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DESIGN OF GROUTS FOR STRENGTHENING THREE OR TWO LEAF MASONRY WITH MUD MORTARS.

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Abstract. *This paper presents the experimental procedure that has been followed, with main goal to develop various grout compositions adequate for strengthening stone masonry constructed with poor quality mortars. Two or three-leaf masonry frequently met in historic masonry structures is very vulnerable to environmental and seismic actions, especially when made with mud (very low strength) mortar. Although significant research effort is devoted to the development of grouts adequate for strengthening masonries made with lime or lime-pozzolan mortar, the respective studies on masonries made with mud mortar are scarce and inconclusive. Within the present work, a comprehensive investigation on mud mortars was conducted on samples that have been selected and sampled from three different buildings and sites, in order to identify their physicochemical and mineralogical properties, as well as their grain size distribution. Based on the studied samples of the aforementioned historical buildings with mud mortars, six wallettes were constructed, in order to study the mechanical properties of the two and three stone masonry before and after grouting. After the construction, non- destructive techniques (radar and boroscopy) were applied for the calibration of the methods and the comparison of the results before and after grouting, with main goal to develop various grout compositions according to the parameters which determine the efficiency of the intervention. Based on the characterization results, various grout mixes will be produced and will be examined in terms of compatibility between the mortar and the grout, as well as*

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injectability, fluidity, stability and penetrability. This research will lead to a number of suitable mixes that satisfy the performance criteria set for their design. The suitability of those mixes will then be checked by injecting them to the constructed wallettes.

1 INTRODUCTION

Mud is one of the oldest building material, which has been used for thousands of years. It has been used on its own or in combination with other materials, such as lime, timber or stone, for the construction of various structures [1,2,3]. Mud-mortars, dated back to 8000BC, were found in structures in Mesopotamia and Babylonia. In Greece, the first examples of mud mortars were identified in the Neolithic settlements of Dimini and Sesklo. Nowadays, there are still buildings with this type of mortar, in several regions of Greece (i.e. Cyclades, Athens, Crete and Prespes Lake) [4].

Despite the long usage of this structure material over centuries, the respective studies on masonries made with mud mortar are scarce and inconclusive and include mainly studies on adobe and earthen structures. As mud mortars have different properties, depending on the parent ground and the climate conditions, a comprehensive investigation has to be conducted, to identify their physical and mineralogical properties, as well as their grain size distribution. These data are a prerequisite for the development of adequate strengthening techniques.

Based on the fact that mud mortars were used to several historic two or three- leaf masonry structures, there is the need to maintain and strengthen them. These masonries are vulnerable to environmental and seismic actions. For this reason, this study aims to (a) determine the physicochemical properties of historic mud mortars, (b) construct wallettes according to the traditional way and subject them to compression, (c) apply non- destructive techniques (radar and boroscopy) to the constructed wallettes for the calibration of the methods and the comparison of the results before and after grouting, with main goal to develop various grout compositions according to the parameters which determine the efficiency of the intervention.

2 EXPERIMENTAL WORK

2.1 Material characterization from samples on historical mud mortars

The sampling and characterization of historical mud mortars aims to determine the type of construction and use similar traditional materials for the reinforcement of this type of structures, based on the principle of the compatibility (repair materials should have similar properties with the authentic ones). At a first step, authentic mud mortars were carefully selected and sampled from three different buildings and sites (Saint Dimitrios, Marousi, Historic Building in Plaka, Rural house in Lasithi, Crete) dated back 19th century. The characterization findings of these indicative mud mortar samples did contribute to the final design of the wallettes that were constructed within this paper.

(a) (b) (c)

Figure 1: Buildings with mud mortars: (a) Saint Dimitrios, Marousi, (b) Building in Plaka, (c) Rural Building in Lasithi

The samples were subjected to chemical analysis with X-RAY fluorescence technique (XRF) (Table 1) and mineralogical analysis with X-RAY diffraction (XRD) (Figure 2).

Chemical analysis with XRF of the samples (Table 1) indicates that the main elements present are SiO2 and CaO, along with Al2O3, Fe2O3 MgO, K2O and Na2O having variable concentration. From XRD analysis (Figure 2), it can be concluded that all samples are composed mainly of Quartz. Particularly in Marousi sample calcite and albite minerals were present whereas kaolinite mineral was also identified in Plaka sample. Additionally, Crete sample is composed mainly of quartz and dolomite minerals.

Chemical elements	**Concentration (%)**		
	Sample I (Marousi)	Sample II (Plaka)	Sample III (Crete)
Na_2O	0.31%	2.23%	0.95%
MgO	1.08%	2.80%	7.04%
Al_2O_3	3.20%	5.07%	10.41%
SiO_2	18.07%	21.13%	32.02%
P_2O_5	0.015%	0.45%	0.20%
SO_3	0.08%	0.59%	0.18%
Cl	0.01%	1.12%	0.09%
TiO_2	0.22%	0.33%	0.66%
K_2O	0.95%	3.25%	2.95%
CaO	37.89%	26.92%	13.12%
Fe_2O_3	2.09%	3.51%	4.75%
ZrO_2	0.82%	0.80%	0.75%

Table 1: XRF results for the three samples of mud mortars.

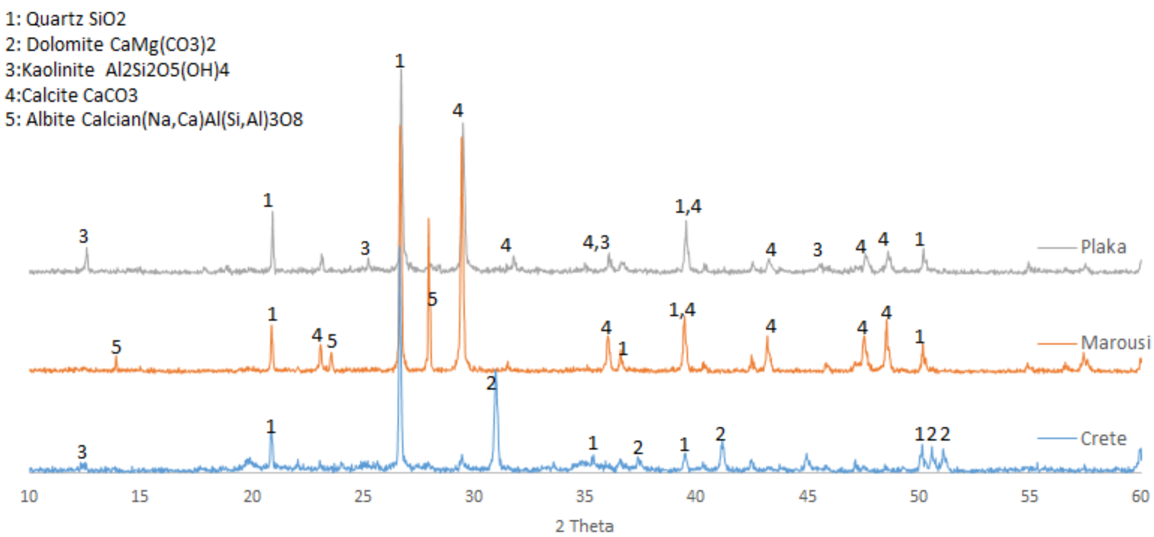


Figure 2: XRD results for the three samples of mud mortars.

Grain size distribution was conducted with combination of sieves for coarse particles and laser particle analysis for finer (<400μm) particles size (Figure 3, Figure 4). The particle mean size value $D_{0.5\mu m}$ was found to be almost similar to all studied samples ($D_{0.5,\text{Sample I}}$ =67.16μm, $D_{0.5,\text{Sample II}}$ =78.21μm, $D_{0.5,\text{Sample III}}$ =70.28μm).

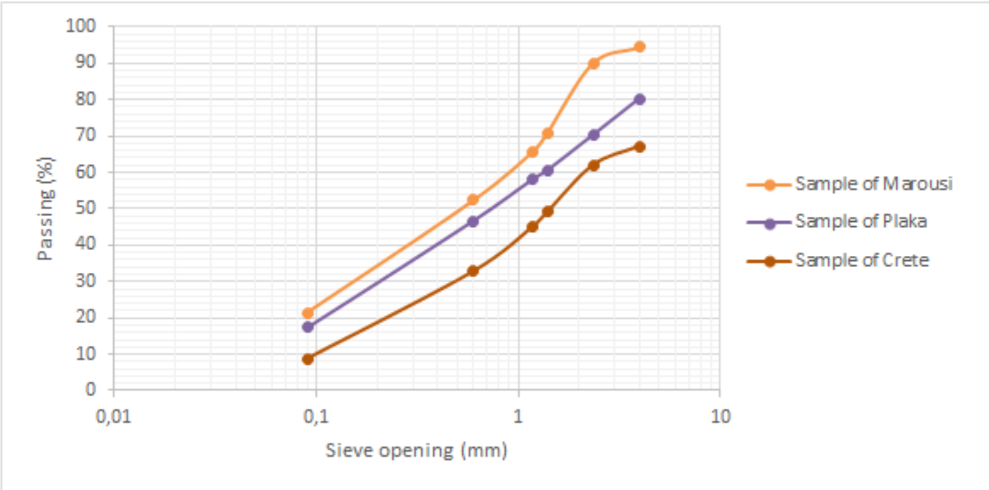


Figure 3 : Grain size distribution with the use of sieves for the three samples of mud mortars.

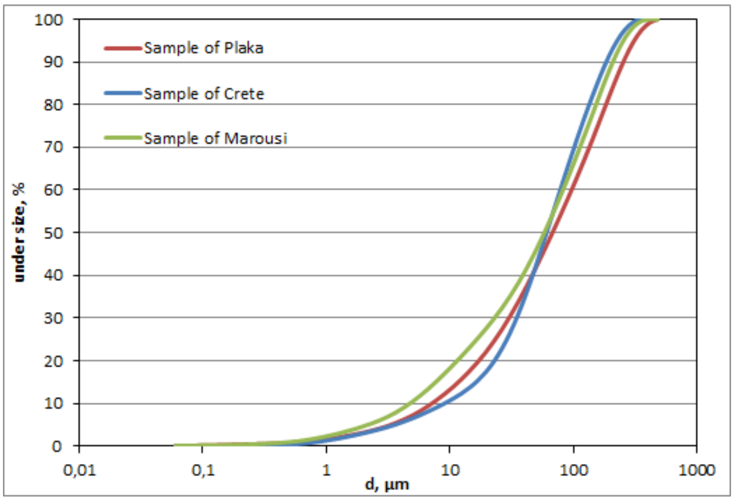


Figure 4: Grain size distribution of fine particles (<400μm) for the three samples of mud mortars.

2.2 Construction of two and three leaf wallettes

In order to study the mechanical properties of the two and three stone masonry before and after grouting, six wallettes were constructed.

2.2.1 Materials

Based on the study of the aforementioned historical buildings with mud mortars, a stone from Sparta (Greece) was used for the construction of the stone masonry wallettes. Its compressive strength is approximately 70 MPa. Two compositions of mortar were used for the external leaves and the infill material of the wallettes. These compositions were selected on the basis of the research of the historic mortars and the relevant literature [5]. The soil used for the mortars was obtained from an Industry at Giannitsa that produces byzantine bricks. The river sand is from Aliartos river.

The proportions of the mortar components are given in Table 2, whereas the compressive and flexural strength of the two mortars at the age of 28 days are presented in Table 3.

From compressive and flexural tests that applied on mud mortars, it was found that the compressive strength of composition I is 35% higher compare to composition II. Additionally, for composition I, the flexural strength is almost half of its compressive one, whereas for composition II, the flexural strength greatly reduces.

Compositions (%)					
	Soil	Sand (0-2.5 mm)	Gravel (0.5-3.5 mm)	Lime putty (with 40% water)	Water/soil (% w/w)
Composition I	80	16	4	-	34.15
Composition II	75	16	4	5	41.09

Table 2: Proportions of the components of the mortars.

	$f_{m,c}$ (MPa)	$f_{m,fl}$ (MPa)
Composition I	4.55	2.76
Composition II	2.92	0.66

Table 3: Compressive and flexular strength of mortars.

2.2.2 Wallettes

Six specimens were constructed. Three specimen with mud mortar (two with two-leaf masonry and one with three-leaf masonry) and other three specimens with mud mortar mixed with lime putty (two of them were made of two-leaf masonry and one of three-leaf masonry, as well). The dimensions of the masonry wallettes were selected to be comparable with other prior studies [6,7]: length=1.00m, height= 1.20m. The wallettes thickness was 0.45m and 0.30m for the three and two leaf masonry respectively. The two external leaves were constructed of stone masonry, with a thickness of 0.15m. Especially for the three leaf masonry the intermediate leaf is made of rubble materials (mortars and small stones) and no connection between the external leaves was considered. On the contrary in two leaf masonry there are connecting stones present. The walls specimens (Figure 5 and Figure 6) left to be curried for three months for future testing.

Upon construction, the wallettes were stepwise built by 30cm layers to avoid slump occurring from the mortar softness. Furthermore several cracks appeared on the exterior of the wallettes due to drying shrinkage of the mud mortar.

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

Figure 5: Two-leaf masonries with mud mortar (a,b) and mud mortar with lime (c,d).

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

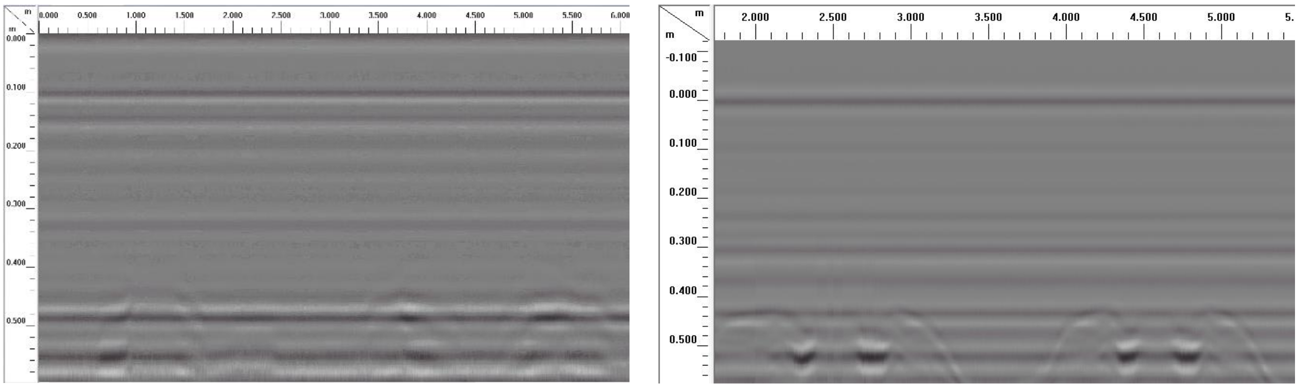
Figure 6: Three-leaf masonries with mud mortar (a,b) and mud mortar with lime adding (c,d).

2.2.3 Non-destructive techniques

In-situ investigations were conducted on the six stone masonry wallettes, using non-destructive techniques, particularly radar technique and boroscopy. The main aim of the investigations was (a) to calibrate the two techniques on mud mortar stone masonry, (b) to check clay interferences on the measurements (clay affects the accuracy of the emitted and received signal of radar, due to the attenuation of the signal [8]) and (c) to gain data for comparison after grouting of wallettes.

Radar technique is a non-destructive technique, therefore suitable for historic structures. The technique is based on the theory of electromagnetic signals. Using a radar system, consisting of a central unit and an antenna of 1600MHz, electromagnetic signals are emitted-through the material under investigation. When the signal meets an interface (be it a void or a discontinuity within the material or a different material), part of the emitted radiation is reflected and recorded by the central unit and part of it travels deeper into the material. Prior to the application, calibration of the measurements has taken place in converting the time units into length units.

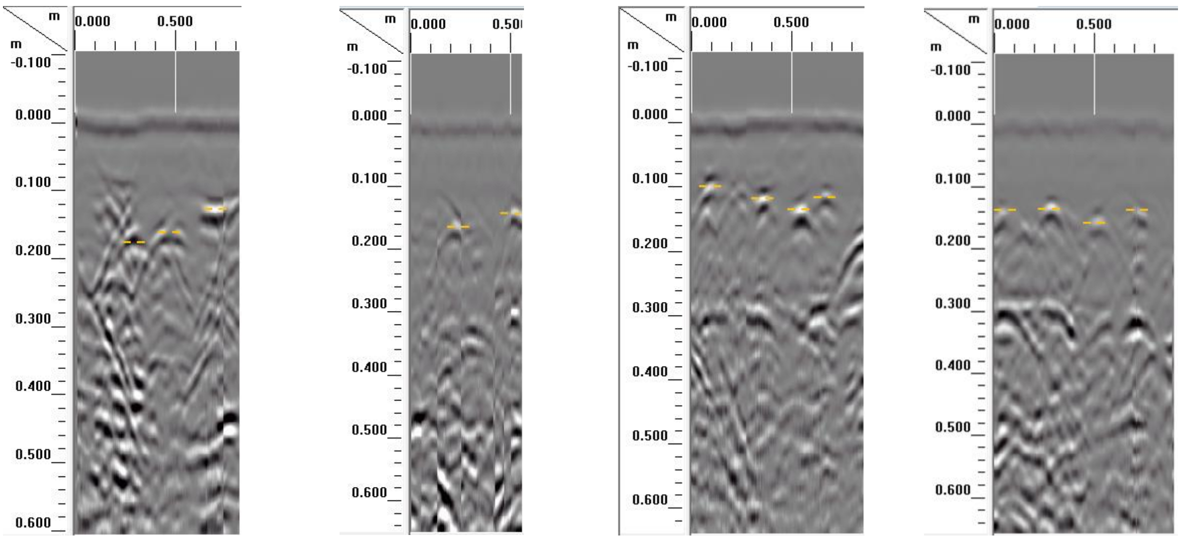
According to the calibration of the method, the dielectic constant of each type of masonry differs, as it depends on the materials, the thickness and the voids in the interior of the examined element. The dielectic constant of the three-leaf masonry with mud mortar mixed with lime was estimated equal to 8.7, whereas for the three-leaf masonry with mud mortar was equal to 10 (Figure 7). The dielectic constant of the two-leaf masonry with mud mortar and lime is approximately equal to 8.5, while for the one with mud mortar, it is equal to 9.0. The value of dielectric constant of two-leaf masonry is smaller, due to the fact that this type of masonry is more compact (smaller voids in the interior of masonry), compared to the three-leaf masonry.



(a) (b)

Figure 7: Static test for calibration on three-leaf masonries: (a) Composition I, (b) Composition II

Despite the fact that clay affects the clarity of the measurements, no significant interactions observed in all the measurements (horizontal and vertical) that were carried out. Clear indications of the stones of the examined leaf were found (Figure 8).

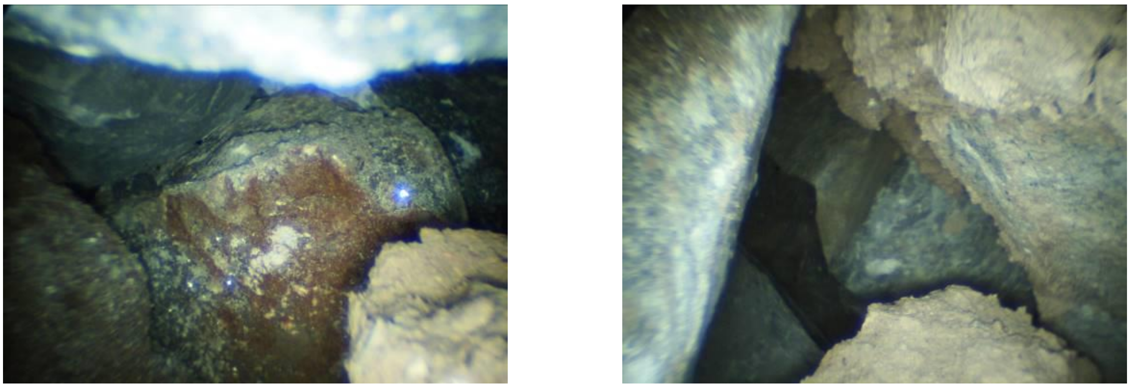


(a) (b) (c) (d)

Figure 8: Radar measurements: (a) Three- leaf masonry with Composition I, (b) Three leaf masonry with Composition II, (c) Two- leaf masonry with Composition I, (d) Two-leaf masonry with Composition II.

Boroscopy is one of the techniques often applied in combination with the radar technique. It is usually applied to historic (two or three leaf) stone masonries, in order to investigate their construction type within the thickness of the wallette. Small diameter holes (25mm or smaller) are drilled in masonry or already formed holes are used. After meticulous cleaning of the hole from dust and loose material, the boroscope is introduced into the hole. The core of the boroscope, consisting of optical fibres, allows for direct observation of the interior of the walls. In addition, pictures can be taken at various depths.

By the use of the boroscope, the voids between the stones, in the interior leaf of the three leaf stone masonry, can be seen in Figure 9.

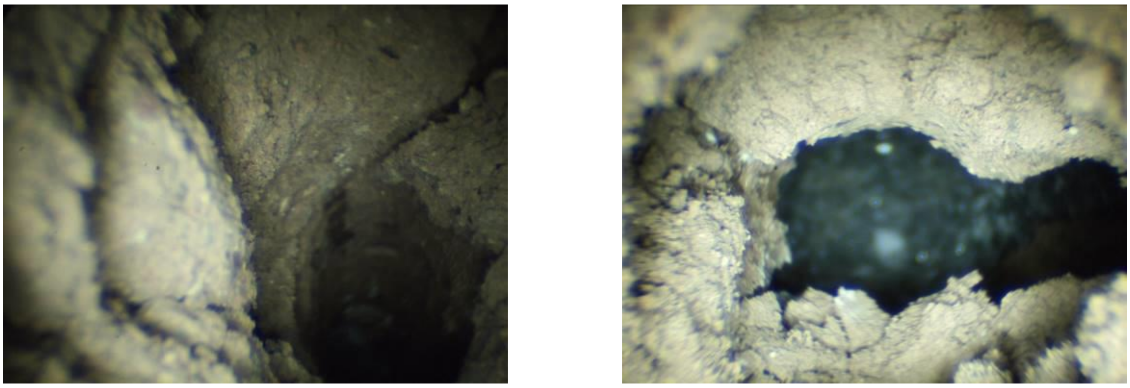


(a) (b)

Figure 9: Voids in the three-leaf wallettes: (a) Composition I, (b) Composition II.

Furthermore, from the application of the method in the two-leaf stone masonries, the different color of the mortars is observed, as it was expected from the construction. There is also voids and discontinuities within the mortar (Figure 10).

The presence of voids in the interior of the masonries indicates that the grouting as a repair technique may be applicable and efficient for the strengthening of two and three leaf masonry having poor mortar quality.



(a) (b)

Figure 10: Voids in the two-leaf wallettes: (a) Composition I, (b) Composition II.

2.3 Grout mixes for strengthening masonry with mud mortars

One of the most frequently applied strengthening techniques for stone masonry is grouting. Two or three-leaf masonry quite common in historic masonry structures tend to loss the bond between the two leaves, especially when made with poor quality mortar [12]. Although significant research effort was devoted to the development of grouts adequate for strengthening masonries made with lime or lime-pozzolan mortar, the respective studies on masonries made with mud mortar are scarce and inconclusive. Investigations determine the properties of earthen structures can be found in [9,10,11]. Within the present work, a comprehensive investigation on mud mortars was conducted on samples, to identify their psychical and mineralogical properties, as well as their grain size distribution. Based on this study, a series of experiments have been designed for the development of grouts adequate for strengthening stone masonry constructed with mud mortars. Compatibility between the mortar and the grout, injectability, fluidity, stability and penetrability are the basic criteria for the selection of the most suitable mixes. For this reason, a thorough research investigation take place to determine the physical, rheological, chemical and mechanical characteristics of the designed mixes. This research will lead to a number of suitable mixes that satisfy the performance criteria set for their design. The suitability of those mixes will then be checked by injecting them to the six masonry specimens that have been constructed. The efficiency of the grouting will be checked by the use of non- destructive techniques.

3 CONCLUSIONS

- The investigation of the physicochemical properties (chemical (XRF) analysis, mineralogical analysis (XRD) and grain size distribution analysis) of authentic mud mortars gives useful information about the components of them for the production of similar mortars, compatible with the authentic ones.
- Non-destructive techniques such as radar technique and boroscopy, were applied to six stone masonry wallettes before grouting, giving valuable information about the voids and the discontinuities in the interior of the wallettes. The results will be used in comparison with the ones after grouting.
- The observation of the interior of the wallettes and the cracks on the exterior leaves promotes the use of grouts for strengthening stone masonry constructed with mud mortars.

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