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MEASUREMENT OF GROUT INJECTION EFFICACY FOR STONE MASONRY WALLS

D. Laefer[1], G. Baronio[2], A. Anzani[2], L. Binda[2]

1. ABSTRACT

For nearly a century, cementitious materials have regularly been injected into masonry structures in attempts to rehabilitate and retrofit them. Typical subjects for this treatment are multiple-leaf, stone walls characterized by poor bonding between external and internal leaves, presence of voids, lack of adhesion between the mortar and the stones, poor cohesion of mortar in the joints and in the rubble infill, possible presence of dry walls in the load bearing system. Unfortunately, most of this has been done without the ability to measure the success of the intervention. Though important progress has been made for establishing potential grout flow through extremely fine material, little is known on the efficacy of treatment in heterogeneous stone walls.

The experimental work presented in this paper provides a contribution in establishing a laboratory correlation between visual verification and ultimate resistance, through the assessment of a material groutability and the determination of compressive strength.

2. KEYWORDS

Stone walls, grouting, injectability, adhesion, compressive strength, efficacy control.

3. INTRODUCTION

After the earthquakes which in recent years affected Italy and other countries, repair and retrofitting of masonry buildings have been extensively performed by grout injection, which for years have been regarded as a suitable technique to restore the homogeneity, uniformity of strength and continuity of masonry walls.
In most situations, the repair has been unfortunately carried out without controlling the efficacy of the intervention which often resulted into an unsuccessful operation.

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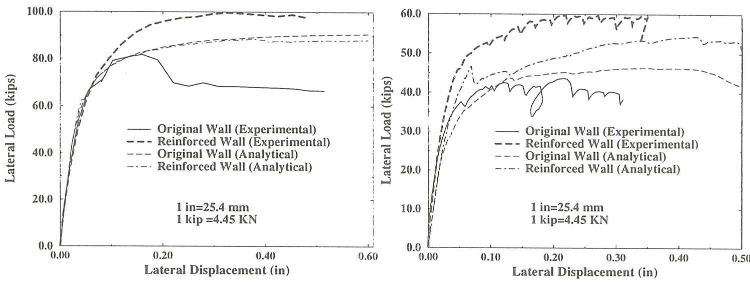
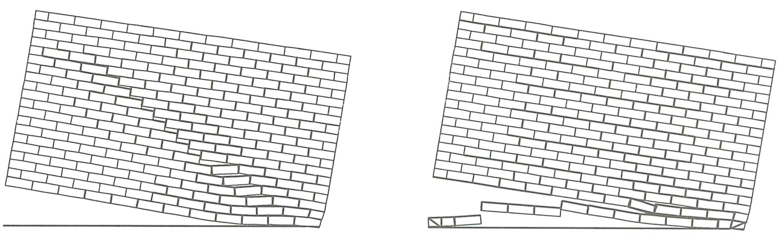
1 Dept. of Civil Engineering, University of Illinois, Urbana-Champaign., USA
2 Dept. of Structural Engineering, Politecnico di Milano, Piazza L. da Vinci 32, 20133 Milano, ITALY. Phone: +39-2-23994208



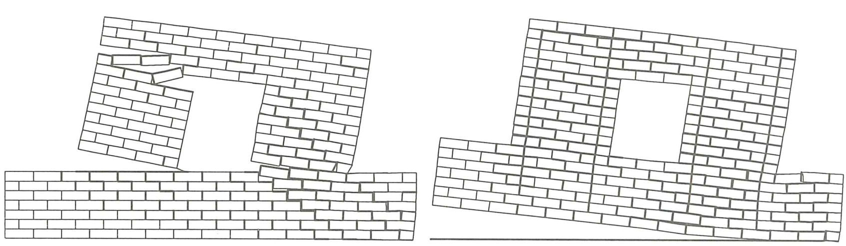
(a) (b)

Figure 8: Comparison of Numerical and Experimental Results: a) Wall #3; b) Wall #4



(a) (b)

Figure 9: Numerical Results on Failure Modes of Wall #3: a) Original Wall; b) Reinforced Wall



(a) (b)

Figure 10: Numerical Results on Failure Modes of Wall #4: a) Original Wall; b) Reinforced Wall

The main problems connected with grout injection of stone walls with cementitious material are: i) the lack of knowledge on the size and distribution of voids in the wall; ii) the difficulty of the grout to penetrate into cracks of thickness less than about two or three millimeters, given the grain size of the cement particles; iii) the presence, in the same wall, of fine and large size voids which makes it difficult choosing the most suitable grain size of the grout: injecting large voids with a fine grained mix can in fact induce grout segregation; iv) the segregation and shrinkage of the grout due to the high rate of absorption of the material to be treated; v) the difficulty of grout penetration of silty and clayey material which may be frequently present within the internal part of multiple leaf walls; vi) the need for sufficiently low injection pressure to avoid either air trapping within the cracks and fine voids or even wall disruption. Therefore the success of a repair by grout injection depends to a great extent on the injectability of the mix used, but also on its mechanical properties and on the injection technique adopted.

As far as the injectability of the grout is concerned, it is influenced not only by its intrinsic properties, but also by its compatibility with the masonry to be repaired.

The present research is part of a systematic work already started some years ago at the Department of Structural Engineering of Politecnico di Milano and consists of a study of the injectability of stone masonry walls constituting some villages in southern Italy, one of which (Sassi di Matera) is considered part of the historic heritage and is protected by the UN. The research is based on a preliminary in situ survey of the architectural features of the villages and of the construction technique adopted, to detect the geometry of the stone walls and their internal section; a laboratory investigation is then described to study the injectability of the internal part of the multiple leaf walls previously analyzed, considering two different cement based grouts.

4. STATE OF THE ART

A vast debate has been taking place in Europe on the best approach for strengthening historical buildings, with particular attention to grout injection and its effectiveness. The first systematic experimental research on the effect of grout injection on masonry prisms was presented by D. Van Gemert in 1983; decayed masonry prisms were injected and the strength increase was measured.

An experimental programme [1986] supported by EEC was developed by L. Binda and G. Baronio in collaboration with the Laboratoire Central des Ponts et Chaussées (LCPC) in Paris and the Politechnic of Athens. Different kinds of grouts (epoxy resins, polymeric grouts, cementitious and hydraulic grouts) were injected into brick masonry prisms previously cracked under compressive tests and the penetration and diffusion of the grouts was studied, together with the different crack patterns of the tested prisms.

At Politecnico di Milano L. Binda and G. Baronio have been carrying out for many years an experimental investigation on grout injection both of brickwork masonry [1, 2, 3] and of stonework masonry [5].

K. Van Balen and D. Van Gemert [10] presented a research on the long-term creep of resin grouted stone masonry and elaborate an extrapolation from the measured creep behaviour according to the relationship proposed by Bazant.

A. Miltiadou [7] presented a PhD Thesis at the École Nationale des Ponts et Chaussées in Paris on the hydraulic grout injection of brick and stone masonry, giving a contribution both from the experimental point of view and from the numerical one. F. Zarri [12] proposed an experimental work on the mechanical behaviour of single-leaf brick panels injected with cement mortar and subjected to various combinations of vertical and horizontal loads.

An International Workshop on "Effectiveness of Injection Techniques for Retrofitting of Stone and Brick Masonry Walls in Seismic Areas" was organized on 1992 by L. Binda and supported by CNR-GNDT on the injection technique. This was probably the first contact between researchers active in the study of the effectiveness of injection technique in the repair of masonry structures: M. Tomazevicz , J. Noland, R.H. Atkinson, M. Schuller, A.M. Paillère, V. Apih, L. Binda, G. Baronio, C. Modena were among the participants.

F. Van Rickstal and D. Van Gemert [11] present an investigation on the injection of brick masonry with cement grout and describe the experimental assessment of the permeability of the wall to be injected and of the stability of the grout.

5. IN SITU SURVEY

Deciding to repair a masonry building and designing a correct intervention is possible provided a careful diagnosis and a complete structural analysis of the construction is previously performed. In the case of stonework structures, the determination of the load carrying capacity under dead and live loads is particularly complex. On the one hand, the physical-mechanical characterization of stones and mortars is very complicated due to the difficulty of obtaining representative samples which often hinder the achievement of significant results. On the other hand strength and deformability parameters (Young modulus, Poisson ratio) of the components, which indeed can complete the mechanical characterization of the materials, can very hardly be used to extrapolate the strength of the masonry as a whole [5].

The attempt to build representative physical models of stone-walls turns out to be a very hard task too, due to the great non-homogeneity of the structures themselves and to the difficulty of reproducing the mortar characteristics. Small-scale models were successfully used for instance to study the overall behaviour of the structure and check the efficacy of grouting and tying of stone masonry walls [8].

For all these reasons the structural diagnosis of stonework masonry buildings tends to be preferably carried out through direct in-situ measurement of the mechanical characteristics of the masonry, either through mechanical testing of full scale masonry panels or, when this is not possible, through flat jack tests. Flat jack can also be adopted after the intervention so to check its efficacy. In the case of grout injection the problem of the injectability also rises, therefore the preliminary analyses of the building should include physical and chemical characterization of the walls: the scheme in fig. 1 summarizes a procedure, which has been set up at the Department of Structural Engineering of Politecnico di Milano in order to assess the injectability of a masonry wall and to check the efficacy of the intervention.

An extensive in situ survey has been conducted in Basilicata (south of Italy) at the villages of Sassi di Matera and of Montescaglioso, where the architecture is mainly characterized by one or two storey living houses, of similar geometry. The horizontal load bearing elements are preferably made by stone vaults as shown in fig. 2.

The construction technique is quite simple being the masonry a three leaf stonework structure, on average 600 - 1200 mm thick, with external wythes regularly built with cut stones and the internal part made of rubble, poorly bound with calcareous lime mortar.

Horizontal connections between the layers are provided by the presence of transversal stone blocks (*diatoni*) two of which are laid every square meters of the wall. The internal section of the walls has been analyzed through a graphical and photographic procedure, fully described by Binda et al. [5], which allowed to determine the percentage area of stones, voids and mortar referred to the surface area analyzed.

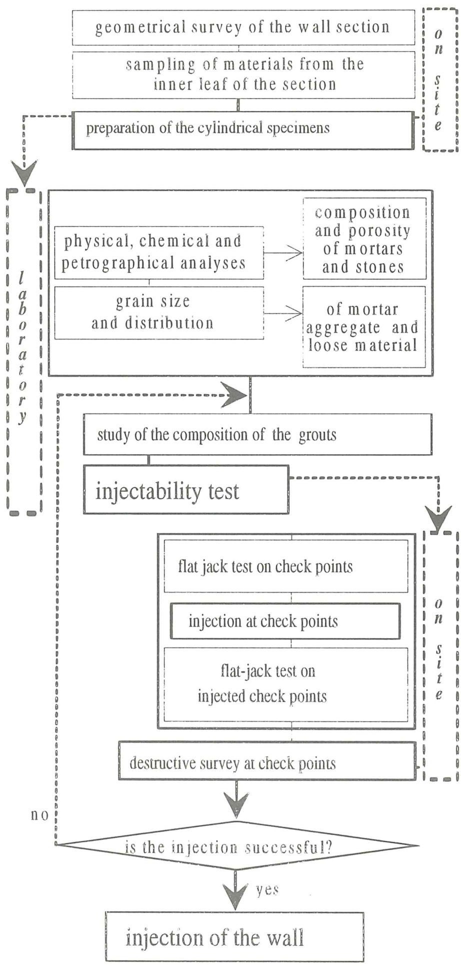


Fig. 1 - Procedure for the evaluation of the efficacy of grouting.

6. MATERIAL CHARACTERIZATION

Materials coming from the internal part of the stone masonry have been sampled in order to evaluate their injectability with two different cement based grouts. Physical, and chemical characterization of the materials sampled has been first performed.

Petrographic analysis of the stone constituting the buildings and of the incoherent material has been carried out. In particular thin sections of the stone, sampled from the quarry of Montescaglioso (MT), was analyzed with the polarized light microscope: it turned out to be a very porous rock, made almost completely by organic carbonatic parts of different nature (micro-fossil fragments and integer macro-fossils) bound with a fine grained calcitic cement.Rare aggregates of limpid calcite grains are also present. It is an organogenic calcarenite, of the Upper Pliocene (Geol. Map F.201 - Mt).

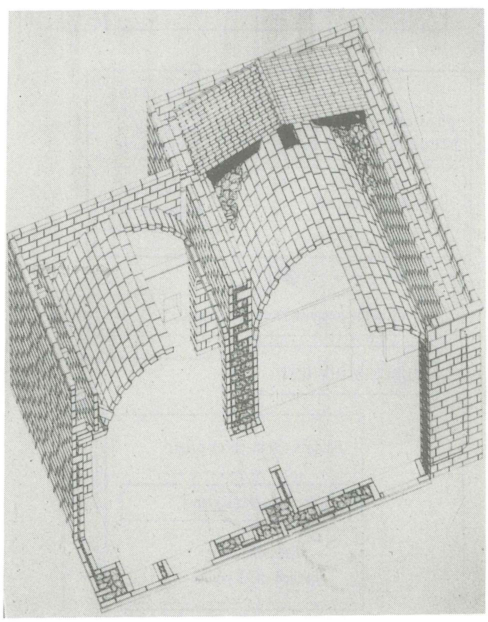


Fig. 2 - Montescaglioso (MT), single storey house (*casa terranea*) in Gravina calcarenite, axonometric view [6].

Chemical analyses on the stone, the mortar and the loose material were also performed which substantially confirmed the petrographic results, whereas in the case of the mortar showed the presence of a great percentage of calcareous fractions.

The absorption coefficient of the stone was also detected which equals 20.09 %.

7. TESTS FOR INJECTABILITY ASSESSMENT

Preparation and injection of the cylinders

Using the material sampled at Montescaglioso (denominated MTSO) and at Sassi di Matera (denominated MT), cylinders have been prepared into plexiglas molds of diameter 120 mm and height 240 mm in order to reproduce in the laboratory the internal part of the walls constituting the *casa terranea*. Care was paid in order to maintain the same percentage of stones, mortar and voids observed previously.
Two different grouts have been used. The first one (denominated Microlite) is a special microfine cement of pozzolanic nature, the second one (denominated Fen-X) is an hydrated lime with additives. Their chemical composition is reported by Binda et al. [5]. The grain size distribution, determined by the producer by a laser granulometer, is shown in fig. 3 and goes for the two mixes from 0.9 to 20 μm, whereas Fen-X shows a larger average particle diameter.

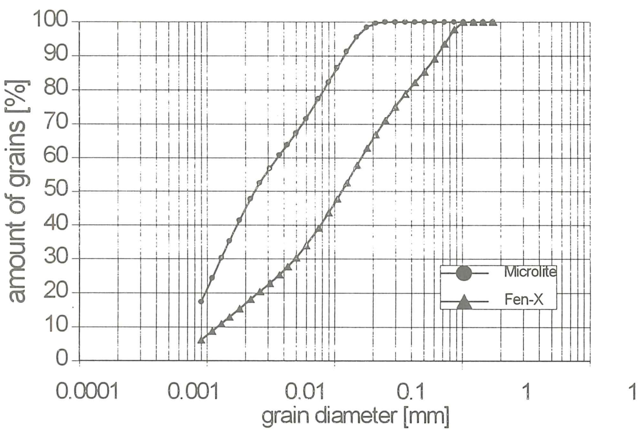


Fig. 3 - Grain size distribution of the grouts used.

From the chemical point of view both grouts turned out to be compatible with the materials of the stone masonry. A pozzolanicy test was also carried out according to the Italian Code of Acceptance and Testing of Cement which gave positive results for both grouts.

The samples have been injected, in controlled conditions of 20°C and 75% RH, using an injector and a pipe connected with a hole at the base of the plexiglas cylinders so to prevent any pressure loss.

Nine cylinders were injected with the Microlite, four with the Fen-X. The water-cement ratio (w/c) adopted and the conditions of the support (wet or dry) are indicated in tab. 1.

Table 1

cylinder	grout	support	w/c	pressure [atm]	σ_f [MPa]
MT1a	Microlite	dry	1.5	0.1	0.676
MT1b	Microlite	dry	1.5	by gravity	0.35
MT1c	Microlite	dry	1.75	0.1	cut
MT2a	Microlite	wet	1.5	0.1	0.65
MT2b	Microlite	wet	1	0.1	0.462
MT6a	Microlite	wet	1.75	0.1 - 0.2	cut
MT6b	Microlite	wet	1	0.4	0.578
MTSO1	Microlite	wet	1	1.02	1.201
MTSO2	Microlite	wet	1	0.9	1.104
MT1d	Fen-X	wet	1.25	0.1	0.44
MT2c	Fen-X	wet	1	0.4	0.236
MT2d	Fen-X	wet	1.25	0.1	cut
MT1e	Fen-X	wet	1.25	0.1	cut

A pressure of 0.1 to 1.02 atm was adopted apart from the case of cylinder MT1b and MT2c when the grout was injected from top by gravity. The upper part of the specimens was kept open during the injection in order for the air to escape. At the end of the operation the specimens have been completely filled adding some grout from top. The samples were cured for 28 days at the same conditions of 20^{o}C and 75% RH.

Some problems rose during the injection procedure, namely the shrinkage of the mix and a segregation especially in the case of the Fen-X. Furthermore there was a common impossibility for the mix to penetrate the incoherent material present in the cylinders, confirming the considerations made by Binda et al. [4].

Visual inspection and compression test of the injected cylinders

Two cylinders injected with each grout were cut vertically to inspect the degree of penetration reached by the mix. In the case of the Microlite a good adhesion between the grout and the stones was observed as shown in fig. 4, both on wet and dry support, whereas a lack of penetration of the fine incoherent material present in the bottom part of the cylinder was noticed.

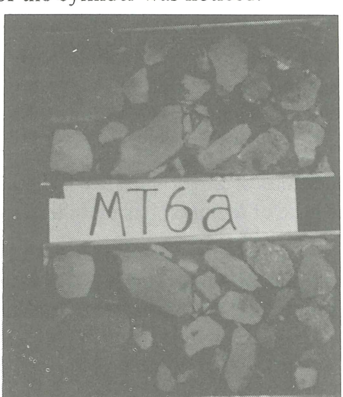


Fig. 4 - MT6a cylinder cut after injection.

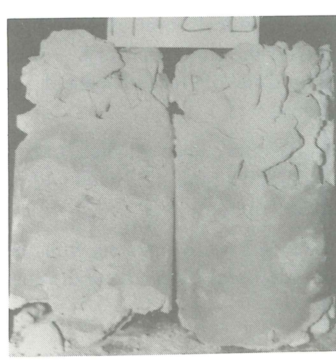


Fig. 5 - MT2d cylinder cut after injection.

In the case of the Fen-X a good adhesion was still observed toward the stones but the same problem of lack of penetration of the fine loose material was noticed, together with a shrinkage effect due to the excessive fluidity of the grout (fig. 5). This phenomenon could be detected immediately after completion of the injection, when bleeding clearly appeared at the surface of the cylinder; small air bubbles within the mix mass were also observed after cutting the cylinders probably due to the presence of the mix additives.

The samples were prepared for the mechanical test in the following manner. A grout top was made using the same material with which the sample was injected. After curing, the plexiglas base of the cylinders was cut off, and a cap was cast on that end too. All caps were permitted to cure for a minimum of 7 days prior to testing. Despite the liquid nature of the cap material and the large quantity of non-consolidated fines at the cylinder's base, little grout intrusion was found to have occurred in the sample material. This was confirmed during specimen dissection after mechanical failure was achieved. The samples could not be tested without the plexiglas cylinders due to the quantity of loose material remaining in the sample, particularly at the lower portion. To reduce the influence of the resistance and the stiffness of the cylinder on the test response, the tests were done cutting through the plexiglas cylinder completely at two points, keeping the cylinder together during testing with weak rubber bands.

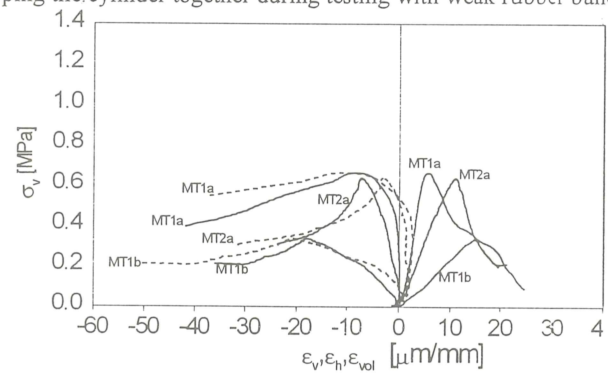


Fig. 6 - Cylinders treated with Microlite at w/c = 1.5; dashed lines correspond to ε_{vol}.

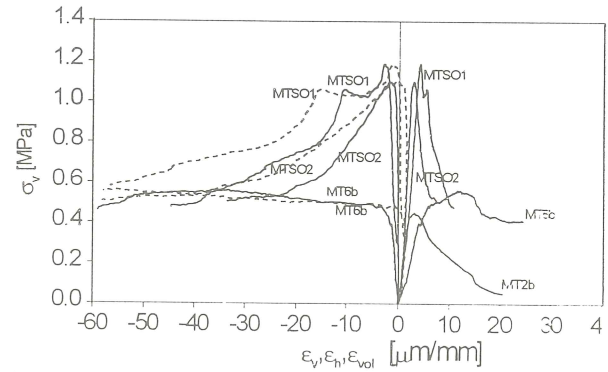


Fig. 7 - Cylinders treated with Microlite at w/c = 1; dashed lines correspond to ε_{vol}.

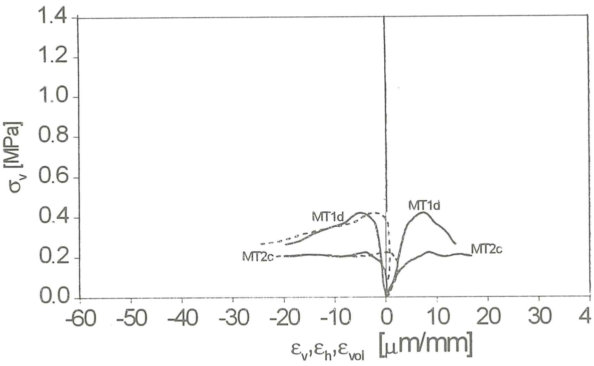


Fig. 8 - Cylinders treated with Fen-X: MT1d at w/c = 1.25; MT2c at w/c = 1; dashed lines correspond to ε_{vol}.

The tests were performed under displacement control, measuring also the horizontal displacement at two points. In all cases stress-strain curves have shown a clear peak, with a subsequent softening phase (figs. 6 - 8). From the observation of the curves the influence of various factors looks evident, although more results would be necessary in order for our considerations to be statistically valid. First of all it appears that the cylinders treated with Microlite gave higher peak stress than those treated with Fen-X.

Considering the cylinders treated with Microlite only, though the cylinders denominated MT were made with the same stones as the other cylinders MTSO, it has to be said that in the first case the stones were sampled more superficially from the walls. Therefore they were much more altered, particularly on the surface where a dust layer was present. This can justify the lower strength performed by the MT samples compared with the MTSO ones at the same w/c, due to the poorer adhesion between the stones and the mix induced by the superficial dust. In this case failure took place mainly by detachment of the grout from the stones (fig. 9), whereas in the case of the other samples failure mainly occurred by fracture which crossed vertically the cylinder and passed through the stones (figs. 11 and 12). The size of the stone blocks also influenced the failure mechanism very much: considering now the two MTSO cylinders it looks that MTSO1, which reached a slightly higher strength, also had larger stone blocks than the MTSO2 (compare figs. 11 and 12), which in fact was also characterized by a certain degree of detachment between grout and aggregate (fig. 10). So the surface aspect and the grain size both influence the crack pattern at failure.

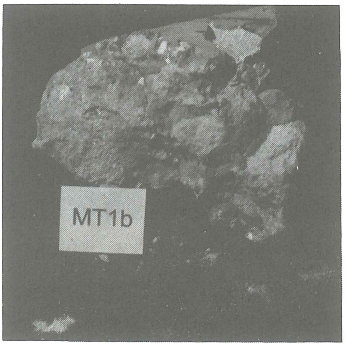


Fig. 9 - MT1b sample after failure.

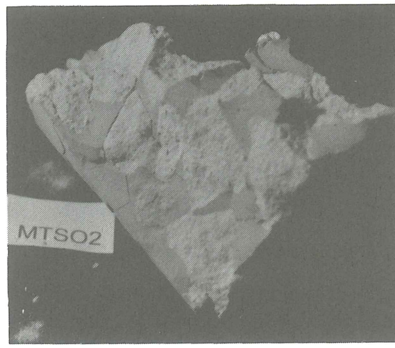


Fig. 10 - MTSO2 sample after failure

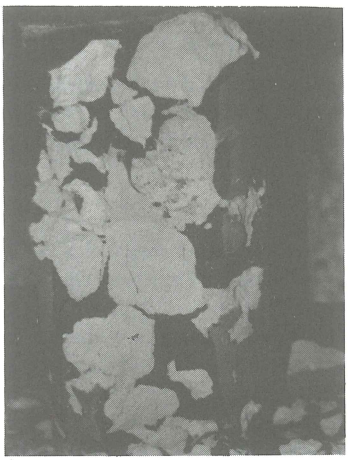


Fig. 11 - MTSO1 sample after failure.

Fig. 12 - MTSO2 sample after failure

As far as the w/c ratio is concerned, its influence does not appear very clearly for the cylinders injected with Microlite because of other factors which covered this effect. Samples MT6b and MT2b with a w/c = 1, for instance, showed a lower strength than those with w/c = 1.5 simply because local effects played a role: in fact in both cases a great amount of fine loose material accumulated at the bottom during the preparation, and this remained non-penetrated by the grout, so lowering the overall strength. This effect was evident from the failure mechanism of the cylinders which after failure showed a *clepsydra* shape at the bottom, where the loose material was concentrated (fig. 13) which was not permeated by the grout.
Considering the cylinders treated with Microlite at w/c = 1.5, the sample which gave a lower strength than the other two is MT1b, which in fact showed a detachment phenomenon between grout and stones, as already shown in fig. 9.

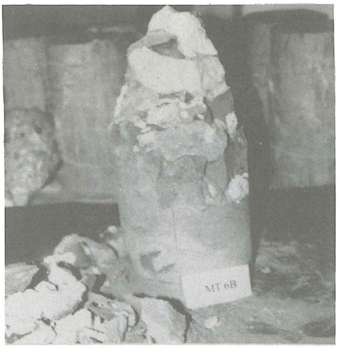


Fig. 13 - MT6b sample after failure. Fig. 14 - MTc sample after failure

Finally, taking into account the cylinders treated with Fen-X only, their lower strength compared with the Microlite specimen is mainly due to a segregation problem which was seen already during the injection phase and to the presence of large air bubbles in the mix mass, bigger than those presented by Microlite and probably due to the mix additives. The failure took place in this case by a global disgregation of the samples (fig. 14), more than by crack propagation as in the previous cases.

Finally, the mechanical tests carried out so far are not enough to draw conclusions on the effect of the support conditions (wet or dry). The two cylinders tested dry at a w/c = 1.5 gave in fact very different compressive strength because of the intervention of other factors, but this has been already commented just above.

Physical assessment of the effectiveness of injection

Some cylinders have been recently prepared, but not yet tested mechanically, on which physical procedures to assess the effectiveness of injection have been applied.
In order to estimate the percentage of voids actually filled by the grout, the volume of voids before injection and the volume of the injected grout is going to be measured. Whereas the first amount has been measured by water immersion of the material contained in the cylinder, after determining the dry weight of the specimen, the second one can be obtained by difference of the dry weight of the untreated sample from the dry weight of the injected cylinder (after curing), known the grout density. Results of this study will be further presented.
The time taken to completely fill the specimens has been recorded on four cylinders injected with Fen-X. In particular, two of them had a wet support and were treated with a grout at w/c = 1.25; the other two, one of which had a wet support, were treated with a grout at w/ = 1. In the case of wet supports the time of injection was basically comprised into a small interval for the three cylinders, regardless to the w/c ratio, whereas in the case of dry specimen it took about a time double than in the other cases to completely inject the sample (fig. 15). Therefore a wet support is probably a better condition for the injection to be successful, since the longer the time of injection the higher the possibility for the grout to loose fluidity. In further work the viscosity of the grout is going to be measured in order to study this problem in more detail.

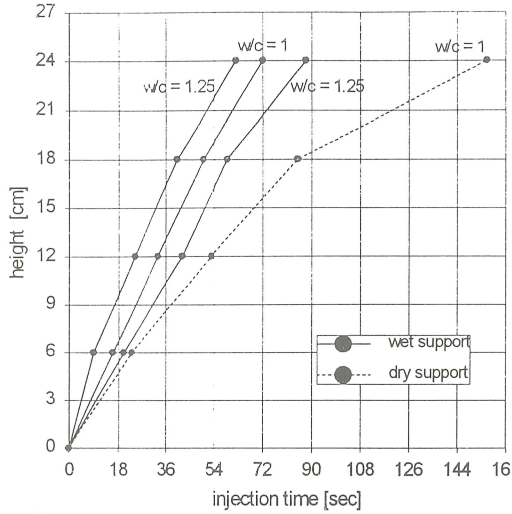


Fig. 15 - Injection time taken by cylinders treated with Fen-X.

8. CONCLUSIONS

A procedure has been proposed for the assessment of the injectability of stonework masonry and of the efficacy of the intervention. An extensive investigation of the stonework walls of ancient villages in southern Italy has been presented in order to study their injectability with cement based grouts. Though the mechanical results obtained so far are not so numerous to be statistically relevant, they allowed to notice many factors which play an important role on grout efficacy: i) the surface condition of the stone blocks to be injected very much influences the adhesion between the wall and the mix, with the presence of dust (which very often can be present within a multiple-leaf wall) hindering a good result; ii) the fine loose material which can occupy big portions of the internal wall section can very hardly be permeated by the grout; iii) segregation processes, which depend on the grout characteristics and can be influenced by its w/c ratio and by the water absorption of the support, result into a bad penetration of the mix and into a lower strength of the treated material; iv) the support conditions can very much influence the injection time and therefore the success of the grouting.

Further research will be carried out in order to better analyze the reciprocal effects of the factors above mentioned and particularly i) the influence of the support conditions; ii) the capacity of the grout to fill the voids; iii) the relationship between the experimental results obtained on small scale cylinders and on big-scale stone walls.

9. ACKNOWLEDGMENTS

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