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THE EFFECT OF HYDRAULIC LIME POZZOLANIC GROUTS ON THE MECHANICAL PROPERTIES OF THREE-LEAF STONE MASONRY IN COMPRESSION

Adami Ch.-E.[1], *Vintzileou E*[2]*., Mouzakis Ch*[3]*., Badogiannis E*[4]*., Kalagri A.*[5]

ABSTRACT

In this paper, the effect of hydraulic lime pozzolanic grouts on the mechanical properties of three-leaf stone masonry wallettes is experimentally investigated. Hydraulic lime grouts are made either of pure St Astier NHL 5 or by its substitution with 10% superfine natural pozzolan, commercially available as μ-silica, W type. Three-leaf stone masonry wallettes (scale 2:3) were prepared and tested in compression before and after grouting. Moreover, cylindrical specimens that simulate the inner leaf of three-leaf stone masonry were also grouted with the same grouts and tested in compression. The experimental results show that both grouts were efficient in improving significantly the compressive strength of the wallettes, without modifying the stiffness of masonry elements. Concerning the cylindrical specimens, infill specimens grouted with pozzolanic additive exhibited better mechanical properties than those grouted with pure hydraulic lime mix.

Keywords: *Grout, Natural pozzolan, Three-leaf stone masonries, Compressive strength*

1. INTRODUCTION

Hydraulic lime-based grouts (hydraulic lime with or without a pozzolanic material) seem to offer a promising alternative to ternary grouts (with limited cement content) due to their similarity with the in-situ materials and their mechanical efficiency for the structural restoration of stone masonry [1, 2]. Several grout mixes based on hydraulic-lime with or without natural pozzolan are investigated in [3]. On the basis of the results of that investigation two of the better performing mixes are selected, in order to investigate their efficiency from the mechanical point of view. Thus, a comparative study between a pure commercial hydraulic lime grout and a grout mix with 10% natural pozzolan was undertaken, as far their effect on the compressive strength and deformability of masonry is concerned. The mechanical properties of grouted cylinders and wallettes, before and after grouting, are evaluated. In the following sections, the experimental programme and the main results of this study are presented and discussed.

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[1] Civil Engineer, PhD, MSc, National Technical University of Athens, Faculty of Civil Engineering, Laboratory of Reinforced Concrete, 5 Iroon Polytechniou Str., 15773 Zografou, Greece, adamis@central.ntua.gr

[2] Professor, National Technical University of Athens, Faculty of Civil Engineering, Laboratory of Reinforced Concrete, 5 Iroon Polytechniou Str., 15773 Zografou, Greece, elvintz@central.ntua.gr

[3] Assistant Professor, National Technical University of Athens, Faculty of Structural Engineering, Laboratory for Earthquake Engineering, 5 Iroon Polytechniou Str., 15773 Zografou, Greece, harrismo@central.ntua.gr

[4] Lecturer, National Technical University of Athens, Faculty of Civil Engineering, Laboratory of Reinforced Concrete, 5 Iroon Polytechniou Str., 15773 Zografou, Greece, badstrat@central.ntua.gr

[5] Chemical Engineer, MSc, National Center for Scientific Research "Demokritos", Institute of Materials Science, 15310 Aghia Paraskevi Greece, anna.kalagri@gmail.com

2. EXPERIMENTAL WORK

2.1. Materials

For the construction of the stone masonry wallettes, as well as of the cylinders, a strong limestone from Paramythia (Epirus, Greece) was used. Its compressive strength is approx. equal to 100 MPa and its apparent density equals 2.68 kg/m^3. As far as the mortar is concerned, a lime-pozzolan mortar was used for the preparation of both the external leaves and the infill material of the wallettes. The composition of the mortar (presented in Tab. 1) was selected so as to be representative of good quality traditional mortars. The water to binder ratio was taken equal to 0.50. In Table 2, the compressive and flexural strength of the mortar determined according to [4] at the ages of 28, 60 and 180 days are presented.

Table 1 Mix proportions of the mortar

Composition [%-wt]				
lime putty (with 40% water)	natural pozzolan	sand (0-3.5 mm)	gravel (0.5-5.0 mm)	gravel (4.0-20.0 mm)
20	20	45	9	6

Table 2 Mechanical properties of the mortar

age [days]	$f_{m,c}$ [MPa]	$f_{m,fl}$ [MPa]	ρ [kg/m^3]
28	3.90	0.65	1.68
60	7.38	1.20	1.80
180	7.75	0.34	1.74

2.2. Grout mixes

The materials used for the preparation of grouts were a commercial natural hydraulic lime NHL5 and a superfine natural pozzolan, commercially available as μ-silica type W. Further details are given elsewhere [3]. Hydraulic lime NHL5, is an argillaceous limestone with siliceous content. It contains mainly calcite and calcium silicate. The natural pozzolan is a pure natural amorphous aluminosilicate mineral from Milos Island (Greece). It contains more than 70.0% of silica (SiO_2) and 12.0-15.0% of amorphous alumina (Al_2O_3) and it occurs in amorphous glassy state of 95.0%, at least. Natural pozzolan has a mean size of approx 6.0 μm and a specific surface of approx 3 m^2/g.

Based on the optimization procedure carried out within [3], only high injectability grouts Gs and GW10s were considered in the present investigation. The mix proportions of the selected grouts, as well as a summary of their main mechanical properties are given in Tables 3 and 4, respectively.

Table 3 Composition (%) of grout design mixes

Mix	NHL5 (%)	μ-silica/W (%)	Water (%)	SPL (%)
Gs	100	–	82.5	0.75
GW10s	90	10	82.5	0.75

Table 4 Flexural strength and compressive strength of the grout mixes [4]

Mix	Flexural Strength [MPa]			Compressive Strength [MPa]		
	28 days	90 days	180 days	28 days	90 days	180 days
Gs	0.5	0.7	0.5	1.6	2.0	2.0
GW10s	0.6	0.6	0.7	1.7	2.9	2.8

2.3. Specimens and Experimental procedure

2.3.1. Cylinders

The two grout mixes considered within this study, were injected at low pressure (0.75 bar) into cylindrical specimens (diameter D = 250 mm, height H = 500 mm), which simulate the intermediate leaf (filling material) of three leaf masonry. Plastic cylindrical moulds were filled with a mix of lime/pozzolan mortar and pieces of stones, in a portion 2/1. In order to reach a percentage of voids of approximately 40% of the total volume of the cylinder, which represents the typical percentage for the infill material of deteriorated historic three-leaf masonry [5, 2], the abovementioned mix was poured without compaction. The entire procedure of preparation of the specimens, as well as of the filling procedure, are described in [1, 6]. Based on previous experience [6] and the fact that, as mentioned above, the infill material was extremely loose, the cylindrical specimens were tested only after grouting. Thus, the constructed sixteen cylinders were filled with a grout mix as follows: Cylinders C1-C8 were grouted with mix Gs (100 %NHL 5), and cylinders CW1-CW8, with grout mix GW10s (NHL 5 to μ-silica/W, 90%:10%). The time needed for filling each cylinder, as well as the consumed volumes of grouts were recorded (see Section 3). Finally, after 180 days of curing (90 ± 5% RH, 20°C), the grouted cylinders were tested in compression. Stress and strain measurements were taken for each specimen.

2.3.2. Wallettes

The wallettes were made of three-leaf stone masonry. Four specimens were constructed. A scale equal to 2:3 was selected, in order to avoid scale effects. The overall dimensions of the stone masonry wallettes were as follows: length = 1.00 m, height = 1.20 m, thickness = 0.45 m. The external leaves were made of rubble stone masonry, approximately 150 mm thick, whereas for the intermediate filling material (~150 mm thick, as well) the same mix and technique used for the preparation of the cylinder specimens was applied. It is noted that no connection between the leaves was considered (wallettes without header stones).

Figure 1 shows the test setup for the wall specimens subjected to compression. Load controlled tests were carried out. The load was applied though a hydraulic jack (maximum capacity: 6000 KN).

Fig. 1 Test setup and instrumentation of wallettes subjected to compression.

The hydraulic jack was fixed on a steel frame. The compression load was applied through a steel beam, in order to obtain uniform distribution over the entire length of the wallette. Deformations on the wallets were measured by means of LVDTs. In detail, four LVDTs (two for each facade) were used to measure vertical deformations; six LVDTs (three for each facade) were placed to measure horizontal deformations and vertical crack openings, while six LVDTs (three per side) were recording the transverse deformations of the wallets (i.e. separation between the external and internal leaves). Each specimen was loaded to its maximum capacity, without being disintegrated though. Then, it was unloaded and removed from the steel frame. Subsequently, the wallettes were strengthened with one of the two abovementioned hydraulic lime-based grouts. Approximately two to three months after the application of grouts, the wallettes were retested to failure.

3. RESULTS AND DISCUSSION

3.1. Cylinders

3.1.1. Grouts in Liquid State

Table 5 summarizes the results regarding the needed filling time and the consumed volume of grout for each cylinder. These recorded data show that the injectability of grout in the infill material, expressed as average filling time, was approximately equal to 110 s for cylinders C1-C8 and 125 s for cylinders CW1-CW8. The average consumed grout volume per cylinder varies between 5.39 lt and 7.48 lt for cylinders C1-C8 and 5.85 lt to 6.70 for cylinders CW1-CW8. These values correspond to an average void percent of 35% for both cylinder groups, a value which satisfactory approaches the designed one (40%).

Table 5 Filling time, volume of consumed grout, voids and filling rate of the cylinder specimens

	Filling time (s)	Grout volume (lt)	Voids (%)	Filling rate (ml/s)
C1	85.91	5.39	29.8	63
C2	122.21	6.57	36.3	54
C3	91.89	5.62	30.8	61
C4	110.71	6.20	34.3	56
C5	114.76	7.48	41.3	65
C6	129.62	6.97	38.5	54
C7	112.11	6.73	37.2	60
C8	118.63	6.43	33.9	54
Aver.	*110.73*	*6.42*	*34.5*	*58*

	Filling time (s)	Grout volume (lt)	Voids (%)	Filling rate (ml/s)
CW1	143.53	6.70	37.0	47
CW2	157.00	6.42	35.5	41
CW3	111.59	5.99	33.1	54
CW4	128.43	6.24	34.5	49
CW5	114.01	5.85	32.3	51
CW6	129.21	6.59	37.3	51
CW7	108.35	5.99	33.1	55
CW8	118.53	5.99	33.1	51
Aver.	*126.33*	*6.22*	*35.2*	*50*

In Figure 2, the filling time (s), the consumed grout volume (lt) and the filling rate (ml/s) are correlated. By comparing the two grout mixes, one may notice that the average values of the consumed grout volume are almost equal, as well as the voids content. However, the average filling rate is lower for the grout mix GW10s, in which μ-silica/W substitutes NHL 5 by 10 %. This observation is in accordance with the higher injectability characteristics (penetrability and fluidity) exhibited by grout mix Gs, as compared to those of GW10s (see [3]).

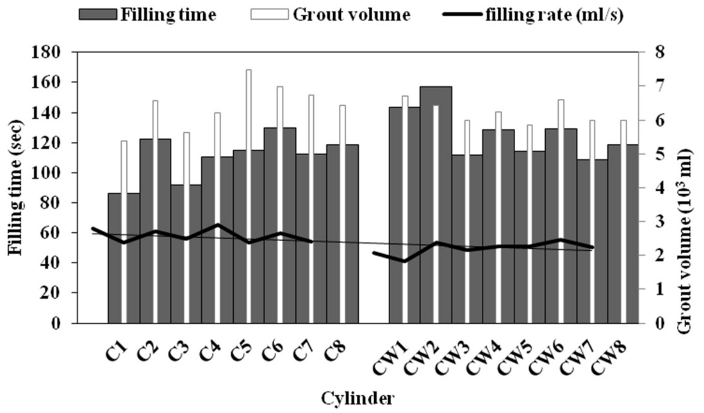


Fig. 2 Filling time, consumed grout volume and filling rate of cylinders, injected with the two gout mixes

3.1.2. Grouts in Hardened State

Independently of the grout mix, the failure mode of cylinders was characterized by the formation of almost vertical cracks (see Fig. 3).

Table 6 summarizes the results for the compressive strength, $f_{inf,s}$ (MPa) and modulus of elasticity, $E_{inf,s}$ (GPa) for the grouted cylinders, at the age of 180 days. One may notice that the comparison of the two alternative grout mixes shows a rather limited effect of the grout composition on the mechanical properties of the grouted filling material (see Tab. 6 and Fig. 4). In fact, the compressive strength of the grouted cylinders varies between 2.18 and 2.97 MPa for the specimens C1-C8, grouted with pure NHL 5. For the specimens GW1-GW8, which were grouted, with 10% μ-silica/W mix the compressive strength varies between 2.44 and 3.73 MPa. The mean compressive strength obtained by specimens grouted with grouts Gs and GW10s is equal to 2.44 MPa and 2.88 MPa, respectively. These values are in agreement with those reported in literature for cylinders grouted with hydraulic-lime based grouts [6, 7]. As far as the moduli of elasticity are concerned, the reported data vary from 3.15 to 6.75 GPa, for the pure NHL5 grouted cylinders. For the cylinders grouted with μ-silica/W mix, moduli of elasticity vary between 4.82 and 6.51 GPa. The average value of $E_{inf,s}$, for the grouted cylinders with pure NHL5 grout is 5.19 GPa and for grouted cylinders with μ-silica/W mix, is 5.69 GPa. These values are significantly (by 2 or 3 times) higher than those available in the literature for similar grout mixes. Actually, values of modulus of elasticity of grouted cylinders between 0.6 and 2.1 GPa were measured by [6] on cylinders made of stones having compressive strength equal to 25 MPa. The significantly higher values measured within the present study are attributed to the high compressive strength of the stones (~100MPa).

Fig. 3 Failure mode of grouted infill material in compression.

Table 6 Compressive strength and moduli of elasticity (measured at 30% of compressive strength) of the grouted cylinders at the age of 180 days

Cylinders grouted with Gs			Cylinders grouted with GW10s		
a/a of cylinder	$f_{inf,s}$ [MPa]	$E_{inf,s}$ [GPa]	a/a of cylinder	$f_{inf,s}$ [MPa]	$E_{inf,s}$ [GPa]
C1	2.97	6.71	CW1	3.29	5.81
C2	2.36	3.15	CW2	2.51	6.51
C3	2.51	4.16	CW3	2.91	5.69
C4	2.37	6.75	CW4	2.73	5.57
C5	2.54	5.92	CW5	2.67	5.58
C6	2.18	5.43	CW6	2.44	5.89
C7	2.62	5.85	CW7	2.71	4.82
C8	1.96	3.55	CW8	3.73	5.72
Aver.	*2.44*	*5.18*	*Aver.*	*2.88*	*5.70*

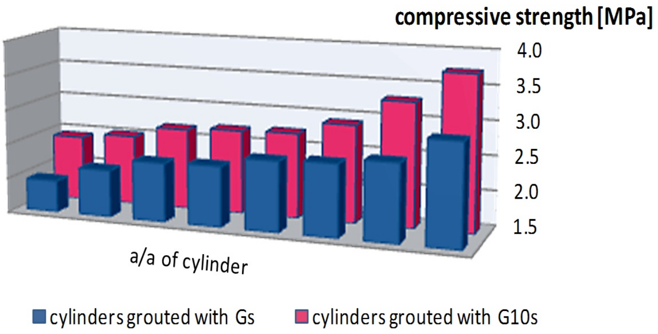
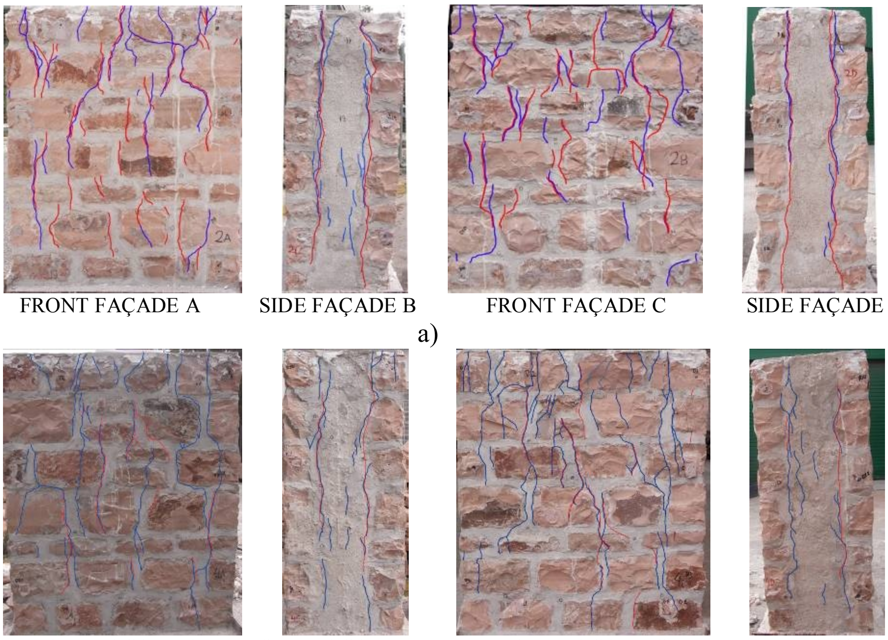


Fig. 4 Compressive strength of grouted cylinders at the age of 180 days.

3.2. Wallettes

3.2.1. Failure mode

Before grouting, all wallettes exhibited the typical for three-leaf masonry failure mode [8, 9] (Fig. 5 – red lines): a) Vertical cracks opened on the facades of the wallettes throughout their height. The extent of cracking in the two opposite faces of the walls was more or less the same. This was due to fact that the two external leaves were of the same construction type and average thickness. The vertical cracks were passing, mainly, through the mortar joints and mortar-to-stone interfaces. To some limited extent, cracks were passing through stones as well. b) A separation between the external leaves and the interior filling material was evident at their interfaces (see vertical cracks in side views B and D in Fig. 5). This typical for three-leaf masonries feature is due to the fact that no connection between the leaves was provided during their construction.


FRONT FAÇADE A SIDE FAÇADE B FRONT FAÇADE C SIDE FAÇADE D

a)

FRONT FAÇADE A SIDE FAÇADE B FRONT FAÇADE C SIDE FAÇADE D

b)

Fig. 5 Failure mode in compression before (red line) and after (blue line) grouting of: a) wallette 2, b) wallette 4

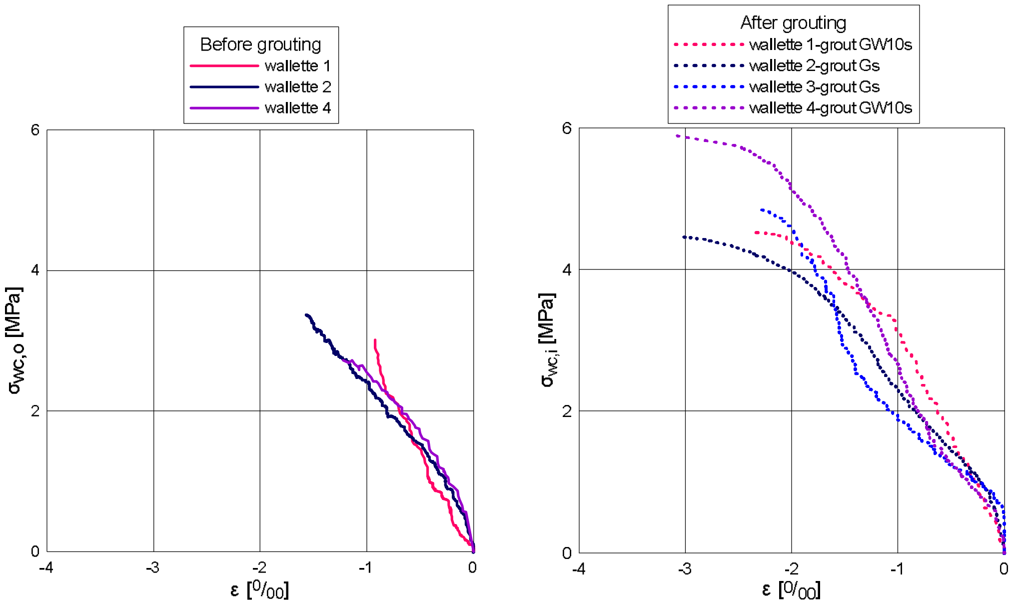
After grouting, the failure mode of wallettes 1, 2 and 3 was similar to that observed in the same wallettes before grouting. In fact, (Fig. 5a – blue lines) vertical cracks have opened both in the faces of wallettes and within their thickness. Some of the cracks that appeared during testing before grouting have opened again. Nevertheless, the majority of vertical cracks appeared in new locations, thus suggesting that grouting provided sufficient strength in previously cracked regions. On the contrary, wallette 4 exhibited a different failure mode (Fig. 5b-blue line), which will be commented upon in the following section.

3.2.2. Stress vs. vertical strain and stress vs. crack openings curves

Figure 6 shows the stress-vertical strain curves for wallettes 1 to 4 before and after the application of grouts. Each of the presented curves is the average curve derived from the vertical LVDTs on the two faces of the wallettes. It seems that the behaviour of the wallettes before grouting is almost linear-elastic up to the attainment of their maximum resistance (Fig. 6a). Grouting does increase quite significantly the compressive strength and the deformability of masonry, without increasing its stiffness (Fig. 6b).

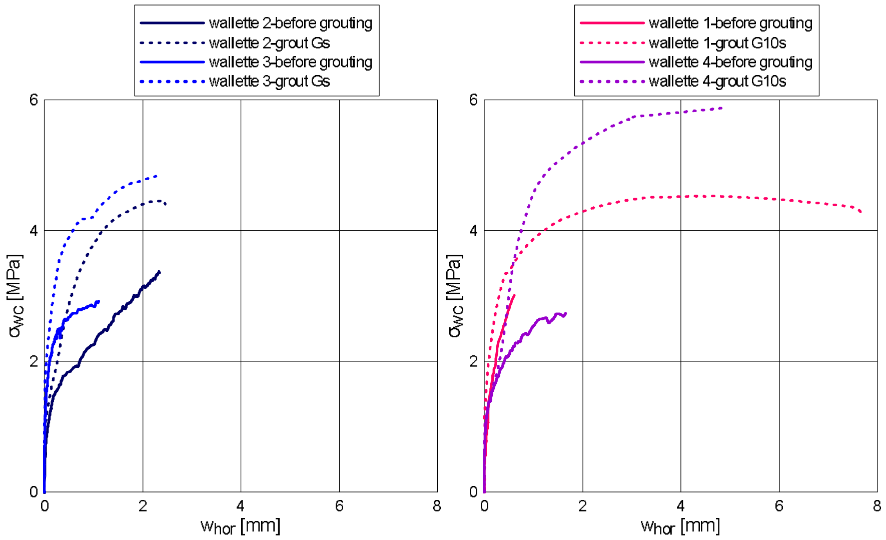
Prior to the application of grouts, the comparison of curves 'vertical stress vs. horizontal deformation' (Fig. 7, solid lines) and 'vertical stress vs. transverse deformation' (Fig. 8, solid lines) at mid-height of specimens, shows that the horizontal deformation (i.e. the total opening of the vertical cracks on the faces of the wallettes) was at maximum equal to ~2.0 mm. On the contrary, transverse deformations (i.e. opening of cracks between external leaves and filling material) reached values between 2.0 and 5.5 mm. It is, therefore, confirmed that the primary cause of failure of this type of masonry is the separation among the three-leaves and the resulting out-of-plane deformation of the external strong leaves, as discussed in detail in [8, 9].

As shown in figs. 6 to 8, as well as in Tab. 7, grouting resulted to a significant enhancement of the compressive strength of masonry (by 32% to 66%). This is attributed [8, 9] to the enhanced mechanical properties of the filling material, as well as to the improved bond between exterior leaves and filling material. In connection to the latter, is observed that wallettes 1 and 4 (grouted with a lime-pozzolan mix) exhibited higher strength enhancement. This is attributed to the better bond properties achieved the interfaces of this type of mixes and in-situ materials [10, 11].



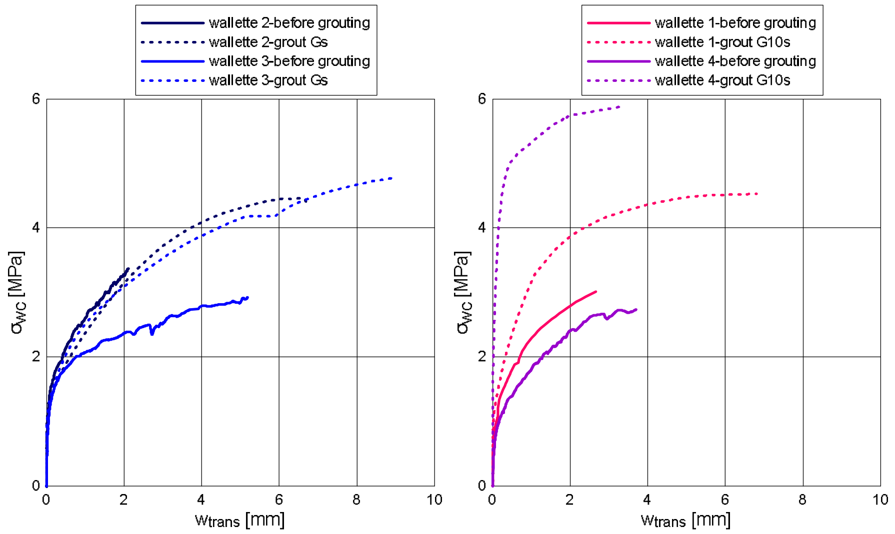
a) b)

Fig. 6 Stress vs. vertical strain curves for wallettes 1 to 4 a) before grouting; b) after grouting



Wallettes grouted with Gs Wallettes grouted with G10s

Fig. 7 Wallettes 1 to 4 before and after grouting. Stress vs. horizontal deformation at mid-height [mm]



Wallettes grouted with Gs Wallettes grouted with G10s

Fig. 8 Wallettes 1 to 4 before and after grouting. Stress vs. transverse deformation at mid-height [mm]

Table 7 Mechanical properties of walls before and after grouting

Wallette	Grout	$f_{wc,o}$ [MPa]	$f_{wc,i}$ [MPa]	$f_{wc,i}/f_{wc,o}$	$\varepsilon_{u,o}$ [$^0/_{00}$]	$\varepsilon_{u,i}$ [$^0/_{00}$]	$E_{wc,o}$ [GPa]	$E_{wc,i}$ [GPa]	$E_{wc,i}/E_{wc,o}$
1	GW10s	3.04	4.53	1.49	-0.93	-2.35	3.05	3.44	1.13
2	Gs	3.37	4.46	1.32	-1.56	-3.04	3.84	3.28	0.85
3	Gs	2.93	4.86	1.66	n/r	-2.31	4.49	3.26	0.73
4	GW10s	2.74	5.90	2.15	-1.24	-3.14	5.63	2.42	0.43

n/r: not reliable test results

It should be noted that wallette 4 exhibited an increase in its compressive strength equal to 115%. This is attributed to the different failure mode exhibited by this wallette, as mentioned in section 3.2.1. Actually, the failure mode of wallette 4 was governed by the formation of vertical cracks on its faces (Fig. 5b – blue lines). This is also evident in Figures 7b and 8b: The total opening of vertical cracks on the faces of wallette 4 are approximately equal to 5.00 mm, whereas the total opening of vertical cracks within the thickness of the wallette is significantly smaller (~3.30 mm). It should be noted that this wallette was cracked during the grouting and pronounced separation between the leaves was observed (Fig. 9). This “accident” may have had a beneficial effect on the final (after grouting) behaviour of masonry, as the interface between filling material and exterior leaves was easily filled with grout and, thus, better bonding was achieved.

Fig. 9 Wallette 4. Application of grouts

Furthermore, it is important to note that the use of hydraulic lime based grouts did not lead to increase of the stiffness of masonry. In some cases, even reduced modulus of elasticity was measured (see Tab. 7). This is attributed to the fact that masonry was grouted after the occurrence of damages. Another positive result is that the strain of grouted masonry at failure is significantly larger than that of the ungrouted masonry (see Tab. 7).

3.2.3. Data related to the consumption of grouts

The data about the consumption of grout per wallette presented in Table 8, prove that the achieved percentage of voids of the filling material (that was positioned without any compaction) was varying between 45% and 52% approximately. Such a percentage of voids is compatible with in situ measurements of rather weak three leaf stone masonries. The precentage of voids estimated in terms of consumed grout is higher than for the cylinders. This is attributed to the fact that the cylinders were grouted before the occurance of any damage, whereas in case of wallettes the grout has filled all the cracks formed during the first loading. It is mentioned that V_{voids}-values were calculated assuming that the total volume of grout was consumed within the filling material.

Table 8 Consumption of grout and percentage of voids

Wallette	Grout	Consumption of grout V_{gr} [lt]	V_{gr}/V_{inf} [lt/m^3]	V_{gr}/V_w [lt/m^3]	V_{voids}/V_w [%]	V_{voids}/V_{inf} [%]
1	GW10s	81.7	454	154	15.4	45.4
2	Gs	92.95	524	176	17.6	52.4
3	Gs	88.62	500	171	17.1	50.0
4	GW10s	84.03	471	157	15.7	47.1

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

4. CONCLUSIONS

The experimental results confirm that for this type of masonry, the main failure mechanism is the separation of the three leaves, followed by the out-of-plane deformation of the external leaves. Moreover, in general, it is observed that grouting did not lead to the modification of the failure mode of the wallettes. In terms of mechanical properties, it was observed that both grouts were efficient in improving significantly the compressive strength of the wallettes, as well as its deformability, without modifying the stiffness of masonry elements. Thus, the experimental results of the present study confirm that the use grouts with low compressive strength (hydraulic lime based grouts) for strengthening of historic masonries, ensures both a mechanically efficient and durable intervention.

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