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Mechanical Properties of Three-Leaf Stone Masonry after Grouting

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ABSTRACT: In order to obtain data regarding the mechanical properties of masonry in Dafni Monastery, a testing program was carried out. Six three-leaf stone masonry wallettes (scale 2:3) were tested in compression or in diagonal compression up to their maximum resistance. After unloading, they were grouted using either a ternary or a hydraulic lime grout. Subsequently, they were tested again in compression or in diagonal compression to failure. For both types of grout, the wallettes exhibited substantial improvement of their behaviour, in terms of compressive strength, tensile strength and reduction of the separation between the three leaves of masonry. The obtained results are presented and commented.

1 INTRODUCTION

This paper constitutes the continuation of the paper by Vintzileou et al. (2006). Six wallettes, made of three-leaf stone masonry, were tested either in compression or in diagonal compression up to their maximum resistance. They were unloaded and grouted with two alternative grouts developed on purpose, in order to select the most appropriate proportions for application in the Katholikon of Dafni Monastery. Wallettes 1 to 3 (1.04m wide, 1.20m high and 0.45m thick) were subjected to compression. Wallettes 4 to 6 (0.99m wide, 1.00m high and 0.45m thick) were subjected to diagonal compression. Subsequently, the wallettes were tested to failure. In the following sections, information is provided regarding the selection of mix proportions of grouts, the main findings of tests on grouted wallettes are presented, whereas comparison with the behaviour of ungrouted wallettes is also given.

2 DESIGN OF GROUTS

The design of high injectability grouts was performed following performance requirements based on the needs of the structural restoration of the monument (Miltiadou et al. 2003). Thus, (a) in order to reach a tensile strength enhancement of the order of 100% and a final compressive strength of the order of 3 MPa, it was estimated (based on Vintzileou et al., 1995 and Tassios, 2004) that the compressive strength of the grout at the age of six months should be between 6MPa and 10MPa; a grout flexural strength larger than 3MPa was required. In addition, (b) the physico-chemical properties of the raw materials should be selected such that the durability of the structure and its precious mosaics be not jeopardized. Finally, (c) the grouts should be injectable enough to fill fine voids and cracks (estimated minimum nominal width of voids and cracks ~200μm).

After a series of laboratory tests on several mixes, carried out at the laboratory of DTRR, two alternative grouts were selected, namely: A ternary grout (white cement, lime, pozzolan) and a natural hydraulic lime (NHL)-based grout. The latter covers all requirements of physico-chemical compatibility; therefore, its use is desirable, provided that it proves to be efficient from the structural point of view as well. The mix proportions of the grouts, along with their mechanical properties and injectability characteristics (penetrability, fluidity, stability), are summarized in Table 1. The standardized sand column test method (NF P18-891) was applied to check the penetrability and fluidity, along with the standard apparatus for testing the fluidity (NF P18-358) and the stability of grouts (NF P18-359). The following limit values were set for the acceptance of grouts: A time limit of 50 sec for the sand column penetrability test (T_{36}); an efflux time of 500ml of grout less than 45 sec (Marsh cone d=4.7mm fluidity test-$t_{d=4.7mm}$); maximum acceptable limit of 5% for the bleeding test (Miltiadou 1990).

Both mixes proved to satisfy the requirements of sufficient mechanical properties and injectability to fine cracks and voids.

Table 1 : Mix proportions of selected grouts (%wt.) and mechanical properties-injectability characteristics thereof.

TERNARY GROUT										
White Danish cement	Lime (powder)	Pozzolan (d_{max}<75μm)	Superplasticizer SP1	Water	Compressive (f_{gc}) and flexural (f_{gt}) strength (MPa)					
					Age (days)					
					28		90		180	
30	25	45	1	80	f_{gc}	f_{gt}	f_{gc}	f_{gt}	f_{gc}	f_{gt}
					4.08	2.11	8.16	2.29	10.6	3.1
NHL5-BASED GROUT										
NHL5 (St Astier)		Superplasticizer SP2		Water						
100		1		80	2.82	2.47	4.50	2.52	6.36	3.8

	T_{36} (sec) Sand column 1.25/2.50 mm (voids ~0.2-0.4 mm)	$t_{d=4.7mm}$ (sec)	Bleeding
TERNARY GROUT	19	20.5	2%
NHL5-BASED GROUT	22.5	22	3%

3 INJECTING THE WALLETTES

3.1 Preparation of wallettes for grouting

The usual procedure of preparation of masonry before grouting was applied. It comprises the following steps: (a) Drilling of injection holes (at a depth of 150mm approximately, at horizontal and vertical distances not exceeding 150-200mm, as well as on cracks opened during the first loading), (b) Insertion of plastic tubes (of various diameters) into the drilled holes. Additional 2.7 and 3.3 mm in diameter plastic tubes were inserted into shallow holes, in order to control the grout flow in the region of mosaics, (c) Sealing of cracks (using a mortar), in order to prevent leakage of the grout. An absorptive (pozzolan/water) paste was used during grouting at places where the grout was leaking and (d) numbering of tubes (to allow for better control of the injection process, Fig. 1).

3.2 Injection of grout

The grouts were mixed using a prototype ultrasound dispersion mixer (capacity: 20lts), assisted by a mechanical device of low turbulence (300rpm). After mixing, each batch was drained into an air-proof cylindrical collector made of Plexiglas to allow for calculation of the consumption of grout. Through a pipe at the bottom of the collector, the grout was introduced to the wallettes at low pressure (~0.70 bar). The pressure was controlled by means of a manometer at the entrance of the grout to the wall. Grouting started from the bottom of the wallette to its top, whereas entrances and exits of the grout from the pre-installed tubes, as well as the consumed quantity of grout were recorded. By observing the progression of moisture on the surfaces of the wallette (Fig. 1), the filling of voids with grout was followed. The data about both the consumption of grout per wallette (Table 2) are in accordance with data in the literature (Vintzileou et al. 1995); in addition, the estimation made on the basis of in-situ measurements, for ~40% voids in the filling material seems to be confirmed. Note that V_{voids}/V_{inf} values were calculated assuming that the total volume of grout was consumed within the infill material.

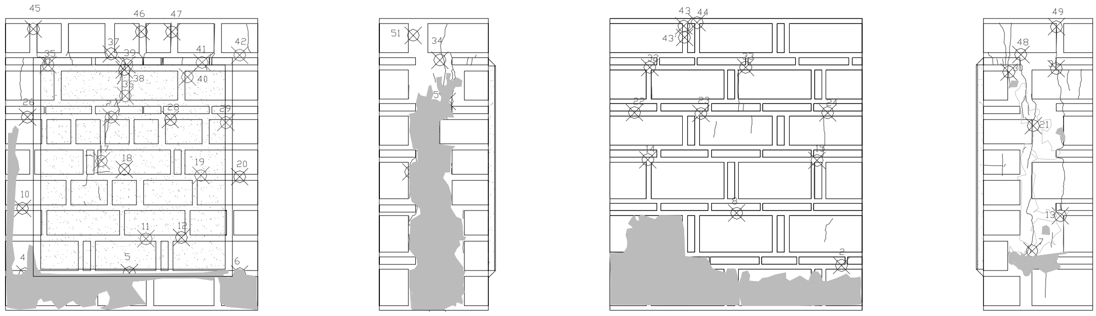


Figure 1 : Wallette 1, Numbering of plastic tubes for grouting, wet surfaces (gray areas) allowing for the progress of grouting to be recorded.

Table 2 : Data related to the consumption of grout, as well as to the percentage of voids

Wallette	Grout	Consumption of grout V_{gr} (lts)	V_{gr}/V_{inf} (lts/m^3)	V_{gr}/V_w (lts/m^3)	V_{voids}/V_w (%)	V_{voids}/V_{inf} (%)
1	NHL5	50.3	328	90	9.0	32.8
2	Ternary	61.4	400	109	10.9	40.0
3	NHL5	55.8	364	99	9.9	36.4
4	NHL5	52.3	393	107	10.7	39.3
5	Ternary	49.3	371	101	10.1	37.1
6	NHL5	50	376	103	10.3	37.6

V_{gr}: consumed volume of grout, V_{inf}: volume of infill material, V_w: total volume of wallette, V_{voids}: volume of voids

4 TESTING PROCEDURE

After completion of grouting, the wallettes remained for approximately 3 months in the laboratory for the grout to gain sufficient strength before testing. The testing procedure was the same as for the loading of wallettes before grouting. Measurements of strains and opening of cracks were taken with the same devices and in the same places as for initial loading (Fig. 2).

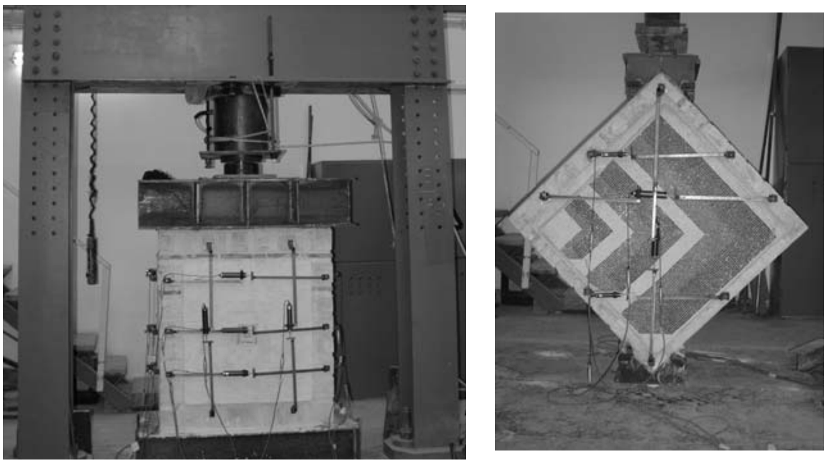


Figure 2 : Testing set up and measuring devices for walettes subjected to compression (Wallettes 1 to 3) or to diagonal compression (Wallettes 4 to 6)

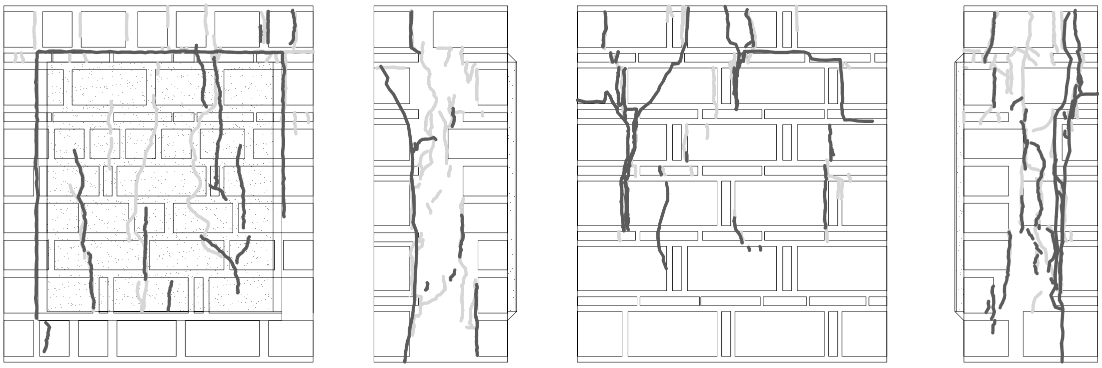


Figure 3 : Crack pattern of Wallette 3 before (light grey) and after grouting (dark grey)

5 TEST RESULTS-WALLETTES IN COMPRESSION

5.1 Failure mode

As shown in Fig. 3, wallettes subjected to compression after grouting exhibited the same failure mode as before grouting. In fact, vertical cracks have opened both in the faces of wallettes and in their sides. Some of the cracks that appeared during testing before grouting have opened again. Nevertheless, the majority of vertical cracks appeared in new locations, thus suggesting that grouting provided sufficient strength in previously cracked regions. Furthermore, as discussed in the following sections, vertical cracks appeared at substantially higher load than for ungrouted wallettes, whereas their openings were small.

In general, the mosaics followed the deformations of masonry and they were cracked, whereas limited debonding of mosaics from masonry was observed.

5.2 Stress-strain and stress-crack opening curves

Fig. 4 shows the vertical stress vs. vertical strain curves for Wallettes 1 to 3 before and after grouting. One may observe the substantial strength enhancement due to grouting. In fact, as shown in Table 3, wallettes grouted with natural hydraulic lime mix showed a compressive strength by 65% higher than the initial compressive strength. The ternary grout led to an increase of compressive strength by 116%, although their final compressive strengths do not differ substantially . In all cases, the enhanced strength of wallettes is reached for substantial larger vertical strain than in the case of ungrouted masonry. It is also interesting to observe that the selected grouts did not result to any substantial stiffness enhancement of masonry. This is an important feature, since in several applications, the increase of stiffness is not desirable. This is the case especially when grouting is applied only to some regions of a structure.

In Fig. 5 the opening of vertical cracks is plotted against the compressive stress; the reported measurements were taken at mid-height of specimens and they refer to vertical cracks both on faces and on sides of wallettes. It may be observed that grouting with either mix led to a substantial reduction of crack openings in both horizontal directions. In fact, as shown in Fig. 5b, the opening of transverse cracks in the strengthened wallettes is approximately equal to zero for an applied compressive stress equal to their maximum resistance before grouting.

Table 3 : Mechanical properties of Wallettes 1 to 3 before and after grouting

Wallette	f_{w0} (MPa)	f_{ws} (MPa)	f_{ws}/f_{w0}	ε_{v0} (‰)	ε_{vs} (‰)	E_0 (MPa)	E_s (MPa)	E_s/E_0
1	1.82	3.00	1.65	*	-1.76	1,000	1,200	1.20
2	1.74	3.75	2.16	-1.6	-2.50	1,440	1,550	1.08
3	2.26	3.73	1.65	-2.25	-3.39	1,500	1,300	0.87

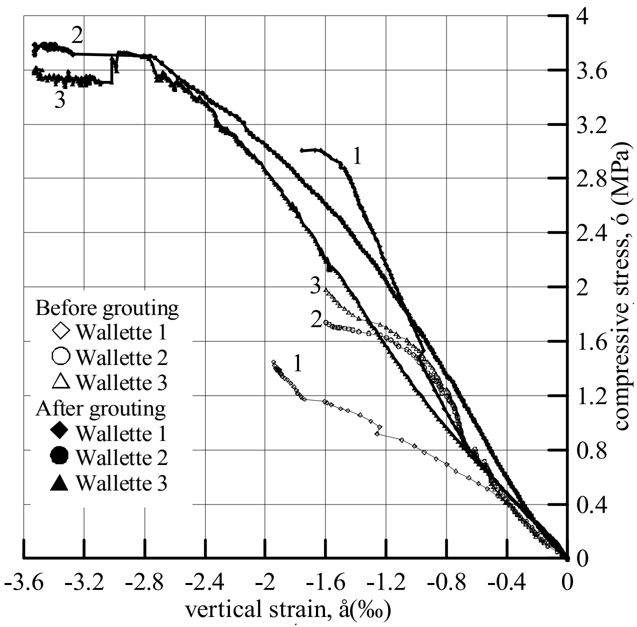


Figure 4 : Wallettes 1 to 3, compressive stress vs. vertical strain curves before and after grouting.

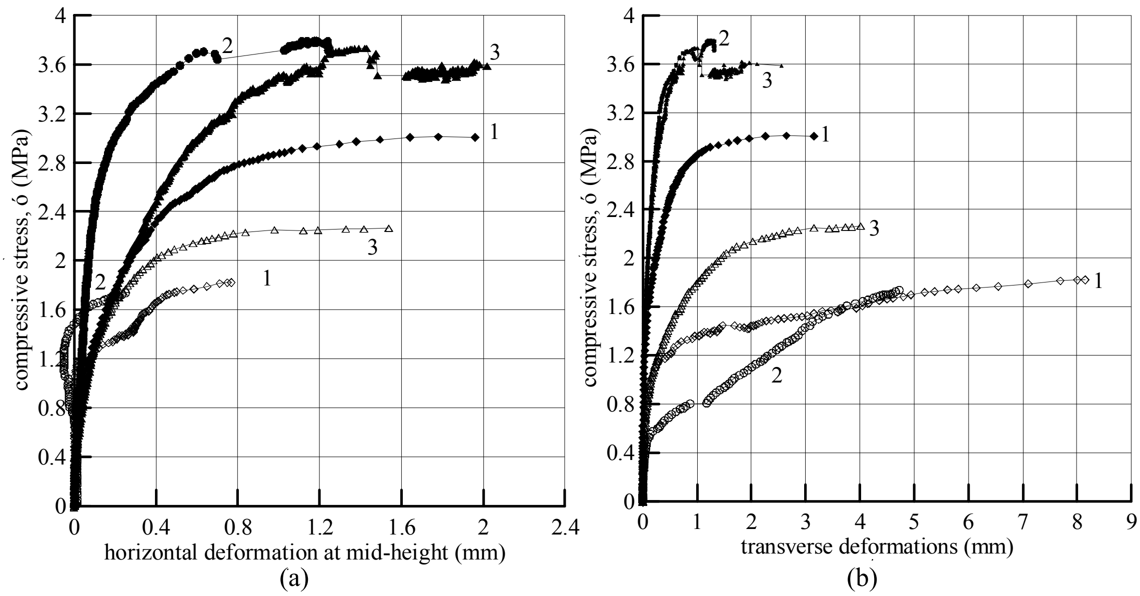


Figure 5 : Wallettes 1 to 3, stress-crack opening curves (a) on wall faces, (b) in transverse direction

6 TEST RESULTS-WALLETTES IN DIAGONAL COMPRESSION

6.1 Failure mode

Wallettes 4 to 6, subjected to diagonal compression exhibited the same failure mode as before grouting (Fig. 6): Most of the cracks formed during the first loading have opened after strengthening, whereas some new cracks appeared. In general, the mosaics followed the cracks of masonry; debonding of mosaics was not observed.

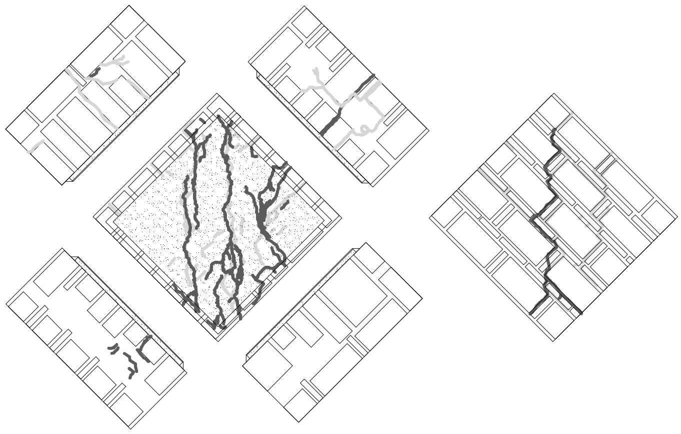
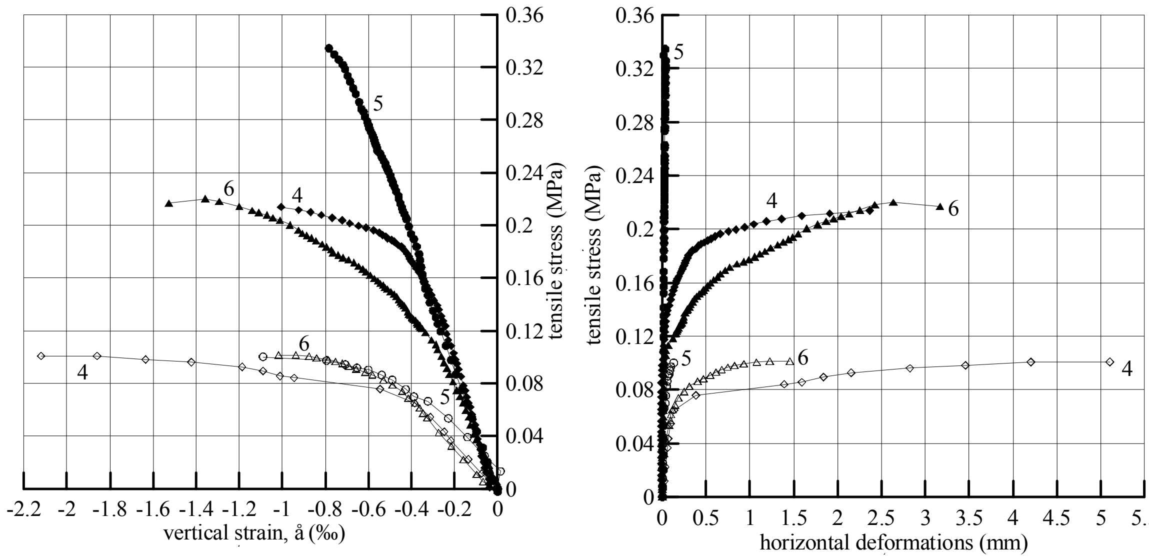


Figure 6 : Wallette 4, Typical failure mode of wallettes subjected to diagonal compression. Cracks of ungrouted masonry (light grey) and cracks of grouted masonry (dark grey)

6.2 Stress-strain curves and stress-opening of cracks curves

The behaviour of wallettes subjected to diagonal compression is summarized in Fig. 7. As shown in Fig. 7a, the tensile strength of masonry has doubled after grouting with the hydraulic lime based grout; the use of the ternary grout led to tensile strength three times that obtained during initial loading. It seems, however, that the ternary grout led to somehow brittle behaviour, since failure of Wallette 5 occurred under small vertical strain, whereas the opening of vertical cracks was very sudden (see Fig. 7b; due to the sudden failure of wallette 5, the opening of the vertical cracks could not be recorded, as the LVDTs lost their support on masonry).



(a) (b)

Figure 7 : Wallettes 4 to 6 before and after grouting, (a) tensile stress-vertical strain curves, (b) tensile stress-opening of vertical cracks at mid-height

7 COMPARISON WITH THE LITERATURE

Table 4 summarizes the main findings of tests on three-leaf stone masonry walls before and after grouting; both results from the literature and those obtained within the present work are included.

Despite of the variety of materials used for the construction of masonry (i.e. compressive strength of stones varying between 25.0MPa and 160.0MPa, compressive strength of mortar between 1.60MPa and 4.35MPa and compressive strength of filling material varying between 0.15MPa and 1.0MPa, see Vintzileou et al. 2006) and although the geometry of the three leaves was different in various test series, one may observe that the differences in the compressive strength of masonry before grouting are not very pronounced. The higher compressive strength values obtained by Toumbakari (2002) may be attributed to the substantial higher compressive strength of the infill material (1.0MPa, as compared with 0.15MPa in other test series).

On the other hand, in all cases, grouting leads to substantial strength enhancement due to homogenisation of masonry that delays the separation between the external masonry leaves and the inner filling material. Strength enhancement by 60% to 100% seems to be feasible even using rather low strength grouts. It is also apparent that the increase in compressive strength of masonry does not relate to the compressive or to the tensile strength of the grout. As proven by Toumbakari (2002) the governing property is the bond between grout and *in-situ* materials. More recent experimental results (Adami et al., 2006) contribute to the investigation of parameters that affect the bond properties of grout to stone or brick interfaces.

It is also interesting to observe that grouting does not increase dramatically the modulus of elasticity of masonry, whereas the vertical strain corresponding to the compressive strength of grouted masonry is normally larger than for ungrouted masonry (Fig. 4). Therefore, grouted masonry is not excessively stiff; it does not become brittle either.

As for the strength of masonry subjected to diagonal compression, one may observe that using a grout of rather low or medium compressive strength, the tensile strength of masonry may be easily increased by 100% to 200%. This is very important for the behaviour of masonry elements subjected to in-plane shear, as it is the case in earthquake prone areas.

Table 4: Summary of the main finding of experimental programs on three-leaf stone masonry walls before and after grouting

	$f_{wc,0}$ (MPa)	$f_{wc,s}$ (MPa)	f_g (MPa)	λ_f	E_{w0} (MPa)	E_{ws} (MPa)	λ_E	$f_{t,0}$ (MPa)	$f_{t,s}$ (MPa)	λ_{ft}
Vallu-	1.70	2.49	5.10	1.46	2210	2347	1.06			
zzi	1.94	2.20	3.23	1.13	1506	2336	1.55			
Toum-	2.02	3.25	9.0	1.61	720	1622	2.25	0.47	0.50	1.06
bakari	2.09	3.36	19.5	1.61	1139	1559	1.37	0.34	0.68	2.00
	2.65	3.51	7.3	1.32	1375	1188	0.86	0.28	0.59	2.11
	2.71	3.29	7.3	1.21	1443	1015	0.70			
Vintzi-	1.60	-		-	4402	-	-			
leou/	1.70	4.20	36.0	2.47	5670	7778	1.37			
Tassios	1.35	4.05	13.0	3.00	5625	8438	1.50			
This	1.82	3.00	4.50	1.65	1000	1200	1.20	0.10	0.21	2.10
work	1.74	3.75	8.16	2.16	1440	1550	1.08	0.10	0.33	3.30
	2.26	3.73	4.50	1.65	1500	1300	0.87	0.10	0.22	2.20

Notation: $f_{wc,0}$: compressive strength of masonry before grouting, $f_{wc,s}$: compressive strength of masonry after grouting, f_g: compressive strength of grout, λ_f: $f_{wc,s}/f_{wc,0}$-ratio, E_{w0}: modulus of elasticity of masonry before grouting, E_{ws}: modulus of elasticity of masonry after grouting, $\lambda_E=E_{ws}/E_{w0}$-ratio, $f_{t,0}$: tensile strength of masonry before grouting, $f_{t,s}$: tensile strength of masonry after grouting, $\lambda_{ft}=f_{t,s}/f_{t,0}$-ratio

8 CONCLUSIONS

The experimental results presented in this paper allow for the following conclusions to be drawn:

1. The design of stable, fluid and highly injectable grouts was proven to be efficient. In fact, as observed during grouting and confirmed after testing, both grouts applied to the specimens were able to fill cracks and voids of masonry.
2. Both grouts were efficient from the mechanical point of view: Substantial enhancement of compressive strength of masonry was observed. In all cases, homogenisation of ma-

sonry was achieved and the separation between the three leaves was substantially delayed. This strength increase was not followed by substantial increase in the stiffness of masonry.

3. Both grouts contributed to the increase of the tensile strength of masonry. The results of this program seem to be in accordance with those reported in the literature.
4. On the basis of the results presented in this paper, it was decided to use hydraulic lime based grouts in the Katholikon of Dafni Monastery: The substantial (compressive and tensile) strength enhancement of wallettes, the rather ductile behaviour under diagonal compression (compared to that of masonry grouted with the ternary grout), the physico-chemical properties that ensure a durable intervention and contribute to the protection of mosaics led to the selection of a hydraulic lime based grout.

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