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Restoration of cultural heritage masonry structures damaged by the 2009 Abruzzo earthquake: Materials and methods

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Summary. — This research is aimed at developing a methodology for the emergency stabilization and restoration of historic buildings damaged by the 2009 Abruzzo earthquake, by means of on-purpose modified injection grouts based on hydraulic binders. Several portions of multi-leaf stone masonry walls from buildings in the towns of Onna, Tempera and Sant'Eusanio Forconese, all located in the province of L'Aquila, were selected for carrying out injection tests with six grouts. Before and after injection, a comprehensive experimental program, including chemical and microstructural tests on original and repair materials and mechanical tests on the masonry walls, was performed. The present contribution describes the tests carried out at the various levels and discusses the main results obtained.

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PACS `61.05.cp` – X-ray diffraction.
PACS `68.37.Hk` – Scanning electron microscopy (SEM) (including EBIC).
PACS `81.70.Bt` – Mechanical testing, impact tests, static and dunamic loads.

1. – Introduction

The mechanical characterization of multi-leaf stone masonry structures, as well as the design and effectiveness control of proper improvement techniques are topical, especially in seismic zones, where this specific kind of masonry shows its great vulnerability [1, 2]. The Italian experience of the 2009 Abruzzo earthquake confirmed what was already clear after the 1997 Umbria-Marche earthquake, *i.e.*: i) the lack of criteria for the selection of proper techniques for the plurality of masonry types and the specific structural problems of the building components, can lead to interventions which may even worsen the original behaviour; ii) once proper techniques and materials have been selected, the achievement

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of real improvement needs to be checked by on-site control of execution and effectiveness [3,4].

In this sense, the experimental validation of the properties of constituent materials, as well as subassemblies behaviour, is crucial to improve the knowledge lying at the basis of the whole restoration process. As for stone masonry walls, some studies are available on the possible application of grout injections, especially where they can be more effective, as in multi-leaf walls, for connecting incoherent materials, improving the homogeneity, etc. [5-8]. Nevertheless, their mechanical characterization is incomplete as regards shear properties, both in terms of strength and deformability. Moreover, although injections are one of the most common interventions applied on masonry structures in seismic areas, the large variety of products available and the absence of specific protocols of intervention, increase unclearness and inaccuracy.

This study focuses on the characterization of masonry walls under shear actions, tested in original and consolidated conditions, by using grouts provided by four different producers, willing to participate directly in the experimental campaign with their expertise and products. Experimental analysis of original materials, mortar in particular, and of grouts, carried out in laboratory at different scale, including the interface between mortar and grouts, completed the evaluation of the effectiveness of the intervention. Results of laboratory and on-site destructive tests are commented in the paper.

2. – Experimental program

The main aim of the experimental program was to characterize the effect of six injection grouts, from four different producers, used to strengthen irregular stone masonry walls, damaged by the earthquake of April 6, 2009. Twenty-one lightly damaged wall portions, from six heavily damaged buildings, were selected in the towns of Onna, Tempera and Sant'Eusanio Forconese, all located in the Aterno valley in the province of L'Aquila.

First, a selection of mortars was sampled from the infilling leafs of the walls in each building. On these samples, both macroscopic and microscopic petrographic analyses were carried out, according to UNI 11176 (2006). Then, the materials were dry disaggregated and sieved and the fraction under $63\,\mu$m, constituted by the binder and the finer aggregate fraction, was mineralogically characterized by means of X-ray powder diffraction (XRPD) analyses. Finally, the samples in $30\,\mu$m thin section were also studied by scanning electron microscopy (SEM) for microtextural and microchemical characterization. Semiquantitative concentration of major elements was also determined both on selected areas of the binder and lime lumps (when present) by using an energy-dispersive X-ray system (EDS). Data allowed the determination of the hydraulicity of the binder, as measured by the hydraulicity index (HI) [9]. The same methodology was adopted to characterize the anhydrous restoration products. For each grout, several test prisms were prepared, according to EN 196-1 (2005). Half of the prisms were cured *in situ*, while the remaining were cured in laboratory. On these samples, mechanical tests to determine the grout flexural strength, compressive strength, and the elastic modulus, were carried out, too. After mechanical tests, the hydrated materials were characterized with the same methodology adopted for the study of the original mortars.

Before carrying out any test on the masonry wall specimens, detailed surveys of the masonry wall texture were carried out. Sonic pulse velocity tests were carried out on all specimens, in their original, unconsolidated state. These tests were then repeated on the twelve masonry portions strengthened by grout injection, to compare sonic velocity increase and quantity of injected admixture. On all specimens, those in original, non-strengthened conditions, and the twelve injected walls, diagonal compression tests were carried out. The selected masonry walls had thicknesses between 0.48 and 0.63 m and they were cut to specimens of 0.80 × 0.80 m (length × height), to carry out the destructive tests. Considering the low cohesion of the original masonry, it was not possible to apply loads by means of steel angles, as generally recommended by ASTM E519 (2010). Hence, the specimens corners were cut to 45°, generating flat loading surfaces, orthogonal to the direction of load application, as can be the case for on-site diagonal compression tests [10].

Finally, after the destructive tests, the effectiveness of the selected restoration protocols and materials on the microstructure was checked through optical and electronic microscopy on the interfacial zones between grouts and original constituents.

In the following, the masonry wall specimens are identified through a code that includes: the specimen number (1-21), the town where the specimen is located (O=Onna, S=Sant'Eusanio Forconese, T=Tempera), the masonry wall condition (C=consolidated, U=unconsolidated), and the type of admixture (A-F). Specimen 8-O_U was already heavily damaged, hence the destructive test was not carried out.

3. – Masonry type and injection procedure

The tested masonry walls are made of two external layers of rough-shaped limestone blocks, whose largest dimensions were about 20–25 cm, bonded in non-horizontal, irregular courses. The infilling core is made of rough-cut limestone fragments of smaller dimensions. Masonry specimens in Sant'Eusanio Forconese (4-5-6-7) are made of limestone mixed with conglomerate. Specimens 19-20-21 have horizontal clay brick courses at regular spacing. This construction practice was introduced in the Abruzzo region after the 1703 earthquake.

To strengthen the walls, injection holes were drilled on one side of the walls only, approximately following a scheme of equilateral triangles. They were spaced about 25–30 cm from one another, where plastic tubes were introduced. Before the injection, mortar joints were repointed and plastic tubes sealed. Through them, a preventive hydrating and cleaning injection was done. The grout was injected at low pressure starting from the bottom of the walls to the top. During the injection phase, the survey of the quantity of used grout provided a gross estimate of the injected percentage of voids (table II).

4. – Characterization of original materials and injection grouts

Based on the petrographic analyses, the historic mortars were classified into three groups:

Group 1 (samples 1-O, 2-O, 3-O, 8-O, 9-O, 10-O, 11-O, 12-O, 13-O, 14-O, 15-O; fig. 1a), constituted by a matrix of cryptocrystalline calcite permeated by an abundant fraction of clay minerals. The filler has a predominant carbonate composition (spathic and bioclastic limestones), with a subordinated siliceous fraction.

Group 2 (samples 19-O, 20-O, 21-O, 4-S, 5-S, 6-S, 7-S; fig. 1b), constituted by a matrix of cryptocrystalline calcite with a low fraction of clay minerals. The filler has a predominant siliceous composition (mainly quartz and chert, rare clinopyroxene, plagioclase, K-feldspar) and a subordinated carbonate fraction.

Group 3 (samples 16-T, 17-T, 18-T; fig. 1c), similar to group 2 mortars, but discernible for the presence of local accumulation of clay minerals and the carbonate nature of the aggregate.

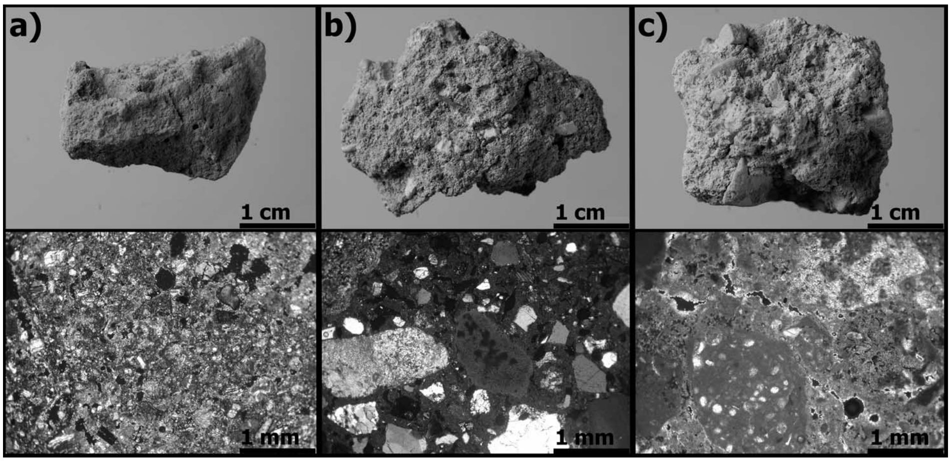

Fig. 1. – Macroscopic images and polarising light micrographs (taken in crossed polars) of the three petrogroups: a) 14-O sample; b) 5-S sample; c) 16-T sample.

The XRPD analysis of the fine fraction of the mortars gave a mineralogical assemblage with a predominant carbonate fraction, mainly constituted by the calcite of the binder, and a subordinate siliceous fraction constituted by predominant quartz and subordinated feldspar and clinopyroxene. A variable fraction of clay minerals (illite, chlorite, smectite) is also present. Semi-quantitative XRPD data are consistent with the results obtained from the petrographic study: group-1 mortars are characterized by a great amount of clay minerals in the binder fraction, while other mortars are distinguishable for the greater purity of the binder matrix. As regards the SEM-EDS analyses, the low values of HI determined (below 0.1) indicate the use of an air binder constituted by lime for the manufacturing of the materials.

As regards the grouts, they were subdivided into three groups:

Group A (grouts B, C, F): grouts based on air lime (portlandite) + hydraulic agent + silty carbonate microfiller. The pozzolanic agent is constituted by blast-furnace slag [11, 12], rich in reduced sulphur. The total reaction of portlandite in the hydrated grouts, with formation of calcite and CSH and AFm phases [13], indicates the reaction between lime and hydraulic agent, associated with partial air reaction of portlandite. The presence of low amounts of ettringite testifies the oxidation process of the sulphur in the AFm interstrate [14], entered in the crystal structure after the breakdown of the slag, and subsequent conversion into an Aft-type phase due to reaction with atmospheric sulphates.

Group B (grout E): grout based on hydraulic lime + pozzolanic agent + sandy filler, predominantly siliceous. The hydraulic lime is mainly constituted by C2S (belite) and rare gehlenite. The pozzolanic agent is constituted by natural pozzolanas. The hydrated grouts show the total reaction of C2S, with formation of portlandite, CSH and AFm phases: this evidence testifies both the hydraulic reaction of the Ca-silicates and the latency of the pozzolanic reaction in the short period. A low amount of ettringite and gypsum was found in the materials, testifying a reduced sulfate attack.

Group C (grouts A, D): ternary grouts based on hydraulic lime + ordinary Portland cement (OPC) + silty carbonate microfiller with subordinated siliceous fraction. The binder fraction is constituted mainly by C3S (alite) and C2S, with rare gehlenite, C3A (aluminate) and C4AF (ferrite). An amount of gypsum is also present in the mixture, added to prevent flash set [13]. The hydrated grouts show the total reaction of C3S and

Table I. – *Mechanical characterization of grouts.*

Series	Flexural strength (N/mm^2)	Compressive strength (N/mm^2)	E, Young modulus (N/mm^2)
A_SC	1.79	37.70	8800
A_EC	2.01	32.82	7500
B_SC	3.22	27.18	10400
B_EC	1.68	25.14	10400
C_SC	1.07	17.72	5900
C_EC	1.75	13.72	3700
D_SC	4.44	30.90	11000
D_EC	2.20	31.63	10300
E_SC	1.83	5.47	5700
E_EC	1.51	4.78	5600
F_SC	1.88	18.13	8100
F_EC	-	-	-

gypsum and the partial reaction of C2S, C3A and C4AF, with formation of CSH and AFm phases, portlandite and ettringite; this evidence testifies the hydraulic reaction of the cementitious phases [13].

The mechanical characterization of the grouts was carried out on 40 × 40 × 160 mm prisms. Flexural and compression tests were carried out according to EN 1015-11 (2007) for mortars. The elastic modulus was evaluated according to UNI 6556 (1976) for concrete, determining the loading steps on the basis of the compression tests results. For each admixture, two series of three samples (two samples for flexural and compression tests, one for the elastic modulus) were tested. One series was cured under standard conditioning conditions (SC), whereas the other was cured on-site, in actual environmental conditions (EC). Table I reports the test results.

In general, the EC series have mechanical properties that do not differ substantially from SC series, confirming that on-site curing conditions were basically proper. More in detail, EC compressive strength and elastic modulus were approximately 90% of the SC series. Conversely, in the case F_EC series, the interventions were carried out at low temperature, which compromised the grout curing process and the intervention effectiveness. Admixtures A, B, and D, have values of strength (in average 30 N/mm^2) and stiffness (in average, elastic modulus of almost 10000 N/mm^2) which are definitely higher than those found on historical mortars. In the case of A and D, this also corresponds to the fact that they are ternary grouts. Admixtures C, E, and F are more compatible under the mechanical point of view, in particular E for compressive strength (around 5 N/mm^2) and all for elastic modulus (between 3700 and 8100 N/mm^2).

5. – Diagonal compression tests

The diagonal compression test set-up is made of three steel beams, composed of two UPN 120 profiles each, following the scheme in fig. 2a. Three hydraulic jacks, with 100 kN load capacity, are placed between the two beams at the specimen top corner. Two threated steel bars, with a 24 mm diameter, connect the top and bottom corner beams, allowing a uniform load distribution during the test. Loads were measured by means

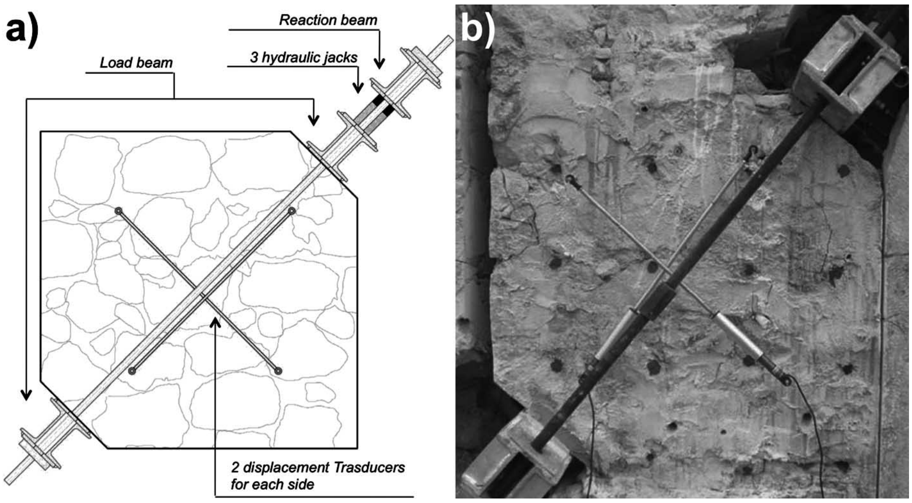

Fig. 2. – Diagonal test set-up (a) and view of a specimen (b).

of a pressure transducer placed in parallel with the three jacks. Four potentiometric displacement transducers (two on each masonry wall façade) measured strains along the two specimen diagonals. All instruments were connected to an automatic data acquisition system, provided with a laptop for data reading and storage.

Shear strength of specimens S_s (N/mm^2) was calculated with eq. (1), where P (N) is the load applied along the diagonal and A_n (mm^2) is the net cross-sectional horizontal area:

$$S_\mathrm{s} = \frac{0.707P}{A_\mathrm{n}}\,. \tag{1}$$

Angular deflection γ (mm/mm) was calculated with eq. (2), where ΔV and ΔH (mm) are the diagonal deformations in compression and tension, and g (mm) is the diagonal length:

$$\gamma = \frac{\Delta V + \Delta H}{g}\,. \tag{2}$$

Shear modulus G (N/mm^2) is the ratio between shear strength S_s and angular deflection γ. It was calculated with eq. (3) in two tensional ranges of shear strength: 0–30% and 30–60%.

$$G = \frac{S_\mathrm{s}}{\gamma}\,. \tag{3}$$

The specimens (1-2-3; 9-10-11) obtained in non-demolished buildings were not disconnected, on their upper side, from the rest of masonry, hence there were still some dead loads applied. In these cases, the Mohr circle representative of the stress state is not centred in the origin, as it is in the case of isolated specimens. Thus, the value of shear stress τ is different from the principal stress σ_I [15].

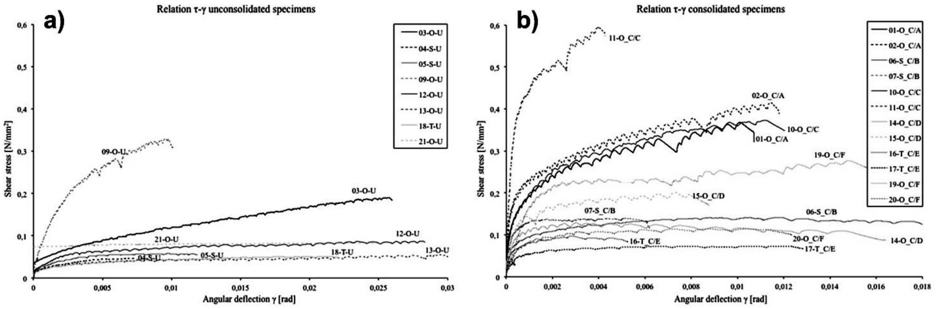

Fig. 3. – Shear stress/Angular deflection diagrams for original (a) and injected (b) specimens.

Figure 3 shows the shear stress/angular deflection diagrams of the unconsolidated (a) and injected (b) walls. The difference between tests executed on freestanding specimens and partially confined specimens can be seen in terms of maximum shear strength, whereas this condition did not affect the initial shear modulus G.

Table II lists the diagonal compression tests results. The results are divided in panels with homogeneous masonry, and type of injected grout. For the consolidated walls,

Table II. – *Results on original (U) and injected (C) walls.*

Specimen	% injected voids	τ_s (N/mm^2)	$G_{0-30\%}$ (N/mm^2)	$G_{30-60\%}$ (N/mm^2)
01-O_C/A*	8.9	0.21 (1.6)	561 (11.2)	309 (17.3)
02-O_C/A*	10.3	0.24 (1.8)	831 (16.5)	479 (26.8)
03-O_U*	-	0.13	50	18
04-S_U	-	0.05	45	10
05-S_U	-	0.06	71	14
06-S_C/B	18.2	0.14 (3.0)	909 (20.0)	67 (6.7)
07-S_C/B	10.2	0.14 (3.0)	701 (15.5)	249 (24.8)
09-O_U*	-	0.21	135	80
10-O_C/C*	11.1	0.24 (1.1)	875 (6.5)	191 (2.4)
11-O_C/C*	13.8	0.34 (1.6)	1202 (8.9)	944 (11.9)
12-O_U	-	0.09	40	15
13-O_U	-	0.06	36	4
14-O_C/D	12.4	0.13 (1.8)	630 (16.6)	381 (38.7)
15-O_C/D	12.7	0.20 (2.9)	747 (19.7)	289 (29.3)
16-T_C/E	12.3	0.10 (1.9)	345 (17.7)	159 (25)
17-T_C/E	11.9	0.07 (1.4)	120 (6.2)	78 (12.3)
18-T_U	-	0.05	19	6
19-O_C/F	15.1	0.23 (2.8)	160 (4.6)	183 (-)
20-O_C/F	7.4	0.11 (1.4)	202 (5.7)	83 (-)
21-O_U	-	0.08	35	-
Average U	-	0.10	54	21
Average C	12.0	0.18 (1.8)	607 (11.2)	285 (13.5)

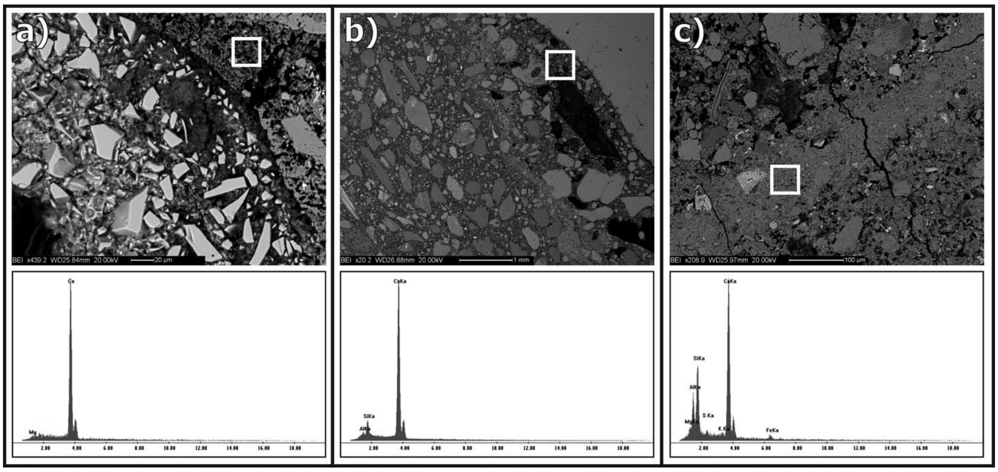

Fig. 4. – SEM-BSE and EDS microanalyses of the grout-original mortar interfaces: a) grout C, microanalysis of the mortar binder; b) grout E, microanalysis of the mortar binder; c) grout A, microanalysis of the grout binder.

table II also lists the percentage of injected voids on the overall wall volume. The values shown in brackets give the ratio of strength or stiffness of the injected to unconsolidated walls. In general, all results confirmed the effectiveness of grout injections on the various masonry walls tested. Shear modulus increase (mean ratio of 13.5) is generally higher than shear strength increase (mean ratio of 11.2), indicating the effect, in terms of internal layer cohesion, given by the grouts.

6. – Characterization of the grout-original mortars interfaces

As regards the SEM-EDS analyses performed at the grout-original mortar interfaces, grouts B, C, F (Group A) show a similar behaviour, filling the macro-porosity of the materials but not saturating the capillary pores. This evidence is confirmed by the carbonate nature of the original mortars at $40\,\mu$m from the interface (fig. 4a). The grouts show a greater degree of hydration at the interface, as highlighted both by the higher HI values and the scarce incidence of unreacted slag grains (fig. 4a). This microstructural evidence is related to the greater availability of water in these portions due both to bleeding phenomena and progressive release of water from the original binder. A localized development of secondary ettringite is also observable at the interface between the materials.

Grout E (Group B) shows a greater diffusion inside the capillary pores of the mortar, as confirmed by the presence of hydrated phases inside the original binder (fig. 4b). The grout is characterized by a uniform degree of hydration, showing reduced influence to phenomena of water accumulation (fig. 4b). The incidence of a reduced sulphate attack is confirmed by the occurrence of sulphur in the binder matrix, indicating the presence of secondary gypsum and ettringite.

Grouts A, D (Group C) show a greater degree of hydration at the interface, as highlighted both by the lower porosity and the scarce incidence of unreacted clinker grains, indicating a significant susceptibility to phenomena of water accumulation. The presence of sulphur in the binder matrix, recognizable by EDS analysis (fig. 4c), indicates the occurrence of primary and secondary sulphates. As regards the rheological behaviour, grouts do not saturate the capillary porosity of the mortars. Moreover, diffuse radial micro-cracks are present in the hardened grouts, related to chemical shrinkage phenomena of the OPC (fig. 4c).

7. – Discussion

The original mortars of the studied historic buildings are all constituted by aerial lime with an inert fraction fully compatible, from a minero-petrographic point of view, with the continental deposits of the Aterno River. They are discernible in three different groups according to binder/aggregate ratio, quantity of dispersed clay fraction in the binder matrix and compositional and granulometric characteristics of the inert fraction. The high quantity of clay minerals in group-1 mortars, associated with an enrichment in fine aggregates, leads to hypothesize a voluntary addition of soil fraction during the manufacturing of these materials in order to reduce production costs, with a consequent qualitative deficit of the mortars. As regards the restoration grouts, they have been divided in three groups according to minero-petrographic characteristics: group A constituted by grouts made with lime, blast-furnace slag and carbonate filler, group B constituted by a hydraulic lime-based grout with natural pozzolan as hydraulic agent and predominant siliceous filler, group C constituted by ternary grouts with predominant carbonate filler.

Considering the minero-petrographic characteristics of the original mortars, group A grouts can be considered the most compatible ones. Group B grout can be considered particularly compatible with group 2 mortars, for similarities in the aggregate typology, and it also shows a range of mechanical properties that are the most compatible, in general, with typical values found for historical mortars and walls. Conversely, it is fundamental to evaluate the long-term resistance of group C grouts, due to possible susceptibilities to chemical attack and incompatibilities with the original mortars related to the presence of cement in the mixtures. These considerations are reflected in the SEM-EDS analyses performed at the grout-original mortar interface, which show the best behaviour, in terms of diffusion inside the capillary pores of mortar and uniform degree of hydration, in the case of group B grout, and an intermediate behaviour, with saturation of macro-pores only and varying degree of hydration, in the case of group A grouts. Localized development of secondary ettringite (groups A and B), and gypsum (group B), is observable at the interface between the materials, hence a further evaluation of the long-term resistance of these materials is also necessary. Nevertheless, group C grouts have the worst behaviour, with a greater degree of hydration at the interface, non-saturation of the capillary porosity of the mortars, diffuse radial micro-cracks due to shrinkage, and occurrence of primary and secondary sulphates.

Under the mechanical point of view, the intervention of grout injection has generally proved to be effective. Despite the volume of filled voids ranges between 7% and 18%, and in average is 12%, the shear strength of the consolidate walls is between 135% and 300% that of the unconsolidated walls, and in average is about 180%. Furthermore, the lowest strength ratio increase (135%) corresponds to the specimens (9-10-11) that had the highest initial (in unconsolidated conditions) strength, with a value ($0.21\,\mathrm{N/mm^2}$) similar to those of the other specimens after grout injection. The increase of shear modulus after the injection is even higher than the increase of shear strength. The ratio of shear modulus of the injected to unconsolidated walls is between 5.15 and 18.15, with a mean ratio of 13.5. The lowest values, in this case, are again found on the specimens (9-10-11) that had the highest initial (in unconsolidated conditions) stiffness (value of $135\,\mathrm{N/mm^2}$), and on those specimens (20-21), grouted with admixture F, on which the interventions were executed at low temperature, compromising, at least in part, the grout curing process.

Finally, if three groups of specimens are taken into account, having similar mechanical properties in the original, unconsolidated conditions (specimens 4-5-6-7 in Sant'Eusanio Forconese, with average shear strength of $0.055\,\mathrm{N/mm^2}$ and shear modulus of $58\,\mathrm{N/mm^2}$; specimens 12-13-14-15 in Onna, with average shear strength of $0.075\,\mathrm{N/mm^2}$ and shear modulus of $38\,\mathrm{N/mm^2}$; specimens 16-17-18 in Tempera, with average shear strength of $0.05\,\mathrm{N/mm^2}$ and shear modulus of $19\,\mathrm{N/mm^2}$), and which were strengthened using, respectively, grout B (group A), D (group C), and E (group B), two main conclusions can be drawn. First, grouts B and D have similar, and rather high, compressive strength and elastic modulus, but grout B is based on air lime and a hydraulic agent, whereas D is a ternary grout. The effect in terms of strengthening is good for both grouts (shear modulus ratio around 18 in both cases) and even better in the case of grout B (strength ratio of 3 for grout B, and 2.35 for grout D). Of course, the chemical compatibility and the interfacial behaviour is much better in the case of grout B. Second, by comparing the effectiveness of a high strength (around $31\,\mathrm{N/mm^2}$) and high stiffness (elastic modulus of $10650\,\mathrm{N/mm^2}$) ternary grout (D), with that of a low mechanical properties (compressive strength around $5\,\mathrm{N/mm^2}$ and elastic modulus of $5650\,\mathrm{N/mm^2}$) hydraulic lime grout, it is possible to see that the strong difference of mechanical properties is not reflected in the final increase of shear strength (ratio respectively of 2.35 and 1.65) and shear modulus (ratio, respectively, of 18.15 and 11.95) obtained in the consolidated walls.

8. – Conclusions

The multi-analytical approach adopted on the selected masonry walls in the Abruzzo region led to a good degree of knowledge on the original mortars of the investigated historical structures, on the chosen restoration grouts, on their interaction under a microstructural point of view, and also on the effectiveness, at the structural element scale, of the grout injection intervention for retrofitting and strengthening multi-leaf, irregular, stone masonry walls. The analytical campaign evidenced the importance of an accurate choice of the proper restoration products for this type of intervention, paying particular attention to the type of binder utilized for the formulation of the grouts. A general suggestion clearly emerging from the study is to reject standard ternary, cementitious and polimeric grouts, due to possible incompatibilities with the original binders and greater subjection to chemical-physical alteration phenomena, preferring lime-based, hydraulic lime-based and pozzolanic grouts, which cause an improvement of the mechanical properties of the restored walls comparable to the one of standard high strength grouts, being at the same time fully compatible from a chemical-physical point of view with the historic materials. The test results are still being processed to better investigate the correlation between information obtained at different levels, from the micro- to the macro-scale. Nevertheless, not only did the experimental campaign described in this paper allow the evaluation of the effectiveness of the grout injection intervention, but also it can be considered a possible comprehensive procedure for future applications.

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