with ISRM 1978 [7]. Ultrasound velocity measurement tests were conducted at various points within the structure and the results are displayed in Table 2. The propagation velocity of compression (Vp) and shear (Vs) pulses was determined in compliance with ASTM D 2845-05 [9].

2.3. Scanning Electron Microscope (SEM)

To gain a deeper understanding of the stones used in the construction of Urla Kamanli Mosque, microstructural analyses were conducted using the Philips XL 30S-FEG scanning electron microscope (SEM). The samples collected from the west section did not reveal any fossils upon examination. However, upon closer inspection of the stone collected from the south section, fossils ranging from 5-10 µm in outer diameter were investigated.

To conduct a complete analysis of the structural composition of the assessed samples used in the construction of Al-Omariya mosque, an electronic scanner with elevated accuracy, the Hitachi-TM 3000 scanning electron microscope, was employed. This advanced technology allowed for a detailed survey of the samples, providing valuable insights into their composition.

2.4. X-Ray diffraction (XRD)

For Urla Kamanli Mosque, the chemical composition of the stones was concluded via Philips X-Pert X-Ray diffraction (XRD) (PANalytical, Almelo, The Netherlands) and was determined to be calcium carbonate ($CaCO_3$).

For Al-Omariya mosque, the mineral composition of historical samples (mortar and brick) was inspected via the X-Ray Diffraction (XRD) test. Rigaku MiniFlex 600 was used for XRD investigation. To ensure the accuracy and precision of the mineral analysis, a meticulous preparation was carried out, involving the creation of crushed powders from small samples. It is obvious to observe that brick samples are composed principally of quartz (SiO_2) and calcite ($CaCO_3$) as well as of clay minerals and gypsum ($CaSO_4 \cdot 2H_2O$) but in few quantities.

3. Destructive methods

3.1. Uniaxial compression

For Hacı Mahmut Mosque, Uniaxial compression investigations (UAC) were conducted as discussed (TS-699, Ulu say et al. 2001) [5]. The average results are shown in Table 3.

In order to comprehensively analyze the structural integrity of Urla Kamanli Mosque, an array of advanced techniques was employed, including the Uniaxial Compression Test. Which adhered to the guidelines set forth by the International Society for Rock Mechanics (ISRM) (1981) [6], involved subjecting mortar core samples, brick, and stone to rigorous compression forces. The testing was carried out using a state-of-the-art mechanical testing machine that accurately recorded the stroke from the loading head. The stress-strain curves obtained from the uniaxial compression tests were utilized to determine the modulus of elasticity, which corresponded to the tangent modulus at 50% of compressive strength. The resulting averages of the modulus of elasticity and the uniaxial compressive strength of the brick, mortar samples, and stone are presented in Table 3, providing vital insights into the structural properties of the materials used in the construction of the mosque.

Table 3. *Uniaxial compression test results*

The mosque	Sample	Compressive strength (MPa)
Hacı Mahmut Mosque	Stone	58.28
	Inner Brick	13.09
	Outer Brick	18.08
	Concrete boarding steps	7.56
Urla Kamanli Mosque	Stone south 1	64.17
	Stone south 2	65.44
	Stone west 1	127.8
	Stone west 2	105.9
	Brick	11.68
	Mortar Masonry	4.19
	Mortar Brick	8.75
Al-Omariya mosque	Brick	7.02
The Historical Sütlü Minaret Mosque	Original Stone	45.20
	Restoration Stone	13.12
	Mortar	2.20

To succeed a comprehensive understanding of the structural integrity of Al-Omariya mosque, a series of rigorous tests were carried out, including the Uniaxial Compression Test. Three cylindrical samples (Ø 40 mm x 50 mm), dried for two days at 60 °C, were subjected to the test in a dry state condition, in accordance with the standard criteria outlined in [10]. The test was performed using the Instron 4485 press machine, a cutting-edge electronic pressure device, at a loading rate of 0.2 mm/min. The results of the test for the old brick samples are presented in Table 3, providing crucial insights into the materials used in the construction of the mosque. It should be noted, however, that due to the limited dimensions of the mortar samples, not all mechanical tests were feasible.

The Historical Sütlü Minaret Mosque underwent a thorough analysis of its structural integrity, which included the preparation of samples conforming to the guidelines outlined in ISRM 1979 [11]. These samples were carefully crafted with a diameter of 54 mm and a length-to-diameter ratio of 2-2.5, ensuring that they provided an accurate representation of the type materials used in the construction of the mosque. The results of the test, presented in Table 3, provide critical data on the materials' ability to withstand compression forces, offering valuable insights into the mosque's overall structural stability.

3.2. Direct and Indirect tension test

For Hacı Mahmut Mosque, indirect tension tests, also known as Brazilian tests, were conducted on the materials used in the construction in accordance with TS-699, Ulusay *et al.* (2001) standards [15]. The results of these examinations are accessible in Table 4.

The structural integrity of Urla Kamanli Mosque was thoroughly evaluated through the implementation of an Indirect Tension Test on mortar core samples, bricks, and stone - all of which were prepared in strict accordance with the guidelines set forth by the International Society for Rock Mechanics (ISRM) in 1981 [6]. The test results are presented in Table 4 and provide valuable insights into the materials' ability to withstand tension forces, which is critical for ensuring the mosque's long-term stability. The data obtained from the test is crucial for identifying any potential weaknesses in the materials used in the mosque's construction, enabling any necessary repairs or renovations to be carried out with precision and accuracy.

To evaluate the structural integrity of Al-Omariya mosque, direct tensile strength tests were executed on three cylindrical samples (Ø 40 mm x 50 mm) in a dry state condition. Prior to the test, the brick testers were dried for two days using an oven set at 60 °C. The examinations were conducted in accordance with standard criteria outlined in [12], and the samples were subjected to a loading rate of 0.2 mm/min using a programmed electronic pressure device (Instron 4485 press machine). The reaching of the direct tensile strength test for the old brick samples are presented in Table 4, providing valuable data on the materials' ability to withstand tensile forces.

For the Historical Sütlü Minaret Mosque, the indirect tensile strength test was conducted by using the Brazilian test [13]. Table 4 presents the data purchased of the analysed materials.

Nº. 2 - 2023, ISSN 2668-4748; e-ISSN 2668-4756
Article DOI: https://doi.org/10.35219/mms.2023.2.03

Table 4. *Data from direct and indirect tensile strength*

The mosque	Sample	Tensile strength (MPa)
Hacı Mahmut Mosque	Stone	6.09
	Inner Brick	1.43
	Outer Brick	1.43
	Concrete boarding steps	0.75
Urla Kamanli Mosque	Stone south 1	5.72
	Stone south 2	7.41
	Stone west 1	8.49
	Stone west 2	9.88
	Brick	1.867
	Mortar Masonry	0.73
	Mortar Brick	0.95
Al-Omariya mosque	Brick	0.65
The Historical Sütlü Minaret Mosque	Original Stone	4.86
	Restoration Stone	1.82
	Mortar	-

4. Conclusions

In this review paper, the authors aimed to provide a detailed view of the characterization of historical bricks and mortar samples from four significant mosques - Hacı Mahmut Mosque, Urla Kamanli Mosque, Al-Omariya mosque minaret, and the Historical Sütlü Minaret Mosque. The objective was to achieve successful future interventions for the preservation and restoration of these precious cultural and historical landmarks. To accomplish this goal, a mishmash of destructive and non-destructive tests was conducted, including Schmidt rebound hardness test and ultrasonic pulse velocity test to evaluate the hardness and quality of the materials, respectively. In addition, several micro-observation tests, such as XRD and SEM investigations, were performed on the historical samples. Furthermore, the mechanical properties of the samples were explored using uniaxial compression test and direct and indirect tensile strength tests. The meticulous attention to detail in conducting these tests and the use of advanced techniques highlights the importance placed on preserving and protecting these significant historical sites. The findings from this study can serve as valuable resources not only for the restoration of historical mosques and minarets but also for the preservation of other historical monuments dating back to the 15th-16th century. The comprehensive characterization of the materials and determination of their mechanical properties are crucial for identifying any potential weaknesses in the structures and enabling any necessary repairs or renovations to be carried out with precision and accuracy, ensuring the preservation of these precious cultural and historical landmarks for generations to come.

To sum up, this review paper aims to analyse the methods used by the researchers to characterize the materials used in historical mosques and minarets, Additionally, we propose a step-by-step procedure for future studies as follows:

1. Collect the samples without compromising the structural integrity.
2. Conduct non-destructive tests such as macrography and ultrasonic pulse velocity tests etc.
3. Proceed to destructive tests: mechanical tests etc.
4. Analyse the results and engage in a discussion.
5. Establish a correlation between the results and the material properties.

Acknowledgment

We would like to thank the Erasmus+ mobility program for doctoral students with Pitesti University in Romania, for funding the project.

References

[1]. Başaran H., Demir A., Ercan E., Nohutçu H., Hökelekli E., Kozanoğlu C., *Investigation of seismic safety of a masonry minaret using its dynamic characteristics*, Techno-Press, Ltd, Earthquakes and Structures, vol. 10, no. 3, p. 523-538, 2016.

[2]. Hussain A., Akhtar S., *Review of Non-Destructive Tests for Evaluation of Historic Masonry and Concrete Structures*, King Fahd University of Petroleum & Minerals, Arab J Sci Eng., DOI 10.1007/s13369-017-2437-y, 2017.

[3]. Teomete E., Aktaş E., *Structural Analyses and Assessment of Historical Kamanlı Mosque in Izmir, Turkey*, Journal of performance of constructed facilities, ASCE, vol. 24, no. 4, p. 353-364, August 1, 2010.

[4]. Al-Omari A., Khattab S., *Characterization of building materials used in the construction of historical Al-Omariya mosque minaret in Mosul's old city, Iraq*, Journal of Building Engineering, vol. 33, 2020.

[5]. Maras M. M., Özmen A., Sayın E., Ayaz Y., *Seismic Assessment of the Historical Sütlü Minaret Mosque*, Periodica Polytechnica Civil Engineering, 66(2), p. 445-459, 2022.

[6]. ***, *Rock characterization, testing and monitoring: ISRM suggested methods*, International Society for Rock Mechanics (ISRM), 1981.

[7]. ***, *ISRM - Suggested Methods for Determining Sound Velocity*, International Journal of Rock Mechanics and Mining Science and Geomechanical Abstract, 15, p. 53-58, https://doi.org/10.1016/0148-9062(78)91678-9, 1978.

[8]. ***, *ASTM - ASTM D 5873-14 Standard Test Method for Determination of Rock Hardness by Rebound Hammer Method*,

ASTM International, West Conshohocken, PA, USA, https://doi.org/10.1520/D5873-14, 2014.
[9]. ***, *ASTM - D2845-05 Standard Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock*, ASTM International, West Conshohocken, PA, USA, https://doi.org/10.1520/D2845-05, 2005.
[10]. ***, *ASTM D2938 - 95 Standard Test Method for unconfined compressive strength of intact rock core specimens*.
[11]. ***, *ISRM - Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials*, International Journal of Rock Mechanics and Mining Sciences, 15, p. 99-103, 1979.
[12]. ***, *ASTM D2936 - 20 Standard Test Method for Direct Tensile Strength of Intact Rock Core Specimens*.
[13]. Briševac Z., Kujundžić T., Čajić S., *Current Cognition of Rock Tensile Strength Testing by Brazilian Test*, The Mining-Geology Petroleum Engineering Bulletin, 30, p. 101-114, (in Croatian), https://doi.org/10.17794/rgn.2015.2.2, 2015.
[14]. ***, ASTM - D2845-97, 1969, *Standard method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock*, USA, 1996.
[15]. ***, *TS-699 - Natural building stones, Methods of inspection and laboratory testing*, Turkish Standard, Turkey, 1987.