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Experimental laboratory design of lime based grouts for masonry consolidation

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ABSTRACT
Conservation and strengthening of historic masonry buildings should preserve their significance and ensure their structural stability. The condition of a structure and the extent of the damage determine the type of actions needed. It is important that the selected strategy maintains the existing aesthetic value of the masonry, as well as its structural integrity and the function of components, both during and after any intervention. Grouting is a well-known technique, 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. Parameters such as rheology, fluidity, and stability of the mix should be considered to ensure the effectiveness of grout injection. Many commercial ready-mix grouts are available but the use of lime-based grouts formulated in laboratory, with the addition of materials like fly ashes, silica fume, bentonite, hydraulic lime, or metakaolin, have been proposed by different researchers. This article addresses the development of ternary grouts, which show satisfactory mechanical and physical properties, and are viable low-cost alternatives to the commercial grouts.

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Consolidation; formulation; Grouts; injection; masonry

1. Introduction

Formulation of compatible materials for mortars to be used in conservation of ancient masonry structures is complex, due to requirements such as low modulus of elasticity and adequate strength, as well as a physical and chemically compatible behavior with the existing materials. In the specific case of injection grouts, the requirements are even more demanding. The complete and uniform filling of masonry voids with grout is essential in consolidation works (Schueremans 2001). The success of this operation depends on several parameters, such as the distance between the injection holes, the injection pressure, the rheological properties of the grout, the water absorption capacity, and the general condition of the masonry (number and width of cracks) (Van Rickstal 2001).

Based on the required performance of the structure, the composition of the grout should improve the behavior of the injected system without affecting the durability. The use of lime-pozzolan-cement grouts seems to be one of the most attractive options (Toumbakari 2002). Even if grout formulations remain, mostly, an empirical process, the effectiveness of ternary compositions has been proven in experimental studies in one and three leaf walls (Luso 2012; Toumbakari 2002; Toumbakari et al. 2004).

Despite the fact that several formulations have been proposed by different researchers, commercial ready-mix grouts are available in the market and have been frequently prescribed, mostly because of their easy preparation. Specially formulated for this purpose, commercial grouts guarantee a greater uniformity in properties and a better flow control. Technical information is usually scarce and it is unclear which standards should be used for control and which requirements are applicable, meaning that the decision to choose a product is often based on marketing, cost, and local availability. Several grout applications for consolidation "in-situ" and laboratory tests are available in the literature (Binda et al. 2003; Kalagri, Miltiadou-Fezans, and Vintzileou 2010; Silva 2008; Valluzi 2000). The use of a commercial grout means that it is impossible to define the properties according to a given application and the cost can be high, also due to transportation and quantities required. An example of application for consolidation of the towers of the Cathedral of Porto is given in Lourenço, Ramos, and Krakowiak (2009).

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A recent evaluation study of the behavior of four commercial grouts under laboratory conditions showed that the performance of the commercial grouts is rather different. Therefore, careful selection of injection materials in practical applications is recommended (Luso and Lourenço 2016). The tests performed to the commercial available (*CA*) grouts include, in the first phase, fluidity tests, exudation and segregation tests, flexural, and compression tests. The second phase of the experimental program described herein was devoted to the characterization of commercial grouts when applied to masonry. The tests considered include injectability tests, compressive and tensile strength of injected cylinders, and bond strength of the grout to stone.

The objective of the experimental program presented in this article is to study the replacement possibility of the commercial products by in-situ prepared grouts with hydrated lime and metakaolin. Considering that the selection of the mix to be used must be based also on laboratory and on site testing, a second objective is to compare properties of a few compositions prepared "in-situ" and commercial products using the tests already performed for *CA* grouts. Finally, the main goal is to find a viable alternative composition and to assess its final cost.

2. Constituent materials of grouts

It is consensual that grouts applied in masonry walls of ancient buildings should: (i) ensure good bond to masonry materials such as stone or brick; (ii) have low or no shrinkage, in order to keep the volume without building new stresses, to prevent loss of adhesion and to reduce moisture penetration through cracks caused by shrinkage; (iii) have low segregation and exudation to maintain the volume and consistency; (iv) have high fluidity and injectability, in order to provide a proper flow and to fill small openings and interconnected voids, even using low pressures; and (v) to resist the action of soluble salts, possibly existent in the walls, and limit the introduction of additional soluble salts. Other properties might need to be considered, such as: resistance development in early ages; aggregate size as function of existing voids; strength and elastic modulus adjusted to the characteristics of the existing masonry; and presence of sand or soil in the existing wall.

The compliance with the above requirements is greatly defined by the constituting materials of the grout, namely binder(s), water, and additives. In general, a binder with water is used, without sand but possibly with some fine aggregate (*filler*). Depending on the type of binder, the grout is classified as: (i) inorganic—using hydraulic limes, hydrated limes, cements and pozzolans; and (ii) synthetic or organic—using a polymeric resin (usually epoxy).

The non-granular texture of organic grouts makes them extremely fluid, with a very small angle of contact, which is sometimes lower than that of water. This property enables the injection of grouts in fine cracks, using low pressures (Valluzi 2000). The disadvantages are as follows: (i) hardening difficulties when subjected to medium-high temperatures, (ii) low resistance to fire (maximum temperature about 80°C); (iii) durability not enough tested, particularly due to the fact that the materials are hydrophobic and possess a very distinct thermal expansion coefficient from masonry; and (iv) high strength and high stiffness, which seems not justified for masonry applications. In addition, generally, the existing voids in old masonry structures are too large to use epoxy resin, because of the prohibitive cost and the structural incompatibilities with the existing materials. In addition, the bond of polymeric binders requires usually dry supports, which, with the frequent presence of moisture in old walls, limits, again its use (Valluzi 2000). For these reasons, the use of epoxy injections should be limited to very specific cases, when there are thin cracks or a very high resistance is needed. Binda, Baronio, and Squarcina (1992) and Perret (2002) have done studies about the application of epoxy resin to strengthen old masonry, highlighting the advantages of filling cracks and voids of very small size. This kind of materials is most suitable for sealing cracks in stone or in concrete structures, having good penetration and good bond characteristics, but they are not recommended for repairing masonry structures (Manzouri et al. 1996). On the contrary, the application of hydraulic binders is encouraged by several authors (Miltiadou-Fezans et al. 2006; Toumbakari 2002; Vintzileou 2006).

As inorganic grouts seem the most appropriate for consolidation works by injection, cement should be limited and replaced by lime. However, the low structural efficiency of lime-based mixtures must also be taken into account. Considering the conceptual basis for the formulation of the composition of masonry grouts, stipulated by Toumbakari (2002), adequate mechanical behavior, durability and structural efficiency are required (Toumbakari et al. 2004). The solution may be the addition of other materials to mixtures containing lime to provide an improvement in mechanical strength and provide hydraulicity. Studies conducted by Toumbakari (2002) and Ignoul, Van Rickstal, and Van Gemert (2005) show that the use of cement, natural pozzolan, and lime allows achieving adequate mechanical strength and properties in short and long term.

Lime has the function of stabilizing and maintaining the fluidity of the mix, while cement provides the required early strength. The use of cement in building rehabilitation is usually considered inadequate (Cazalla et al. 2000; Degryse, Elsen, and Waelkens 2002; Moropoulou et al. 2002; Oliveira et al. 2005; Penelis, Karaveriroglou, and Papayianni 1988; Peroni 1982; Rodriguez-Navarro, Hansen, and Ginell 1998), because of its high mechanical strength and stiffness, and the presence of soluble salts, among other properties. Still, a relatively low addition of this hydraulic component may provide better bond, as well as better strength and stiffness development.

The possibility of combining different materials with different ratios results in a variety of mixtures with very different characteristics. Even if the research done in this area is not abundant, it is important to revise the studies previously carried out and evaluate the potential of these grouts for use in stone masonry walls.

3. Literature survey

The first approaches to the formulation of hydraulic grouts to historic buildings are due to Ferragni et al. (1982) and Rocard & Bouineau (1982), with the use of cement and marble powder. Later, Ferragni et al. (1985) opted for the addition of pozzolans and stone powder, with the objective of reducing shrinkage (<4%) and of controlling the mechanical strength (the intention was to obtain compressive strength in the range of 3–8 MPa and 0.3–1.2 MPa in the diagonal compression test). These authors also used fluidizers and water reducers (Ferragni et al. 1985). Later, new formulations were evaluated using ternary grouts with hydrated lime, cement, pozzolana and superplasticizers (Adami and Vintzileou 2008; Kalagri, Miltiadou-Fezans, and Vintzileou 2010; Miltiadou, 1990; Penelis, Karaveriroglou, and Papayianni 1988; Toumbakari 2002; Toumbakari et al. 2004). The particular use of metakaolin is found in the work of Adami et al. (2006). However, beyond cement, pozzolan and lime, other compositions were also studied, for example using hydraulic lime (Valluzi 2000; Kalagri, Miltiadou-Fezans, and Vintzileou 2010; Bras and Henriques 2012; Baltazar et al. 2013); gypsum (Trautmann 1992); silica fume (Miltiadou 1990; Trautmann 1992; Baltazar et al. 2014; Vintzileou and Tassios 1995; Toumbakari et al. 2004) and bentonite (Ignoul, Van Rickstal, and Van Gemert 2005).

In previous works, the analysis of the behavior of grouts comprise an evaluation from the rheological point of view, the characterization of mechanical strength (flexural, tensile, and particularly bond) at the short and long term, and also an assessment of their ability for injecting a granular medium. With regard to compressive strength, many of the mixtures found in literature have values above 10 MPa, with a percentage of binder higher than 50% of cement, justifying thus the high mechanical strength obtained. Compositions with complete absence of cement were studied by Valluzzi (2000), Kalagri, Miltiadou-Fezans, and Vintzileou (2010) and Baltazar, Henriques, and Cidade (2015) (hydraulic lime and superplasticizer, SP) and satisfactory results were obtained in terms of fluidity and mechanical strength (compression). Given these results, the reduction of the amount of cement or even their complete elimination seems to be an option to consider.

According to Adami et al. (2006) and Toumbakari (2002), lime-pozzolan-cement systems, with a maximum of 30% of cement, ensure physical and chemical compatibility, and allow the development of a wide range of mechanical properties, suitable for application in old masonry, including shrinkage and resistance values close to the substrate. A lower content of cement (percentages below 10%) makes the introduction of cement insignificant and would lead to instabilities related to the mechanical properties of the grout (Toumbakari 2002). The introduction of pozzolans as a mineral additive can be beneficial from the rheological, economic, and structural point of view. These grouts showed also adequate results in adhesion tests. Thus, lime-based ternary grouts allow the simultaneous reduction in the percentage of cement used in the composition, while satisfying physical and chemical compatibility with existing materials (Adami and Vintzileou 2008).

The addition of different materials, as mentioned above, significantly influences the fluidity of the grouts. The grouts characterized by the absence of superplasticizer (*SP*) in the composition generally have a relatively high flow time. Compositions that have essentially one component (cement or hydraulic lime) with the addition of *SP* can present good rheological behavior without large amounts of added water (Valluzi, 2000). The amount of hydrated lime in composite mixtures seems to affect slightly the fluidity of grout. Apparently, the lime content in the mixture increases the time of fluidity and lowers exudation. Addition of silica fume also affects the rheological properties (Baltazar et al. 2014; Toumbakari 2002).

It should be noted that a direct comparison between different grouts is risky and no definitive conclusions can be made from the literature research. The raw materials used in the compositions are very different, such as various types and cement classes, a wide variety of plasticizers with different characteristics and also rather distinct reactivity of pozzolanic materials. Cazalla et al. (2000) found, for example, significantly different results using the Marsh cone flow test varying a very small percentage (0.05%) of plasticizer. Moreover, for each particular pozzolanic product there is a particular formulation that yields optimal results. Therefore, further studies as the one presented here are justified.

4. Experimental program

In order to verify the performance of building materials, it is common to assess their behavior under laboratory conditions. The experimental program described in this study consists of two phases. The first phase of the experimental work was essentially empirical and consisted of three steps. After defining the compositions to consider in the experimental laboratory, three types of tests were carried out for each of the compositions immediately after preparation, which served as preliminary tests. These tests included the determination of the flow time through the Marsh cone, exudation tests in graduated cylinders with 100ml capacity and finally moulding 16x4x4 cm^3 prismatic tests-specimens for flexural and compression tests at 28 days age.

The second phase assesses the behavior of these grouts using three stone supports to evaluate the performance of grout injection adopting different stone materials as substrate. These tests included the determination of injectability, the determination of the bond strength and the evaluation of mechanical characterization of stone/grout cylinders. The preparation of specimens and the test procedures were similar to those done for commercial grouts in Luso and Lourenço (2016) and followed the standards given in Table 1.

5. Lime-based grouts formulation in laboratory

5.1 Cement-free grouts

Lime-based mixtures for use in repair and strengthening of stone masonry are evaluated next, as an alternative to commercially available grouts. The choice of materials as well as the choice of the proportions for the preparation of the grout were based in the literature review. The materials used in this study were hydraulic lime NHL5 (*HL*), fly ash (*V*), limestone filler (*LL*), metakaolin (*MK*), and hydrated lime type CL90 (*CL*), all easily available. Two different plasticizers were also used in the mix, providing about one hundred mixtures to be tested. The water was used at 20ºC and the formulations were mixed for 10 min. The grouts were mixed using a simple mechanical mixer during 10 min, as it is current practice in local engineering practice.

Compositions with low water /solid ratio (≈0.6), aiming at a flow time in the Marsh cone lower than 50 sec (1 L) and without cement, were first chosen. Applying these criteria, the compositions *F1* and *F2*, shown in Table 2, provided adequate results. These two compositions are similar, with a water/solid ratio equal 0.6 and differing only in the use of *HL* in grout *F1* and *LL* in *F2*. Here, the number after the material designation indicates the percentage in the mix (by weight of solid material).

The next phase of the experimental work consisted in preparing additional specimens for the evaluation of the development of mechanical strength of these grouts over time. The tests took place at 28, 60, 90, 135, 180, and 360 days of age and the results are shown in Figure 1.

In the composition *F2*, both the compressive strength (in 40x40x40 mm^3 samples) and flexural strength (test pieces 160x40x40 mm^3) decreased over time from 28 days of age. It seems that a tendency to decrease the compressive strength after 180 days was also found in the composition *F1*. This phenomenon is known in grouts involving metakaolin, although the underlying reasons are not entirely clear. A discussion is held in (Aggelakopoulou, Bakolas, and Moropoulou 2011; Cizer 2009; Toumbakari 2002). On the other hand, the main property affecting the behavior of grouted walls is the shear bond strength of the grout-stone interface (Adami et al., 2006; Vintzileou 2006).

Table 1. Summary of the tests done in the experimental program.

Test		Summary
Fluidity	Derived from ASTM C939 (2003) and EN 445 (2007)	Determination of flow through the tip of a Marsh cone of given dimensions, immediately, and 30 min and 60 min after mixing
Segregation/Bleeding	Derived from ASTM C940 (2010) and EN 445 (2007)	Measuring of the quantity of water that bleeds onto the surface of a given volume of grout.
Flexural Strength	Derived from EN 196-1 (2005)	Flexural strength tests of 16x4x4 cm^3 prismatic specimens.
Compressive Strength	Derived from EN 196-1 (2005)	Compressive strength tests of half-specimens obtained after rupture of the 16x4x4 cm^3 specimens during flexural tests.
Injectability	Derived from NF P 18 (1986)	Evaluation of the ability of the grout to pass through a column of a given particle size aggregate.
Mechanical characterization of stone/grout cylinders	LNEC E397 (1993) and ASTM C469 (2010)	Compressive strength tests under control of axial displacement, for determination of modulus of elasticity, fracture energy, and ductility index.
Bond Strength	No standard	Determination of the maximum force that must be applied in a circular area of grout applied to a stone support.

Table 2. Cement-free grouts. Coefficients of variation (%) in brackets.

Grout	Flow Time Cone Marsh 1000 mL§ (seconds) t = 0 min	t = 30 min	t = 60 min	Bleeding§ (in 100 mL graduated cylinders)	Compressive Strength# at 28 days (MPa)	Flexural Strength§ at 28 days (MPa)
(*F1*) CL35+HL30+MK35	47	55	58	0	18.1 (7.8)	5.8 (3.3)
(*F2*) CL35+LL30+MK35	30	33	35	0	17.5 (5.5)	4.9 (13.3)

§*Mean result of three tests*
#*Mean result of six tests*

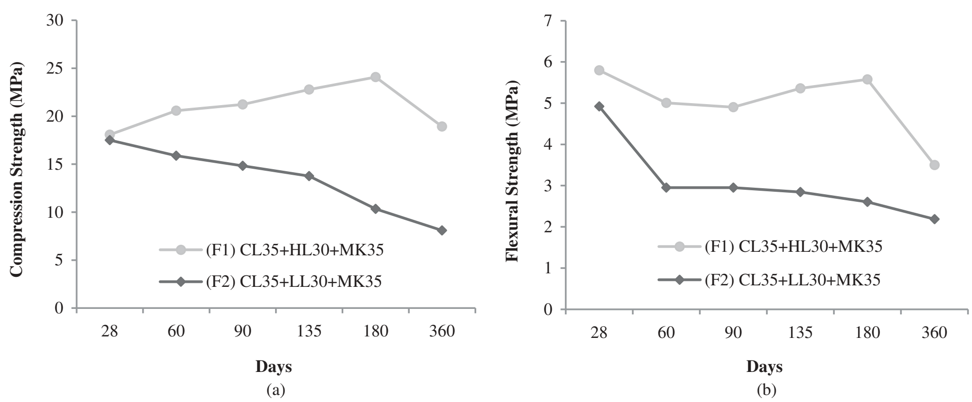

Figure 1. Evolution of mechanical strength over time: (a) compression; (b) flexural.

For this reason, bond strength tests were performed using pulloff tests, in composite stone-grout specimens with the grouts *F1* and *F2* and three different stones: limestone, shale, and granite. The cement-free formulations studied did not provide satisfactory values, with bond strength close to zero (Luso 2012), requiring the addition of cement as a necessary alternative.

5.2 Grouts with the inclusion of cement

Table 3 shows the main results using new compositions (*F3, F4, F5*, and *F6)*, with cement CEM II B/L-32,5R (*CEM*) added, metakaolin, hydrated lime and SP (3,33% of *Dynamon SR1, Mapei, for F4 and F6*, 5,5% of *Dynamon SR1, Mapei for F5 and 2,75% of V3008, Sika + 1,25% of EH1, Sika, for F3*), changing also the quantities of material. These mixtures presented the best results in the rheological and mechanical tests, namely in tensile bond strength, see Figure 2, in comparison with dozens of other mixtures done in laboratory that can be seen in Luso (2012).

The composition with 35% of hydrated lime, 30% of cement and 35% of metakaolin, denoted by *F6*, constitutes the grout with best mechanical performance (3.33% of superplasticizer was added together with 60% of water). The results obtained are within the range of the commercial grouts in terms of fluidity, mechanical, and bond strength. After this testing program, two compositions were selected to proceed with a more extensive experimental campaign - *F4* and *F6*. It is noted that the first results indicate that grout *F4*: (i) obtained lower bond strength values than *F6*; (ii) presented always rupture at the interface adhesion tests; and (iii) showed a slight decrease in compressive strength after 60 days of age, still maintaining very satisfactory values. It is also noted that the mixing of

Table 3. Grouts with cement. Coefficients of variation (%) in brackets.

Grout	Flow Time Cone Marsh 1000 mL§(seconds) t = 0 min	t = 30 min	t = 60 min	Bleeding§ (in 100 mL graduated cylinders)	Compressive Strength# at 28 days (MPa)	Flexural Strength§ at 28 days (MPa)
(*F3*) CL50+CEM30+MK20	35	38	41	0	24. 9 (4.3)	6.0 (9.2)
(*F4*) CL17,5+CEM30+MK52,5	42	47	54	0	24.3 (3.8)	6.8 (4.0)
(*F5*) CL35+CEM30+MK35	37	44	45	0	19.6 (10.5)	4.7 (10.7)
(*F6*) CL35+CEM30+MK35	40	42	45	0	21.5 (25.2)	3.5 (10.8)

§*Mean result of three tests*
#*Mean result of six tests*

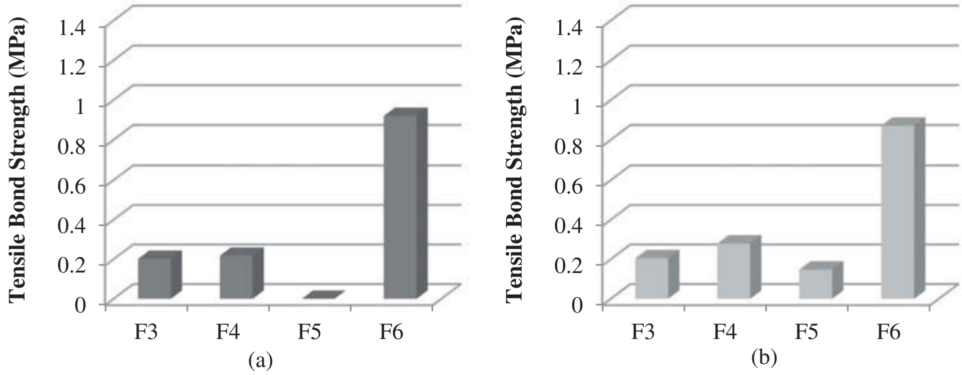

Figure 2. Mean values obtained in tensile tests with wet granite: (a) 28 days; (b) 90 days.

grout F4 was more difficult than F6. With lime-based grouts it is essential to place a portion of the water sufficient to cover the bottom of the mixing container to facilitate the process. Tests to evaluate the injectability of these two compositions were carried out and a comparison between the formulations and a commercial grout was also carried out.

6. Comparison between prescribed grouts and a commercial grout

Grouts *F4* and *F6*, resulting from the first step of the testing phase, are now applied into masonry specimens. The tests considered include injectability tests and compressive and tensile strength of injected cylinders, with height of 300 mm and diameter of 150 mm, as detailed in Luso and Lourenço (2016). After filling the cylindrical mould with yellow granite aggregate with fractions 5/10 and 10/15, each grout was prepared using the procedure adopted in the previous tests. Each composition was injected in 6-cylinders using 1.5 bar filling pressure. The time needed to completely fill the mould and at ¼, ½, and ¾ of the total height was recorded; see Figure 3.

The results of injectability tests for the two products are presented in Figure 4. The graph shows also the results of the same test obtained in a commercially available grout (*Mape-Antique I*, from *Mapei*), denoted herein as *Grout A*. As stated in the technical sheet *Grout A* it´s a "super-fluid, salt resistance, fillerized hydraulic binder, based on lime and eco-pozzolan for making injection slurries for consolidation masonry". Table 4 show the main properties of *Grout A* obtain by Luso and Lourenço (2016). It can be seen, in Figure 4, that *F4* and *F6* require much less injection time (only 25%) than *Grout A*.

After removing the moulds, the cylinders were cured in a saturated chamber during 28 days. Subsequently, uniaxial compression tests on three of the cylinders and diametrical compression tests in the other three cylinders were carried out. The tests for compressive strength (*fc*) were performed under axial displacement control (5 µm/s), which allowed the characterization of behavior of the material after obtaining the maximum load (post peak), namely by obtaining the fracture energy (*Gf*) and the ductility index (*du* = *Gf*/*fc*); see Luso and Lourenço (2016) for details.

The Table 5 show the average of these inelastic properties together with the modulus of elasticity (*E*) and the corresponding coefficients of variation in brackets. Furthermore, the last column shows the ratio between tensile and compressive strength (*ft*/*fc*).

Comparing the values of fracture energy in compression resulting from these tests for the three grouts with

Figure 3. Example of filling cylindrical moulds (Grout *F6*).

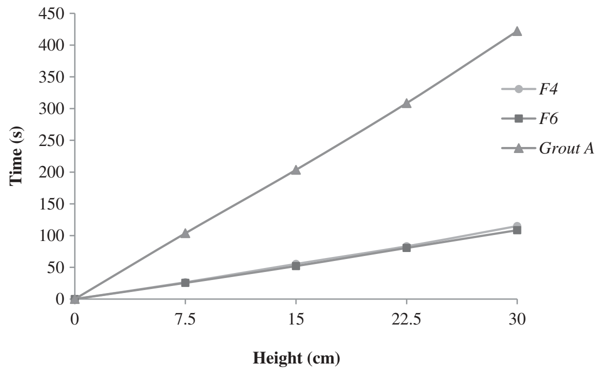

Figure 4. Average time of six-cylinder filled with yellow granite.

There are differences with regard to the commercial *Grout A*, in particular injectability time and in the mechanical properties of stone/grout cylinders. Between the two grouts formulated in laboratory, *F6* presented a higher bond strength capacity and a positive evolution of hardening, increasing over time, while slightly decreasing in the case of *F4* and after 60 days of age. Figure 6 shows the results of compression tests in prismatic test pieces obtained from 28 days of age until 3 years.

In conclusion, mix *F6* seems to meet the necessary requirements by an injection grout. An analysis of the cost of this grout compared to commercial grout *A* is provided as an example, for Portugal and year of 2015. For this cost analysis, the cost of grout and the cost of hand labor, which naturally differs, were taken into account. Grouts prepared "in-situ" imply greater coordination of work and a time of preparation and mixing was estimated at 2 min/kg of material for *F6*, which is the double time considered for the grout *A* (1 min/kg of material). The cost of hand labor was assumed 10€/hour,

Table 4. Main properties of Grout A. Coefficients of variation (%) in brackets.

Flow Time Cone Marsh 1000 mL							
t = 0 min	t = 30 min	t = 60 min	Bleeding (in 100 mL graduated cylinders)	Compressive Strength at 28 days (MPa)	Flexural Strength at 28 days (MPa)	Tensile Bond Strength at 28 days * (MPa)	Tensile Bond Strength at 90 days* (MPa)
79	105	110	0	21. 4 (4.9)	4.1 (2.7)	0.97 (14.7)	1.26 (16.6)

**Mean values obtained in tensile tests with wet granite*

Table 5. Results obtained in the mechanical tests. Coefficients of variation (%) in brackets.

Grout	Age (days)	f_c (MPa)	*E* (GPa)	*Gf* (N/mm)	d_u (mm)	f_t (MPa)	f_t/f_c
F6	28	13.9 (6.7)	7.3 (11.7)	23.2 (11.2)	1.64 (5.1)	1.30 (5.0)	11%
F4	28	11.8 (11.8)	7.8 (4.6)	21.5 (6.6)	1.80 (9.8)	1.30 (2.1)	9%
Grout A	28	23.5 (6.1)	17.3 (16.9)	32.0 (9.4)	0.60 (22.7)	1.37 (13.7)	17%

the values for concrete in Model Code 90 (CEB – FIP, 1993), there seems to be some reasonable agreement; see Figure 5. The fracture energy proposed in the code follows Equation (1).

$$G_{f_c} = 15 + 0,43 f_c - 0,0036 f_c^2 . \quad (1)$$

The results show that among the grouts *F4* and *F6*, there is no significant difference in the values found.

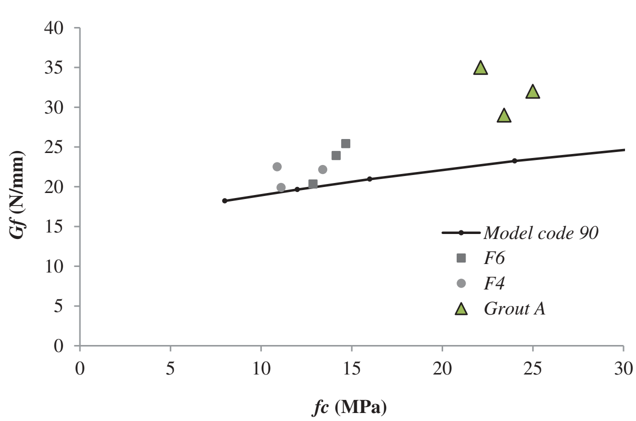

Figure 5. Relationship between compressive strength (*fc*) and fracture energy (*Gf*).

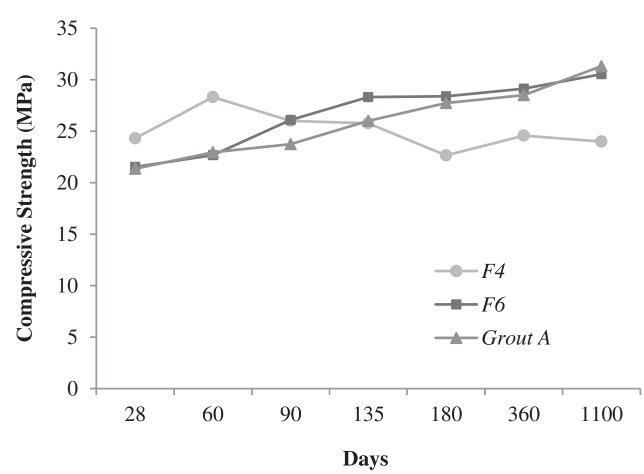

Figure 6. Compressive strength average in six specimens.

Table 6. Cost analysis of grouts.

Grout	Mean price of each component per kg				Total/kg	Total/liter	Relative cost
	Hydrated Lime	White Cement	Metakaolin Optipozz-Sc	Plasticizer SR1			
F6	0,188€	0,246€	0,74€	0,85€	0,427€	0,403€	0,43
A	0,65€				0,650€	0,929€	1,0

Table 7. Final cost analysis with labor cost.

Grout	Hand Labor (Lab)				Grout Cost per kg	Total cost /kg	Total cost /liter	Saving from commercial grout
	Lab time	Cost Lab/h	Cost Lab/kg	Cost Lab + taxes/kg				
F6	2 min/kg	10,00 €/h	0.333 €/kg	0.410 €/kg	0.427 €	0.837 €	0.789 €	−35%
A	1 min/kg	10,00 €/h	0.167 €/kg	0.205 €/kg	0.650 €	0.855 €	1.222 €	

see Table 6 and Table 7. From the economic point of view, grout *F6* seems to have much lower cost (about 65% of the cost of the commercial grout *A*), even using metakaolin, which has a cost per kilogram much higher than cement.

7. Conclusions

This experimental program provides results for the definition of lime-based grouts with suitable characteristics for injecting existing masonry structures. The results revealed similarities and differences between commercial products and some grouts that were developed in the laboratory. The addition of natural or artificial pozzolans has been encouraged by many authors as a potential replacement for cement. The most appropriate formulation obtained for a ternary grout has a percentage of cement about 30%, while the percentage of hydrated lime varied between 25% and 70%. The addition of pozzolans can help to improve durability, if properly used (Massazza 1998) and the use of superplasticizer is recommended. The addition of cement in the composition is essential to obtain adequate bond strength capacity.

Prescribed lime-based grouts require, however, a detailed study to evaluate the mechanical and rheological characteristics, as done in the article.

The experimental campaign included the study of a series of compositions with good characteristics in terms of rheological behavior, exudation, and mechanical resistance, however, most of them showed very poor results in terms of adhesion. Compared with one commercial grout, only one of the compositions had a similar bond strength. This grout comprises 35% hydrated lime, 30% white cement, 35% metakaolin, 3.33% of superplasticizer, and 60% water. It was not possible to obtain a water /solid ratio lower than 0.6, even changing the percentage and type of plasticizer added (Luso 2012). Compared to the commercial grout, the prescribed grout achieved better results in terms of fluidity, exudation, volume variation, and injectability. However, the grouts have different densities both when wet and dry (1830 kg/m^3 for commercial grout and 1530 kg/m^3 for prescribed grout). As the commercial grout is more compact, this is reflected in the compressive strength and elasticity modulus in grout+stone cylinders, where higher values were obtained.

From an economic point of view, the prescribed mix seems to have 35% cheaper application costs. The disadvantage of using different components for the grout is the possible variability of their characteristics, within a given class, meaning that there is no guarantee of uniform properties compared to what is expected from a pre-mixed compositions. Therefore, it is recommended to test a prescribed composition before application. Another disadvantage of using a prescribed grout is the need for adequate weighing the materials and in the mixing of the grouts, which can significantly change the properties of the final product.

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