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EFFECTIVNESS OF THE GROUT INJECTION ON RUBBLE STONE MASONRY SPECIMENS: AN EXPERIMENTAL RESEARCH

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Abstract

The paper presents a research work developed aiming to study the improvements introduced by the grout injection strengthening technique for the structural rehabilitation of old buildings, with rubble stone masonry walls. First, cyclic shear tests were performed on two unstrengthened rubble stone masonry specimens which were built with hydraulic lime mortar and traditional limestone. Then, a specific grout, based on hydraulic lime and cement, was developed taking into account the characteristics of some rubble stone masonry walls existent in old buildings in Lisbon, Portugal and aiming to strengthen the masonry walls. Afterwards, the specimens previously tested were strengthened by this injection grout and the cyclic shear tests were performed again. The results obtained showed that this strengthening technique was successful in allowing the damaged specimen recovered the initial characteristics and in successfully restore their load carrying capacity.

Keywords: Rubble stony masonry; In-plane static cycle shear test; Strengthening; Grout Injection.

1. Introduction

The old masonry buildings constitute a large percentage of the building stock of Lisbon, and they are generally exposed to a very high seismic risk due to the high probability of earthquake occurrence. The need for intervention in this type of structures is increasing, as they have been subjected to significant careless structural modifications in their lifetime, and it is necessary to identify weaknesses and implement appropriate methods of rehabilitation. Grouting constitutes one of the most common techniques applied for the repair and strengthening of masonry structures applied by many authors. The injections in the cracks, internal or at the face, of a masonry wall are a solution of strengthening that is irreversible. They are, however, used frequently because they preserve the original aspect of the exterior of the wall, what is especially useful for restoring or stabilizing historic structures.

This work presents an experimental research where the grout, based on hydraulic lime and cement, was specially developed to be used for the strengthened of rubble stone masonry walls, paying special attention on the compatibility with the materials present in old masonry buildings in Portugal. Furthermore, grout was deeply analyzed before it was applied on the masonry specimens [1]. In the scope of this experimental campaign, two rubble stone masonry specimens with hydraulic mortar were previously tested as unstrengthened [2]. Then they were repaired by grout injection and tested by applying static cyclic horizontal load at the top, combined with a pre-compression level, following the major concepts of ASTM Standard [3] and the work of Vasconcelos [4]. Results of comparison between the unstrengthened and strengthened specimens, as well as the characterization of the used materials providing the basic details of the strengthening schemes applied will be presented in the paper.

It is worth mentioning that this research was developed to be applied to a specifically typology of old buildings existing in Lisbon, i.e. mixed masonry-reinforced concrete (RC) buildings (known as “Placa”), which represent around 30% of Lisbon’s building stock, paying special attention to the compatibility with the existing material found in these buildings. Very few experimental data exist in assessing the cyclic behavior and the effectiveness of strengthen solutions in rubble stone masonry walls existent in these buildings; thus a need for a number of specific experimental tests on such structural elements is crucial for their preservation.

It should be highlight that the main contribution of this work is the study of the effectiveness of the repairing strategy by injection of the proposed grout in specimen’s representative of masonry walls of these old buildings. However, taking into account the similarity of the masonry walls, existing in this mixed buildings located in Lisbon, with other old masonry or mixed masonry-RC buildings, the proposed technique with the grout herein developed could be used in a wider scope.

2. Description of the static cyclic test

Two rubble stone masonry specimens, S1 and S2, (1.20m x 1.20m x 0.40m) with hydraulic mortar were built in the laboratory and subjected to static cyclic shear test to study the behavior in unstrengthen condition [2]. These specimens were first subjected to a vertical compression load of 144 kN through the four steel bars (cables) where each one was equipped with the actuator at the top (Fig. 1). This force was kept approximately constant during the all test. Then, the horizontal load was applied by a horizontal double acting hydraulic jack, with capacity 300 kN, linked to the reaction wall. In order to prevent sliding at the base, the specimens were fixed to a steel profile and clamped down using steel beams, which was vertically presstressed. The test setup is shown in Fig. 1. The cyclic tests were conducted under displacement control by means of the horizontal LVDT connected to the left side of the specimen, as can be seen in Fig. 2a). Each cycle was repeated three times with monotonic increase of the maximum amplitude (Fig. 2b). The displacements of the wall under cyclic loading were measured through a set of LVDTs indicated in Fig. 2a). The vertical displacement of the top and bottom of the specimen was measured by the TSV1 and TSV7, respectively, whereas the TSV3 and TSV5 were used to measure vertical displacement on different heights of the specimen. Transducers TSH1, TSH3, TSH5 and TSH7 were instrumented on the specimen to measure horizontal displacements on different heights. The same arrangement of the LVDTs was made on both faces of the wall. In order to avoid any damage of the instrumentation, all transducers (except the control one) were removed when the behavior of the specimens started to indicate that it could be close to failure (when the opening of the shear crack on the main sides or the vertical crack on back sides was significant).

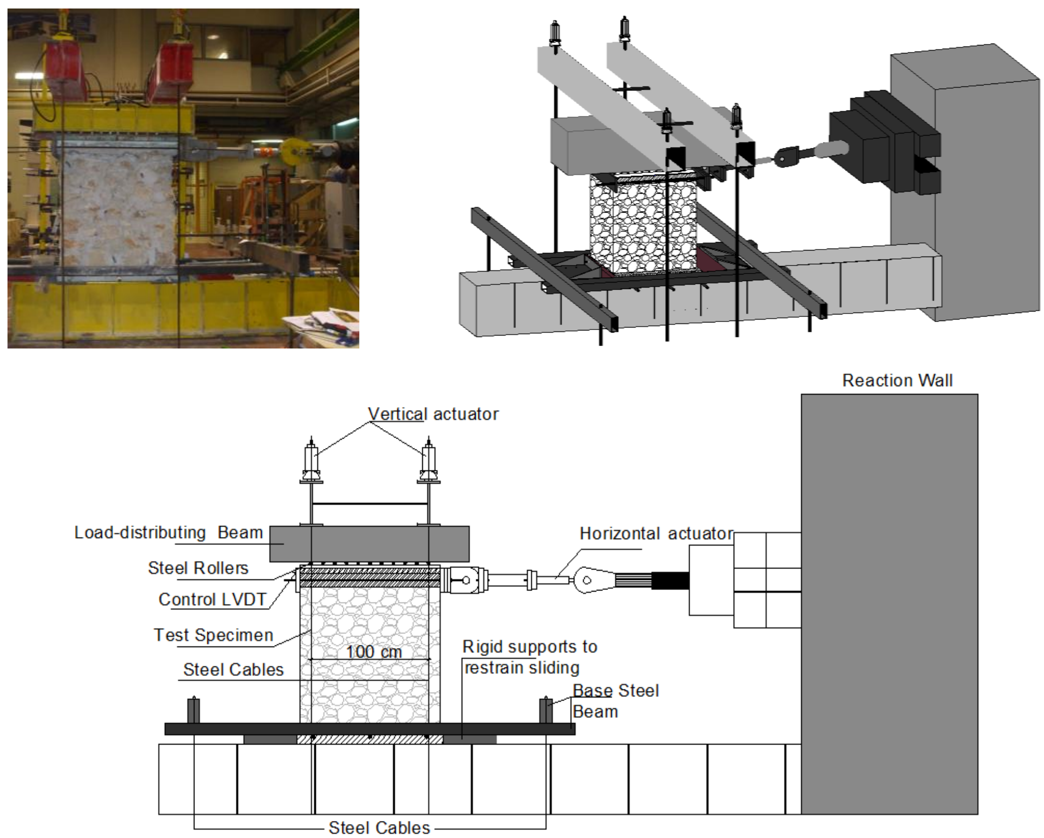
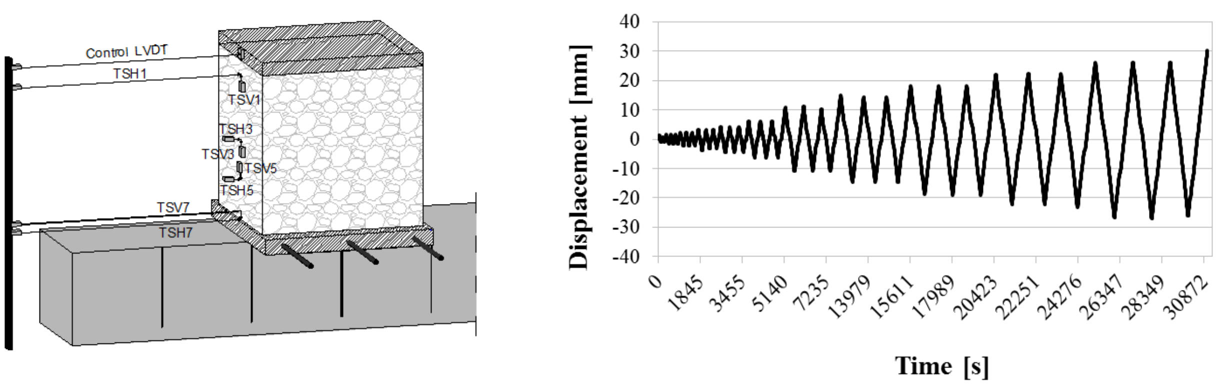


Fig. 1 – Setup for static cyclic shear test



(a) (b)

Fig. 2 – (a) Position of transducers and (b) Loading history

3. Definition and evaluation of an injection grout

The grout used in consolidation of masonry walls should fill the existing voids and cracks, in order to restore or increase the continuity of the wall; thus contributing to an increase of their mechanical properties, in particular its overall strength, by restoring an adequate distribution of loads. It should be recall that grout was designed particularly for this experimental campaign, establishing the compatibility, as much as possible, with the material used in the old masonry existing in some Portuguese buildings.

The selection of the grout was performed based on the requirements defined initially: flow time measured by method of cone around 10±2 seconds; absence of exudation and volume variation; compressive strength at 28 days of age, more than 20MPa.

After intense study of the multiple grouts with different compositions, the conclusion was that the grout with a ratio of 1:1 (cement:hydraulic lime), with 0.2% superplasticizer and a water/binder ratio of 0.45 is the most appropriate grout. The constituent materials correspond to the natural hydraulic lime NHL5 and pozzolanic cement CEM IV/B 32,5R.

The grouts were made by adding the dry elements to the total mixing water, which was previously drained into the mixing container. The curing conditions (T = 20±2ºC, RH (relative humidity) = 95±5%) were chosen according to the standard NP EN 445 [5], for the characterization of cement grouts.

To characterize the grout in the fresh state, the standards NP EN 445 [5] and NP EN 447 [6] were followed. This approach enabled the evaluation of the fluidity (cone and scattering methods) and density immediately after production and also 30 min after (to verify requirement set in NP EN 447 [6]), and the evaluation of stability of the grout's properties for a period of 3 hours, with a 30 min of intervals, mixing the grouts continuously.

The characterization of the grout in the hardened state were determined on prismatic, cubic and cylinders specimens at 7 and 28 days of maturity according to the standards NP EN 445 [5], NP EN 447 [6], NP EN 196-1 [7] and NP EN 12390-3 [8]. For this purpose, to obtain the flexural and compression strengths of the grout, prismatic samples (40mm x 40mm x 160mm) were tested (Fig. 3). The capacity of injection by gravity was performed in cubic specimens previously filled with a mixture of two types of aggregates: (i) crushed stone 1 with aggregates of dimensions between 6mm and 12mm (Fig. 4a) and (ii) crushed stone 2 with aggregates of dimensions between 12mm and 20mm (Fig. 4b). To obtain a lower volume of voids, about 70% of crushed stone 1 was considered appropriate and the remaining space were filled by crushed stone 2. Furthermore, the evaluation of the ability of injection under pressure was performed based on the standard NF P 18-891 [9] and on the research work developed in this area [10], [11], where compression and diametrical compression strength of cylindrical samples was evaluated.

(a) (b) (c)

Fig. 3 – (a) Prismatic samples; (b) Flexural strength test; (c) Compression strength test

(a) (b)

Fig. 4 – Crushed stone used in the test of the evaluation of injection of the grout by gravity: (a) Crushed stone 1 (6-12mm); (b) Crushed stone 2 (12-20mm)

Concerning the obtained results, it was observed that the grout has a flow time around 14 seconds and does not present any variation of volume or exudation, remaining homogeneous during 24 hours. Compressive strength of prismatic specimens reaches the value of 27 MPa, satisfying the initial requirement. It should be mentioned that comparing the compression strength presented by the other authors [12], [13], [14], the studied grout showed remarkably higher compression strength. However, overall compression behavior and resistance of the strengthened structure is not influenced with the higher compression strength of the grout, as it was already confirmed in [12], [15], [16], [17].

The evaluation of the injection capacity of grout by gravity has shown that the grout under study has good drainage characteristics and good ability to fill the voids present between the particle mixtures (Fig. 5a), as well as grout presents good penetrability in porous medium, since it presents a minimum percentage of voids and good connection between them (Fig. 5b) and c)).

(a) (b) (c)

Fig. 5 – Specimens resulting from the evaluation of the injection capacity of grout after compression test: (a) cubic specimen; (b) and (c) cylindrical specimens.

4. Injection grout in masonry walls

As already mentioned, specimens were tested first without any strengthening techniques (reference specimens) in order to simulate ancient masonry walls, typical for the old buildings in Lisbon (such as type mixed masonry-reinforced concrete buildings). At the end of the tests, the specimens remained intact, showing however a high level of damage with a considerable percentage of cracks (Fig. 10a), Fig. 10b), Fig. 11a) and Fig. 11b)).

During the application of the grout injection, performed in the laboratory, standard procedure was followed as much as possible. The injection tubes were placed in existing cracks (Fig. 6a), where the small openings were held whenever was necessary. Cleaning of the holes was performed by removing any dust inside, before placing the tubes. Then, transparent plastic tubes with diameter about 8mm were placed in the holes, slightly inclined in relation to the horizontal direction and with depth of 20 to 25cm. The sealing of the tubes and the other existing cracks in the remaining re-closure specimens were carried out (Fig. 6b), with the mortar which has the same characteristics as mortar used in the construction of reference specimens (hydraulic mortar). The injection tubes were placed on both sides of each specimen, trying to achieve a triangular geometric distribution of the holes [13]. Moreover, the spacing between the tubes has not been constant since the dimensions of the stones vary. Other smaller tubes were also placed with air purge function.

The injection was done by gravity on the masonry specimens (Fig. 6c), starting from the upper row of the tubes, passing into the next tube on the same horizontal line and thereby continuing progressively until the lower row of tubes. The injection into each tube was completed when it appeared that the grout flowing through an adjacent tube. As it was expected, the amount of injected grout was lower in specimen S2, since that this specimen presented less cracks, as well as a smaller crack's openings. The two strengthen specimens would be designated from now on as SR1 and SR2. It should be mentioned that usually grouts will be injected into a void with low pressure due to the fact that better results could be achieved. However, in this work a grout injection under gravity is recommended as the specimens, already subjected to cyclic shear tests had a certain level of degradation.

(a) (b) (c)

Fig. 6 – Preparation of the specimens: (a) Placement of the tubes; (b) Sealing the tube and closing the cracks; (c) Injection of the grout by gravity

5. Results and discussion

5.1 Failure mode

In order to better understand the results presented in this section, the test scheme used is observed in Fig. 1 where the side A is the side visible from the front face of the specimen, whereas the side B corresponds to the part behind the masonry specimen. The side where the control transducer was placed is designated as C, while D corresponds to the side where the horizontal load is applied through the actuator. The positive displacement corresponds to the displacement applied from right to left (Fig. 1).

Regarding the specimen SR1, the first visible crack (displacement around 6mm), characterized by diagonal shear crack, were located in the central area of the specimen. At the same time, it was possible to notice the small horizontal cracks in the lower part of the specimen (Fig. 7a), particularly after the first layer of stone, indicating the flexural behavior. The first significant shear crack, with the imposed displacement of -10mm, was observed on the specimen's side A (Fig. 7b). Moreover, it was noticed that the largest diagonal crack (imposed displacement of 18mm) was located in the middle of the specimen on the side A (Fig. 7c) propagating towards the bottom right and upper left corners, making connection with the previously registered crack at the bottom left corner. The crack in the bottom corner was expected due to the fact that existing cracks (registered after the test of reference specimen) in the bottom of the specimen showed small opening and in stage of repair/reinforcement of specimen S1 was not possible to inject grout in this zone. In addition, the specimen also showed a crack pattern characterized by crushing at the bottom corners. Fig. 7d) and Fig. 7e) present the final stage of damage pattern for both sides of the specimen.

(a) Side B (b) Side A (c) Side A (d) Side A (e) Side B

Fig. 7 – Specimen SR1. First visible crack (a-c); Collapse mechanism (d and e)

In case of the specimen SR2, as in the specimen SR1, horizontal crack in the base of the specimen was also noticed for small horizontal displacement (Fig. 8a). The first diagonal shear crack (prescribed lateral displacement of 10mm) were spreading from the center to the bottom left side of the specimen (Fig. 8b). Additionally, with the increase of the imposed displacement, spreading of the initial cracks have been noticed and in addition to the shear behavior of the specimen's side A, the side B is characterized by flexural behavior (Fig. 8c). The failure of the specimen was attributed to the opening of the crack at the bottom right corner of the side B (Fig. 8d) and Fig. 8e)).

(a) Side B (b) Side A (c) Side B (d) Side A (e) Side B

Fig. 8 – Specimen SR2. First visible crack (a-c); Collapse mechanism (d and e)

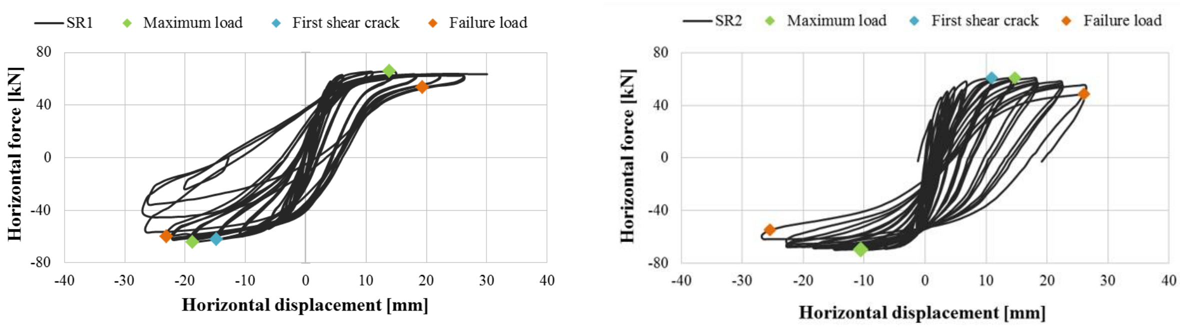
5.2 Hysteresis diagrams

Important information about the behavior of tested specimens are also provided in terms of horizontal force-horizontal displacement relationship, where the horizontal displacement is the one recorded using the control LVDT.

In case of the both specimens (SR1 and SR2), the tests were stopped at a stage in which it seems the specimens were about to fail, showing some separated stones from the rest of the specimen. At this stage the failure load was around 80% of maximum horizontal load (Fig. 9a) and b)), except for the value which corresponds to the negative side of the curve for the specimen SR1, where it was possible to observe and register the moment of collapse: the horizontal force achieves the value of 59.8 kN with horizontal displacement of about -22mm, what is around 90% of maximum horizontal load. As can be seen, the hysteresis diagram for the specimen SR1 is related with the mixed deformation, i.e. flexural and shear cracking, which correspond to the behavior of the specimen observed by the failure mode (see Fig. 7). Additionally, the asymmetric behavior caused by different patterns of damage to different sides of the specimen, is apparent in the diagram presented in Fig. 9. Namely, the strength degradation is evident for the negative side in the graphic, matching with the side of the specimen where first shear crack was observed, whereas on the side related with positive displacement flexural behavior was noticed.

Mixed behavior of flexural and shear cracking characterized the behavior of specimen SR2. In this specimen, asymmetry is more highlighted on the positive side of the graphic, due to the appearance of the crack first in the positive direction of the displacement and therefore as result of high level of accumulation of damage, there is a further weakening of the corresponding specimen's side (side C).

As can be observed, the differences obtained for the maximum lateral resistance of the specimens are minimal. However, in larger amplitude cycles, after the maximum load, small degradation of the strength can be noticed in the negative and positive side for specimens SR1 and SR2, respectively. This outcome can be caused by the absence of the grout in these areas of specimens, due to the appearance of only small cracks in these regions after the test of unstrengthen specimen. Relevant values of the force-displacement diagram, related to the maximum lateral load, the first shear crack and the force and displacement at failure are defined and results are presented in Table 1.



(a) (b)

Fig. 9 – Horizontal force vs. Horizontal displacement: a) SR1; b) SR2

Table 1 – Cyclic shear tests

		Negative Side			Positive Side		
		First shear crack	Maximum lateral load	Failure load	First shear crack	Maximum lateral load	Failure load
SR1	F (kN)	61	64.37	59.83	-	65.75	53.25
	d (mm)	10	18.80	22.00	-	13.86	19.35
SR2	F (kN)	-	69.90	54.85	61	61.24	48.80
	d (mm)	-	10.55	25.50	10	14.78	26.00

6. Comparison to unstrengthen specimens

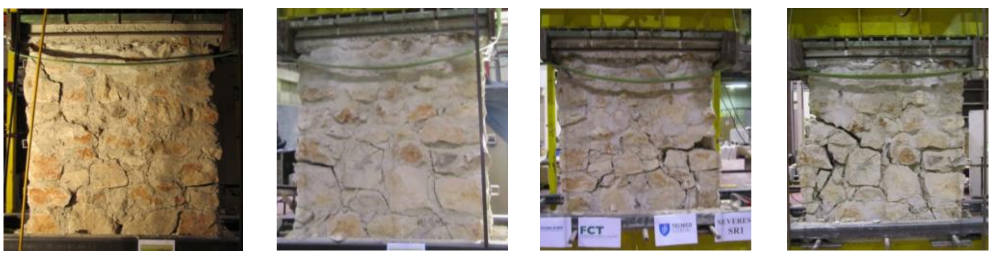
In order to evaluate the effectiveness of the strengthened technique performed, in this section the comparison of behavior with unstrengthen specimens is presented.

As it can be observed in Fig. 10a) and b), the distribution of the cracks obtained at the end of specimen S1, allowed the introduction of significant amount of grout with good penetration, comparing to the specimen S2, where less amount of grout was introduced.

Observing the failure mode obtained for the specimen S1 and SR1 (Fig. 10a)-d)), can be noticed that crack which appeared in the specimen S1, side A (diagonal crack form the upper left corner to the center of the specimen), was not observed in the specimen SR1 what confirms the good penetration of the grout through this diagonal crack. On the other side, significant cracking was noticed in the lower right area of the specimen SR1, what was expected, since that the existing crack in the specimen S1 (in the lower right area) had negligible openings and it was not possible to apply the strengthening techniques by injecting the grout.

Unstrengthen specimen S2 was characterized by insignificant amount of cracks (Fig. 11a) and b)), thus this specimen was not provided good results, since that was not possible to inject appropriate amount of grout. Injection process is an effective technique in masonry walls with an interconnecting network between the voids and where the voids index is between 2% and 15%. On the other side, if the voids index is below the 2% [13] and 4% [18] the results are generally weak, what corresponds to the condition observed in specimen SR2. Due to the fact that only few small cracks were recognized after the testing the specimen S2 and impossibility to introduce appropriate amount of grout on that specimen's side (side A), the similar crack pattern was noticed for these two specimens, i.e. specimens S2 and SR2 (Fig. 11a) and c)). On the other side, on side B, where the stones were completely demolished after the first test (Fig. 11b), in the lower right and left corner, repaired and connected with hydraulic mortar, leaving a larger gap in order to place a tube for the grout injection in that area, the specimen showed good behavior not allowing to the stone units to fall apart (Fig. 11d).

In addition, should be mentioned that there are the appropriate non-destructive tests (for instance sonic tests), which can be performed to estimate the effectiveness of the grout injection technique. These tests should be performed before and after grout injection in order to assess the condition of the specimens. In this experimental work it was not possibility to perform these tests, which could be helpful to avoid the situation in case of the specimen S2/SR2.



(a) Side A (b) Side B (c) Side A (d) Side B

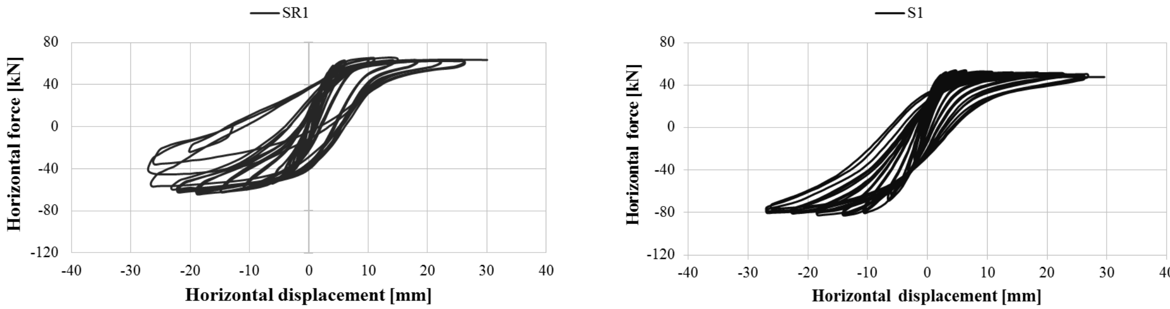
Fig. 10 – Specimen at the end of the test: (a) and (b) S1; (c) and (d) SR1

(a) Side A (b) Side B (c) Side A (d) Side B

Fig. 11 – Specimen at the end of the test: (a) and (b) S2; (c) and (d) SR2

Analyzing the hysteresis diagrams, can be noticed that the force-displacement diagrams show the great similarity in behavior between the two specimens (SR1 and S1), with a significant degradation in the specimen SR1 when is subjected to lateral negative displacement (Fig. 12). This result is consistent with the behavior and failure mode of this specimen, where clearly diagonal crack appeared, revealing the shear behavior.

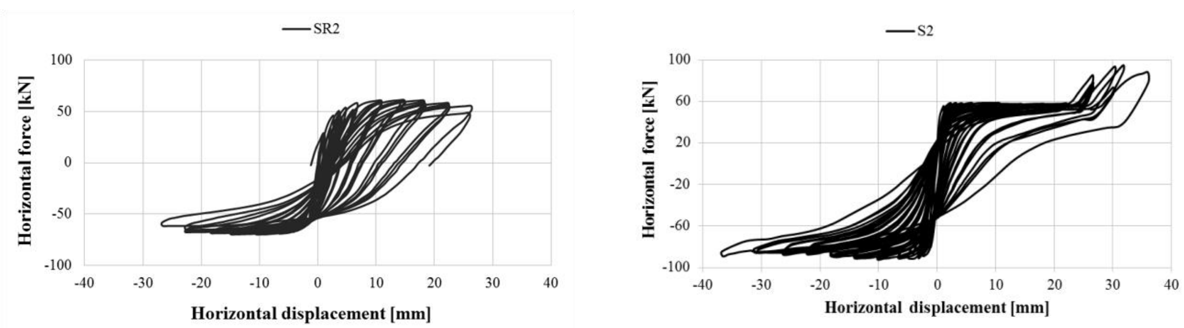
In case of the overall strength of the specimens, maximum total force of 136.5 kN (specimen S1) and 130.1 kN (specimen SR1) was registered, which corresponds to the 5% of decreasing. However, regarding the results obtained, can be concluded that with the grout injection was possible to recover the initial strength of structural element. Additionally, the injection of the grout shown to be the most effective in improving the rigidity (around 15%) and ductility of the specimens (around 23%).



(a) (b)

Fig. 12 – Horizontal force-Horizontal displacement diagram: (a) SR1; (b) S1

The great difference in the strength capacity of the specimens SR2 and S2, showing the greater degradation to positive lateral displacement, can be seen in theFig. 13, where the force-displacement relation is presented. Due to the fact that reading problem appeared in the upper part of the test specimen S2 [2], it was not possible to perform a real analysis of the corresponding area (Fig. 13b). However, taking into account the overall strength, 152.4 kN for specimen S2 and 131.1 kN for specimen SR2, the reduction of about 13% was perceived. In terms of the stiffness and ductility there is no any improvement, due to the limited quantity of the grout in these specimens.



(a) (b)

Fig. 13 – Horizontal force-Horizontal displacement diagram: (a) SR2; (b) S2

7. Conclusions

The main goal of this work is to propose a grout appropriate for strengthening old mixed masonry-reinforced concrete buildings (known as “Placa”) existent in Portugal, particularly in Lisbon. The experimental campaign carried out contributed to show the effectiveness of the repairing strategy by injection of the grout in specimen’s representative of masonry walls of these buildings, as well as for other types of old masonry buildings in Portugal due to the similarity of the materials present in all of them.

Regarding the definition of a grout, the objective was fulfilled; the grout developed has the characteristics essentials to be used in injection strengthening technique of masonry walls and has a compressive strength of 27 MPa. Anyway, the obtained compression strength corresponds a value higher than the values obtained by other authors [12], [13], [14], which is not necessary an outcome indicative of better global compression strength. However, can be concluded that this technique was effective, since the initial characteristic of damaged specimens were restored. This is especially valid for specimen S1/SR1, where the improvement in terms of stiffness, load carrying capacity, ductility and maximum displacement can be noticed, due to the fact that it was possible to introduce a great amount of grout comparing to the specimen S2/SR2. Truly, after removing the test setup of specimen SR2, the specimen could not remain intact; it could be verified that there was practically no grout inside of the specimen. In order to avoid the situation which happened in case of specimen S2/SR2, sonic tests should be performed in order to estimate the effectiveness of injectability. Unfortunately, in the presented work, it was not possible to perform this type of test. In addition, the obtained results in this study are comparable with the results presented in [19], where the tested specimens injected with cement-lime grout were also capable of restoring the specimen initial strength and lateral displacement capacity.

Next to the fact that the initial strength of the specimens was restored, efficiency of grout could be confirmed by means of the ability to establish good connection between the voids in the damaged places, whenever it was possible to introduce the grout. The representativeness of the results obtained is low, since that this experimental campaign consists of limited number of tested specimens. Nevertheless, it is worth noting the conclusions herein obtained, after the evaluation of the grout injected into the specimens, are in accordance with the outcomes presented in Miranda [1], where it was found that the grout had a good penetration in the area with a certain percentage of interconnected voids.

Due to these facts, can be stated that the studied grout is appropriate to be used in the strengthening of the old masonry buildings. Nevertheless, further developments of the presented techniques are essential to be accomplished, where other grout compositions should be studied and more cyclic tests performed, in order to propose the most effective one.

4. Acknowledgements

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