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EXPERIMENTAL TESTS OF SCHIST MASONRY WALLS STRENGTHENED WITH GROUTS

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ABSTRACT

Grouting is a well-known technique for conservation and strengthening of historic masonry buildings which can be durable and mechanically efficient, whilst preserving the historic value. The selection of a grout for repair is based on the physical and chemical properties of the existing masonry. Compatibility between the existing and the injection material is a major factor in the success of the intervention. The effect of ternary grouts and hydraulic lime-based grouts on the compressive and shear strength of three-leaf stone masonry has been widely investigated. However, few studies have been done on walls with one or two leafs.
Subsequently, in the present research an experimental campaign addressing the behaviour of masonry walls of schist stone with one or two leafs, when subject to injection grouting, was performed. The analysis of the mechanical behaviour of masonry walls of schist, very common in old buildings in the northeast or Portugal and also in the north of Spain, was carried out based on experimental results of uniaxial compression tests. The influence of strengthening by injection grouting was analysed considering two types of grouts (one commercially available and another prescribed). A comparative mechanical analysis was performed between the walls tested and also the bond strength capacity was tested between the grouts and schist. The interior of walls were inspected, after dismantling, in order to check the amount of voids filled after the intervention. The results obtained showed that these strengthening techniques were successful in increasing the compressive strength of the walls and in improving their behaviour under compressive loads.

KEYWORDS: Schist Masonry, Grouts, Injection, Walls.

1. INTRODUCTION

The use of stone masonry is very common in many historic constructions, both architectural monuments and whole urban and rural centers, especially in Europe, many of which generally made of various and very poor materials namely different type of stones (granite, schist or limestone) and low strength lime mortars, arranged in irregular morphologies [1]. The common typology construction encountered is the multi-leaf masonry wall, which is characterized by a large presence of voids and very sensitive to brittle collapse. Schist constructions, in particularly, are an important cultural, architectural and historical legacy in northeastern of Portugal and also in cross-border zone with Spain, whose preservation is of importance, see Figure 1. Schist masonry typically has two types of constructions: with mortar joints, usually with mixtures based on clay or lime; or with dry joints, normally used in encircling walls, mills and shelters.

Figure 1: Buildings with schist masonry walls

Similar to other stone masonry constructions, schist masonry buildings suffer damage due to their weak tensile strength. Therefore, they frequently need stabilization, repair or strengthening. Cement and lime-based grouting is a well-known intervention technique, which can be durable and mechanically efficient whilst preserving the historical nature of the structure to a reasonable extent. One of the doubts of this technique is what kind of grout must be injected. Despite the fact that several formulations have been proposed by different researchers, a extensive experimental study on the mechanical and rheological behaviour of dozens of grouts has been done at University of Minho, during the pass few years [2-5]. The experimental campaign consisted in determinate the different properties of the grouts (both commercial available and laboratory formulations) in terms of fluidity, shrinkage, bleeding, compressive and flexural strength and its behaviour with different stones, in terms of injectability and bond strength. However, despite all these studies, it would be ideal to test all compositions in real walls or prototypes, which would give us insight into the effectiveness of the injection technique. But doing these analysis in all of the studied grouts is almost impossible. Thus, the aim of the presented research is to characterize the effectiveness of injection technique of two of those previous study grouts in schist masonry walls, with a building typology of one or two leafs with the aim to increase the mechanical strength of the walls and improve their deformability. Four walls were subsequently injected with two types of lime-based grout. One of the chosen grouts was a ready-mix commercially available grout (*Mape-Antique I of Mapei*), which was studied with other commercial grouts in [2]. The second grout adopted was a composition formulated in the laboratory [3] with similar results compared to the commercial grout.

2. EXPERIMENTAL PROGRAM

The experimental research presented in this paper involved the construction, injection and testing of three sets of schist masonry walls injected with two different grouts.

2.1. Walls

The schist used for the construction of the walls came from *Vila Nova de Foz Côa*, a village in the north of Portugal. These stones break easily along their foliation planes [6], when applying a stroke with a hammer and, if necessary, with a pointer and a chisel. Then, the pieces are cut according to the required shape for the wall construction, resulting in irregularly shaped stone pieces. A detailed description of these materials can be found in Barros [7].

The mortar used in the construction of the walls was compound by a fine grain sand from a local supplier, hydrated lime CL90-S, from *Lusica*l and the natural hydraulic lime NHL5 of *Cimpor* company. The binder/sand proportion adopted was 1:2, while a water binder ratio of 0.4 (all ratios in weight). The choice of materials used was based on studies conducted by Rodrigues [8] and the mechanical properties of the mortar is described in Luso [9].

The six walls in schist masonry (*P1*, *P2*, *P3*, *P4*, *P5* and *P6*) were built in the Structures Laboratory of the University of Minho in Portugal by the same experienced team of masons. The most common schist masonry typology (two leaves) was reproduced using traditional building techniques. The number of specimens was limited due to the size of the walls and due the space available in the laboratory for the storage of the walls for the necessary period of curing and testing, so only two replicas were built for each specimen type. The walls remained in place after construction for ten weeks curing and then the grouting work began.

Two of walls were not injected (*P4 nI* and *P5 nI*) and the others were previously prepared and injected from the bottom to the top, with the usual technique of injection. Each type of grout was injected into two walls (*P2* and *P6* with *Grout A*, *P1* and *P3* with *Grout B*). Hereafter, the walls are designated as *P2 IA* and *P6 IA* for the walls injected with *Grout A* and finally *P1 IB* and *P3 IB* for the walls injected with *Grout B*. The consumption of the prescribed grout in the injection of the two walls was similar. In the case of the commercially grout, the quantity injected in the two walls was different, due to the typology of the specimen, which led to some dispersion of the results. Additional details on the construction and injection procedure can be found in [9, 10].

2.2. Grouts

Therefore, two grouts were chosen for the injection of the walls: *Grout A* is a hydraulic grout developed by *Mapei* – Italy, for historical masonry (Mape-Antique I); *Grout B* is a hydraulic grout prescribed with 30% of white cement CEM II B/L-32,5R from company *Secil* – Portugal, 30% of hydrated lime type CL90 from *Baptistas* – Portugal, 35% of metakaolin Optipozz-sc, water/binder ratio equal 0.6 and superplasticizer (Dynamon SR1 from Mapei). Table 1 shows some of the main properties obtained for the grouts [2-4].

Table 1 – Main properties of the *Grouts A* and *B*. Coefficients of variation (%) in brackets [2-4]

	Flow Time Cone Marsh 1000mL (seconds)			Bleeding§ (in 100mL graduated cylinders)	Compressive Strength§ at 28 days (MPa)	Flexural Strength§ at 28 days (MPa)	Tensile Bond Strength# at 90 days (MPa)
	t = 0 min	t = 30min	t = 60min				
Grout A	79	105	110	0	21.4 (4.9)	4.1 (2.7)	1.26 (16.6)
Grout B	40	42	45	0	21.5 (15.2)	3.5 (10.8)	0.87 (9.5)

§ Mean result of three tests of 160x40x40 mm^3 specimens
 # Mean result of six tests in yellow granite substrate

The bond mechanism was studied in composite grout/stone specimens, as the shear bond strength of the grout-stone interface is the main property affecting the behaviour of grouted walls [4]. These tests were done with the grouts in yellow granite, limestone and schist, but there was a significant difference in the type of schist used in those tests and the applied in the execution of these masonry walls. Thus, new specimens with *Grout A* and *Grout B* in some of the shale pieces coming directly from the pallet used in the execution of the walls, were prepared. Thus, a total of 24 specimens of *Grout A* and *Grout B* were performed for traction tests at 28 and 90 days of age. The bond mechanism in stone-to-grout interfaces was done using pull-off tests which determined the maximum traction force applied in a circular area of grout applied to the substrate, see Figure 2 (a). The results obtained are summarized in Table 2. Despite being lower than the values found in the case of the support being granite (see Table 1), *Grout A* still presents a higher bond strength than *Grout B*.

Table 2: Test results for schist specimens with *Grout A* and *Grout B*

Grout	Age	Tensile Bond Strength# at 90 days (MPa)	Rupture type
A	28 90	0,80 (35,0) 0,71 (24,8)	Interface/Schist Interface/Schist
B	28 90	0,36 (7,1) 0,51 (12,6)	Interface Interface

The type of rupture found after tests was always by the interface in the *Grout B* and by the interface / schist in *Grout A* since, in general, the specimens showed a slight stone film glued to the grout specimen, see Figure 2 (b and c).

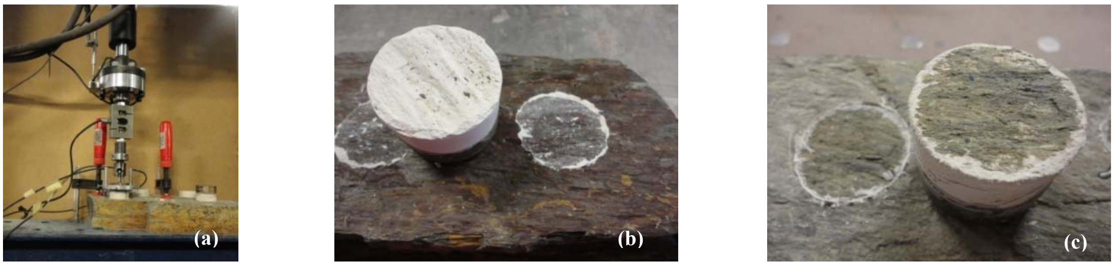


Figure 2: (a) Aspect of tensile test; (b) *Grout B* rupture through interface; (c) *Grout A* rupture through the interface /schist

3. TESTING SETUP AND MEASUREMENTS

In order to investigate the performance of grouting, after 90 days all wall specimens were tested under monotonic compression using a 2MN closed-loop servo-controlled testing machine. The tests were performed under displacement control at a constant rate of 5 μm/s. The deformations of walls were measured using linear variable displacement transducers (lvdt´s), disposed as follows: four lvdt´s (two in *face B* and two in *face D*) were used to measure vertical deformations; four lvdt´s (two per face at two levels) were recording horizontal deformations; more two lvdt´s were installed to measure vertical crack openings, (one in *face A* and one in *face C*) and finally one external lvdt (lvdt, v5) was used to measure the displacement between the plates of the testing machine and to control the tests.

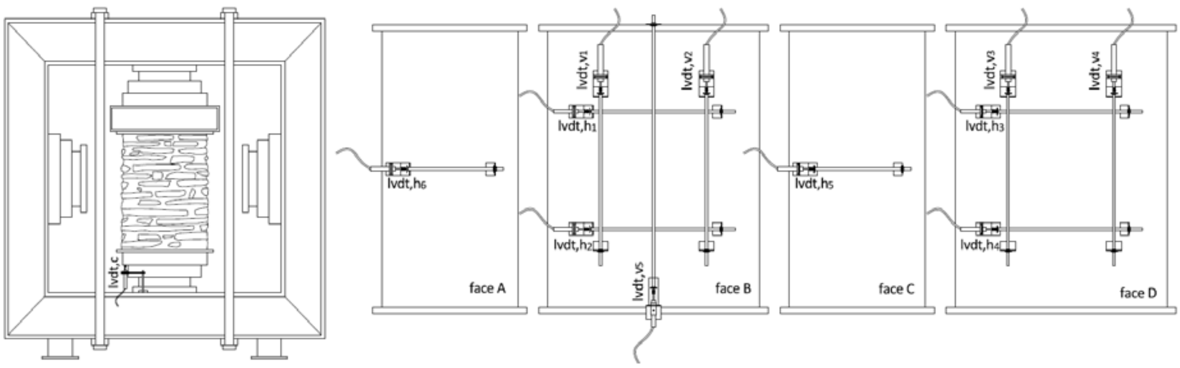


Figure 3: Test setup of the walls: location of the displacement transducers (*faces A, B, C* and D are, respectively, left, front, right and back with respect to first figure)

In the case of the walls strengthened by injection (*P1, P2, P3* and *P6*), the external leaves were carefully dismantled after testing, in order to check the quality of the strengthening procedure. Figure 4 shown some images of the walls subjected to compression as the aspect of wall *P6* during dismantling where is visible the *Grout A* (with blue/grey colour) in the interior of wall filling very well the previous existing voids.

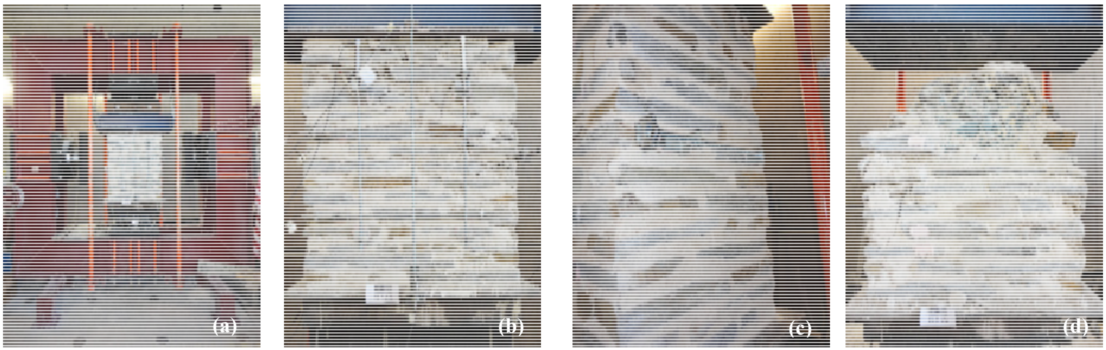


Figure 4: (a) Test setup of the walls: testing machine; (b) Wall *P3* during the test with visible cracks; (c) Position of *lvdt* in lateral; (d) Dismantling of *P6*.

4. RESULTS AND DISCUSSION

The value of the compressive strength of each wall ($f_{c,w}$) was calculated by equation (1) where $f_{c,w}$ is the maximum force reached by the wall and A_w is the average cross-sectional area of the wall.

$$f_{c,w} = \frac{F_{c,w}}{A_w} \tag{1}$$

The average value of compressive strength obtained for unreinforced walls (*P4 nR* and *P5 nR*) is about 1.4 MPa. This is a relatively low strength but in the order of current values in stone masonry walls [11-13] here different constructive typologies are presented.

The modulus of elasticity E_0 was determined by the slope of the straight line resulting from the application of a linear correlation by the “minimum squares method” within the range of 0% to 20% of the resistant stress of each wall of the vertical extension-axial stress curve. The modulus $E_{[30-60]\%}$ was determined in the same way as the previous one, but applying the linear correlation to the range of 30 to 60% of the maximum resistant stress of each wall. As for compressive strength, the average modulus of elasticity obtained in the two unreinforced walls are low. Table 3 summarizes the results of the compressive tests carried out on the walls in terms of compressive strength ($f_{c,w}$), vertical and horizontal strain ($\varepsilon_{v,p}$, $\varepsilon_{h,p}$) at peak load, Young´s modulus computed in the [0%-20%], stress range (E_0) and in the [30%-60%] stress range (E_{30-60}) and Poisson’s ratio in the [30%-60%] stress range (ν_{30-60}).

Table 3: Results obtained in compression tests for all masonry walls

Wall	$f_{c,w}$ (MPa)	$\varepsilon_{v,p}$ (%)	$\varepsilon_{h,p}$ (%)	E_0 (MPa)	$E_{[30-60\%]}$ (MPa)	$\nu_{[30-60\%]}$
P4 nI	1.34	0.80	0.24	513.3	296.9	0.15
P5 nI	1.39	1.17	0.64	467.3	263.0	0.21
P2 IA	4,5	0,56	0,09	4272,0	2500,0	0,01
P6 IA	3,4	1,48	0,42	980,2	533,3	0,13
P1 IB	4,4	1,08	0,48	1978,5	597,0	0,20
P3 IB	4,1	0,68	0,42	2661,1	1053,0	0,10

Following the analysis of the results of each wall, Figure 5**Erro! A origem da referência não foi encontrada.** shows the vertical stress-strain diagrams for the six walls tested, with and without grouting, in order to facilitate comparison.

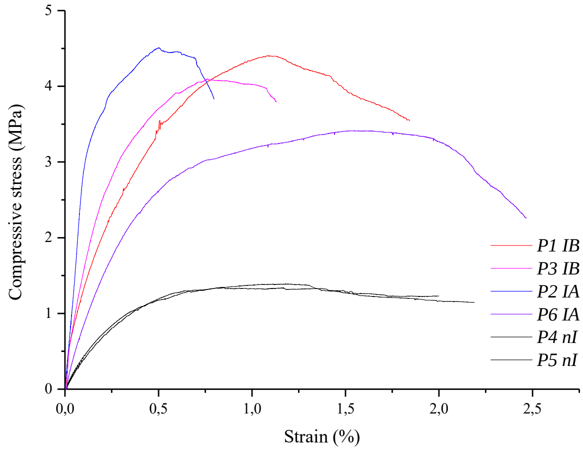
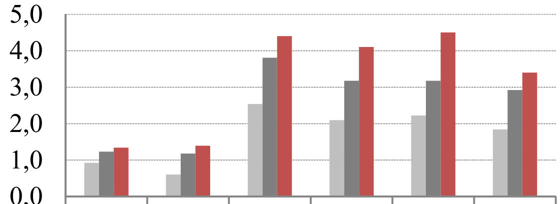


Figure 5: Compressive stress-strain graphs for all tested walls

It is found that the injection has significantly increased the compressive strength of the walls (about three times) and also the stiffness of the walls, about five times. The two grouted walls seem to have performed similarly in terms of strength and initial stiffness. These results seems to be in accuracy comparing with the grouts properties namely the compressive and bond strength.
On basis of systematic testing of cylinders made of filling material and grouted, empirical formulas, based on the results of different researchers, were proven adequate for the prediction of the compressive strength of grouted masonry, however, only on the mechanics of three-leaf masonry [13-16]. A common result is that the injection increases the load capacity and stiffness of the walls. But the direct comparison of the remaining values with those formulas is risky because the procedures and test schemes are different from work to work, with multiple aspects that influence the results obtained. Attempted analytical modelling of two-and-one-leafs masonry using finite element methods with different types of stone and even earth, is an objective to be achieve in future research. So further research is needed towards the development of physical models able to describe the behaviour of typical schist masonry before and after grouting.
Regarding to the present study, the appearance of the first horizontal and vertical cracks, as well as the respective applied load, is given in Figure 6.



	P4 nI	*P5 nI*	*P1 IB*	*P3 IB*	*P2 IA*	*P6 IA*
Stress (MPa) HOR	*0,9*	*0,6*	*2,5*	*2,1*	*2,2*	*1,8*
Stress (MPa) VERT	*1,2*	*1,2*	*3,8*	*3,2*	*3,2*	*2,9*
fc (MPa)	*1,3*	*1,4*	*4,4*	*4,1*	*4,5*	*3,4*

Figure 6: Compressive stress level for which the first crack with horizontal (*Stress HOR*) and vertical (*Stress VERT*) direction appears vs. maximum compressive strength (*fc*)

On average, the first horizontal cracks appear at about 50% of the maximum load, while vertical cracks arise at about 80% of the maximum load. The crack initiation was defined by the *lvdts* and is rather objective, corresponding to a significant increase of measurements.
The appearance of the interior of the injected walls during the dismantling can be seen in Figure 7Figure 7 a) and b). Comparing these results to those of Figure 7 (c) where it is clear the existence of voids in the non-injected specimens, it is possible to check the injected grouts were very well distributed for both grout types, filling the voids of the wall.

Figure 7: Appearance of the interior of the wall after dismantling: (a) *P1*; (b) *P6*; (c) *P4*

It is consensual that grouts to be applied in masonry walls of ancient buildings not only should have good bond to masonry materials such as stone, brick or earth; low or no shrinkage, in order not to create additional stresses, to limit the loss of adhesion between grout and existing material and to reduce moisture penetration through shrinkage cracks and have low segregation and exudation to maintain the volume and consistency, but also they should have high fluidity and injectability, in order to provide a proper flow and to fill both large and small openings and interconnected voids, even using low pressures. Although the results of fluidity and injectabilty for the applied grouts were relatively different [17] it seem acceptable values because no large voids were founded in the wall specimen and the mechanical behaviour is not so different.

5. CONCLUSIONS

This work aimed at contributing for a better knowledge of single leaf walls made of schist stone and a lime based mortar, a structural element that is present in many buildings of the northeast and centre of Portugal, including some villages in the north of Spain. The available information on this type of walls is still very scarce, demanding more investigation.

This work is a first attempt to characterize such walls, analysing in this case, the effect of injection technique in the mechanical behaviour of real walls specimens under compression forces. The results of mechanical and rheological behaviour of the applied grouts were summarized in this paper. Six walls were constructed, two were not strengthened and four strengthened with injection of two different grouts. The injection of grouts proved to be a effective intervention in homogenizing, increasing the ultimate load capacity (even more than the 50% of the original strengths), improving the bond among the layers and the failure mode. It should be noted that: (i) the injection technique has led to an increase in compressive strength of three times, and an increase to the modulus of elasticity of five times; (ii) the applied strengthening technique did not lead to a significant difference in strains corresponding to the maximum stress, thus increasing the brittleness of the response [10].

The Italian regulation [18] recommends to increase the mechanical characteristics through injection to the double, which the present work confirms as conservative, meaning that it can be adequate for practical purposes.

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