Methodology for in situ application of hydraulic grouts on historic masonry structures. The case of the Katholikon of Dafni Monastery

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ABSTRACT: Grouting can be a durable and mechanically efficient intervention technique, not only when the grout composition is suitably designed, but also when the technique is correctly implemented following an adequate methodology. Such a methodology has been developed for the in situ application of grout in the Katholikon of Dafni Monastery in Athens. Hereby are presented the main features of this methodology. Apart from the information regarding the masonry preparation for grouting, the necessary quality control of the grout prepared at the worksite and the injection process, the importance of collecting specific data during the injection process, which allow monitoring the movement of the grout into the masonry and estimating the grout volume consumed in the masonry, is underlined.

1 INTRODUCTION

The Byzantine monastery of Dafni, already inscribed in the world heritage list of UNESCO, is one of the most important monuments of middle Byzantine period, famous worldwide for the excellent mosaics of its 11th century Katholikon (Delinikolas et al. 2003). All the structures of the monastic complex and especially the Katholikon (main church of the Monastery) have suffered severe damage during the September 1999 earthquake that affected the region of Attica. Numerous cracks have appeared both on the three leaf stone masonry walls and the vaulted roof, as well as on the mural mosaics situated on their internal faces (Miltiadou et al. 2004).

On the basis of the results of a series of research programs, investigations and the structural restoration study realized by the competent authorities of the Hellenic Ministry of Culture, the application of adequate hydraulic grouts injections was decided for the repair and strengthening of the Katholikon (Miltiadou et al. 2003) as well as for the in situ conservation of its mural mosaics (Chryssopoulos et al. 2003).

Before the application of this specific technique to the Katholikon of Dafni Monastery, extended experimental investigations were carried out in order (a) to design adequate grout compositions, (b) to assess the mechanical properties of masonry elements, before and after grouting, and finally (c) to evaluate the effect of grouting on their mechanical properties (Vintzileou et al. 2004, 2006, Miltiadou et al. 2006, Kalagri et al. 2007, Miltiadou et al. 2007).

However, the proper design of a grout composition and its application cannot ensure on their own the successful completion of the grouting intervention in situ. Evidently, particular care has to be taken of the adequate execution of the whole intervention on a daily basis. To this end a specific application methodology has been developed, based on the experience gained from applications to various monuments and, in particular, to the Columns of the Opisthodomos of the Parthenon of the Athens Acropolis (Miltiadou et al. 2005). This methodology has been proposed by the structural restoration study (Miltiadou et al. 2003), later tested on the aforementioned wallets (Miltiadou et al. 2006) and finally applied in situ, during the structural restoration works.

The methodology comprises specific instructions for a) the preparation of masonry for grouting and the survey of exit and entrance tubes, b) the mixing procedure, the equipment and the quality control of the grout prepared at the worksite, c) the injection process and the data to be collected, and d) the elaboration of these data in order to monitor the grout movement in the
The design of high injectability grouts was applied on the basis of the methodology proposed by Miltiadou & Tassios (2006). First, were taken into account the performance requirements deriving from the structural restoration study (Miltiadou et al. 2003), and then the following target values were set for the basic mechanical properties of the grouted masonry: tensile strength approximately double that of the masonry before grouting, and compressive strength approximately equal to 3.0 MPa.

On the basis of the available literature (Vintzileou & Tassios 1995, Tassios 2004), it was estimated that the compressive strength of the grout at the age of six months should lie between 6MPa and 10MPa; a grout flexural strength of the order of 2-3MPa was required. In addition, the physical-chemical properties of the raw materials should be selected in a way that the durability of the structure and its precious mosaics would not be jeopardized. Finally, the grouts should have high injectability capacity, so that, under low pressure (~0.075 MPa), they enter and fill fine voids and cracks, with a nominal minimum width (W$_{\text{nom}}$) equal to two tenths of millimeter.

According to literature (Miltiadou 1990, Toubakari 2002, Valluzzi 2000) and previous investigations carried out by the Directorate for Technical Research on Restoration (DTRR, Hellenic Ministry of Culture), two main categories of grouts could satisfy injectability, strength and durability requirements: (i) ternary grouts composed of a low cement content (30%), lime 25% and pozzolan 45%, and (ii) hydraulic lime – based grouts.

Thus, various grout mixtures, belonging to the above two categories, were designed and tested (in order to assess their physical, chemical and mechanical properties) at the laboratory of DTRR. The use of white Danish cement in the ternary grout was chosen, due to its fineness, low alkali content and high sulphate resistance. As far as the hydraulic lime – based grouts are concerned, various types of natural hydraulic limes (classified by EN 459 as NHL2, NHL3.5, NHL3.5-Z and NHL5), were tested in the laboratory of DTRR, and grout formulations, with or without superplastizer, were examined. The main results of the research are reported in Kalagri et al. (2007).

In order to determine the injectability characteristics, the penetrability, fluidity and stability of the suspensions were fully examined in various water/solids ratios, with or without additives. The grouts were prepared by using an ultrasound dispersion mixer, assisted by a mechanical device of low turbulence. The standardized sand column test method (NF P18-891, pr. EN 1771), was used to check the penetrability and fluidity, along with the standard apparatus for testing the fluidity (NF P18-358) and stability (NF P18-359) of the suspensions. In each case, a time limit of 50 sec for the sand column penetrability test ($T_{36}$); an efflux time of 500 ml of grout ($t_{ef}=4.7$) shorter than 45 sec (Marsh cone $d = 4.7$ mm fluidity test), and a maximum acceptable limit of 5% for the bleeding were set initially (Miltiadou 1990) for the laboratory investigations.

The compositions presenting satisfactory injectability capacity were further tested to evaluate their behavior to salt decay and estimate their mechanical characteristics (compressive and flexural strength). Six alternative grout formulations presenting similar injectability, were injected at low pressure into twenty eight cylindrical specimens, simulating the infill material of three-leaf stone masonry, which were then subjected to compression in different hardening ages (Kalagri et al. 2007). After comparative evaluation of the results, two grout compositions (the ternary grout and a natural hydraulic lime NHL5-based grout) fulfilled simultaneously the injectability, the strength and durability requirements. Therefore, they were selected to be applied to six three-leaf stone wallottes, simulating the masonry of the upper parts of the monument, subjected either to compression or to diagonal compression up to their maximum resistance, before and after grouting (Vintzileou et al. 2006, Miltiadou et al. 2006).

The substantial (compressive and tensile) strength enhancement of wallottes, the rather ductile behaviour under diagonal compression (compared to that of masonry grouted with the ternary grout), the physicochemical properties that ensure a durable intervention and contribute to the protection of mosaics led to the selection of the natural hydraulic lime-based grout for the application in the Katholikon of Dafni Monastery. Given that these hydraulic limes are characterized by a relatively high percentage of available lime, the addition of pozzolan, in adequate proportion, is expected to have beneficial effect. Thus, in order to improve the hydraulic lime based grout, the addition of fine natural pozzolan ($d_{\text{max}} < 75 \mu m$) in various proportions was investigated. The addition of a small percentage of pozzolan (10%) was decided, on the basis of additional data deriving from porosity measurements, salt.
Table 1. Composition and injectability characteristics of the selected grout measured in the laboratory and in situ at the first pilot preparation.

<table>
<thead>
<tr>
<th>GROUT COMPOSITION</th>
<th>NHL5 (St Astier)</th>
<th>Pozzolan</th>
<th>Superplasticizer (1), (2)</th>
<th>Water (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90%</td>
<td>10%</td>
<td>1%</td>
<td>80%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GROUT PROPERTIES</th>
<th>In lab</th>
<th>In situ</th>
</tr>
</thead>
<tbody>
<tr>
<td>T36 (sec) – Sand column</td>
<td>19–22</td>
<td>19–22</td>
</tr>
<tr>
<td>1.25/2.50 mm (voids)</td>
<td>0.2–0.4 mm</td>
<td>0.2–0.4 mm</td>
</tr>
<tr>
<td>Bleeding</td>
<td>&lt;1%</td>
<td>1%</td>
</tr>
<tr>
<td>Apparent viscosity – $t_{d=4.5}$ (sec)</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>Apparent density (gr/cm$^3$)</td>
<td>1.5050</td>
<td>1.4978</td>
</tr>
</tbody>
</table>

(1) % of the solid phase of the grout.
(2) superplasticizer based on polycarboxylic ether.

3 APPLICATION METHODOLOGY

The application of grouts comprises the preparation of the mix to be injected, the execution of the injections and, finally, cleaning and finishing the surface of the grouted masonry.

The in situ application of injection grouting techniques in the Katholikon of Dafni Monastery had to be implemented without removing the old pointing mortars that have survived on the external façades, and, of course, without removing the mural mosaics decorating its interior. Figure 1 presents the historical pathology of the external east façade of the Katholikon of Dafni Monastery. Uncolored joints still preserve the old Byzantine pointing mortars (Delinikolas et al. 2003). In all the uncolored joints, the old byzantine pointing mortars are still preserved in situ. In Figure 2 a fissured mosaic in the upper part of the internal east façade is shown. In order to protect these valuable elements, the injections had to be realized using entrance and exit tubes of small diameter in these areas, while the pressures developed had to be low, and absolutely controlled, so that not to exceed the 1 atm. Furthermore, a methodology of monitoring the movement of the grout in the masonry had to be applied in order to ensure that the grout reached and filled the numerous cracks and fissures. To achieve these goals, a specific application methodology has been proposed by the relevant study (Miltiadou et al. 2003), to be followed during the structural restoration works in the...
Katholikon of Dafni Monastery. The methodology has been tested and further refined during the injections of the aforementioned wallettes, and then applied to the whole injection project for the repair of the monument’s masonries. The most important aspects of this methodology are presented below, together with a synthesis of indicative quality control data, concerning its in situ application in the Katholikon of Dafni Monastery.

3.1 Preparation of the masonry

a) After the removal of the renderings from the interior of the building, all the areas that did not conserve old mortars were prepared for deep re-pointing, while all the deteriorated old mortars were consolidated in situ by competent Conservators. Stone or brick or titanium stitches were installed in order to key the areas with severe cracks, dislocations or local reconstructions. During this first step, a refinement of the detailed survey (Delinikolas et al. 2003), presenting the joints conserving old mortars in the external façade of the monument, was made, and the possible positions for drilling holes for the installation of grouting tubes were clearly identified, as well as their possible respective size, ranging between 1 to 10 mm.

b) A similar and more detailed procedure has been undertaken by the competent Conservators for the survey and documentation of the state of preservation of the mural mosaics including: historical and recent pathology, detachments of substrata presented on manual sonic maps or GPR maps, etc (Chryssopoulos et al. 2003, Côte et al. 2004, 2008). In this way the location of adequate areas for the installation of grouting fine tubes on the mosaics was defined.

c) On both faces of masonry and at adequate distances, holes were drilled in mortar joints, in order to form a kind of grid. Given the fact that the thickness of the walls is \( \sim 80 \) cm, the distance of consecutive holes has to be between 0.5 to 1.0 m. The nodes of the interior grid should be arranged at mid-distances of those of the exterior grid, both horizontally and vertically. Half of the holes should be located at a depth equal to \( \frac{1}{3} \) of the masonry thickness, and the rest of them to \( \frac{1}{2} \) of the masonry thickness. All the above arrangements are necessary because they provide the possibility, not only to inject the grout, but also to ensure the air exit and the control of the grout overflow. Thus, the holes had to be realized in such a way so as to reach (i) the interface between external leaves and the infill material, (ii) the infill material of the three leaf masonry and (iii) the interior of the path of the crack.

In areas conserving old mosaics or frescoes or old mortars, a denser grid of holes was formed on the internal façade of the masonry (when it was not decorated). In case of decorated internal areas, it has to be noted that it is essential to drill the maximum possible number of holes, and install tubes (mainly tubes of small diameter, used as exits) in order to avoid further damages, due to grout pressure or uncontrollable leakage of the grout, and follow the grout path from this face of the structure.

d) Subsequently, re-pointing or sealing of cracks has taken place. Simultaneously, transparent plastic tubes of a diameter of 1–10 mm (depending on the already predefined diameter of the holes) were installed into the drilled holes, and sealed to the wall using the same mortar as that for re-pointing (usually a lime-pozzolan based mortar). Both on the masonry and the mosaics, all kind of cracks, including the small and fine ones were sealed, in order to allow efficient injection, and avoid uncontrollable leakage. On the mosaics, fine tubes of adequate diameters were placed at two depths, 1.5 cm and 3 cm, in order to reach and control the eventual masonry grout flow behind the substrata and tesserae, respectively. In cracked areas, when possible, tubes were installed to a certain depth in order to create exits for the masonry grout. The protruding part of all kinds of transparent plastic tubes should be of approximately 0.5 m. The inner part of the tubes should be perforated at two positions, while the edge of the tube should be cut inclined (\( \sim 45^\circ \)), to allow the grout flow through masonry, even if the edges of tubes are in contact with an in situ material. In Figures 3 and 4 examples of preparation for grouting of masonry and mosaics are shown respectively.

Plastic tubes reaching different depths in masonry should be adequately marked and reported in drawings or sketches. They should also be numbered consecutively from bottom to top of masonry. In the case of the Katholikon of Dafni Monastery, due to its large dimensions and in order to avoid confusion resulting from this way of numbering (tubes with numbers consisting of many digits), a predefined way of tube numbering was followed.
A special code was adopted, comprising letters, relating to the region of the masonry, accompanied by numbers in an ascending sequence. The numbering and surveying of grouting tubes is extremely useful, as it is absolutely necessary to record all the entrances and corresponding exits during grouting, together with the volume consumed per entrance, and the pressure variations at the entrance of the grout, in order to be sure that the damaged areas of the monument have been reached and filled with the grout. Finally, perforated plastic bags were placed on the edge of each tube, in order to protect the wall from grout leakage, and avoid extensive surface cleaning, thus protecting the patina of external facades.

3.2 Worksite equipment

The main characteristics of the grouting equipment used in the worksite were in accordance with the requirements prescribed in the study (Miltiadou et al. 2003) and consisted of the following units: a high turbulence colloidal mixer, an agitator, a grouting pump equipped with control system and manometer, all the necessary grout lines, a grout recorder, nozzles of adequate diameter, proportionate to the ones of the entrance tubes. A manometer and a triode valve were installed near the nozzle, in order to control continuously the pressure in the entrance of the wall, and be able to take immediately corrective measures in case of a sudden overpressure. Further description of the worksite equipment is beyond the scope of this paper. However, it is very important to underline the importance of using a grout recorder when injecting masonry structures. This equipment permits to record automatically and in function with time, the pressure and the flow rate, as well as, when suitably programmed, the grout volume consumed during a given period of time or even per each injection entrance. It has to be noted that this recorder has to be specially manufactured for masonry structures (due to the relatively low flow rates and pressure values).

3.3 Grout preparation and injection process

In general, before mixing starts, all materials have to be separately weighted and be ready to be introduced in a high turbulence colloidal mixer (1,500–2,000 rpm), as the mixing time is rather short to allow for delays. In this case, the water and the superplasticizer were placed first into the mixer and then the solid materials followed, in the order of increasing grain size (pozzolan, hydraulic lime). The mixing time was in total 4 minutes (2 min/solid constituent). As the mixing procedure is a very important parameter for the production of a stable and fluid grout, the accurate timekeeping was underlined. Another parameter that affects the injectability characteristics of the grout is the ambient temperature. It has to be mentioned that the whole grouting procedure was stopped, when this temperature reached extreme values (<10°C and >35°C).

After mixing, the grout was discharged into an agitator, so as to ensure a continuous process of injection. Before starting the grouting application on the monument, a trial grouting preparation was performed, in order to check the skills of the technical staff, the adequacy of the equipment, as well as the injectability characteristics of the grout. In this way, it was ensured that the grout prepared in situ presented the same characteristics with those of the grout prepared and investigated in the laboratory (Table 1).

Injections started from the bottom (proceeding along the length of the element to be grouted) to the top. When grouting was in process in one entrance tube, the grout supply should not be interrupted unless pressure at the nozzle reached the maximum accepted value of 0.5–1 atm. Interruption of the injection before exhausting the potential of a tube to consume more grout, may result in failure of filling all the interconnected voids. As a matter of fact, if one tries to repeat injection from an entrance abandoned even a few minutes earlier, injection is rarely feasible, as the entrance has already been blocked. During injection, pressure was constantly checked at the entrance to the masonry. Its upper limit should remain within the range of 0.5–1.0 atm. Only in lower areas, without any old mortar or mosaics or frescoes, the pressure was allowed to reach 1.5 atm, while in the areas bearing heavily damaged mosaics, the lower upper limit of 0.5 atm was kept. In cases of sudden overpressure, the use of the triode valve permitted the immediate deviation of the grout to a plastic vessel, thus avoiding harming the masonry or the connections of the pipes of the system. During the whole procedure, competent Conservators were present, when grouting was applied in areas adjacent to mosaics or frescoes.

After the inflow and/or outflow of the grout had been terminated, the tubes were firmly tied and fixed.
upwards, since grout should be kept under pressure inside masonry until its hardening is completed. In some cases, when overflow of grout had taken place at locations that no tubes had been installed, the leakage was stopped with the help of pozzolan powder, or an adequate paste (pozzolan paste, clay paste or paper pulp, etc.). Cement or lime was absolutely avoided. After that, the masonry was immediately cleaned.

4 GROUTING QUALITY CONTROL

4.1 Grout quality control tests

Fluidity, stability and apparent density of the mixture were tested at the worksite at least twice per day, in order to ensure the quality of the intervention. All the tests results were noted on a specially prepared daily calendar, together with the total number of batches prepared.

4.1.1 Fluidity – Apparent viscosity test

The efflux time of 100 ml, 500 ml and 1000 ml of grout through a Marsh cone having a nozzle-diameter equal to 4.7 mm was measured. The total efflux time of 500 ml of grout had to be of the order of 25 sec, according to the limits set for this specific case (see also § 2). In Figure 5 the average values of grout apparent viscosity measured in situ after mixing (twice per day, during the whole grouting period, 20 weeks in total), are presented. These values were very close to the values of the laboratory and pilot tests, and lower than 25 sec. The small variations were daily assessed, together with the bleeding and density results were linked to worksite conditions (temperature, new delivery of superplastisizer, etc).

4.1.2 Stability – Bleeding test

The grout was sealed into three transparent volumetric cylinders of 100 ml (diameter 25 mm, height 25 cm) and after remaining in a shadowed place for three hours, bleeding water volume was measured. The grout bleeding was given by the average value of the three measurements, and had to be <3% and in no case >5%, according to the limits set for this specific case (see also § 2). The measured bleeding variations were considered generally acceptable, given the fact that the grout was prepared in the worksite (Fig. 6), and taking into account that, the first six weeks, the ambient temperature was relatively high due to summertime.

4.1.3 Stability – Apparent density test

After mixing, several measurements of apparent density versus time were made. Apparent density was determined by weighting known grout volume (50 ml), collected from the same position of a 2000 cc volumetric tube (usually at the 2/3 of its height). The apparent density values measured in situ had to be 1.50 gr/cm³, with an acceptable variation of ±1%. As shown in Figure 7, all density values measured in situ during the whole project satisfied this limit.

Furthermore, except for the aforementioned quality tests of stability and fluidity, of the grout after
Table 2. Apparent density values of grout outflows.

<table>
<thead>
<tr>
<th>Grout Density (gr/cm³)</th>
<th>No. of entrance tube</th>
<th>No. of exit tube</th>
<th>After mixing</th>
<th>Outflow</th>
<th>Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AE74</td>
<td>AE78</td>
<td>1.4885</td>
<td>1.5254</td>
<td>2.48</td>
</tr>
<tr>
<td>AM18</td>
<td>AE178</td>
<td>AE178</td>
<td>1.5056</td>
<td>1.5298</td>
<td>1.61</td>
</tr>
<tr>
<td>AM288</td>
<td>AM276</td>
<td>AM276</td>
<td>1.5013</td>
<td>1.5126</td>
<td>0.75</td>
</tr>
<tr>
<td>BE68</td>
<td>BE65</td>
<td>BE65</td>
<td>1.4936</td>
<td>1.5024</td>
<td>0.59</td>
</tr>
<tr>
<td>BE86</td>
<td>BE3</td>
<td>BE3</td>
<td>1.4858</td>
<td>1.5015</td>
<td>1.06</td>
</tr>
<tr>
<td>BE517</td>
<td>BE493</td>
<td>BE493</td>
<td>1.5022</td>
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<td>1.45</td>
</tr>
<tr>
<td>NE36</td>
<td>NE43</td>
<td>NE43</td>
<td>1.5023</td>
<td>1.5298</td>
<td>1.83</td>
</tr>
<tr>
<td>KP405</td>
<td>KP385</td>
<td>KP385</td>
<td>1.4989</td>
<td>1.5143</td>
<td>1.03</td>
</tr>
<tr>
<td>KP404</td>
<td>KP328</td>
<td>KP328</td>
<td>1.4983</td>
<td>1.5196</td>
<td>1.42</td>
</tr>
<tr>
<td>TH431A</td>
<td>TH422</td>
<td>TH422</td>
<td>1.5048</td>
<td>1.5152</td>
<td>0.69</td>
</tr>
<tr>
<td>D45/1155</td>
<td>X260</td>
<td>X260</td>
<td>1.5048</td>
<td>1.5068</td>
<td>0.13</td>
</tr>
<tr>
<td>T358</td>
<td>T361</td>
<td>T361</td>
<td>1.4982</td>
<td>1.5045</td>
<td>0.42</td>
</tr>
<tr>
<td>K251</td>
<td>K260</td>
<td>K260</td>
<td>1.5038</td>
<td>1.5036</td>
<td>−0.01</td>
</tr>
<tr>
<td>K116</td>
<td>K109</td>
<td>K109</td>
<td>1.4809</td>
<td>1.4953</td>
<td>0.97</td>
</tr>
</tbody>
</table>

mixing, the apparent density of the grout collected from selected exit positions was also controlled, where it was possible (42 grout outflows were checked). The acceptable density variation was set at <5%.

This experimental procedure is essential for controlling the stability, fluidity and penetrability of the grout. Table 2 presents indicative density values of grout after mixing, and of grout selected from corresponding exits. It has to be noted that even in the cases the exit of grout had been taken place at a distance of two or three meters, the variation of density was retained at <5%. This has shown that the grout has retained its properties during its movement through the porous masonry materials, thus confirming both the quality of the grout (e.g. segregation or water loss due to absorption, etc) and of its application.

4.1.4 Mechanical properties test
Flexural and compressive strengths of the grout were tested at the age of 28, 90, 180 days etc, on prismatic specimens (40 × 40 × 160 mm), which were prepared at the worksite at certain time intervals. Table 3 summarizes the results of mechanical properties on the specimens tested until now. Taking into account that the specimens have been taken and cured in the worksite the very first days, the strength values are considered satisfactory, compared to those of the laboratory study (Miltiadou et al. 2007).

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>28</th>
<th>90</th>
<th>180</th>
<th>270</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural strength (MPa)</td>
<td>1.01</td>
<td>2.80</td>
<td>2.41</td>
<td>2.20</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>2.02</td>
<td>5.26</td>
<td>6.04</td>
<td>6.33</td>
</tr>
</tbody>
</table>

Figure 8. External east façade – Schematic presentation of grouting consumption.

the grout are recorded on a time basis, together with any change of pressure at the entrance to the wall. All these data are noted on specially designed daily calendars, with reference to the area of grouting application. These manually collected data and those collected by the Grout Recorder (pressure, flow rate and grout volume consumed) are then combined, and the grout volume corresponding to the various groups of entrances and exits is determined, together with the total volume of the grout consumed during the corresponding day. All the recorded data are organized in tables and after appropriate processing the volume of the grout consumed into the masonry is extracted. Then the data collected are reported on the aforementioned series of drawings presenting the positions and numbers of the grouting tubes. Thus a good estimation of the grout movement and consumption in relation to the various regions of the structure can be achieved. The aforementioned procedure was followed during the whole project in the Katholikon.

In Figures 8 and 9 the corresponding drawings for the internal and external façade of the east wall of the monument are presented. One can easily recognize the areas with high grouting consumption, and those with a lower one. The tubes with no consumption are also noted. Thus for this specific wall the volume of the grout consumption was estimated to reach 6.5% of the total volume of the wall. In the case of the west wall of the monument, which was reconstructed during past restoration interventions (Delinikolas et al. 2003), the

4.2 Application quality control
In order to control better the injection process and to ensure the quality of the intervention, during the whole project, entrances and corresponding exits of...
estimated grout consumption attaining 2.5% of its total volume. The elaboration of data is still in progress.

Furthermore, such drawings, consist the “as built-drawings” of this non visible intervention, and give the possibility of an overall assessment of the grouting intervention. In this way, grouting process is better monitored during its application and the quality of the intervention is ensured.

The effectiveness of the grouting interventions should be tested also a certain period after the accomplishment of the works, by applying appropriate non-destructive techniques, in combination, if permitted, with semi-destructive techniques. In earthquake prone areas, the comparison, before and after grouting, of the records of a seismic monitoring system installed on the structure can also give important information about the grouting effect.

In the case of the Katholikon of Dafni Monastery sonic transmission measurements and sonic tomographies were undertaken in selected areas. The results obtained until now confirmed the efficiency of grouting (Côte et al. 2004, 2008), thus proving that both the grout and its application were adequately designed and implemented. Finally, the seismic monitoring data (before and during grouting), have also shown the grouting effect on the overall behaviour of the monument (Mouzakis et al. 2008).

5 CONCLUSIONS

The holistic design of grouts based on rational criteria, laboratory and in situ pilot tests, led to an optimum composition, exhibiting the adequate stability, fluidity and injectability characteristics, as proven by the in situ quality control tests.

The proposed grouting application methodology gives the possibility for a more rational and fully controlled implementation of injections, not only to ordinary structures, but also to important monuments bearing mosaics, frescoes and old mortars, that have to be preserved in situ.

The whole procedure and quality controls can be easily applied by qualified scientific and technical personnel, and allow for corrective measures to be taken during the project. Moreover, the collection and elaboration of all the proposed data during the works is absolutely necessary for an overall assessment of the grouting application.

This assessment should be further supported, by means of non destructive techniques especially in case of important historic structures.

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