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PEACE BUILDING IN CYPRUS THROUGH THE PRESERVATION OF ENDANGERED HERITAGE: IN-SITU AND LABORATORY CHARACTERIZATION OF MATERIALS FROM THE PANAGIA APSINTHIOTISSA MONASTERY

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ABSTRACT

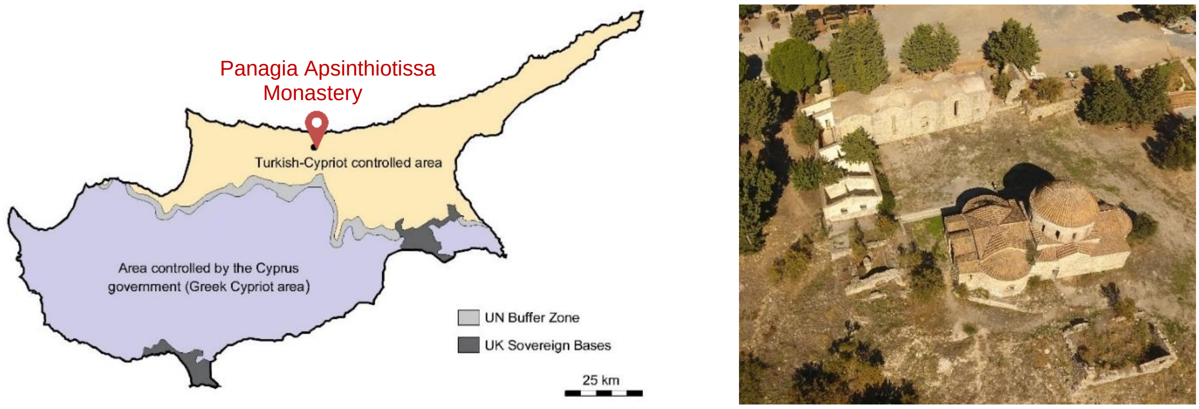
This paper presents experimental results for the characterization of masonry materials from the Byzantine Monastery of Panagia Apsinthiotissa in Cyprus. Stone samples obtained from the monument were subjected to laboratory tests to determine their apparent density, capillary absorption coefficient and compressive strength. Furthermore, XRD analysis of stone, brick and fractionated mortar samples was performed to investigate the materials' mineralogy. Micro-destructive drilling tests and non-destructive rebound hammer and Karsten tube absorption tests were also undertaken in situ aiming to enrich the database of information regarding the properties of the stones and bricks. The experimental data point towards the use of locally sourced building stones and mortar aggregates. The use of lime-based mortars with additions for improving their setting properties and for imparting hydraulicity to the composites was identified. The properties of the bricks were found to be influenced by their composition and variable degree of deterioration. The study is a contribution to systematic efforts for the preservation of the cultural heritage of Cyprus in the context of the peace-building process supported by the United Nations and the European Union.

KEYWORDS: Byzantine monument, natural building stones, lime mortars, historic fired clay bricks, XRD analysis, Drilling Resistance, non-destructive testing, conservation, preservation

1. INTRODUCTION

The Panagia Apsinthiotissa Monastery is situated on the southern foothills of the Pentadaktylos Mountains, near the village of Sichari/Kaynakkoy in Cyprus (Fig. 1a). The site comprises a series of stone masonry structures, which originally formed a building complex with area > 4500 m^2 (Fig. 1b). These include a Byzantine Church and a Refectory, as well as more recent single-storey monastic rooms that were built after the 17th century.

The Church (Figs 2a and b) is of the domed octagon type and consists of three parts: a domed nave, a tripartite sanctuary with an apse and a narthex with rib vaulting. The original structure dates back to the 11th century and comprises additions made between the 12th and 16th centuries (Enlart, 1899; Papageorgiou, 1963). The Refectory (Figs. 2c and d) is also dated in the 11th century (Papageorgiou, 1963). It is an elongated cross-vaulted hall with an apse featuring a semi-dome on the east. It is worth noting that this is one of only two Byzantine refectories that survive in Cyprus (Papacostas, 2015). Fragments/traces of frescoes are found in both the Church and the Refectory. The walls of the two structures are composed of two-leaf rubble stone masonry measuring 0.6-1 m in thickness. The masonry is composed of irregularly sized undressed sedimentary stones and is characterized by the absence of clearly defined horizontal bedding orientations. Fired clay bricks were used for the construction of arches, piers and pendentives.



(a) (b)

Figure 1. Map of Cyprus showing the location of the Panagia Apsinthiotissa Monastery (a) and aerial view of the site (b).

(a) (b) (c) (d)

Figure 2. Photographs from the exterior and interior of the Monastery's Church (a and b) and Refectory (c and d).

Accounts from pilgrims (Wallace et al., 1990) indicate that the Church exhibited severe structural damage (possibly caused by earthquakes) by 1735 AD. By the late 19th century, the Monastery was in ruinous condition and had been abandoned by monks (Enlart, 1899). Extensive restoration works were carried out by the Cyprus Department of Antiquities between 1965-69. The interventions to the Church included the reconstruction of the dome, of the missing vault parts of the narthex and nave and of the damaged sections of the piers and squinches. In the Refectory, the missing parts of the walls were also reconstructed, along with the semi-dome of the apse and the cross-vaults. After the 1974 events, which led to the division between the southern and northern areas of the island, the Monastery remained without maintenance and suffered considerable deterioration.

In 2018, the United Nations Development Programme and the Technical Committee on Cultural Heritage commissioned the preparation of designs for the conservation of the monument. The project was subsidized by the European Union and is part of an ongoing effort for the preservation of Cyprus endangered cultural heritage (see also Illampas et al., 2020), within the scope of reunifying the island. The conservation study was undertaken by a multidisciplinary team of Greek and Turkish Cypriot architects, civil engineers, archaeologists and conservators. To aid the designers' efforts, the authors carried out an extended experimental campaign for the characterization of the monument's building materials. The campaign included combined laboratory and field investigation for the determination of the physico-mechanical and mineralogical characteristics of building stones, brick masonry units, jointing mortars and coating plasters (in line with other relevant published engineering works by Theologitis et al., 2021; Sina Noei 2022; Al Sekhaneh et al., 2020; Fernandes et al., 2010; Kumar Mishra et al., 2021; Marrocchino et al., 2021; Livingston et al., 1992; Spathis et al., 2021).

This paper presents the findings of the experimental campaign carried out at the Panagia Apsinthiotissa Monastery. The experimental results obtained provide valuable information regarding the properties of the materials used in this medieval monument. Such data have a significant scientific merit as they enable engineers to assess the composition and pathology of the historic building elements and can act as a guide in the design of compatible interventions for their conservation and repair. More importantly, the case study hereby presented showcases the critical role that heritage preservation can pose in the peace building process. The study of monuments that are important symbols for both Greek and Turkish Cypriots, encourages the communities to learn about each other and to respect the cultural heritage of the island. This is a powerful tool for reconciliation and peaceful cooperation.

2. MATERIALS AND METHODS

Building materials were characterized by means of laboratory tests on samples collected from the field and by non- and micro-destructive tests performed in situ. The positions where building materials were sampled from and/or subjected to field tests are shown in Fig. 3.

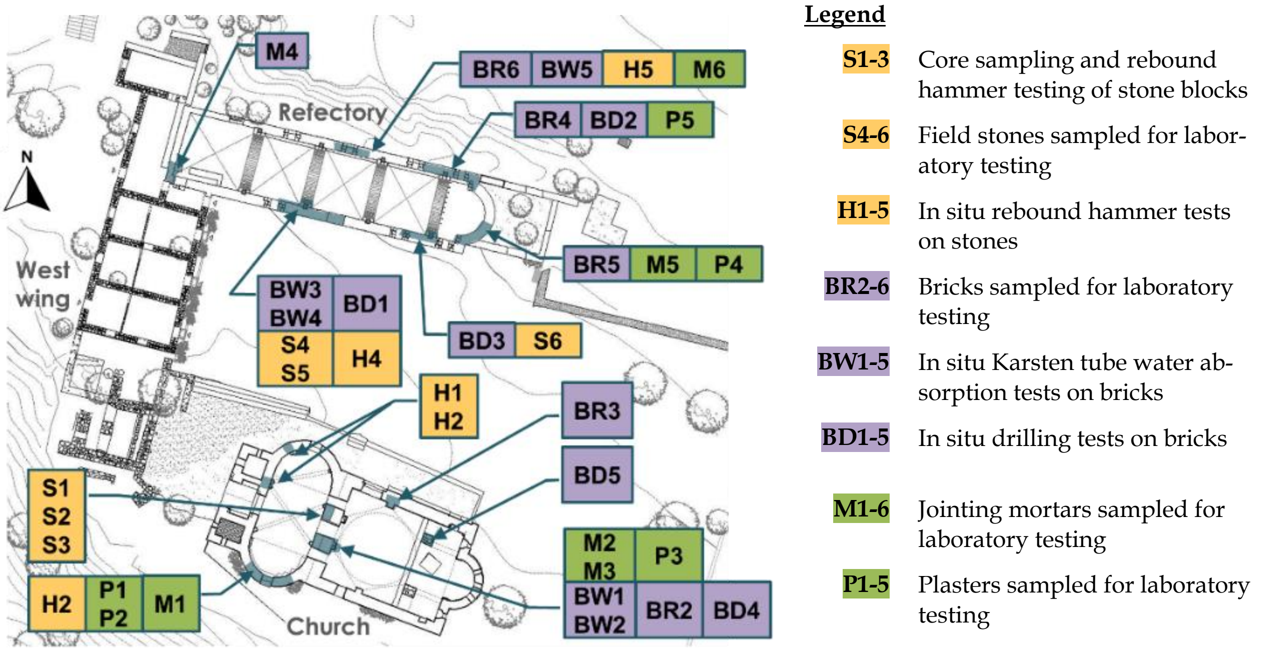


Figure 3. Plan view of the Panagia Apsinthiotissa Monastery showing the positions where building materials were sampled from and/or subjected to field tests.

Stone sampling included core drilling and collection of field stones. From the interior of the Church, core samples were obtained from three stone blocks (S1-3). Cores were extracted in the direction perpendicular to the face of the masonry using a core-drilling machine equipped with a 55 mm diameter bit. From the Refectory, full-sized blocks were extracted from masonry sections (S4-6). A total of five bricks were sampled from the Church (BR2-3) and Refectory (BR4-6) structures in order to perform laboratory tests. The samples were taken from the supportive piers of the structures and comprised of relatively small material fragments. Mortars were also sampled in the form of fragments. Six fragments of jointing mortar were obtained from the stone masonry walls in the interior of the Church (M1-3) and the Refectory (M4-6). From the same areas, five pieces of plaster

(P1-5) were sampled. In order to avoid extensive coring and sampling of the historic fabric, in situ rebound hammer, micro-drilling and Karsten tube absorption tests were carried out on stone and brick masonry units. These provided additional data regarding the materials' physico-mechanical properties. Since both structures hereby examined were heavily restored during the 1960s and hence incorporated a substantial amount of contemporary materials, emphasis was placed on selecting samples the texture of which implied that these belonged to an earlier (i.e. historic) construction phase.

2.1. *Testing of building stones*

Initially, the stone samples were visually examined under a stereomicroscope to determine their textural characteristics. They were then cut into cylindrical test units with a nominal diameter of 55 mm and a height of 55-100 mm. These were subjected to vacuum saturation tests as per EN 1936 for the determination of their apparent density (ρ_b) and open porosity (p_o), and to water absorption tests as per EN 1925 for the determination of their capillary absorption coefficient (C) (Fig. 4a). Compressive strength ($f_{c,s}$) was assessed via uniaxial loading tests as per EN 1926 (Fig. 4b). The results of compression tests were processed using the shape correction factors specified in EN 772-1 to account for the variability in the test units' height-to-diameter ratio. In all tests, 3 test units from each sample were examined.

The mineralogy of the stones was examined via X-Ray Diffraction (XRD) analyses. These were performed on portions cut from the sampled stones, following grinding into fine powder (< 0.063 mm) using a planetary mill. The powdered specimens were subjected to locked-coupled continuous scans at 2θ angles from 2^o to 70^o at a scan rate of 2^o/min using a Bruker D8 Advance instrument. The diffractograms obtained were subjected to qualitative and semi-quantitative analysis for the determination of the crystalline phases and the evaluation of their relative quantities.

For the indirect evaluation of the compressive strength of the stone blocks, non-destructive rebound hammer field tests were also conducted. Tests were performed on the three stone blocks of the Church that were subjected to core sampling (S1-3) (Fig. 4c) and on another five different stone blocks, three of which were incorporated in the narthex of the Church (H1-3) and two in the Refectory hall (H4-5). For the implementation of the tests, a concrete rebound hammer that generates an impact energy of 2.207 ± 0.1 J was used. At each stone block, at least 8 readings at different points were taken. In order estimate the weighted average rebound value (R_L) for each stone examined, only readings differing from the cumulative average of all measurements by less than 7 units were taken into account, as suggested in ASTM D5873. The compressive strength ($f_{c,s}$) was evaluated from the average rebound value (R_L) using the empirical relation proposed by Katz et al. (2000) for limestones and sandstones with strength in the range 11-273 MPa:

$$f_{c,s} = 2.21\ e^{0.07\ R_L} \quad (1)$$

(a) (b) (c)

Figure 4. Experimental setup used for the determination of the capillary absorption coefficient (a) and compressive strength (b) of the stone samples and in situ rebound hammer testing of a stone block previously subjected to core sampling (c).

2.2. Testing of brick masonry units

The absorption characteristics of the bricks were examined by means of in situ Karsten tube measurements based on EN 16302 (Figs. 5a and b). Karsten tubes having a water column height of 10 cm and a brim with d = 2 cm internal diameter were used. These were affixed on pre-wetted substrates using impermeable adhesive putty and were filled with deionized water. The quantity of water absorbed by the test substrate (Q_i) was measured directly from the graduated pipe at regular time intervals (t_i) for a period of 60 minutes. The tubes were topped up during the tests to maintain a steady water pressure. By calculating the volume of water absorbed per unit area of material ($W_i = Q_i/[\pi d^2/4]$), the water absorption rate (W_R) and the total water absorption at 60 minutes (W_{60}) could be determined. The latter is the measure prescribed in EN 16302 for expressing the outcome of Karsten tube tests. The water absorption rate was estimated based on linear regression analysis of the recorded data.

The compressive strength of the bricks was indirectly evaluated via drilling tests conducted using a portable system cordless DRMS (Drilling Resistance Measurement System) device from SINT Technology (Fig. 5c). The device is equipped with a D = 5 mm diameter diamond drill bit. During the tests, the rotational speed was set at 600 rpm, the penetration rate at 10 mm/min and the target penetration depth at 10 mm. At each of the 5 bricks tested, 2 to 3 drilling measurements at different points were taken. The average drilling force was obtained following analysis of the data recorded at penetration depths between 2-8 mm. Low strength dips and high strength peaks were removed from the force profiles used for calculating the average drilling force, as these were considered to be associated with the presence of local defects within the mass of the material (i.e. voids) or aggregate grains of appreciable size, both of which may greatly influence the resistance against drilling, without really affecting the overall mechanical behaviour of the brick unit. The compressive strength ($f_{c,b}$) was estimated using the correlation proposed by Fernandes and Lourenço (2007) for historic fired clay bricks having strengths in the range 2.5-25 MPa:

$$f_{c,b} = 9.196\,(4F_d/\pi D^2)^{0.609} \quad (2)$$

Brick fragments sampled from the field were visually studied under a stereomicroscope. They were then milled into fine powder and subjected to qualitative and semi-quantitative XRD analyses. A scan range between 2-70° and a rate of 2°/min were adopted in the analyses.

(a) (b) (c)

Figure 5. In situ water absorption measurements on bricks using Karsten tubes for the testing of horizontal (a) and vertical surfaces (b) and drilling resistance measurements on bricks (c).

2.3. Testing of jointing and coating mortars

The textural characteristics of all mortar samples (M1-6 and P1-5) were examined with a stereo-microscope. In order to obtain information regarding the mix components and the mineralogy of the mortars, the sampled fragments were fractionated and their constituents were subjected to qualitative and semi-quantitative XRD analysis. The mortar fragments were initially crushed using a porcelain mortar and pestle to roughly segregate the aggregates from the binder. The processed samples were then immersed in acetone and were sonicated in an ultrasound bath so that the binder particles would detach from the aggregate granules. At the end of the sonication cycle, samples were sieved through a 63 μm sieve. The material retained on the 63 μm sieve was subjected to another sonication cycle at the end of which it was sieved again. This process was repeated until no deposits of binder could be visually detected on the surfaces of the aggregates. Afterwards, the segregated constituents of the samples were left to dry and the weights of the fractions passing through (m_b) and retained (m_a) on the 63 μm sieve were measured. Based on the hypothesis that the material with particle size <63 μm consists mostly of the binder, the binder:aggregate ratio (b:a) of each mortar sample was computed as m_b:m_a.

Separate XRD analyses were carried out on the binder material obtained from the fractionation process and on samples prepared by pulverizing the segregated aggregates. The analyses parameters adopted were the same as for the stones and bricks.

3. RESULTS AND DISCUSSION

3.1. Properties of the building stones

The results of the laboratory tests on the stone samples are presented in Table 1. Stereomicroscopic images of the stone materials are shown in Fig. 6.

Table 1. Mineralogical composition and average physico-mechanical properties (coefficient of variation) of building stones determined from laboratory tests on 6 different samples.

Sampling location	Sample ID	Lithology	Mineralogical composition	ρ_b (kg/m³)	p_o (%)	C (g/m²s^1/2)	$f_{c,s}$ (MPa)
Church	S1	Dolostone	Dolomite: 94% Calcite: 5% Gypsum: traces	2727 (1%)	2.7 (28%)	5.83 (33%)	41 (10%)
	S2	Limestone	Magnesium Calcite: 99% Dolomite: traces Silicates: traces	1950 (11%)	25.5 (30%)	253 (31%)	23 (28%)
	S3	Limestone	Calcite: 77% Silicates: 16% Dolomite: 6% Gypsum: traces	2347 (2%)	11.0 (13%)	9.58 (55%)	49 (11%)
Refectory	S4	Dolostone	Dolomite: 98% Magnesium Calcite: traces	2813 (1%)	1.4 (13%)	2.18 (55%)	35 (37%)
	S5	Dolostone	Dolomite: 53% Calcite: 47%	2690 (1%)	2.5 (9%)	5.72 (75%)	49 (52%)
	S6	Dolostone	Dolomite: 96% Calcite: 4% Silicates: traces	2713 (1%)	3.5 (23%)	5.35 (8%)	45 (26%)

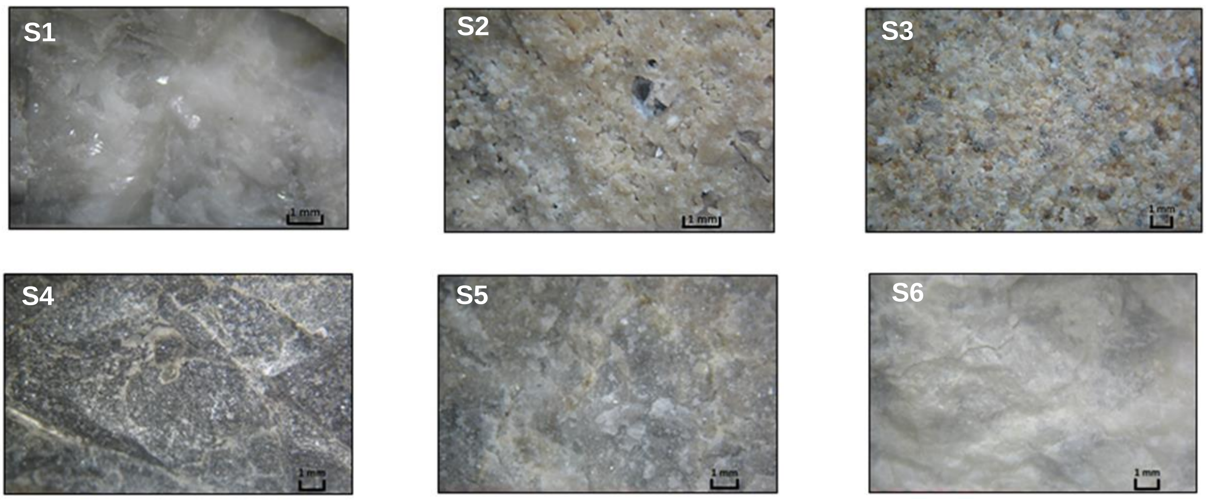


Figure 6. Stereomicroscopic images of the stone samples obtained from the Church (S1-3) and Refectory (S4-6) of the Panagia Apsinthiotissa Monastery.

Samples S1 and S4-6 are light- to dark-grey sedimentary rocks belonging to the Sykhari Geological Formation. This formation belongs to the Pentadaktylos succession and comprises massive to thickly bedded dolomitic limestones that are mostly recrystallized and brecciated (Ducloz, 1972). S1, S4 and S6 are dolostones consisting almost exclusively of dolomite (> 90% w/w) and some small amounts of calcite (≤ 5 % w/w). On the other hand, S5 is abundant in both dolomite and calcite at a ratio ca. 1/1. The aforementioned samples are microcrystalline and have possibly been formed following recrystallization by metamorphism. A few white veins were observed throughout samples S1 and S6, possibly from calcite and/or magnesite precipitation into pre-existing cracks. Due to their microcrystalline structure and the dominant presence of dolomite in their mineralogy, these samples exhibit high apparent density (2650 to 2850 kg/m^3) and relatively low porosity (< 4%). They also have low coefficients of capillary absorption (< 6 $g/m^2s^{1/2}$). Their compressive strength was found to be between 35 and 50 MPa.

Samples S2 and S3 belong to a different lithological group. These are coarse-grained stones of brown-orange colour that possibly originate from the Nicosia Geological Formation. As outcrops of this formation do not occur in the close vicinity to the monument, the material may have been intentionally brought to the site for the construction of carved architectural members, since it can be more easily shaped than the hard dolostones found in the area. It is also possible that these stones were added at a later stage in the course of restoration works. The stones are rich in calcite (>75% w/w) and may therefore be classified as limestones. Their structure is characterized by the presence of calcitic grains of diameter ≤ 2 mm, held in a sparry calcitic matrix. One of the two samples exhibits rather high porosity (~ 25%) which increases the sorptivity of the material (~ 250 $g/m^2s^{1/2}$) and limits its load-bearing capacity (~ 20 MPa). The other sample has a more consistent structure with a lesser amount of open pores (11%) and noticeably higher compressive strength (49 MPa).

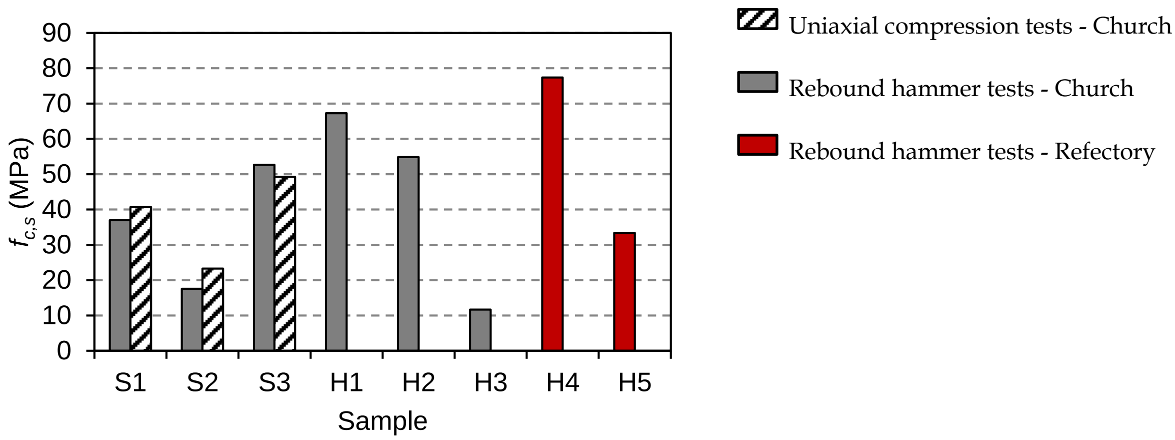


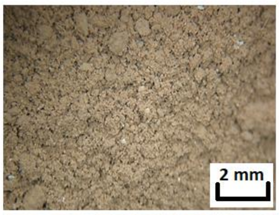
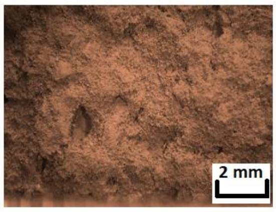
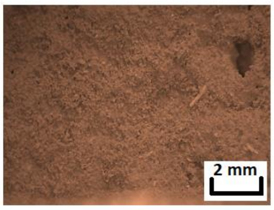
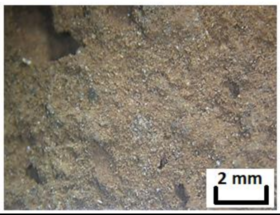
Figure 7. Comparison between the compressive strength values obtained from non-destructive re-bound hammer tests performed in situ and standardized uniaxial compression laboratory tests.

The outcomes of the rebound hammer tests performed on the masonry stone blocks are presented in Fig. 7. The results are totally in line with the outcomes of destructive loading tests. Overall, the load bearing capacities derived from rebound measurements vary from 12 to 77 MPa. Variations among the results of rebound hammer tests are attributed to the presence of masonry materials of different lithological origin, the natural randomness and inhomogeneity of building stones and the variable levels of material degradation encountered at different areas of the masonry (Kolaiti and Papadopoulos, 1993).

3.2. *Properties of the fired clay bricks*

Table 2 shows the texture of the brick samples examined and the results of the XRD analyses. Samples BR2-5 were found to include high amounts of clay minerals, such as chlorite and illite. These samples also include large quantities of carbonate minerals (calcite, Mg-calcite and dolomite). Samples BR3-5 further include silicates and minor amounts of gehlenite. Sample BR6 comprises major amounts of silicates (quartz, feldspars and chloritoid) and traces of chlorite and gehlenite. Phyllosilicates (biotite and muscovite) and oxides (hematite and periclase) were also found in BR6. The presence of calcite and the absence of high firing temperature products, such as mullite, spinel and christobalite, indicate that the firing temperature of this brick probably did not exceed 900 °C. In line with the findings of this study, Ulukaya et al. (2016), who analysed Byzantine bricks sampled from monuments in Istanbul, also found that these were produced from calcium rich clay that was fired at temperatures near 850-900 °C.

Table 2. Stereomicroscopic images and results of XRD analyses performed on brick fragments.

Sampling location	Sample ID	Stereomicroscopic image	Mineralogical composition
Church	BR2		Calcite: 42% Dolomite: 17% Silicates: 4% Clays: 37%
Refectory	BR3		Calcite: 36% Dolomite: 15% Silicates: 22% Clays: 26% Gehlenite: traces
	BR4		Calcite: 27% Dolomite: 12% Silicates: 25% Clays: 36% Gehlenite: traces
	BR5		Magnesium Calcite: 29% Dolomite: 7% Silicates: 22% Clays: 38% Gehlenite: 4%
	BR6		Calcite: 6% Silicates: 76% Phyllosilicates: 10% Oxides: 6% Clays: 2% Gehlenite: traces

The measurements obtained from the implementation of Karsten tube absorption tests and drilling resistance tests are reported in Fig. 8. Table 3 gives the total values of water absorbed per unit area of material for a testing period of 60 minutes (W_{60}) and the computed water absorption rates (W_R), as well as the average drilling forces and the corresponding compressive strength predicted for each tested brick.

The values of total water absorption assessed following the testing of bricks at the interior of the Church (BW1-2) are in the range 3.5-4.5 ml/cm^2 and the respective water absorption rates are close to 0.07 ml/cm^{2}min. Consistently higher values were obtained in the case of the Refectory. Two of the bricks examined from this structure (BW3-4) gave total water absorption values near 15 and 30 ml/cm^2, while their absorption rates were found to be between 0.25 and 0.5 ml/cm^2. The third sample examined from the Refectory (BW5) exhibited excessively high water absorption. In fact, monitoring of the amount of water adsorbed into this particular brick seized after 2.5 minutes. By extrapolating from the data recorded, it is estimated that after 60 minutes the material would have absorbed 185 ml of water per cm^2. The computed absorption rate for sample BW5 is also very high as it exceeds 3 ml/cm^{2}min. The dissimilar hydric behaviour of the bricks found in the two structures is possibly associated with differences in the composition of the materials (see also the outcomes of stereomicroscopic investigation and XRD analysis) and the degree of deterioration sustained by the various parts of the monument. The response recorded for sample brick BW5, in particular, is assumed to be related to long-term exposure of the material to damaging agents associated with the presence of moisture. Indeed, the north wall of the Refectory, where this sample is located, is subject to infiltration of water due to surface runoffs shed along the base of the hall. As a result, the masonry materials at this section of the structure are prone to moisture-driven decay, which can adversely influence their resistance to water penetration.

Most bricks subjected to drilling tests gave compressive strength values in the range 3.7-4.7 MPa. An exception was noted in the case of sample unit BD5, whereby the measured strength was 7.5 MPa. These results are in line with the 3-10 MPa compressive strength values obtained in Fernandes and Lourenço (2007) from the testing of 12th to 19th century historic bricks from Portugal. Stefanidou et al. (2015), who performed laboratory loading tests on Byzantine bricks sampled from monuments in Greece, reported compressive strength values between 4.5 and 8 MPa for structures dating from the 11th to the 15th century. However, these researchers found higher compressive strengths (> 10 MPa) for bricks originating from earlier constructions dating before the 8th century.

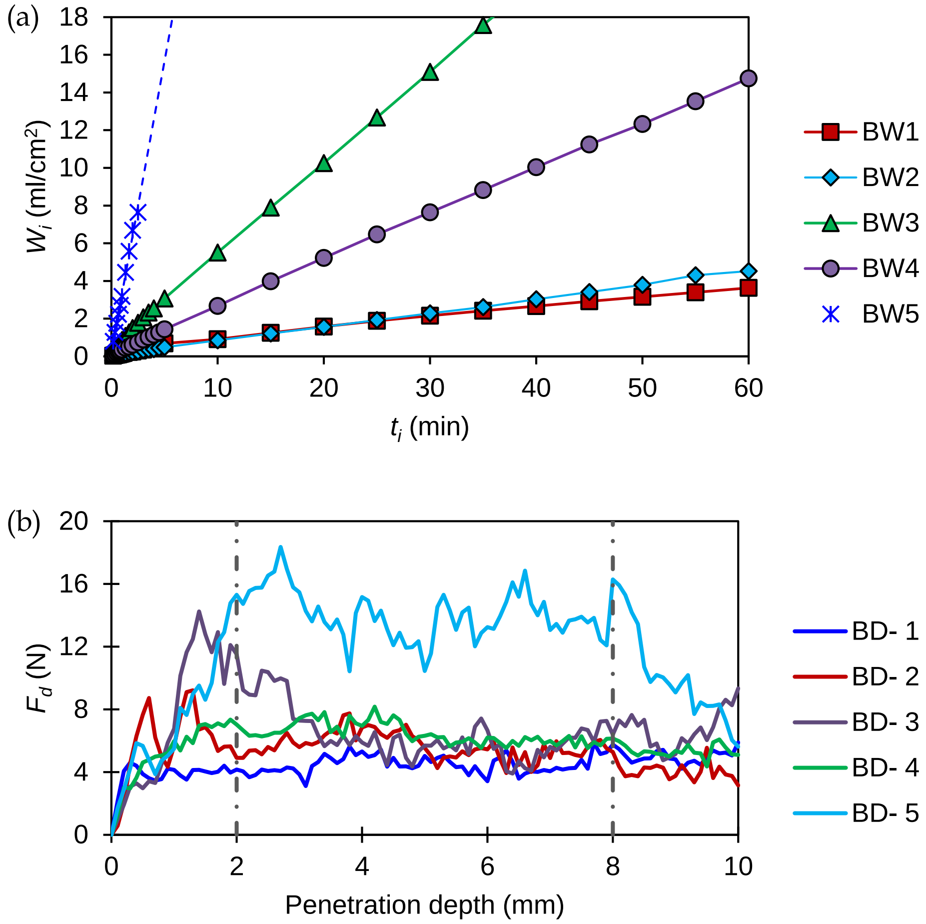


Figure 8. (a) Variation of the amount of water absorbed per unit area of material (W_i) in relation to time (t_i) recorded following the implementation of in situ Karsten tube tests on five different brick samples. (b) Variation of the drilling force (F_d) as a function of the penetration depth recorded following the implementation of in situ drilling resistance tests on five different brick samples. The drilling force reported for each brick unit is the average of 2 to 3 measurements.

Table 3. Results obtained from Karsten tube absorption tests and drilling resistance measurements conducted on masonry bricks.

Testing location	Absorption tests			Drilling resistance tests		
	Sample ID	W_{60} (ml/cm²)	W_R (ml/cm²min)	Sample ID	F_d (N)	$f_{c,b}$ (MPa)
Church	BW1	3.6	0.06	BD-4	6.45	4.7
	BW2	4.5	0.07	BD-5	14.1	7.5
Refectory	BW3	29.7	0.49	BD-1	4.49	3.7
	BW4	14.7	0.25	BD-2	5.69	4.3
	BW5	185*	3.08	BD-3	6.45	4.7

*Value extrapolated from measurements conducted up to 2.5 min.

3.3. *Properties of the jointing and coating mortars*

The results of the laboratory tests performed on the jointing and coating mortar samples are summarized in Table 4 and Table 5. The two tables report the type of mortar and plaster material identified in each case, along with the mineralogical composition of each sample's constituents and the binder:aggregate (b:a) ratio assessed. Stereomicroscopic images showing the texture of the samples are also given in the Tables.

Table 4. Types of jointing mortar identified, stereomicroscopic images of the samples and corresponding mineralogical composition and binder: aggregate (b:a) ratios assessed from XRD analysis and fractionation of samples.

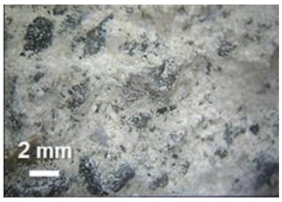
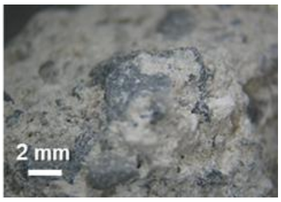
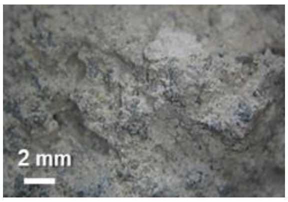
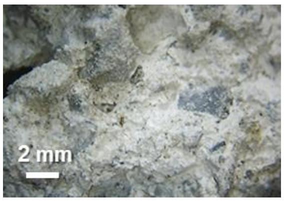
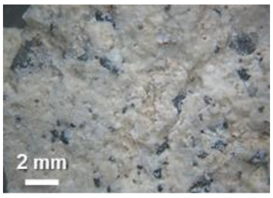
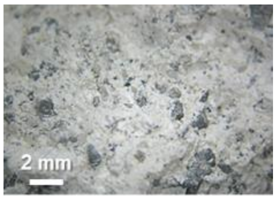
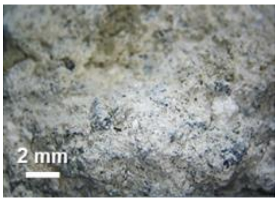
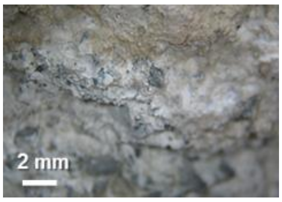
Sampling location	Sample ID	Mortar type	Stereomicroscopic image	Mineralogical composition		b:a (w/w)
				Binder	Aggregate	
Church	M1	Lime-based jointing mortar with traces of gypsum		Calcite: 56% Dolomite: 10% Magnesite: 11% Gypsum: 4% Gehlenite: 3% Niter: 16%	Calcite: 16% Dolomite: 67% Magnesite: 4% Gypsum: 3% Niter: 8% Gehlenite: traces	1:3
	M2	Lime-based jointing mortar with traces of crushed ceramic		Calcite: 68% Dolomite: 18% Magnesite: 13%; Gehlenite: traces Silicates: traces	Calcite: 17% Dolomite: 73% Magnesite: 6%; Gehlenite: 3% Silicates: traces	1:4
	M3	Lime-based jointing mortar with traces of crushed ceramic		Calcite: 60% Dolomite: 26% Magnesite: 13%; Gehlenite: tr Silicates: traces	Calcite: 16% Dolomite: 74% Magnesite: 7%; Gehlenite: 3% Silicates: traces	1:5
Refectory	M4	Lime-based jointing mortar		Calcite: 64% Dolomite: 10% Magnesite: 25%; Silicates: traces	Calcite: 39% Dolomite: 46% Magnesite: 15%; Silicates: traces	1:1.5
	M5	Lime-based jointing mortar		Calcite: 89% Dolomite: 11% Silicates: traces	Calcite: 39% Dolomite: 61% Silicates: traces	1:3
	M6	Lime-based jointing mortar with traces of crushed ceramic		Calcite: 62% Dolomite: 16% Magnesite: 20%; Gehlenite: traces Silicates: traces	Calcite: 20% Dolomite: 16% Magnesite: 13%; Gehlenite: traces Silicates: traces	1:6

Table 5. Types of plaster coatings identified, stereomicroscopic images of the samples and corresponding mineralogical composition and binder: aggregate (b:a) ratios assessed from XRD analysis and fractionation of samples.

Sampling location	Sample ID	Mortar type	Stereomicroscopic image	Mineralogical composition		b:a (w/w)
				Binder	Aggregate	
Church	P1	Lime-based plaster with traces of crushed ceramic		Calcite: 28% Dolomite: 20% Magnesite: 10% Gehlenite: 3% Silicates: 5% Jarosite: 3%	Calcite: 47% Dolomite: 41% Magnesite: 6% Silicates: 4% Gehlenite: traces Gypsum: traces Jarosite: traces	1:2
	P2	Lime-based plaster with traces of crushed ceramic		Calcite: 43% Dolomite: 30% Magnesite: 18% Silicates: 4% Gypsum: 3% Gehlenite: traces	Calcite: 20%; Dolomite: 65% Magnesite: 10% Silicates: traces Gypsum: traces Gehlenite: traces	1:4
	P3	Lime-based plaster		Calcite: 94%; Dolomite: 6% Silicates: traces	Calcite: 91% Dolomite: 9%	1:0.5
Refectory	P4	Lime-based plaster		Calcite: 88% Silicates: 5% Dolomite: traces Gehlenite: traces Magnesite: traces	Calcite: 73% Dolomite: 22% Magnesite: 13%	1:1
	P5	Lime-based plaster		Calcite: 59% Dolomite: 28% Magnesite: 13%	Calcite: 19% Dolomite: 77% Magnesite: traces Gehlenite: traces Silicates: traces	1:4

Samples M1-6 are white/light grey lime-based jointing mortars with b:a ratios ranging from ca. 1:1.5 to 1:6 w/w. The samples are rich in carbonate minerals (calcite, dolomite and magnesite / hydromagnesite), both in the aggregate and the binder fraction. They contain black/dark grey aggregates, which are possibly dolomites originating from the Keryneia Terrane and the Sykhari geological formation. The results obtained from the XRD analysis of the aggregates are generally in line with those reported for the stones sampled from the same monument. It is, therefore, quite possible that aggregates for the preparation of the mortars were sourced from the area where the monument is built. The latter is rich in sedimentary and low-grade metamorphic rocks, comprising predominantly (>50%) of calcium carbonate (i.e. calcite) and/or dolomite. Traces of silicates (quartz, feldspars and epidote) and gehlenite were also found in most of the mortar samples. The presence of gehlenite, in particular, is indicative of the use of crushed ceramic fragments fired at 800-1060 °C. The intentional addition of crushed ceramic in mortars first appeared in Cyprus in the Late Bronze Age (Theodoridou et al., 2013) and aimed at enhancing the materials' performance by inducing hydraulicity (Theodoridou et al., 2016). Gypsum was observed in the aggregate and the binder fractions of M1; this mineral was probably intentionally added to the mortar to enhance its setting and hardening. Indeed, a broad study for the characterization of historic mortars from the eastern Mediterranean area revealed that both crushed ceramic and gypsum were widely used as binder additions during the byzantine and post-byzantine periods (Moropoulou et al., 1995). Sample M1 also includes niter; this is the form of potassium nitrate [KNO_3]

found in animal litter. Its presence may be linked with practices used in historic construction.

Samples P1-5 are lime-based plasters with b:a ratios estimated between c.a. 1:0.5 and 1:4. Their mineralogical composition is similar to that of the jointing mortars. All plaster samples have high amounts of carbonate minerals (calcite, magnesite and dolomite). Silicates and gypsum were also identified, albeit in much lower amounts. Traces of crushed ceramic, indicated by the presence of gehlenite, were observed in P1 and P2 (both in the aggregate and binder fraction). P4 and P5 also include gehlenite, either in the binder or aggregates, respectively. XRD analyses also showed the presence of jarosite in P1 and P5, and of thaumasite (silicate mineral with SO_4^{2-} ions in its composition) in P4. These minerals are generated by the weathering (oxidation) of sulfide minerals found in dolomitic limestones. Halite was further observed in plaster sample P4; this mineral may have been formed by the alteration of the frescoes overlaying the sampling area. In medieval times, minerals containing chloride ions, such as lazurite (a tectosilicate mineral with deep blue color), were used in wall frescoes (Bicchieri et al., 2001; Clark et al., 1997; Frison and Brun, 2016).

4. CONCLUSION

An extensive experimental campaign was conducted for the characterization of historic masonry materials from the Byzantine Monastery of Panagia Apsinthiotissa in Cyprus. XRD analyses showed that dolostones sourced from geological formations within the vicinity of the monument were primarily used in the masonry construction and mortar production. Coarse-grained limestones that were either originally used for the fabrication of carved architectural members or were introduced in the course of restoration works were also identified in the walls of the Monastery's Church. The building stones gave compressive strengths in the range 35-50 MPa and densities from 1950 to 2850 kg/m^3, depending on their lithology. The limestones were found to be more porous and absorbent, compared to the dolostones. Lime-based jointing and coating mortars were also identified. Some of the mortars were found to contain additives, such as gypsum and crushed ceramic. Minerals pointing towards the weathering of the mortars' aggregates and the alteration of frescoes overlaying the mortar coatings were also detected. The mineralogy of the brick masonry units indicates that these were probably fired at low temperatures (< 900 ^{o}C). Bricks in sections of the monument that exhibit moisture infiltration problems showed noticeably higher water absorption rates. Micro-drilling tests gave predictions in the range 3.5-7.5 MPa for the compressive strength of the bricks.

The experimental results obtained in this study contribute towards improving existing knowledge regarding the properties of historic materials used in the monuments of Cyprus. Such systematic investigations are part of an ongoing initiative (see also Illampas et al., 2021, 2020; Kyriakou et al., 2022) for the creation of a database of information regarding the building materials of the island's heritage sites. This database will cover a wide range of monuments that represent the shared heritage of the various communities of the island, and will include Orthodox, Maronite and Armenian churches/monasteries, Muslim mosques and minarets, fortifications, hammams, aqueducts and watermills. In this respect, the provision of scientific data that can assist in the preservation of the cultural heritage can pave the road towards peace and reunification.

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