ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Engineering Structures ▮ (▮▮▮▮) ▮▮▮–▮▮▮

ENGINEERING STRUCTURES

www.elsevier.com/locate/engstruct

Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime-based grouts

Elizabeth Vintzileou[a,*], Androniki Miltiadou-Fezans[b,1]

[a] *Department of Structural Engineering, National Technical University of Athens, Laboratory of Reinforced Concrete, 5, Iroon Polytechniou Str., GR 15773 Zografou, Greece*

[b] *Directorate for Technical Research on Restoration, Hellenic Ministry of Culture, 8-10 Tziraion str., GR 11742 Athens, Greece*

Received 6 December 2006; received in revised form 11 September 2007; accepted 5 November 2007

Abstract

Masonry made up of two exterior leaves of stone masonry with the space between them filled with poor quality mortar and large size aggregates is quite common in structures belonging to the built cultural heritage. Grouting of this type of vulnerable masonry with cement-based grouts (cement content: 50–75%wt.) was proven mechanically efficient. However, the need to protect frescoes, mosaics and decorative elements, as well as the need to avoid problems of durability encountered due to the high content of cement, led to the development of grouts with reduced cement content, as well as to hydraulic lime-based grouts. In this paper, the effect of ternary grouts (mixes of cement [∼30%], pozzolan and hydrated lime) and hydraulic lime-based grouts on the compressive and on the shear strength of three-leaf stone masonry is experimentally investigated. Although the mechanical properties of the applied grouts are substantially lower than those of grouts with higher cement content, homogenization of masonry is achieved leading to a substantial improvement of the mechanical properties of masonry.

Keywords: Historic masonry; Three-leaf stone masonry; Grouting; Ternary grout; Hydraulic lime-based grout; Injections; Mechanical properties

1. Introduction

Three-leaf masonry is one of the most vulnerable types of masonry. Separation between the external leaves and the filling material, occurring due to ageing and/or due to various actions, leads to the independent action of each leaf. The slenderness of the external leaves being increased after separation, their bearing capacity to both in-plane and out-of-plane actions is reduced. Grouting using a highly injectable and stable mix is one of the most appropriate techniques for strengthening this type of masonry. In fact, an adequately designed hydraulic grout that may fill even small voids and cracks (as narrow as 0.20–0.30 mm) improves the mechanical properties of each individual leaf; it also ensures the joint action of the three leaves, thus alleviating the vulnerability of this type of masonry. Cement-based grouts constitute the first application of grouts to masonry structures. They were initially pure cement grouts. However, it was proven that their injectability properties were inadequate for filling the small size voids and cracks of historic masonries (because of clogging). This drawback of pure cement grouts led Paillère et al. [15–17], Aitcin et al. [2] and Miltiadou [8] to the addition of ultra fine materials (on the basis of specific granularity criteria). In this way grouts of both high injectability and adequate mechanical properties were reached. On the other hand, the need for a wide range of mechanical properties of grouts to be available (in order to serve the specific needs of each historic structure) was recognized. Thus, binary grouts (mixes of cement and hydrated lime, natural or artificial pozzolans, silica fume, etc.) and ternary grouts (cement, hydrated lime and natural or artificial pozzolans) were developed. The cement percentage was varying mainly between 50% and 75%. Grouts of this type were proven to be efficient in enhancing the mechanical properties of masonry to which they are injected [8,22]. Nevertheless, mechanical tests [22] did not confirm the need for grouts with high cement content, as the strength enhancement of masonry is not proportional

* Corresponding author. Tel.: +30 210 7721272; fax: +30 210 7721273.
E-mail addresses: elvintz@central.ntua.gr (E. Vintzileou), amiltiadou@culture.gr (A. Miltiadou-Fezans).

1 Tel. +30 210 9240527; fax: +30 210 9240511.

0141-0296/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2007.11.003

to the compressive strength of the grout. Furthermore, the use of grouts with reduced cement content or the use of hydraulic lime-based grouts is expected to be beneficial for the protection of mosaics, frescoes and decorative elements on masonry surfaces, as physical–chemical incompatibility with the *in situ* materials is prevented [5,6]. Thus, enhanced durability of the intervention is expected. All this led to the development and investigation of alternative mixes, namely ternary grouts with lower cement content (30–50%wt.), as well as hydraulic lime-based grouts. The mechanical adequacy of ternary grouts was proven experimentally by Toumbakari [19], whereas tests by Valluzzi [21] have shown that hydraulic lime-based grouts may also lead to the significant enhancement of mechanical properties of three-leaf stone masonry. Nevertheless, (a) the limited number of available experimental results on the efficiency of ternary and hydraulic lime-based grouts, as well as (b) the specific needs of restoration of an important Byzantine monument imposed the design and execution of an experimental programme. The purpose of this programme was to select appropriate grout mixes for the restoration of the Katholikon (main church) of the Dafni Monastery [20]. In this paper, the obtained experimental results are presented and commented upon.

Photo 1. The Katholikon (main church) of Dafni Monastery.

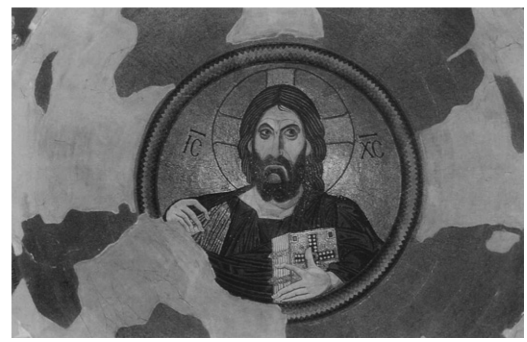

Photo 2. The mosaic of Pantocrator.

2. Construction type of masonry

The Katholikon of Dafni Monastery (Photo 1), famous for its mosaics (Photo 2), has suffered severe damages during the September 1999 earthquake (Magnitude 6.0 on the Richter scale) that affected the region of Attica [9]. Within a series of research programs (undertaken by the Directorate for Technical Research on Restoration, Hellenic Ministry of Culture, in cooperation with the Laboratory of RC, Nat. Technical University of Athens) with the aim to acquire information that is necessary both for the assessment of the monument and for the subsequent stage of interventions, considerable effort was devoted to the identification of the construction type of masonry, since it constitutes a key parameter for the assessment of mechanical properties of masonry and by way of consequence of the monument as a whole. Furthermore, decision-making regarding intervention techniques (e.g. feasibility of grouting), design of adequate intervention materials and estimation of post-intervention mechanical properties strongly depend on the construction type of masonry.

For this purpose, radar and boroscopy were applied in a systematic way. The in-depth geometry of the perimeter stone masonry was rather accurately identified [23]. As anticipated, the approximately 0.80 m thick masonry of the upper part of the monument is a three-leaf masonry (externally unplastered, with the interior face plastered and in large part covered with mosaics); it presents some peculiarities, namely: (a) As shown in Fig. 1, the two exterior leaves are of unequal thickness (average thickness of the external and internal leaf equal to 200 mm and 280 mm respectively), (b) The external leaf is made of bigger stones than the internal one, whereas solid bricks are arranged along both the horizontal and vertical joints in the external masonry leaf. The percentage of bricks in the internal leaf is substantially smaller and their pattern is random, (c) The thickness of stones in both leaves is varying, both in-length and in-height of walls. Thus, the thickness of the intermediate filling material (made of small size stones, fragments of bricks and mortar) is also varying both horizontally and vertically. It has to be noted that all available experimental data on three-leaf masonry were obtained from testing wallettes in which both the external leaves were identical in geometry, of the same (constant in-height) thickness.

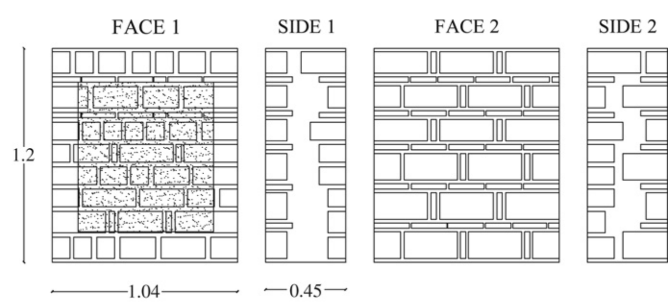

Fig. 1. Geometry of specimens subjected to compression (dimensions in [m]).

During the extensive repair works undertaken at the end of the 19th century, when some parts of the monument were rebuilt [10,11], the original construction type of masonry was followed. Mosaics belonging to collapsed or heavily damaged structural elements were removed and replaced after reconstruction. The technique used for bonding the mosaics onto masonry was different than that applied by the Byzantine artists [4]; this was

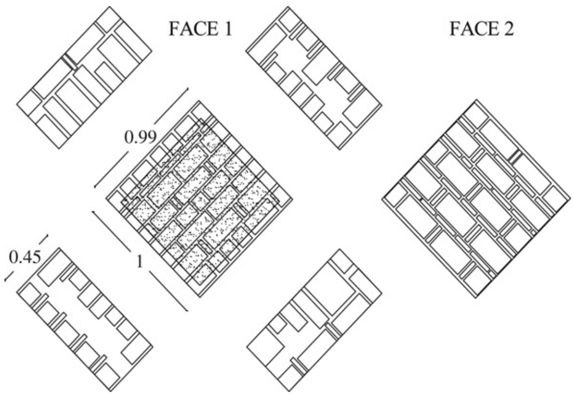

Fig. 2. Geometry of specimens subjected to diagonal compression.

taken into account in the testing program, as explained further on.

3. Testing program

3.1. Geometry of specimens

The geometry of wallettes was chosen to simulate the upper and more vulnerable part of the perimeter masonry in the Katholikon of the Dafni Monastery. In order to avoid scale effects, a scale of almost 2:3 was selected. Six wallettes were constructed. Three of them (Wallettes No. 1, 2 and 3) were tested in compression, the remaining three (Wallettes 4, 5 and 6) were subjected to diagonal compression. The overall dimensions of Wallettes 1 to 3 (Fig. 1) were as follows: Length = 1.0 m, height = 1.2 m, thickness = 0.45 m, average thickness of external leaves = 192 mm and 135 mm, average thickness of internal leaf (filling material) = 123 mm. The respective geometrical data for Wallettes 4 to 6 (Fig. 2) were as follows: Length = height = 1.0 m, thickness = 0.45 m, average thickness of external leaves = 182.5 mm and 129 mm respectively, average thickness of internal leaf (filling material) = 138.5 mm.

3.2. Materials and construction of specimens

In order to simulate the behaviour of the in situ masonry, the materials used for the construction of wallettes were carefully selected. Several types of stones were identified in the monument. Nevertheless, the most commonly used types were fossiliferous marl limestone and solid sandy marl sandstone. A travertine having similar properties to those of the in situ main type of stones (Table 1) was used for the construction of wallettes.

The solid bricks used for the construction of wallettes were of mean compressive strength equal to 17.0 N/mm^2 (compared to approximately 15.0 N/mm^2 for the in situ bricks).

Based on the type of mortar encountered on the monument, a lime-pozzolan mortar was designed for the construction of wallettes with a mixed aggregate matrix composed of siliceous river sand and limestone gravels. More specifically, lime putty and natural pozzolanic additive from the Milos island were used as binding materials. The aggregates were siliceous river sand and coarse limestone aggregates with a maximum diameter of 1.5–2.0 cm. The binder to aggregates ratio was 1/1.5. The lime to pozzolanic additive ratio was 1/1.5 as well. A water to binder ratio (w/b) of 0.65 was selected so that to obtain mortars with a consistency of 15.5–16.0 cm. Specimens taken from the mortar during the construction of wallettes were tested at 1, 3, 6, 9, and 12 months after hardening. Since the wallettes were tested approximately three months after their construction, the tensile strength due to flexure and the compressive strength of the mortar at the same age are given here: 1.58 MPa and 4.35 MPa respectively.

Table 1
Properties of stones in the monument; properties of travertine used for the construction of specimens

Stone type	Compr. strength (N/mm^2)	Bulk density (g/cm^3)	Abs. water (%ΔB)
Fossiliferous marl limestone	23.0	1.97	18.0
Solid sandy marl sandstone	21.8	1.93	9.0
Travertine	25.0	2.1	5.0

Photo 3. Wallette during construction.

The inner part of the wallettes was a mix of small stones (size 20–50 mm) and mortar (the one used for construction of the exterior leaves) in a proportion of 2/1. This mix was poured in layers without compaction to fill the space between the external leaves. An average percentage of voids for the filling material of approximately 40%, similar to that detected in situ, was calculated. The compressive strength of the filling material, measured on cylinders was approximately equal to 0.15 N/mm^2 at the time of testing the wallettes [7].

The specimens were constructed by experienced masons, according to the construction type identified in situ (Photos 3 and 4). They were cured wet for one month approximately.

Wallettes to be subjected to compression were constructed on a stiff steel base (Photo 5). An identical steel beam was placed on top of the wallettes after completion of construction (to allow for uniform distribution of the vertical load).

Wallettes to be subjected to diagonal compression were constructed in a vertical position resting on a steel plate, as well as on a stiff steel corner, placed at the left corner of the wallette. After curing, when the wallettes were transferred close

Please cite this article in press as: Vintzileou E, Miltiadou-Fezans A. Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime-based grouts. Engineering Structures (2007), doi:10.1016/j.engstruct.2007.11.003

Photo 4. Wallette during construction.

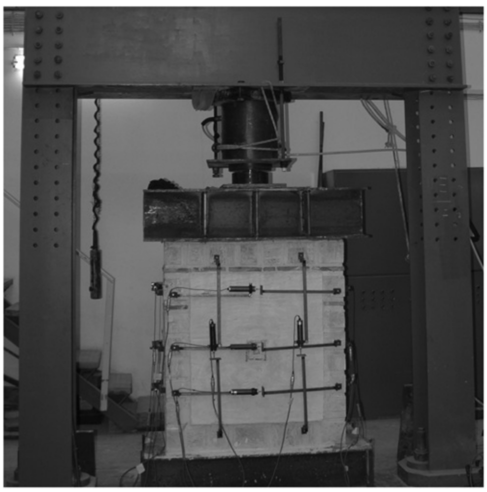

Photo 5. Test setup for wallettes in compression.

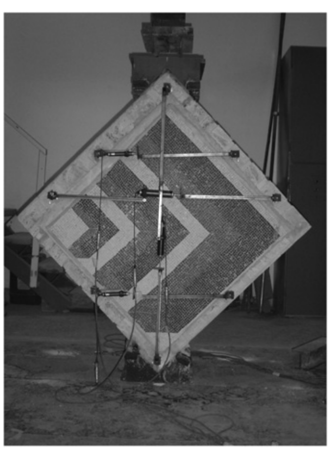

Photo 6. Test setup for wallettes in diagonal compression.

to their testing position, each specimen was rotated by 45° (anti-clockwise). The steel plate was removed and the specimen was resting on the stiff steel corner element (Photo 6). An identical steel element was placed (using mortar) on top of the specimen.

3.3. Mosaics

Following the techniques of placing mosaics on masonry, mosaics models were prepared and placed on the face of wallettes simulating the interior leaf of the masonry, in order to check whether there is an effect of the substrate of mosaics on the after damage grouting of masonry (essential for the protection of mosaics).

Three types of mortars were applied, as follows: (a) in Wallettes 1 and 4, Byzantine (lime–straw) mortar (simulating the composition of authentic mosaics substrate) was used, (b) in Wallettes 2 and 5, lime–cement mortar (similar to that of a mid-20th century intervention) was used, whereas in Wallettes 3 and 6, a natural hydraulic lime (NHL) mortar was used. This mortar was applied to simulate that revealed in the monument, as applied during the so-called “Novo” intervention.

Each substrate consists of two layers, the inner and the bedding layer, 3.5 cm and 1.5 cm thick respectively. The mosaics were prepared and placed on the wallettes (immediately after the completion of construction) by Conservators of the Directorate for the Conservation of Ancient and Modern Monuments of the Hellenic Ministry of Culture, specialized in mosaics.

3.4. Testing setup and measurements

In Photos 5 and 6, the test setup both for the wallettes subjected to compression and for those subjected to diagonal compression is shown. The load was applied through a hydraulic jack. The jack was fixed in vertical position on a steel frame. Stress controlled tests were carried out. The load was applied in steps of 3 kN approximately, at a mean speed of 15 kN/min.

The deformations of wallettes were measured using LVDTs, as follows: For wallettes in compression, four LVDTs (two per face) were used to measure vertical deformations, six LVDTs (three per face at three levels) were recording horizontal deformations and vertical crack openings, whereas another six LVDTs (three per side at three levels) were installed to measure transverse deformations of wallettes and separation between exterior leaves and filling material. In wallettes subjected to diagonal compression, vertical deformations were measured by two LVDTs (one per face); horizontal deformations and opening of vertical cracks were measured by six LVDTs (three per face at three levels).

Each specimen was tested either to compression or to diagonal compression, until its maximum resistance was reached. Subsequently, it was unloaded and removed from the testing frame. Since wallettes were to be retested after grouting, during this first phase of testing, care was taken not to disintegrate the specimens. After completion of testing of the six wallettes, grouting was performed. Approximately three months after grouting, wallettes were tested again up to failure.

4. Experimental results for ungrouted wallettes

4.1. Wallettes in compression-failure mode

Wallettes 1 to 3 exhibited the same failure mode, illustrated in Fig. 3: Vertical cracks opened on the two faces of wallettes, crossing mortar joints and stones. The vertical cracks were apparent on the mosaic as well (see Face 1 in Fig. 3), whereas partial debonding of mosaics from masonry occurred.

Please cite this article in press as: Vintzileou E, Miltiadou-Fezans A. Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime-based grouts. Engineering Structures (2007), doi:10.1016/j.engstruct.2007.11.003

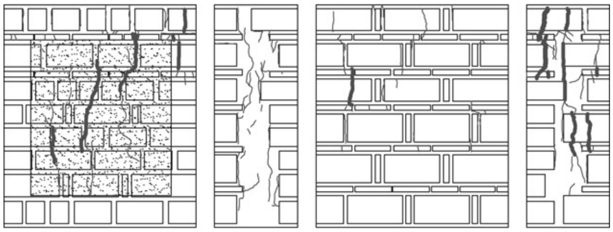

Fig. 3. Typical failure mode of wallettes in compression; Wallette 3.

The specimens exhibited the characteristic for three-leaf masonry separation between the external leaves and the interior filling material (observe vertical transverse cracks, Sides 1 and 2, in Fig. 3). It should be noted, however, that transverse cracks appeared not only at the interface of the external to the interior leaf: In fact, there are cracks passing within the filling material; limited cracking of protruding stones was also observed.

It has to be mentioned that a systematic difference was observed in the degree of cracking in the two opposite faces of the wallettes. This is partly due to the inevitable eccentricity of the applied load. It is, however, believed that this behaviour is mainly due to the inherent eccentricity of wallettes that reproduces the real in situ conditions. In fact, the two external leaves were of different construction type, of unequal average thickness and made of stones with different size.

4.2. Wallettes in compression-stress vs. strain and stress vs. crack opening curves

In Fig. 4(a), vertical stress–vertical strain curves are shown for Wallettes 1 to 3. The curves reported in Fig. 4(a) constitute average curves obtained from the four vertical LVDTs on the two faces of the wallettes. Table 2 summarizes the experimental results. It seems that the scatter of the experimental results lies within the margins expected for masonry for both the compressive strength and the initial modulus of elasticity (E_0 denotes the inclination of the initial linear part of the vertical stress–vertical strain curve).

Table 2
Summary of results of compression tests

Wallette	σ_{max} (MPa)[b]	ε_v (‰)	E_0 (GPa)	E_0/σ_{max}
1	1.82	[a]	1.0	594.45
2	1.74	−1.6	1.44	827.59
3	2.26	−2.25	1.5	663.72

[a] Unreliable measurements of some of the LVDTs.
[b] Note that in Fig. 4(a), the stress–strain curves end before the attainment of the maximum resistance. This is due to the following reason: For each specimen, the stress–strain curve is a mean curve (drawn on the basis of the measurements of four LVDTs). At a load value, close to the maximum resistance, one or more LVDTs were loosing support (due to the opening of cracks). Beyond that point, no mean curve could be drawn.

In Fig. 4(b), the curves of compressive stress–horizontal deformation at mid-height of specimens are presented. It should be noted that horizontal deformations are given in (mm). As the tensile deformation of masonry before cracking is very small, the horizontal deformations represent the total opening of vertical cracks that appeared on the faces of each wallette. This holds true for the transverse deformations of Fig. 5 that represent the total opening of vertical cracks measured along the width of the specimens, at mid-height of the specimens. The main characteristic behaviour of the three-leaf masonry can be observed by the comparison of curves plotted in Fig. 4(b) with the curves presented in Fig. 5. In fact, the total opening of the vertical cracks on the faces of wallettes was at a maximum equal to ∼1.6 mm. On the contrary, transverse deformations (i.e. opening of cracks between external leaves and filling material) reached values between 4.0 and 8.0 mm. This shows clearly that the primary cause of failure of this type of masonry is the separation among the three leaves and the resulting out-of-plane deformation of the external strong leaves, as discussed in detail in Vintzileou [24]. The compressive strength of the ungrouted masonry was calculated on the basis of the model by Tassios [18] and it was found

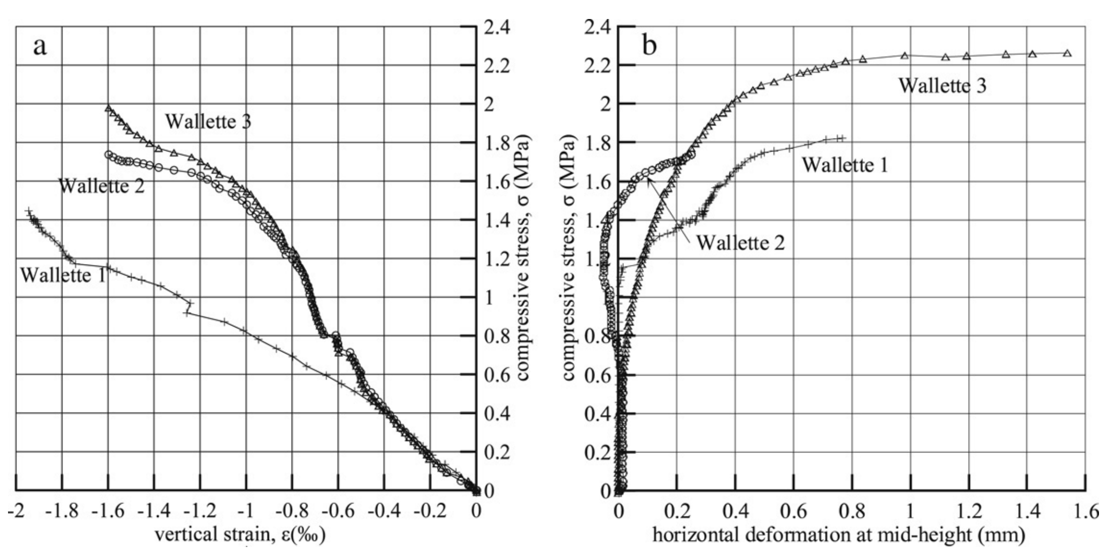

Fig. 4. Wallettes 1 to 3, (a) vertical stress–vertical strain curves (see Note (b) in Table 2), (b) vertical stress–horizontal deformations at mid-height of the specimens.

Please cite this article in press as: Vintzileou E, Miltiadou-Fezans A. Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime-based grouts. Engineering Structures (2007), doi:10.1016/j.engstruct.2007.11.003

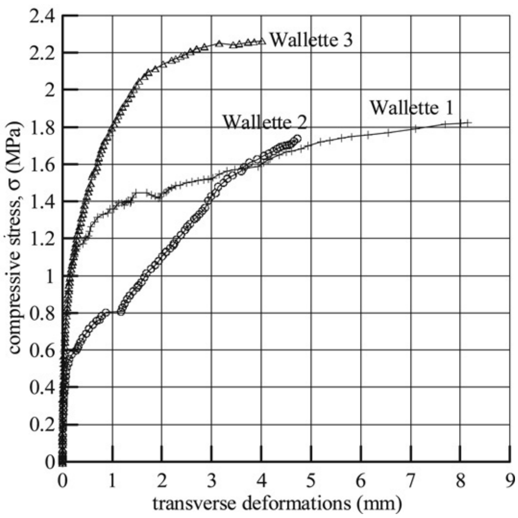

Fig. 5. Transverse deformations of Wallettes 1 to 3, subjected to compression.

equal to 1.90 N/mm^2. This value fits quite satisfactorily with those obtained experimentally. As the model by Tassios [18] was developed for three-leaf masonries with external leaves of constant thickness along the height, one would expect higher compressive strength for the masonry tested within this program: Due to the varying thickness of stones (both in-length and in-height of the wallettes), the contact area between the external leaves and filling material is increased, whereas additional mechanical interlock due to the protruding stones could be expected. However, as shown in Fig. 3, transverse cracks were passing mainly through the exterior to the inner leaves' interfaces. Therefore, the aforementioned favourable mechanism was not mobilised. On the contrary, as discussed upon in Section 7.2, the effect of the improved bond due to the in-thickness geometry of the tested masonry becomes apparent.

4.3. Wallettes in diagonal compression-failure mode

Fig. 6 shows the typical failure mode of wallettes subjected to diagonal compression. It is interesting to observe the difference in the cracking pattern between the two faces of the specimens, observed also in situ: On face A (simulating the interior leaf of the wall made of rather small stones) the cracks parallel to the loading axis appear as more or less continuous lines; on face B – made with larger stones – the cracks follow the path of horizontal and perpendicular mortar joints. Some minor cracks appeared also between the external leaves and the filling material.

4.4. Wallettes in diagonal compression-stress vs. strain and stress vs. crack opening curves

In order to calculate the tensile strength of masonry (from the load applied diagonally to the specimens), the formula $\sigma = 2P/\pi A_w$ was applied (P denotes the vertical load and A_w is the vertical area of the specimen). As shown in Fig. 7, Wallettes 4 to 6 reached almost equal tensile strengths (approximately equal to 0.10 MPa), under vertical strains comparable to those recorded in the case of Wallettes 1 to 3. On the contrary, the

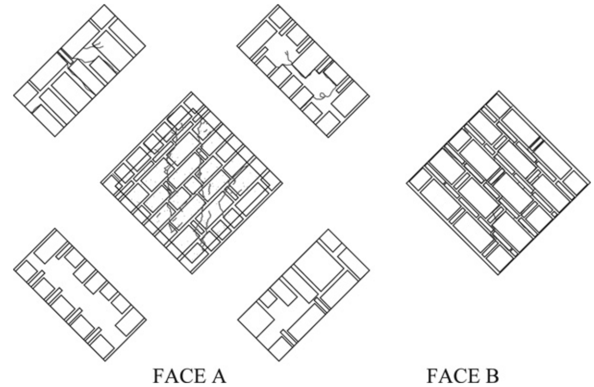

Fig. 6. Typical failure mode of specimens subjected to diagonal compression: Wallette 4.

value of vertical cracks opening at the maximum stress seems to be quite scattered.

5. Design of grouts

The design of high injectability grouts was performed following performance requirements based on the needs of the structural restoration of the monument [10]. Actually, at a first stage, a series of parameter analyses allowed to reproduce analytically the main damages observed in the monument [11]. Subsequently, analytical work was carried out taking into account the actions expected to be imposed to the monument, as well as the intervention techniques that are proposed in order to improve the behaviour of the monument. This analytical work also allowed for the desired mechanical properties of the grouted masonry to be estimated. Thus, the following target values were set for the basic mechanical properties of the grouted masonry: Tensile strength approximately double that of masonry before grouting and compressive strength approximately equal to 3.0 MPa.

On the basis of the available literature [22,18], it was estimated that the compressive strength of the grout at the age of six months should lie between 6 and 10 MPa; a grout flexural strength larger than 3 MPa was required.

In addition, the physical–chemical properties of the raw materials should be selected such that the durability of the structure and its precious mosaics would not be jeopardized. Finally, the grouts should be injectable enough to fill fine voids and cracks (estimated minimum nominal width of voids and cracks ∼200 μm).

Based on the aforementioned requirements, six grout mixes were designed and tested (to assess their physical, chemical and mechanical properties) at the laboratory of the Directorate for Technical Research on Restoration (DTRR, Hellenic Ministry of Culture). Selected results of those tests are reported in Kalagri et al. [7]. That laboratory study led to the selection of two alternative grouts for use in the mechanical tests that are presented in this paper: A ternary grout (white cement, lime, pozzolan) and a natural hydraulic lime (NHL)-based grout.

It has to be mentioned that the Danish white cement used in the ternary grout was selected for its fineness, low alkali content and high sulphate resistance [7].

Please cite this article in press as: Vintzileou E, Miltiadou-Fezans A. Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime-based grouts. Engineering Structures (2007), doi:10.1016/j.engstruct.2007.11.003

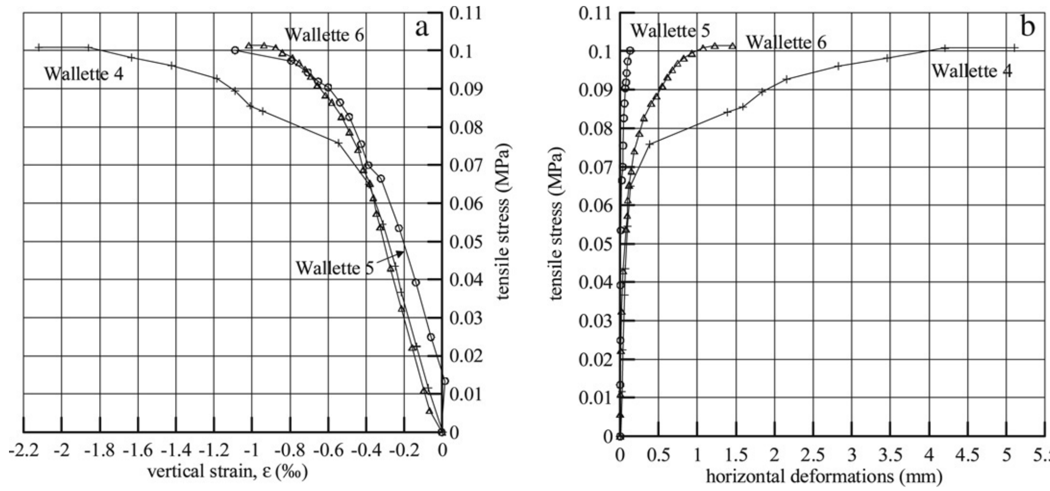

Fig. 7. Wallettes subjected to diagonal compression, (a) tensile strength–vertical strain curves, (b) tensile stress–horizontal deformation at mid-height of specimens.

Table 3
Mix proportions of selected grouts (%wt.) and mechanical properties—injectability characteristics thereof

Ternary grout										
White Danish cement	Lime (powder)	Pozzolan ($d_{max} < 75$ µm)	Superplasticizer SP1	Water	Compressive (f_{gc}) and flexural (f_{gt}) strength (MPa)					
					Age (days)					
					28		90		180	
30	25	45	1	80	f_{gc}	f_{gt}	f_{gc}	f_{gt}	f_{gc}	f_{gt}
					4.08	2.11	8.16	2.29	10.6	3.13
NHL5-Based grout										
NHL5 (St Astier)		Superplasticizer SP2		Water						
100		1		80	2.82	2.47	4.50	2.52	6.36	3.87
			T_{36} (s) Sand column 1.25/2.50 mm (voids ∼ 0.2–0.4 mm)			$t_{d=4.7\ mm}$ (s)		Bleeding		
Ternary grout				19		20.5		2%		
NHL5-based grout				22.5		22		3%		

As for the hydraulic lime selected for used in the hydraulic lime-based grout, it was selected among five materials available on the market, mainly on the basis of its physical/chemical properties. The mix proportions of the selected grouts, along with their mechanical properties and injectability characteristics (penetrability, fluidity, stability) are summarized in Table 3. The grouts were prepared using an ultrasound dispersion mixer assisted by a mechanical device of low turbulence. The standardized sand column test method (NF P18-891 [14]) was applied to check the penetrability and the fluidity of grouts. The standard apparatus for testing the fluidity (NF P18-358 [13]) and the stability of grouts (NF P18-359 [13]) was used. Based on the previous experience of the DTRR, the following limit values were set for the acceptance of grouts: A time limit of 50 sec for the sand column penetrability test (T_{36}); an efflux time of 500 ml of grout shorter than 45 sec (Marsh cone $d = 4.7$ mm, fluidity test—$t_{d=4.7\ mm}$). In addition, a maximum acceptable limit of 5% was set for bleeding test [8].

Both mixes proved to satisfy the requirements of sufficient mechanical properties and injectability to fine cracks and voids. It has to be noted that, before the application of the selected grouts to the specimens, their injectability was checked and confirmed by its application to cylinders made up of filling material [7].

6. Injecting the wallettes

6.1. Preparation of wallettes for grouting

The masonry was prepared for grouting, following the procedure established within the Hellenic Ministry of Culture, on the basis of the experience gained from the applications to various monuments (e.g. [12], for the application to the Parthenon of the Athens Acropolis). This procedure comprises the following steps:

(a) Drilling of injection holes: Holes were drilled approximately 150 mm deep into masonry, so that to allow grout to reach the filling material. Holes were drilled in a grid with horizontal and vertical distances not exceeding 150–200 mm. Holes were drilled also along the cracks

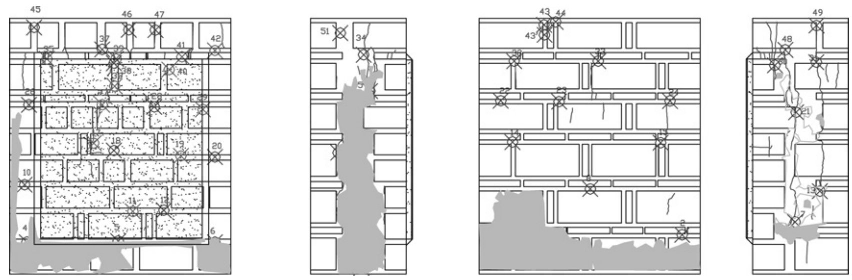

Fig. 8. Wallette 1, numbering of plastic tubes for grouting, wet surfaces (gray areas) allowing for the progress of grouting to be recorded.

Table 4
Data related to the consumption of grout, as well as to the percentage of voids

Wallette	Grout	Consumption of grout V_{gr} (l)	V_{gr}/V_{inf} (l/m^3)	V_{gr}/V_w (l/m^3)	V_{voids}/V_w (%)	$V_{\mathrm{voids}}/V_{\mathrm{inf}}$ (%)
1	NHL5	50.3	328	90	9.0	32.8
2	Ternary	61.4	400	109	10.9	40.0
3	NHL5	55.8	364	99	9.9	36.4
4	NHL5	52.3	393	107	10.7	39.3
5	Ternary	49.3	371	101	10.1	37.1
6	NHL5	50	376	103	10.3	37.6

V_{gr}: consumed volume of grout, V_{inf}: volume of infill material, V_w: total volume of wallette, V_{voids}: volume of voids.

opened during the first loading. It should be noted that, in order to control the flow of grout and, hence, protect the mosaics, shallow holes of small diameter were drilled also in the area covered by mosaics.

(b) Insertion of plastic tubes (of various diameters, 4, 4.7 and 10 mm) into the drilled holes. Additional 2.7 and 3.3 mm in diameter plastic tubes were inserted into the shallow holes, in the region of mosaics.

(c) Sealing of cracks (using a mortar), in order to prevent uncontrollable leakage of the grout. Since leakage of grout during its application cannot be excluded, the necessary materials were available close to the wallettes for the preparation of an absorptive (pozzolan/water) paste. This paste was used during grouting at places where the grout was leaking. Finally,

(d) All tubes were numbered (Fig. 8) and reported on sketches, to allow for better control of the injection process.

6.2. *Injection of grout*

The grouts were mixed using a prototype ultrasound dispersion mixer (capacity: 20 l), assisted by a mechanical device of low turbulence (300 rpm). After mixing, each batch was drained into an air-proof cylindrical collector made of Plexiglas to allow for the calculation of the grout quantity that was consumed. Through a pipe at the bottom of the collector, the grout was introduced to the wallettes at low pressure (∼0.70 bar). The pressure was controlled by means of a manometer at the entrance of the grout to the wall. Grouting started from the bottom of the wallette to its top, whereas entrances and exits of the grout from the pre-installed tubes, as well as the consumed quantity of grout were recorded. By observing the progression of moisture on the surfaces of the wallette (Fig. 8), the filling of voids with grout was followed. The data about the consumption of grout per wallette (Table 4) are in accordance with the data in the literature [22]; in addition, the estimation made on the basis of in situ measurements, for ∼40% voids in the filling material, seems to be confirmed. It is to be noted that $V_{\mathrm{voids}}/V_{\mathrm{inf}}$ values (V_{voids} being the volume of voids in masonry and V_{inf} being the volume of the filling material) were calculated assuming that the total volume of grout was consumed within the filling material. This is an acceptable approximation, since the quantity of grout filling voids and pores of the mortar and the masonry units is very small compared to that introduced to the filling material.

Regarding the effect of the various substrates of mosaics, it was observed that, thanks to the care taken during both the preparation of the wallettes and the application of grouts, no major leakage of the grout on the surface of mosaics was observed. In limited number of cases where some leakage occurred, immediate cleaning of the mosaics prevented any permanent damage.

After the completion of grouting, the wallettes remained for approximately 3 months in the laboratory for the grout to gain sufficient strength before testing. The testing procedure was the same as that for the loading of wallettes before grouting. Measurements of strains and opening of cracks were taken with the same devices and in the same places as for initial loading (Photos 5 and 6).

7. Experimental results for grouted wallettes

7.1. *Wallettes in compression-failure mode*

As shown in Fig. 9, wallettes subjected to compression after grouting exhibited the same failure mode as before the grouting. In fact, vertical cracks have opened both in the faces of wallettes and in their sides. Some of the cracks that appeared during testing before grouting have opened again. Nevertheless, the majority of vertical cracks appeared

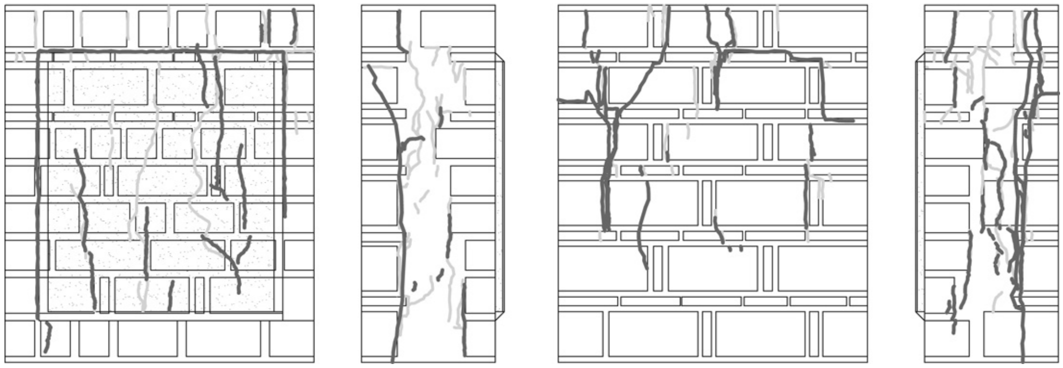

Fig. 9. Crack pattern of Wallette 3 before (light gray) and after grouting (dark gray).

Table 5
Mechanical properties of Wallettes 1 to 3 before and after grouting

Wallette	f_{w0} (MPa)	f_{ws} (MPa)	f_{ws}/f_{w0}	ε_{v0} (‰)	ε_{vs} (‰)	E_0 (MPa)	E_s (MPa)	E_s/E_0
1	1.82	3.00	1.65	[a]	−1.76	1000	1200	1.20
2	1.74	3.75	2.16	−1.6	−2.50	1440	1550	1.08
3	2.26	3.73	1.65	−2.25	−3.39	1500	1300	0.87

[a] Unreliable measurements.

in new locations, thus suggesting that grouting provided sufficient strength in previously cracked regions. Furthermore, as discussed in the following sections, vertical cracks appeared at substantially higher load than for ungrouted wallettes, whereas their openings were small.

In general, the mosaics followed the deformations of masonry and they were cracked, whereas limited debonding of mosaics from masonry was observed.

7.2. Wallettes in compression-stress vs. strain and stress vs. crack opening curves

Fig. 10 shows the vertical stress vs. vertical strain curves for Wallettes 1 to 3 before and after grouting. One may observe the substantial strength enhancement due to grouting. In fact, as shown in Table 5, wallettes grouted with natural hydraulic lime-based grout showed a compressive strength 65% higher than the initial compressive strength. The ternary grout led to an increase of compressive strength by 116%. Nevertheless, although the compressive strength of the ternary grout is almost double that of the hydraulic lime-based grout (see Table 3), this difference is not depicted in the achieved final compressive strength of the wallettes. This finding is in accordance with the literature (summarized in [24]): It seems that the key parameter for the strength enhancement is the bond strength between grout and in situ materials [19] and not the compressive strength of the grout. Systematic experimental work on the bond properties between cement or ternary grouts and stones has demonstrated [1] that indeed tripartite grouts with reduced cement content may reach bond strengths equal to or higher than that exhibited by a cement grout of significantly higher compressive strength.

In all cases, the enhanced strength of wallettes is reached for substantially larger vertical strain than in the case of

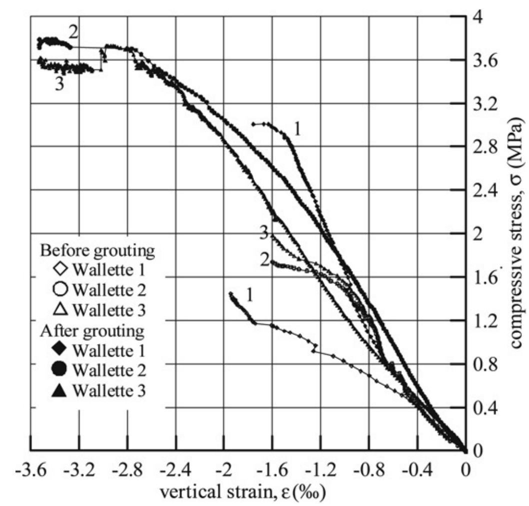

Fig. 10. Wallettes 1 to 3, compressive stress vs. vertical strain curves before and after grouting (see Note (b) in Table 2).

ungrouted masonry (Table 5). It is also interesting to observe that the selected grouts did not result in any significant stiffness enhancement of masonry. This is an important feature, since in several applications of grouts to monuments, the increase of stiffness is not desirable. This is the case especially when grouting is applied only to some regions of a structure.

In Fig. 11, the opening of vertical cracks is plotted against the compressive stress; the reported measurements were taken at mid-height of specimens and they refer to the vertical cracks both on faces and on the sides of wallettes. It may be observed that grouting with either mix led to a substantial reduction of crack openings in both the horizontal directions. In fact, as shown in Fig. 11(b), the opening of transverse cracks in the strengthened wallettes is approximately equal to zero for an applied compressive stress equal to their maximum resistance before grouting.

In order to estimate the compressive strength of masonry after grouting, $f_{wc,i}$, the simple formula proposed by Vintzileou [25] was applied:

$$f_{wc,i} = f_{wc,0}\left(1 + \frac{V_i}{V_w}\frac{f_{i,s}}{f_{wc,0}}\right) \quad (1)$$

where,

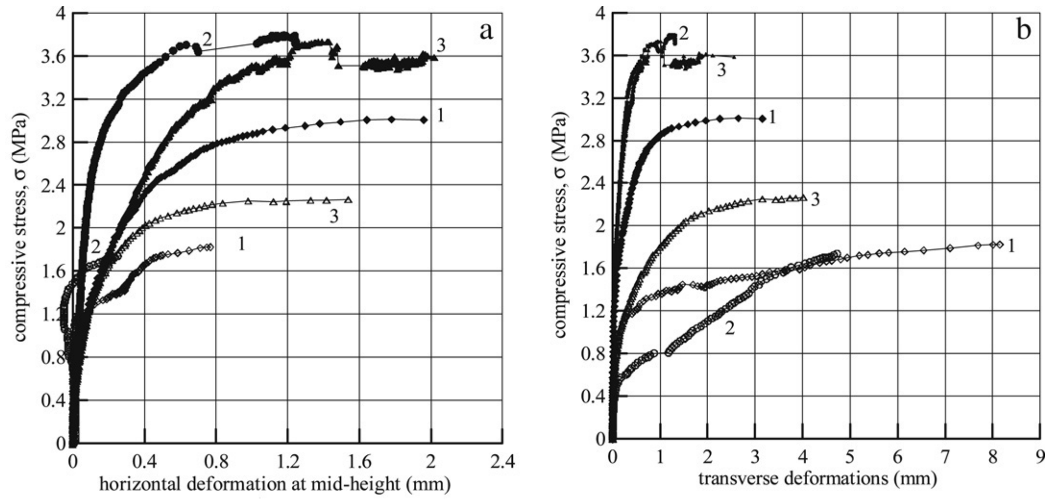

Fig. 11. Wallettes 1 to 3, stress–crack opening curves: (a) on wall faces, (b) in transverse direction.

$f_{wc,0}$ denotes the compressive strength of ungrouted masonry (equal to 1.90 N/mm^2, see Section 4.2),
$f_{i,s}$ denotes the compressive strength of the grouted filling material,
V_i and V_w denote the volume of the filling material and the total volume of the wall, respectively.

The compressive strength of the grouted filling material is calculated using the following expression:

$$f_{i,s} = 1.60 + 0.50 f_{gr,t} \quad (2)$$

where,

$f_{gr,t}$ denotes the tensile strength of the grout.

By applying Eqs. (1) and (2) for Wallettes 1 to 3, the following values are calculated for their compressive strength after grouting, $f_{wc,i} = 2.24$, 2.16 and 2.60 N/mm^2. These values are significantly smaller than the measured ones. This is attributed to the fact that the simple formula (1) does not take into account the fact that the bond between the leaves of masonry is improved as the interface between external leaves and filling material is keyed. As proved by Binda et al. [3], keyed joints lead to higher compressive strength of masonry, as compared to masonry with collar joints between consecutive leaves. However, in the tests presented in this paper, the positive effect of keyed joints became apparent only after grouting, as illustrated by comparing the crack pattern of wallettes before and after grouting. By comparing Figs. 3 and 9, one may observe that before grouting, the weak bond between external leaves and filling material leads to transverse cracks passing mainly along the interfaces. On the contrary, the improved bond ensured by grouting leads to strong interfaces. Thus, transverse cracks are almost continuous (crossing also protruding stones).

7.3. Wallettes in diagonal compression-failure mode

Wallettes 4 to 6, subjected to diagonal compression exhibited the same failure mode as before grouting (Fig. 12): Most of the cracks formed during the first loading have opened after strengthening, whereas some new cracks appeared.

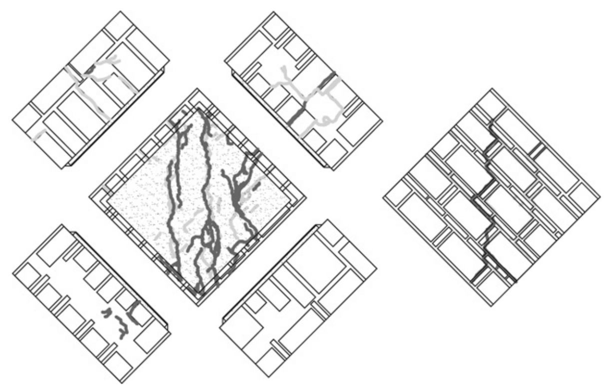

Fig. 12. Wallette 4, typical failure mode of wallettes subjected to diagonal compression. Cracks of ungrouted masonry (light gray) and cracks of grouted masonry (dark gray).

In general, the mosaics followed the cracks of masonry; debonding of mosaics was not observed.

7.4. Wallettes in diagonal compression-stress vs. strain curves and stress vs. opening of cracks curves

The behaviour of wallettes subjected to diagonal compression is summarized in Fig. 13. As shown in Fig. 13(a), the tensile strength of masonry has doubled after grouting with the hydraulic lime-based grout; the use of the ternary grout led to tensile strength three times of that obtained during initial loading. It seems, however, that the ternary grout led to somehow brittle behaviour, since failure of Wallette 5 occurred under small vertical strain, whereas the opening of vertical cracks was very sudden (see Fig. 13(b); due to the sudden failure of wallette 5, the opening of the vertical cracks could not be recorded, as the LVDTs lost their support on masonry). However, both grout mixes provided significantly higher strength increase than the targeted one (∼100%).

8. Conclusions

The experimental work presented in this paper

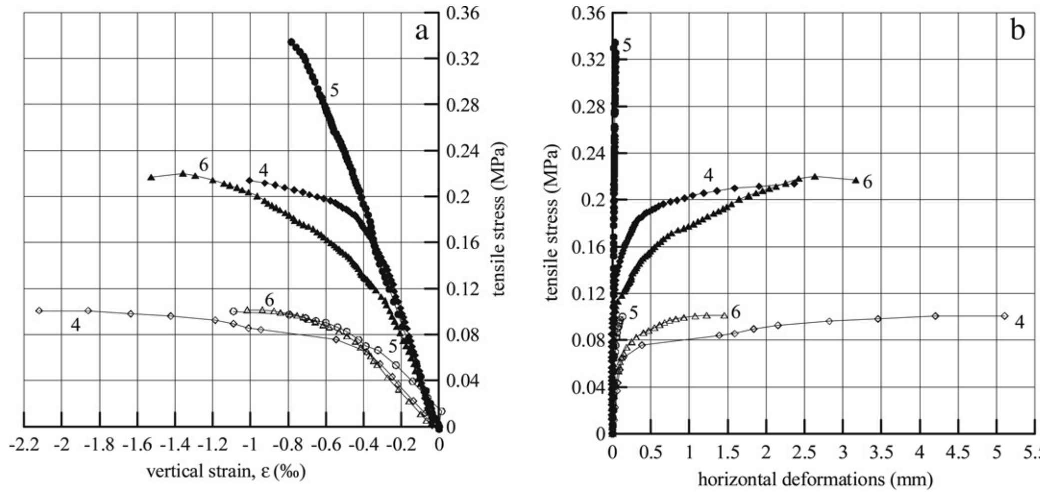

Fig. 13. Wallettes 4 to 6 before and after grouting: (a) tensile stress–vertical strain curves, (b) tensile stress–opening of vertical cracks at mid-height.

1. Confirmed the failure mechanism of three-leaf stone masonry in compression: Early separation between exterior strong leaves and internal weak filling material leads to failure of masonry under significant out-of-plane deformations (due to vertical cracks within the thickness of masonry).
2. Has proven that the load causing diagonal cracking of this type of masonry is very low, mainly due to the poor quality of mortar used for the construction of historic masonries.
3. Has proven that the use of stable, fluid and highly injectable grouts is efficient. In fact, as observed and thoroughly documented during grouting and confirmed after testing, the two grout mixes used within the program were able to fill the cracks and the voids of the masonry.
4. Has demonstrated that both the ternary and the hydraulic lime-based grouts were efficient from the mechanical point of view: Substantial enhancement of compressive strength of masonry was observed. In all cases, homogenization of masonry was achieved and the separation between the three leaves was substantially delayed. This strength increase was not followed by substantial increase in the stiffness of masonry.
5. Has also demonstrated that both grouts contributed to the increase of the tensile strength of masonry.

It has been reported that, on the basis of the results presented in this paper, it was decided to use hydraulic lime-based grouts in the Katholikon of Dafni Monastery: The substantial (compressive and tensile) strength enhancement of wallettes, the rather ductile behaviour under diagonal compression, the physical–chemical properties that ensure a durable intervention and contribute to the protection of mosaics led to the selection of a hydraulic lime-based grout.

Acknowledgments

The authors of this paper wish to acknowledge the continuous support of Prof. T.P. Tassios.

S. Anagnostopoulou, A. Kalagri, A. Vrouva and E. Papadopoulou contributed to the design of materials and testing.

The contributions of N. Delinikolas, N. Minos, D. Chrissopoulos, E. Anamaterou, F. Georganis, E. Zarogianni, V. Sideraki, K. Papastamatiou, A. Kordoulas (Hellenic Ministry of Culture) and A. Zagotsis (NTUA) are also acknowledged.

Thanks are due to the Scientific and Technical personnel of the Directorate for Technical Research on Restoration for preparing and grouting the wallettes.

The project was included in the Operational Program "CULTURE". It is co-funded by the European Regional Development Fund (ERDF-75%) and by National Funds (25%).

References

[1] Adami C-E, Vintzileou E. Interventions to historic masonries: Investigation of the bond mechanism between stones or bricks and grouts. RILEM Materials and Structures 2007 (published on line 20 March 2007) [in press].

[2] Aitcin P-C, Pinconneault P, Roy, Della M. Physical and chemical characterization of condensed silica fumes. American Ceramic Society Bulletin 1984;63(12):1487–91.

[3] Binda L, Pina-Henriques J, Anzani A, Fontana A, Lourenco PB. A contribution for the understanding of load-transfer mechanisms in multi-leaf masonry walls: Testing and modelling. Engineering Structures 2006; 28:1132–47.

[4] Delinikolas N, Miltiadou-Fezans A, Chorafa E, Zaroyianni E. Study on restoration of the Katholikon of Dafni Monastery, Phase A — Architectural and historical Survey, Ministry of Culture. 2003 [in Greek].

[5] Ferragni D, Forti M, Malliet J, Mora P, Teutonico JM, Torraca G. Injection grouting of mural paintings and mosaics. In: Brommelle NS, Pye EM, Smith P, Thomson G, editors. Proceedings of the conference on adhesives and consolidants. London: IIC; 1984. p. 110–6.

[6] Gaetani MC, Santamaria U. I Materiali di Restauro: le malte da inezione. Diagnosi et Progetto per la conservazione dei materiali dell' Architettura, ICR/Ministero per i Beni Culturali e Ambientali, Edizioni De Luca, Roma; 1998. p. 357–75.

[7] Kalagri A, Miltiadou-Fezans A, Vintzileou E. Design and evaluation of hydraulic lime grouts for the strengthening of stone masonry historic structures. In: International symposium on studies on historical heritage. 2007. p. 371–8.

[8] Miltiadou A. Etude des coulis hydrauliques pour la réparation et le renforcement des structures et des monuments historiques en maçonnerie. Thèse de doctorat, Ecole Nationale des Ponts et Chaussées, Paris, France. Published in 1991 by LCPC in Collection 'Etudes et recherches des Laboratoires des Ponts et Chaussées', série Ouvrages d'art, Paris, France; 1990.

Please cite this article in press as: Vintzileou E, Miltiadou-Fezans A. Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime-based grouts. Engineering Structures (2007), doi:10.1016/j.engstruct.2007.11.003

[9] Miltiadou-Fezans A, Tassios TP, Delinikolas N, Chorafa E, Zarogianni E, Chandrinos I. Earthquake structural problems and urgent measures undertaken to support the Katholikon of Dafni Monastery in Athens, Greece. In: Proceedings of the 8th international conference STREMAH 2003: Structural studies, repairs and maintenance of heritage architecture. 2003.

[10] Miltiadou-Fezans A, Delinikolas N, Chorafa E, Zaroyianni E. Study on restoration of the Katholikon of Dafni Monastery, Phase A — Structural survey, analysis and remedial measures. Ministry of Culture. 2003 [in Greek].

[11] Miltiadou-Fezans A, Vintzileou E, Delinikolas N, Zaroyianni E, Chorafa E. Pathology of the Dafni Monastery: Survey, monitoring of cracks, interpretation and numerical verification. In: Proceedings of the fourth international seminar on structural analysis of historical constructions, vol. 2. 2004. p. 1285–94.

[12] Miltiadou-Fezans A, Papakonstantinou E, Zambas K, Panou A, Frantzikinaki K. Design and application of hydraulic grouts of high injectability for structural restoration of the column drums of the Parthenon Opisthodomos. In: International conference on structural studies, repairs and maintenance of architectural heritage IX, 2005.

[13] Normes Françaises P18-358 and P18-359. Adjuvant pour bétons, mortiers et coulis-Coulis courants d'injection pour précontrainte-Mesure de la fluidité et de la réduction d'eau - Mesure de l'exsudation, Paris, France. 1985. 8p + 4 p.

[14] Norme Française P18-891. Produits spéciaux destinés aux constructions en béton hydraulique-Produits à base de résines synthétiques ou de liants hydrauliques pour injections dans des structures en béton-Essai d'injectabilité à la colonne de sable en milieu sec et/ou humide. Paris, France. 1992. 12 p.

[15] Paillère A-M, Guinez R. Recherche d'une formulation de coulis à base de liants hydrauliques pour l'injection dans les fines fissures et les cavités. Bull. liaison Laboratoire des Ponts et Chaussées 1984;130:51–7.

[16] Paillère A-M, Serrano J-J, Buil M. Possibilités offertes par l'emploi d'ultrafines siliceuses dans les coulis. Bull. liaison Laboratoire des Ponts et Chaussées 1986;141:123–5.

[17] Paillère A-M, Buil M, Miltiadou A-E, Guinez R, Serrano J-J. Use of silica fume and superplasticizers in cement grouts for injection of fine cracks. In: 3rd international conference on the use of fly ash, silica fume, slag and natural pozzolans in concrete. 1989. p. 1131–57.

[18] Tassios TP. Rehabilitation of three-leaf masonry. In: Evoluzione nella sperimentazione per le costruzioni, Seminario Internazionale. Centro Internationale di Aggiornamento Sperimentale – Scientifico (CIAS); 2004.

[19] Toumbakari E-E. Lime-pozzolan-cement grouts and their structural effects on composite masonry walls. Doctor thesis. Katholieke, Belgium: Universiteit Leuven; 2002.

[20] Unesco, World Heritage Centre. Year of inscription of Dafni Monastery: List of monuments, 1990. See http://whc.unesco.org/en/list/537.

[21] Valluzzi M-R. Comportamento meccanico di murature storiche consolidate con materiali e tecniche a base di calce. Doctor thesis. University of Trieste. 2000.

[22] Vintzileou E, Tassios TP. Three leaf stone masonry strengthened by injecting cement grouts. Journal of Structural Engineering, ASCE 1995; 121(5):848–56.

[23] Vintzileou E, Miltiadou-Fezans A, Palieraki V, Delinikolas N. The use of radar techniques and endoscopy in investigating old masonry: The case of Dafni Monastery. In: Modena C, Lourenco PB, Roca P, editors. Proceedings of the 4th international seminar on structural analysis of historical constructions, vol. 2. Rotterdam: Balkema; 2004. p. 351–60.

[24] Vintzileou E. Grouting of three-leaf stone masonry: Types of grouts, mechanical properties of masonry before and after grouting, Keynote paper. In: 5th international conference on structural analysis of historical constructions. 2006 p. 41–58.

[25] Vintzileou E. Iniezione di miscela fluida in muratura a sacco: Risultati sperimentali e previsione delle caratteristiche meccaniche. In: Seminario CIAS Evoluzione nella sperimentazione per le costruzioni. 2007. p. 191–211.

Please cite this article in press as: Vintzileou E, Miltiadou-Fezans A. Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime-based grouts. Engineering Structures (2007), doi:10.1016/j.engstruct.2007.11.003