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Original article

Evaluation of consolidation of different porous media with hydraulic lime grout injection

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ABSTRACT

The grout injection is a technique widely used for structural consolidation of the multi-leafs stone masonry, which often present low compactness and weak links between the internal and external leaves. Grouts can be seen as mixtures of binder with water, with or without special additives. To ensure an adequate flow of the grout and a correct filling of the internal voids inside the masonry, it is essential to assure good fresh grout properties, such as stability, water retention and a rheological behaviour. The grout specification involves the knowledge of the flow capacity within the masonry inner core and physic-chemical compatibility with the original materials present in the historic materials. Thereby, the scope of this paper is to evaluate the injection performance of hydraulic lime based grouts as a function of the porous media to be injected. For this purpose, simplified models were created to allow injectability tests in controlled conditions. To enable the simulation of different permeabilities and internal structures of masonries, the models were created by filling plexiglass cylinders with different grain size distributions of limestone sands and crushed bricks. Since, these materials exhibit different water absorption coefficients, it also was possible to study the influence of water loss from grout to porous media in grout injectability. Another variable studied with influence on grout injectability was the water content of porous media. As it is not expected that masonries are always dried, the pre-wetting of some cylinders by simple injection of water is of extreme relevance to compare the results of grout injectability in the two opposite situations. The grout injection performance was analysed both in the fresh and hardened states. The injectability of the grout as well as its link to the materials within the inner core of old masonries was assessed by tomography and mechanical tests. The mechanical results showed good correlation with injectability and high dependence with the position of the specimen analysed on the cylinder injected, creating tensile strength gradients along the height of the cylinder. Regarding the tomography, the tomographs demonstrate the compactness of the porous media after grout injection. In fact, according to the results obtained, it can be stated that the tomography allows the evaluation of the grout injection capacity to improve the physical and mechanical properties of the inner core of old masonries.

1. Research aims

This work studied the efficiency of grout injection in porous media simulating old masonries, by analysing the performance of the grout injection capacity as a function of the porous media to be injected.

The injections tests were performed on small size models filled with the porous media studied; the aims were to understand the grout flow inside the porous media and to establish a relation between the grout injection capacity and the different parameters associated to porous media, namely permeability, voids volume, water content and grain size distribution.

Regarding the hardened state, mechanical and ultrasonic tests (the raw data for tomography) were performed to evaluate the effectiveness of grout injection along the maximum injection height reached for the different porous media, as well as to verify if there are some kind of relationship between the values of these tests. Another purpose was to compare the information obtained from the visual inspections on injected models with the tomograms in order to check if tomography can be used as a tool to control the effectiveness of the grout injection technique.

2. Introduction

Grout injection has been regarded as a suitable technique to restore the homogeneity, uniformity of strength and continuity of

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masonry walls. Research has been carried out in these last two decades on the effectiveness of the technique [1–5].

In general, the aims of the technique are:

- to fill large and small voids and cracks increasing the continuity of the masonry and hence its strength;
- to fill the gaps between two or more leaves of a wall, when they are badly connected.

These aims can only be fulfilled by knowing with a good precision the morphology of the wall section, the composition of the materials constituting the wall in order to avoid chemical or physical incompatibility with the grout, crack distribution and size, percentage and distribution of voids [1,3]. Therefore, the effectiveness of a repair with grout injection depends not only on the characteristic of the mix, but also on the knowledge of wall type [6]. It is noted that the permeability and moisture content are also important properties in the assessment of injectability [7]. For this reason, in the injectability tests the porous media were created using two materials with different water absorption coefficient in order to study the influence of water loss from grout to porous media in grout injectability. The injectability test was performed by injecting samples with a cylindrical shape which attempt to reproduce as much as possible the inner core of old multi-leafs masonries.

When a good filling and a good bonding of the grout to the masonry original materials are achieved, the load bearing capacity of the structure will significantly improve after the grout is cured [6,8,9]. Thus, the importance of an optimal grout composition from both fresh and hardened states is crucial. In order to study injectability and bond strength splitting tests of previously injected cylinders were adopted. Aiming at controlling the effect of grout injections on the compactness of masonries tomography was used [10]. Given the small size of the models used in the laboratory, ultrasonic data are used to supply the required information to generate the tomographs (ultrasonic tests are more suitable than sonic test since the frequency is higher and hence it is expected a higher accuracy on the results). In fact, the tomography can be usefully applied to detect the internal morphology of the structural elements created, giving a qualitative information about their compactness [11,12]. In this way the locations in which injection is more difficult to penetrate can be detected. For this purpose, a comparative ultrasonic tomography of porous media after injection was carried out.

3. Materials studied

3.1. Field of use and materials selection

In principle, the selection of a binder to be used in grouts for injection should take into account the compatibility with the original materials to be injected. Therefore, the present research program used natural hydraulic lime grout, since it presents mechanical, physical and chemical composition closer to the original materials used in historic masonries – which was the objective of the study – comparatively with high content cement-based grouts [6]. Trying to enhance the performance of the grouts, superplasticizers were also used in an attempt to get advantages on their rheological properties [6,13].

Taking into consideration all these points, several porous media were tested/injected with the chosen grout in order to understand this influence in grout injectability.

Table 1
Grout composition tested.

Binder	NHL5	SP	Glenium Sky 617 (BASF)
W/b	0.5	% SP	1.2

Table 2
Different porous media studied.

Porous media	Grain size ranges		
	0.15–2 mm (fine)	2–4.75 mm (media)	4.75–9.5 mm (coarse)
A	1/3	1/3	1/3
B	1/3	–	2/3
C	1/6	–	5/6
D	–	1	–
E	–	1/2	1/2

3.2. Grout

The used binder was NHL5 hydraulic lime (EN459-1) produced in Portugal by Secil-Martingança; the formulation of the grout is presented in Table 1.

Many parameters may affect the characteristics of hydraulic lime grouts and its injectability in particular, namely the ratio water/binder, the type and percentage of superplasticizer and the mixing procedure. The water/binder ratio (w/b) tested was 50% in weight (Table 1). According to the bibliography and particularly following the recommendations proposed by Valluzzi [6], a minimum value of water/binder = 55% (in weight) should be used, although in this case only 50% was used due to the presence of the superplasticizer.

During our experiments it seemed virtually impossible to create a reasonable injectable grout without the use of superplasticizers (analogous results were obtained by Valluzzi [6]), since the amount of required water was so high that the stability became problematic. After various preliminary attempts [14] with different brands and percentages, a polycarboxilate (Glenium SKY 617) produced by BASF was chosen.

3.3. Porous media for injection tests

Injectability tests were performed to study the penetrability of the grouts. Since it is hard to reproduce a real masonry, masonry samples were simulated by combining three different crushed limestone sands and three different crushed brick (Fig. 1). In order to simulate masonries with different permeabilities, five different grain size media types were adopted (Table 2).

According to Van Rickstal [7], the internal structure of the masonry, the permeability, the crack size distribution and the moisture content are the most important properties of the masonry with regard to injectability. The total porosity of each porous media type was evaluated by measuring the volume of water that could be filled inside each cylinder (Table 3). As the grout is a non-Newtonian fluid, the volume that can penetrate inside the porous media is much smaller.

Based on the study of some authors [15–17], some parameters were adopted (Table 3) to characterize the different porous media. These parameters are: the average voids size (which correspond to d_{50} – the diameter through which 50% of the total mass is passing) [4], as well as the parameter d(90) and d(10) (respectively the diameter through which 90% and 10% of the total mass is passing). From Table 3, it is noticed that the difference in values for the parameters presented is low and no trend is observed between the limestone sand and crushed brick porous media.

Through the mercury intrusion porosimetry technique (MIP) was studied the water absorption capacity of each porous medium.