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ORIGINAL ARTICLE

# Design and evaluation of hydraulic lime grouts for the strengthening of stone masonry historic structures

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**Abstract** The present paper discusses an experimental procedure realized in order to design hydraulic lime based grouts adequate for the strengthening of stone masonry historic structures. With the aim to minimize incompatibility problems between the original materials and the grouts, several natural hydraulic lime based grouts, as well as a ternary (lime–pozzolan–cement) grout with reduced cement content, have been studied. The selection of the most suitable grouts was performed based on a set of criteria, namely injectability, mechanical and durability characteristics. The selected grouts were subsequently injected into cylindrical specimens that simulate the infill of three-leaf stone masonry. The experimental results obtained from mechanical tests carried out on the injected cylinders demonstrated that all grout mixes studied within this work were efficient in strengthening the infill material; they exhibited, however, differences in terms of durability properties. Finally, an empirical formula was developed to predict the compressive strength of the injected infill, as a function of the mechanical properties of grouts.

**Résumé** *Dans cet article on présente une méthode expérimentale appliquée dans le but d'étudier des coulis à base de chaux hydraulique qui seraient adéquats pour le renforcement de constructions historiques en maçonnerie en pierre. On a étudié plusieurs types de coulis (coulis à base de chaux hydraulique ainsi que coulis ternaires [chaux-pouzzolane-ciment] à pourcentage réduit de ciment) dans le but de minimiser les problèmes d'incompatibilité entre les coulis et les matériaux originaux. La sélection des coulis les plus adéquats a été effectuée sur la base d'un groupe de critères concernant l'injectabilité, ainsi que des propriétés mécaniques et de durabilité. Les coulis choisis ont été ensuite injectés dans des éprouvettes cylindriques qui simulent le remplissage d'une maçonnerie historique. Les résultats expérimentaux obtenus sur les éprouvettes cylindriques ont montré l'efficacité du point de vue mécanique de tous les coulis choisis. Il a cependant été constaté qu'il y a des différences en ce qui concerne leur durabilité. Finalement, il a été développé une relation empirique qui permet de calculer la résistance du remplissage en compression après l'injection, en fonction des propriétés mécaniques du coulis.*

**Keywords** Hydraulic lime · Grout · Three-leaf masonry · Infill material ·

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Injectability · Mechanical characteristics · Durability

## 1 Introduction

Grouting constitutes one of the most common techniques applied for the repair and strengthening of masonry structures or fissured architectural members, when interconnected voids in adequate percentage are present. It has the advantage of retrieving the continuity, cohesion and strength of the damaged structures without altering their morphology and load-bearing system. Given that grouting is an irreversible intervention, the design of the grout as well as the method of its application to historic structures must satisfy a series of performance requirements, comprising that of re-treatability. The performance requirements involve injectability, strength and durability aspects and they are set on the basis of an overall approach of the structure to be repaired, before and after intervention (i.e. the construction type and the dimensions of the structure, the nature of the existing materials, the nominal minimum width of voids to be filled and the distribution of voids, the eventual existence of soluble salts, the desired behaviour after repair, etc).

Among the above requirements, the injectability capacity of the grout constitutes a key parameter for a successful intervention. Specific criteria for the design of grouts, which link the estimated nominal minimum width of voids to be filled ($W_{nom}$) with basic properties of the grout composition, have been proposed in the literature [1–3]. Based on these criteria and using commercial materials, one can prepare hydraulic grouts injectable in voids and cracks of a nominal minimum width of 0.1–0.2 mm. For lower nominal minimum widths, that correspond to very fine silt or clay, the penetrability of hydraulic grouts cannot be satisfactory. That is why when an important percentage of clay and silt is present as loose material, a successful injection cannot be assured.

Due to the great variety of masonry types and materials, and in order to better take into account the aforementioned difficulties of hydraulic grouts to penetrate in extremely fine voids, the importance of evaluating the injectability capacity of the grout for each specific case before intervention (by injecting plexiglas cylinders containing samples of the real materials taken from the internal leaf of the masonry to be repaired), was recognized and a methodology was suggested for site and laboratory investigation [4–7].

**Fig. 1** **a** Three-leaf stone masonry wallettes, simulating the masonry of the Katholikon of Dafni Monastery and **b** the infill material

Further research on the subject led to a proposal of new rational criteria for the holistic design of hydraulic grouts, [8], as well as to the development of modern practical guidelines for the application of injections and the in situ quality control of the whole intervention, including detailed records of the grout consumption per masonry volume [9, 10].

In this framework, a comparative study was undertaken for the design of grouts using a series of commercial hydraulic limes. In fact, although hydraulic lime-based grouts (hydraulic lime with or without a pozzolanic material) seem to offer a promising alternative to the 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, only few studies have been devoted to them so far [6, 11, 12].

The present research aims to contribute to the documentation of hydraulic lime based grouts; it examines some of the most important parameters that influence their performance, namely the injectability and durability characteristics and the mechanical properties of the examined compositions. The study is completed with mechanical tests on large scale (2/3) specimens that simulate the infill material of three-leaf stone masonry, strengthened by the selected grouts. It should be noted that this investigation was carried out to support the selection of grout mixes adequate for injection into three-leaf stone masonry wallettes (1.00 × 1.20 × 0.45 m and 1.00 × 1.00 × 0.45 m, see also Fig. 1) that simulated the masonry of the Katholikon of Dafni Monastery, one of the most important monuments of middle Byzantine period in Greece, inscribed in the world heritage list of UNESCO. The results of the entire experimental program on wallettes are published elsewhere [13].

## 2 Materials

Four natural hydraulic limes (A: NHL5 of St. Astier, B: Chaux Blanche NHL 3.5Z of Lafarge, C: Calx Romana of IAR and D: Albaria Calce Albazzana of Degussa), as well as a premixed grouting material with binder based on natural hydraulic lime (Unilit B Fluid 0/0 of Unilit), have been examined. According to the laser grain size analysis, the diameter corresponding to i) the 85% passing and ii) the 99% passing of the solid phase of the grouts fulfilled the penetrability grading criteria for voids and cracks of nominal minimum width $W_{nom} \sim 200$ μm (i.e. $d_{85} < (W_{nom}/5) = 40$ μm and $d_{99} < (W_{nom}/2) = 100$ μm, respectively) [2].

The chemical and mineralogical analysis of the examined hydraulic limes (see Tables 1 and 2) showed that all the samples contain calcite as a major phase. Furthermore, NHL5 (A) and Chaux Blanche NHL 3.5Z (B) contain higher amounts of larnite and portlandite than the other materials; they are, therefore, expected to be more reactive. The presence of significant quantities of quartz, as well as the presence of albite and muscovite in the samples of Calx Romana (C) and Albaria Calce Albazzana (D) indicates either a higher amount of argillaceous substances in the raw materials or the addition of pozzolanic material in the hydraulic lime binder (to increase its hydraulicity). Finally, in Albaria Calce Albazzana, which showed the highest content of $SiO_2$, gehlenite is also present, whilst in Chaux Blanche small amounts of 3CaO $SiO_2$ were detected. As stated by its classification according to EN 459-1, Chaux Blanche is not a pure NHL but it contains additional material, which can be a pozzolanic or hydraulic material, probably cementitious [14].

## 3 Grout design

The design of hydraulic lime-based grouts was performed with the aim to ensure high injectability under low pressure, even in cracks of width of two tenths of millimetre ($W_{nom} \sim 200$ μm). For this purpose, the penetrability, fluidity and stability characteristics of the suspensions were fully examined for various water/solids ratios, with or without the use of additives [1–3]. The standardized sand column test method (NF P18-891, EN 1771) was applied to check the penetrability and fluidity along with the standard apparatus for testing the fluidity and the stability of the suspension (NF P18-358 & P18-359). Additionally, a ternary grout [composed of low cement

**Table 1** Chemical analysis (XRF) of the examined hydraulic limes

| Material | $Al_2O_3$ | CaO | $SiO_2$ | MgO | $Fe_2O_3$ | $K_2O$ | $Na_2O$ | $SO_3$ | $TiO_2$ | $P_2O_5$ | LOI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1.80 | 61.90 | 19.00 | 0.95 | 0.64 | 0.28 | 0.00 | 0.37 | 0.08 | 0.04 | 15.73 |
| B | 0.75 | 68.20 | 14.50 | 0.40 | 0.27 | 0.06 | 0.00 | 0.49 | 0.04 | 0.03 | 17.28 |
| C | 5.31 | 44.77 | 24.37 | 1.11 | 1.75 | 1.00 | 0.00 | 0.49 | 0.19 | 0.05 | 20.73 |
| D | 6.68 | 41.65 | 30.77 | 1.57 | 2.70 | 1.74 | 0.00 | 0.61 | | | 14.11 |

**Table 2** Mineralogical analysis (XRD) of the examined hydraulic limes

| Material | $CaCO_3$ | $Ca(OH)_2$ | $C_2S$ | Quartz | $C_3A$ | CA | $C_3S$ | Anorthoclase | Albite | Gehlenite | Muscovite |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | +++ | +++ | +++ | ++ | + | + | | | | | |
| B | +++ | +++ | +++ | + | | + | + | | | | |
| C | +++ | + | ++ | +++ | | | | + | + | | |
| D | +++ | + | ++ | +++ | | | | | | + | + |

+++, major; ++, minor; +, low

percentage (30%, Danish white cement), lime (25%), pozzolan (45%) and superplasticizer (1%)] was examined. An ultrasound dispersion mixer, assisted by a mechanical device of low turbulence, was used throughout the program. The mixing time was 3 min for the hydraulic lime-based grouts and 6 min for the ternary grout (2 min/solid component).

The following limit values were set for the acceptance of grouts: A time limit of 50 s for the sand column penetrability test ($T_{36}$); an efflux time ($t_{d=4.7\ mm}$) of 500 ml of grout less than 45 s (fluidity test using a Marsh cone with a nozzle-diameter d = 4.7 mm) and fluidity factor higher than $0.7 \times 10^3$ mm/s (based on measurements with a Marsh cone with 3 mm nozzle-diameter), [3]; maximum acceptable limit of 5% was set for the bleeding test [1]. In order to reach similar injectability characteristics for all grout mixes with the lowest possible water content, the use of an adequate superplasticizer was necessary for some of the grout compositions. The selection of the type and percentage of superplasticizer was performed on the basis of a preliminary study for each grout solid phase composition. As presented in Table 3 for the grouts G1, G2 and G4 three different types of superplasticizer were used respectively: SP1, SP2 and SP3, based on naphthalenesulfonate polymer (Rheobuild 5000 of Basf), lignonaphthalene salts (CHEM SPL M of Domylco) and polycarboxylic ether (Glenium 51 of Basf).

The evaluation of the grouts capacity was performed on the basis of their injectability (fluidity, penetrability, stability), their resistance to salt decay and their mechanical characteristics (flexural and compressive strength). Tables 3, 4 and 5 summarize the main test results.

For the evaluation of the mechanical properties of grouts, specimens of 40 × 40 × 160 mm were used. The curing conditions were kept constant at 90 ± 5% RH and 20°C (EN 459/2) until the execution of the tests at the ages of 28, 90 and 180 days. Because of the lack of specialized standards for the mechanical testing of grouts, the procedure adopted here was based mainly on standard NBN EN 1015-11 (1999) and similar researches reported in the literature [1, 11, 15–17].

In general, the compressive strength (measured on 40 × 40 × 40 mm specimens) of the selected grouts increased with time (grouts G1, G2, G3 and G4) or remained approximately constant (grouts G5, G6 and G7) after the age of 90 days. On the contrary, their flexural strength (measured by three-point bending test on 40 × 40 × 160 mm specimens) showed a decrease with time for grouts G5, G6 and G7, after the age of 90 days. This reduction of flexural strength can be attributed to the micro-cracking [16, 17] caused by the significant carbonation observed (by applying phenolphthalein) in specimens of grouts G5, G6 and G7, between the age of 90 and 180 days. This microcracking is attributed to the difference between the regions of grout that are close to the surfaces of the specimen and, hence, carbonated, and those away from edges that are still hydrating. Hydration causes chemical shrinkage and induces tensile stresses (and thus microcracking) at the interface of a carbonated (and thus inert) part of the material and a non carbonated (and thus hydrating) part of it [16, 17]. Nevertheless, this reduction of flexural strength in some of the grouts was not taken as a criterion for rejecting the respective mixes, as significant carbonation is not expected to occur within the mass of masonry under consideration.

On the basis of their compressive ($f_{gc}$) strength (at 6 months), the selected grouts (Table 3) can be classified in three categories: (a) ternary grout (W/S = 0.8), having $f_{gc}$ = 10.6 MPa and $f_{gt}$ = 3.1 MPa, (b) hydraulic lime-based grouts (W/S = 0.8), having $f_{gc}$ of 6–6.7 MPa and $f_{gt}$ of 1.0–3.9 MPa and (c) hydraulic lime-based grouts (W/S = 0.7), having $f_{gc}$ of 2.5–2.9 MPa and $f_{gt}$ of 0.6–1.1 MPa.

Sodium sulphate salt durability tests were carried out (following a procedure described in [18] for stone specimens, slightly adapted, since grouts cannot be subjected to a drying procedure at 105°C). At ambient temperature (20°C), grout specimens (cubes 20 × 20 × 20 mm) cured up to the age of 9 months under 90 ± 5% RH and 20°C, are impregnated with mirabilite ($Na_2SO_4 \cdot 10H_2O$) saturated solutions and dried for six cycles at 20°C. After the sixth cycle, half of the specimens were dried at 20°C and the others at 50°C until constant mass was reached. Table 4 summarizes the results of the salt decay tests. The figures included illustrate the indicative damage patterns observed for each grout formulation.

**Table 3** Optimum grout compositions (% w/w) and evolution of their strength

| Composition (% w/w) | | | | | | Compressive and flexural strength (MPa) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Ternary grout* | | | | | | | | | | | |
| N° | White Danish cement | Lime (powder) | Pozzolan ($d_{max}$ < 75 μm) | SP1[a] | Water[a] | Age (days) | | | | | |
| | | | | | | 28 | | 90 | | 180 | |
| G1 | 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 | 3.13 |
| *Hydraulic lime-based grouts* | | | | | | | | | | | |
| | NHL5 (St Astier) | | | SP2[a] | Water[a] | | | | | | |
| G2 | 100 | | | 1 | 80 | 2.82 | 1.90 | 4.50 | 2.52 | 6.36 | 3.87 |
| G3 | 100 | | | | 80 | 2.06 | 1.10 | 4.88 | 1.75 | 6.00 | 2.70 |
| | Chaux Blanche | | | SP3[a] | | | | | | | |
| G4 | 100 | | | 0.7 | 80 | 3.10 | 1.65 | 4.67 | 2.19 | 6.72 | 1.05 |
| | Calx Romana | | | | | | | | | | |
| G5 | 100 | | | | 70 | 2.25 | 1.51 | 3.04 | 1.39 | 2.88 | 1.08 |
| | Albaria Calce Albazzana | | | | | | | | | | |
| G6 | 100 | | | | 70 | 1.69 | 1.02 | 2.60 | 0.88 | 2.49 | 0.65 |
| | Unilit B Fluid 0 | | | | | | | | | | |
| G7 | 100 | | | | 70 | 1.53 | 1.27 | 2.56 | 1.53 | 2.53 | 0.98 |

[a] % of the solid phase of the grout. SP1, SP2 and SP3 superplasticizers based on naphtalenesulfonate polymer, lignonaphthalene salts and polycarboxylic ether, respectively

**Table 4** Mass changes (%) and damage pattern during salt durability tests

| Grout | Mass changes until the 6th cycle. Drying at 20°C and high RH | Mass changes from 7th to 11th cycle. Drying at 20°C (up to) | Mass changes from 7th to 9th cycle. Drying at 50°C and low RH (up to) |
|---|---|---|---|
| G1 | 33% | 7% (edge rounding) | 8% (fracturing) |
| G2 | 21% | −1.6% (edge rounding) | −4% (edge rounding) |
| G4 | 29% | −6.3% (delamination) | −25% (delamination & severe edge rounding) |
| G5 | 13% | 3.4% (edge rounding) | Collapsed into pieces |
| G6 | 18% | 4.6% (edge rounding) | Collapsed into pieces |

| Grout | G1 | G2 | G4 | G5 | G6 |
|---|---|---|---|---|---|
| 11th cycle. Drying at 20°C |  |  |  |  |  |
| 9th cycle. Drying at 50°C and low RH |  |  |  |  |  |

The results of Table 4 show that grout G2 exhibited the best behaviour, even under the most severe conditions (drying at 50°C). This grout formulation (G2) does not suffer any substantial mass loss and/or damage. Since reference data for salt resistance of grouts are still missing, exposure to salt

**Table 5** Injectability characteristics of the optimum grout compositions

| GROUT | G1 | G2 | G3 | G4 | G5 | G6 | G7 |
|---|---|---|---|---|---|---|---|
| $T_{36}$ (s): Sand column 1.25/2.50 mm (voids: 0.2–0.4 mm) | 19 | 18 | 37 | 26 | 17 | 12 | 22 |
| $t_{d=4.7\ mm}$ (s): 500 ml of grout | 21 | 22 | 26 | 24 | 22 | 23 | 22 |
| Bleeding | 2% | 2% | 1% | 1% | 1% | 1% | <1% |
| Fluidity factor ($\times 10^3$ mm/s) | 1.15 | 0.99 | 0.76 | 0.81 | 1.04 | 1.00 | 0.99 |

influences should be carefully investigated before intervention (in the laboratory and even in situ when possible).

After characterization was completed, all these grout formulations (G1–G7) of similar injectability characteristics (see Table 5), were injected at low pressure (0.75 bar) into cylindrical specimens that were constructed in purpose in the laboratory to simulate the infill material of the three-leaf stone masonry under consideration. The main objective of this investigation was the comparison of the selected grouts regarding their capacity to improve the mechanical characteristics of the infill material.

## 4 Mechanical properties of filling material before and after grouting

To produce specimens simulating in a reproducible way the intermediate leaf (filling material) of three-leaf masonry, plastic cylindrical moulds (diameter D = 250 mm, height H = 500 mm) were filled with a mix of predetermined amounts of lime/pozzolan mortar and pieces of travertine stone, in order to reach a percentage of voids of approximately 40% of the total volume of the cylinder, which is a typical percentage for the infill material of deteriorated historic three-leaf masonry [1, 11]. The entire procedure for the preparation of specimens was similar to that described elsewhere [1, 15]. Thus, for each specimen 22.5 kg of stones (size: 20–50 mm) and 10.5 kg of mortar were mixed manually and then the mixture was disposed by hand without compaction in the mould, in a way to keep the distribution of empty spaces dispersed in a relatively uniform way. Both at the bottom and top of the mould a 2 cm-thick layer of mortar was bedded. The dimensions of cylindrical specimens were selected with the purpose to reproduce (almost in natural scale) the filling material of the three-leaf stone masonry of the specific monument. Scale effects (e.g. by carrying out tests on cylinders according to ASTM Standard C943) were not considered, as it was assumed that the results of this research are realistic (being conducted practically under natural scale) and conservative enough as testing on smaller cylinders would result to higher mechanical properties.

Although initially it was planned to test the cylinders before grouting (to their maximum resistance), only three (out of twenty-eight) cylinders were tested in compression before grouting (Table 6). The testing program was modified for the following reasons: (a) the examined infill is composed by pieces of stone with a low content of mortar, and hence a high percentage of voids (including large voids, but also very fine ones especially in the mortar and in the interfaces between mortar and stones); thus, large axial deformations and excessive lateral dilatancy of the cylinders were observed, as already reported in the literature [15], and the moulds could not be re-used for the procedure of grouting and (b) due to the texture of the ungrouted cylinders, vertical strains could not be measured in a reliable way, since measuring devices could not be fixed on the cylinders (Fig. 2a). On the basis of the results obtained from testing three ungrouted cylinders, a mean compressive strength of 0.15 N/mm$^2$ was measured for the ungrouted filling material.

The specimens (placed in their moulds) were injected at constant pressure of $\sim$0.75 bar, using specially manufactured equipment (Fig. 2b, c). The injections were performed from the bottom of the moulds; the time needed for filling each cylinder and the consumed volume of grout were recorded (Fig. 3). These recorded data show that the injectability of grout in the infill material, expressed as the approximate average filling time, was quite satisfactory and fit well with similar data reported in the literature [6, 11], taking into account the greater dimensions of the specimens used in the present

**Table 6** Summary of the experimental results obtained from mechanical tests carried on cylindrical specimens

| Mechanical properties of | | | | | | |
|---|---|---|---|---|---|---|
| Grout | Ungrouted cylinders | Grout | | Grouted cylinders | | |
| | $f_{i,0}$ (MPa) | $f_{gc}$ (MPa) | $f_{gt}$ (MPa) | $f_{i,s}$ (MPa) | $E_{i,s}$ (GPa) | $\lambda_f$ |
| Valluzzi [11, 19] | | | | | | |
| C7-C8 | – | 3.23 | 0.35 | 0.82 | 0.343 | – |
| C9-C10(A) | – | 3.23 | 0.35 | 0.80 | 0.245 | – |
| C11-C12 | – | 5.10 | | 1.99 | 1.518 | – |
| C13(A) | – | 5.10 | | 2.15 | 1.201 | – |
| C14-C15 | – | 3.21 | | 1.43 | 1.499 | – |
| C17-C18 | – | 3.65 | | 1.38 | 1.253 | – |
| C27-C28 | – | 3.35 | | 1.71 | 1.747 | – |
| C26(A) | – | 3.35 | | 1.39 | 1.354 | – |
| Miltiadou [1, 15] | | | | | | |
| 75% C + 25% DSF | 0.48 | 30.00 | 2.50 | 8.8 | 13.70 | 18.33 |
| | 0.48 | 30.00 | 2.50 | 10.5 | 10.50 | 21.87 |
| 50% C + 22.5% DSF + 27.5% L | 0.48 | 13.00 | 1.40 | 16.3 | 16.60 | 33.95 |
| Present work | | | | | | |
| G1 | 0.15 | 10.58 | 3.13 | 3.04 | 1.662 | 20.3 |
| G2 | 0.15 | 6.36 | 3.87 | 2.79 | 1.683 | 18.6 |
| G3 | 0.15 | 6.00 | 2.70 | 3.26 | 1.556 | 21.7 |
| G4 | | 6.72 | 1.05 | 3.25 | 2.097 | |
| G5 | | 2.88 | 1.08 | 2.65 | 1.928 | |
| G6 | | 2.49 | 0.65 | 2.26 | 1.355 | |
| G7 | | 2.53 | 0.98 | 2.01 | 0.618 | |

Average percentage of voids: G1 (7 cylinders) = 39.5%, G2 (5 cylinders) = 42.2%, G3 (6 cylinders) = 41.30%, G4 (3 cylinders) = 42.2%, G5 (3 cylinders) = 38.1%, G6 (2 cylinders) = 42.2%, G7 (2 cylinders) = 35.5%

$f_{i,0}$: Compressive strength of ungrouted cylinders; $f_{gc}$ and $f_{gt}$: Compressive and flexural strength of grout; $f_{i,s}$ and $E_{i,s}$: Compressive strength and modulus of elasticity of grouted cylinders; $\lambda_f = f_{i,s}/f_{i,0}$

*C* cement, *DSF* densified silica fume, *L* lime

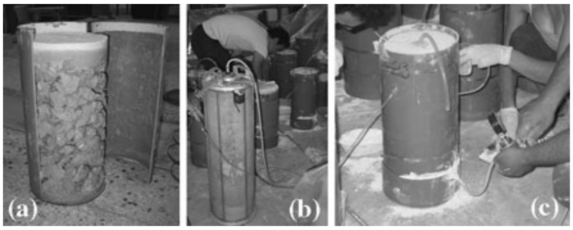

**Fig. 2** **a** Ungrouted cylinder, **b** and **c** injecting the cylinders

work. The average grout volume consumed per cylinder vary from 7.3 to 9.1 lt; this means that 35.5–42.2%, of the total volume was filled with grout (see Table 6).This is a very satisfactory result, as the total porosity of the specimens was of the order of 40%. Apart of the filling of large voids between pieces of stones, an important part of the very fine voids of the mortar itself were also filled improving the cohesion of the mixed material and the adherence at the interfaces, as already reported in the literature [15]. Evidently, the very fine voids, having a width lower than the nominal minimum one taken into account for the design of the grouts were not filled. After 180 days of curing (under 90 ± 5% RH, 20°C), the grouted cylinders were tested in compression.

Table 6 summarizes the results of testing of the grouted cylinders, whereas typical stress–strain curves are given in Fig. 4. The failure mode of cylinders was characterized by the formation of almost vertical cracks, typical for cohesive/adhesive failure (Fig. 5).

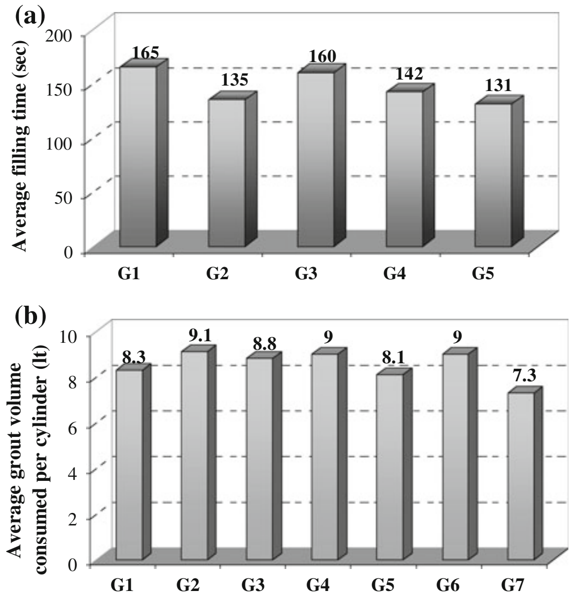


**Fig. 3** **a** Time needed for filling of the cylinders, **b** Average grout volume consumed per cylinder

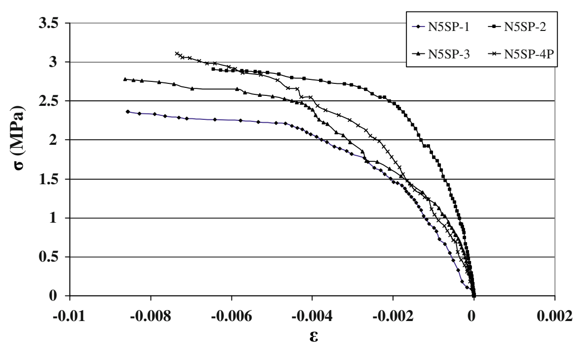


**Fig. 4** Typical stress–strain curves (cylinders injected with grout G2)

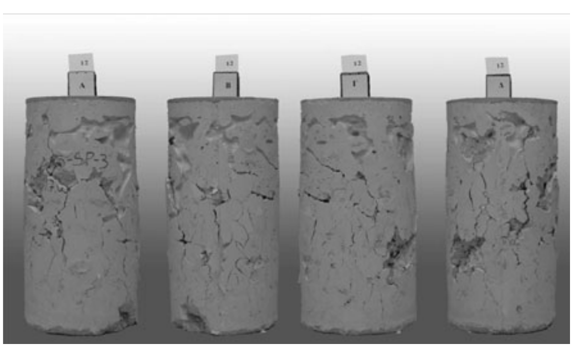

**Fig. 5** Typical failure mode of injected cylinders

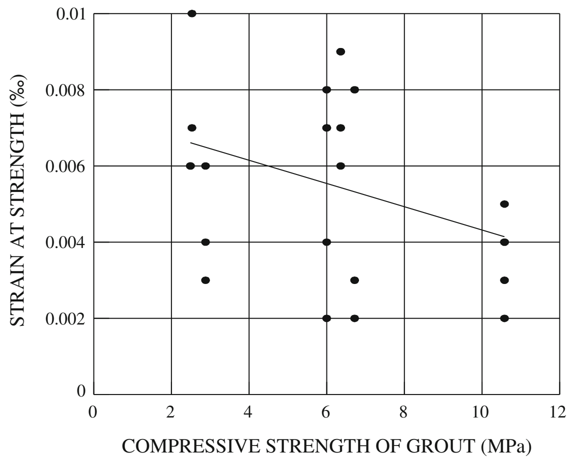


**Fig. 6** Relationship between the strain at strength and the compressive strength of the grout

Although the compressive strength of the grouts varies between 2.5 and 10.5 MPa, allowing for a rough classification of the grouts into three categories as mentioned in Sect. 3, the measured compressive strength of the grouted cylinders varies only between 2.0 and 3.3 MPa. This indicates that the compressive strength of the grout is not the decisive property for its mechanical efficiency in the strengthening of the infill material, as already reported in the literature [1, 20–22].

One may observe (Fig. 6) that, in general, the strain corresponding to the compressive strength of grouted cylinders is smaller for higher compressive strength of the injected grout. As shown in Fig. 6, although the scatter of the measured strain values is rather high, there is a tendency of stronger grouts to produce a stiffer grouted filling material.

This is confirmed by the data of Fig. 7, where the secant modulus of elasticity of grouted cylinders (at a compressive stress equal to 1/3 of the compressive strength) is plotted against the compressive strength of the injected grout, as well as by the data of Fig. 8, where the ratio between the strain at max strength and the respective compressive strength of grouted cylinders is plotted against the compressive strength of the cylinders.

The moduli of elasticity vary from 0.6 to 2 GPa, showing good agreement with published data for such type of grouts [11]. It should be noted that the measured differences in moduli of elasticity are not in direct relationship with the compressive strength of the grout: for a compressive strength of grout varying

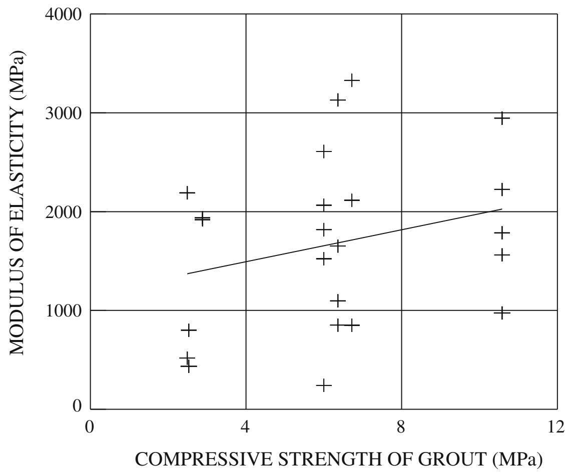


**Fig. 7** Modulus of elasticity of grouted cylinders as a function of the compressive strength of the injected grout

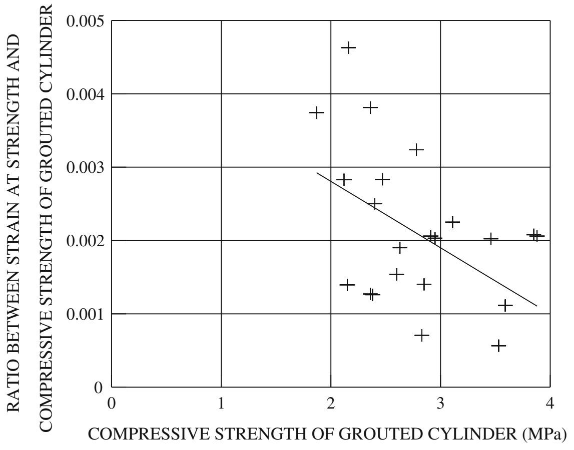


**Fig. 8** Ratio between the strain at strength and the respective compressive strength of grouted cylinders against the compressive strength of the cylinders

roughly between 2 and 10 MPa, moduli of elasticity between 600 and 2000 MPa were measured (Fig. 7).

## 5 Estimation of the compressive strength of grouted infill and grouted masonry

Vintzileou and Tassios [23], based on previous work [20, 24], as well as on their experimental results, developed a simple formula (Eq. 1), allowing for the calculation of the compressive strength of three-leaf masonry after grouting. The formula is based on the assumption that grouting affects mainly the mechanical properties of the filling material.

$$f_{wc,i} = f_{wc,0}\left(1 + 1.25\frac{V_i}{V_w}\frac{\sqrt{f_{gr,c}}}{f_{wc,0}}\right) \quad (1)$$

where, $f_{wc,0}$ and $f_{wc,i}$ compressive strength of the masonry before and after grouting; $V_i$ and $V_w$ volume of the filling material and of the whole wall, respectively; $f_{gr,c}$ compressive strength of the grout.

In Eq. 1, the square root of the grout compressive strength was introduced as an estimator of the tensile strength of the grout. This is because tests on wallettes made of three-leaf masonry before and after grouting [16, 23, 25], have demonstrated that the strength enhancement of masonry is proportional to the tensile rather than the compressive strength of the injected grout.

On the other hand, Valluzzi [11, 26] has used the Eq. 2 to calculate the compressive strength of grouted masonry. In that equation, the compressive strength of the filling material is calculated as a function of the compressive strength of the injected grout (Eq. 3).

$$f_{wc,i} = f_{wc,0}\left(1 + \frac{V_i}{V_w}\frac{f_{i,s}}{f_{wc,0}}\right) \quad (2)$$

$$f_{i,s} = 0.31 f_{gr,c}^{1.18} \quad (3)$$

where, $f_{i,s}$ denotes the compressive strength of the grouted filling material.

It seems, however, that the predicted values of the compressive strength of grouted masonry, calculated using Eqs. 2 and 3 do not fit in a satisfactory way with the experimentally obtained values (Fig. 9). Actually, in order to reach conservative compressive strength values, adequate for the design of the intervention, a partial safety factor, $\gamma_{Rd}$, value as high as 1.80 is needed.

Based on the observation that the compressive strength of grouted masonry depends on the tensile strength of the injected grout rather than on its compressive strength, Vintzileou [21] has related the experimental results presented in this paper with the tensile strength of the grout. Thus, Vintzileou [21] proposed the following Eq. 4 for the prediction of the compressive strength of the grouted filling material:

$$f_{i,s} = 1.60 + 0.50 f_{gr,t} \quad (4)$$

where, $f_{gr,t}$ the bending tensile strength of the grout.

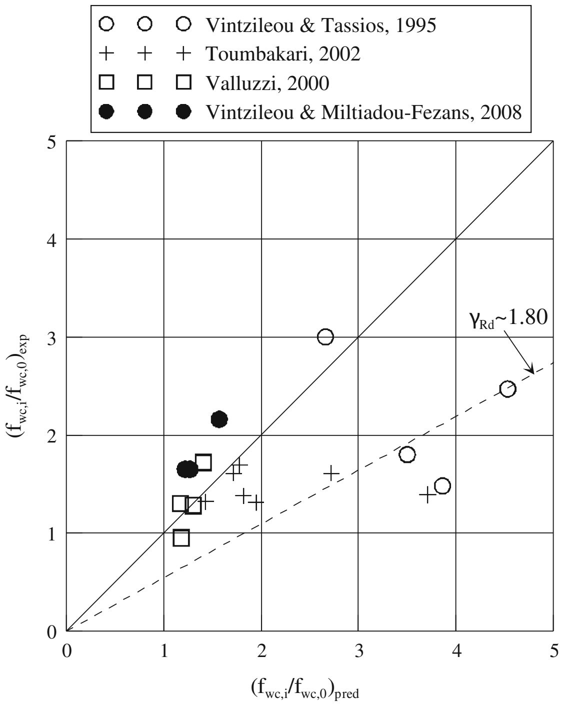


**Fig. 9** Compressive strength of grouted three-leaf masonry: comparison of predicted and experimental values using the combination of Eqs. 2 and 3

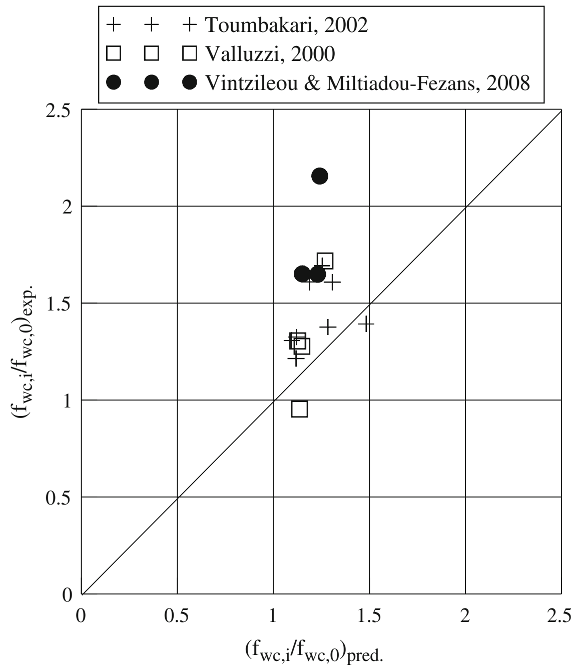


**Fig. 11** Compressive strength of grouted three-leaf masonry: comparison of predicted and experimental values using the combination of Eqs. 2 and 4

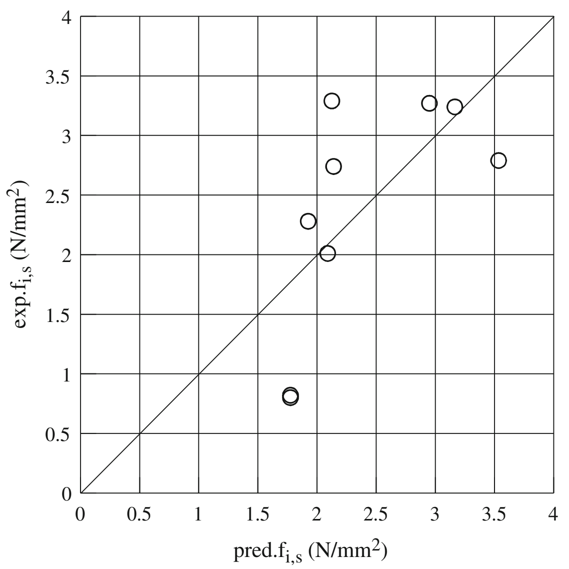


**Fig. 10** Comparison between experimental and predicted values of compressive strength of grouted filling material (Eq. 4)

The comparison of predicted $f_{i,s}$ (using Eq. 4) and experimental values is shown in Fig. 10. From simple visual inspection, it seems that the predicted values fit quite well with the experimental ones.

As shown in Fig. 11, by introducing in Eq. 2 the compressive strength of the grouted filling material, $f_{i,s}$, calculated according to Eq. 4, the calculated values of compressive strength of grouted masonry are in good agreement with the experimental ones [13].

## 6 Conclusions

Grouting is a technique used to fill the voids and reinstate the continuity of the structural components of a deteriorated masonry. To this end a holistic design of the grout is necessary taking into account injectability, durability and mechanical characteristics of the grout, as well as of the structure to be repaired before and after injection. Such an approach was followed in the experimental research presented in this paper.

The results obtained allow for the following conclusions to be drawn:

(a) The holistic methodology followed for the design of stable, fluid and highly injectable grouts was proven to be very efficient. In fact, as observed during grouting and confirmed after testing, all grouts applied to the specimens were able to fill cracks and voids having a width equal or larger than the nominal minimum width of voids ($W_{nom} \sim 200$ μm) taken into account for their design. Thus the importance (i) of selecting appropriate raw materials which fulfill the penetrability grading criteria and (ii) of executing all the adequate stability, fluidity and penetrability tests is highlighted.

(b) In order to avoid incompatibility problems, the importance of selecting the appropriate raw materials, on the basis of their chemical, physical and mechanical characteristics, taking into account the properties of the structure to be injected, was also underlined. The comparison of grout formulations based on hydraulic limes of different type among them and with a ternary cement–lime–pozzolan grout (composed of low cement percentage, 30% Danish white cement) allowed for a preliminary evaluation of their durability capacity, thus contributing to the research on this critical matter still not sufficiently investigated. Of the five formulations examined under the salt crystallization test, the grout G2 (based on natural hydraulic lime NHL5) exhibited the best behavior.

(c) Seven grout mixes of similar injectability characteristics having the lowest possible water content were selected and used for the injection of cylinders simulating the infill material of three leaf masonry. The mechanical characteristics of the seven grouts selected permitted their classification on the basis of their compressive ($f_{gc}$) strength (at 6 months) in three categories: (a) ternary grout (W/S = 0.8), having $f_{gc}$ = 10.6 MPa and $f_{gt}$ = 3.1 MPa, (b) hydraulic lime-based grouts (W/S = 0.8), having $f_{gc}$ of 6–6.7 MPa and $f_{gt}$ of 1.0–3.9 MPa and (c) hydraulic lime-based grouts (W/S = 0.7), having $f_{gc}$ of 2.5–2.9 MPa and $f_{gt}$ of 0.6–1.1 MPa.

(d) The experimental results obtained from mechanical tests carried out on the injected cylinders have demonstrated the efficiency of all seven grouts in strengthening the infill material, despite of the differences in their mechanical properties. In fact, for compressive strength of the grouts varying between 2 and 10 MPa, the compressive strength of the injected cylinders varies between 2 and 3.3 MPa approximately. The moduli of elasticity vary from 0.6 to 2 GPa, showing good agreement with published data for such type of grouts. Experimental data show that significant strengthening of the filling material and, by way of consequence, of the entire masonry, is reached even with grouts of low to medium compressive strength.

(e) Taking into account the preponderance of hydraulic lime based grouts studied, in terms of physical and chemical compatibility with in situ materials, their contribution to the enhancement of the mechanical properties of stone masonry makes them a viable alternative to higher strength cementitious grouts.

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