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ORIGINAL ARTICLE

Interventions to historic masonries: Investigation of the bond mechanism between stones or bricks and grouts

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Abstract Within the present work, the mechanism of bond is studied in composite grout/substrate specimens. Three types of tripartite (lime-pozzolan-cement) grouts are examined, combined with three substrates (two types of limestone and bricks). The interfaces between grout and substrate are characterized by means of mechanical tests in direct tension and shear. The in-time development of the tensile and shear bond strength is also investigated. In order to correlate the characteristics of the substrates and the obtained strengths of the interfaces, their surfaces and porosity are examined. The main conclusions of this study are that the studied tripartite grouts can develop tensile and shear bond strength comparable to Portland cement-based grouts, and that the value of the reached bond strength is governed mainly by the substrate characteristics and the binding properties of the grouts. The results of this project confirm the efficiency of tripartite lime-pozzolan-cement grouts with reduced Portland cement content for repair and strengthening of historic masonries.

Résumé *Dans ce travail, on étudie le mécanisme d'adhérence le long des surfaces matériau de base/coulis. On examine trois types de coulis tripartis (chaux-pouzzolane-ciment), en combinaison avec trois types de matériaux de base (deux types de pierres calcaires et briques). Les interfaces entre coulis et matériaux de base sont caractérisées par des épreuves en traction et au cisaillement. On examine aussi le développement de la résistance en traction et au cisaillement avec le temps. Afin de corréler les caractéristiques des matériaux de base et les résistances mesurées des interfaces, on fait des observations sur l'état et la porosité des interfaces. Les conclusions principales de cette étude sont que les coulis tripartis qu'on a étudié peuvent développer des résistances en traction et au cisaillement semblables à celles de coulis à base de ciment Portland et que l'adhérence obtenue dépend surtout des caractéristiques des matériaux de base ainsi que des caractéristiques d'adhérence des coulis. Les résultats de ce travail confirment l'efficacité des coulis tripartis (à contenu de ciment réduit) en tant que matériau de réparation et de renforcement des maçonneries historiques.*

Keywords Tripartite grouts · Direct tension · Shear · Interfacial transition zone · Bond mechanism

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1 Introduction

Grouting is one of the most commonly applied techniques in the field of conservation of the built cultural heritage. Several types of grout mixes (such as polymeric, cementious and hydraulic grouts) were used for the repair and strengthening of historic masonry structures. The effectiveness and the durability of these types of interventions were experimentally investigated (e.g. in [1] and [2]). Grout mixes applied for the purpose of filling cracks and voids in historic masonries should simultaneously satisfy the following two requirements: (a) physical-chemical compatibility with the in situ materials and (b) efficiency from the mechanical point of view.

The use of hydrated lime and pozzolans in various proportions, with parallel reduction of the cement content of the mix, satisfies the first requirement and leads to more durable interventions. However, the mechanical properties of the grout are also reduced. On the other hand, mechanical tests on ungrouted and grouted three leaf stone masonry [3–7] have proven that the key parameter for the mechanical properties of grouted masonry is not the compressive strength of the grout. As suggested by Toumbakari [4], the efficiency of grouting depends on the bond properties of grout-to-in situ materials interfaces. This is qualitatively confirmed by the totality of available experimental results. However, the design of adequate grout mixes, as well as the prediction of the mechanical properties of a grouted masonry needs to be based on quantified data regarding the bond properties of interfaces. The importance of the subject and the very limited number of available experimental data related to historic masonry calls for a systematic study. The present study focuses on the bond properties of tripartite grouts with existing materials, as grouts of this type satisfy the previously mentioned requirement (a), whereas available tests have proven that, when adequately designed, they may also satisfy the requirement (b).

2 The mechanism of bond

A systematic review of the literature regarding the bond mechanism shows that the vast majority of previous studies concern concrete (aggregate-to-cement paste interfaces and old-to-new concrete interfaces). A limited number of studies are devoted to interfaces between mortar and masonry units, whereas data regarding stones or bricks-to-grout interfaces are scarce. In this section, the main findings of the previously published studies are summarized, since it is assumed that they may apply also to the interfaces examined within the present work, in a qualitative way though.

It is well known that bond between mortar or cement paste and stone or aggregates respectively, is due to two mechanisms, namely a chemical and a mechanical one. Chemical bond is due to chemical reactions that take place between the materials in contact along an interface. Early studies by Farran [8] have proven that there are differences between the paste surrounding aggregates in concrete and the bulk paste. Later, Lyubimova and Pinus [9] confirmed the results by Farran, through a series of microhardness measurements across cement-aggregate interfaces. Since then, the zone of the matrix, adjacent to the aggregates, referred to as "interface transition zone" (ITZ), was extensively studied, in case of cement pastes. Thus, it was demonstrated that binders consisting of cement particles alone tend to cause a concentration of large crystals in the ITZ due to the inefficient packing of the cement particles at the aggregate surface (known as "wall effect") [10]. As a result, the porosity of the ITZ increases and the bond strength decreases. On the contrary it was observed that when a pozzolan is added to the binder, a more dense and uniform ITZ is created. Thus, higher bond strength resistance is obtained [11]. Moreover, it was shown that the surface roughness of masonry units may counteract the wall effect at the unit interface (Lange et al. [12] quoted in Reda Taha and Shrive [13]). Among the factors affecting chemical bond is the mineralogy of the substratum, the porosity of its surface, the type of the binder, the presence of pozzolanic or inert fines (i.e. silica fume). Chemical bond is mobilized under practically zero slip along an interface; it is normally decreasing down to zero, when slip is initiated.

Mechanical bond that constitutes the most important part of the mechanism does also depend on characteristics of the substrate. The roughness of the substrate appears to have a positive effect on the bond strength between concrete and repair materials due to the higher mechanical interlock achieved between the hydrated products of the binder and the substrate [14–16]. For mortars to aggregate (concrete or stone) interfaces the type of the substrate [17] and the compressive strength of the binder [18] affect the mobilized bond strength. For masonry interfaces (between bricks and mortars), it was shown that properties of the substrate, such as strength, surface porosity [19], water content and water absorption [20] affect the mechanical interlocking between the hydration products of the binder and the substrate. It was shown, moreover, that shear bond strength depends on the properties of the binding material, namely its strength and thickness (thicker mortar joints lead to lower values of shear bond strength), as well as the applied normal stress at the interface [21]. The effect of some of the abovementioned parameters (porosity of the substrate, degree of saturation of the stones, thickness of the joint, as well as the effect of the binder) on the behaviour of interfaces between binary or tripartite cement grouts (with cement content varying from 50 to 75%) and calcareous substrates has already been observed by Miltiadou [22].

The present work deals with the bond mechanism between tripartite grouts and in situ masonry units. Regarding the grouts to be used, the decision was made to design mixes with reduced cement content and to add lime and natural pozzolans in suitable proportions, so that to optimize the pozzolanic reaction. This approach permits the development of binders that address both mechanical and durability requirements, although they are of low mechanical properties [23]. The use of cement in the tripartite grouts allows for the development of bond strength at early age of the grout, whereas the pozzolanic reaction contributes to further enhancement of the mechanism mainly after the age of 28 days. On the other hand, lime (basic material of historic mortars) is essential for the pozzolanic reaction and the formation of the calcium-silicate hydrates (C-S-H). Thus, two types of high injectability lime-pozzolan based grouts with a reduced cement content equal to 30%-wt, were investigated (Adami 2006, under preparation). In one of the tripartite grouts, metakaolin was used for its higher pozzolanic activity and fineness as compared to natural pozzolans, as pozzolan from Milos Island, that was selected for the second type of tripartite grouts. A reference cement-based grout with identical injectability properties is also used for the sake of comparison.

3 Experimental study

3.1 Materials

The mechanism of bond between grout and substrate is investigated by testing composite specimens made of two stone or brick pieces, connected through a grout joint. The selection of the substrates to be used was based on the frequency of their use in historical buildings. Thus, two types of limestone with different porosity (Dionysos marble and travertine) and solid bricks were used. Table 1 shows some basic properties of these materials. One may observe that travertine is a material of very variable

Table 1 Mechanical properties of stones and bricks

	Compressive strength (MPa)	Tensile strength (flexural) (MPa)	Apparent porosity (%)
Dionysos marble[a]	83/70[b]	8.7/-[c]	0.2
Travertine	12.1–95.5	4.0–21.5	16.8–2.9
Brick	12.2		21.4

[a] Values obtained by Vardoulakis et al. [24], Vardoulakis et al. [25]

[b] The two values refer to marble's strength in the strong and weak direction

[c] Unreliable test results for loading along the weak direction

quality. In fact, both compressive and tensile strength of travertine is affected by the percentage of pores, as well as by the presence of argillaceous discontinuities. Thus, pronounced scatter of experimental results is anticipated in case of travertine.

The materials used for the grouts mixes were: hydrated lime (HL), Portland cement CEM I 42.5 (C), commercial pozzolan from Milos Island (0–75 μm) (LA), commercial metakaolin METASTAR 501 (0–16 μm) (MK). The mix proportions of the grouts are given in Table 2. The lime to pozzolanic materials ratio was estimated with the aim to reach optimization of the pozzolanic reaction. In fact, a surplus of either lime or pozzolan in the mix means that part of the constituent materials does not react and, therefore, it does not contribute to strength through a hydration mechanism [4]. The water to solids (w/s) ratio was between 0.8–0.9 (for grouts G1 and G4) and 1.1 (for grouts G2 and G3). The values for w/s ratio were based on the design of grouts (that preceded this study) that could penetrate to voids smaller than 0.3 mm. To increase fluidity, superplasticizer Sikament ECO 4 was used (1.2–1.5%-wt of solids). The grouts were prepared by using a mechanical mixer at 2400 revolutions per minute. The use of finely ground metakaolin did not require the use of specific mixing devices, even though the increase of fineness led to an increase of the required water content from 0.8–0.9 to 1.1.

The compressive and flexural strength of the grouts (measured by means of three-point loading test) are given in Table 3. As expected, the cement grout develops its strength within the first weeks after casting. On the contrary, the pozzolanic activity (with pozzolan grains ground to cement fineness) contributes to the strength of tripartite grouts approximately 2–4 weeks after casting. Strength gain continues several months after production of tripartite grouts G2 and G4. As for the obtained compressive strength, grout G2 reached in 230 days the same compressive strength as grout G1 in 90 days, thus proving the potential of tripartite blends, provided the lime to pozzolan ratio is optimized. The increase of the lime content in grout G3 (from 35 to 47%) resulted, as expected, to a drop of the achieved strengths.

As for the very sensitive mechanical property of flexural strength, despite some fluctuations in the obtained values, flexural strength of the tripartite grouts generally increased (for grout G2) or remained constant (for grouts G3 and G4) with time. The increase in the flexural strength of grout G2 is attributed to its progressively gaining density microstructure, thanks to

Table 2 Mix proportions of the studied grouts

Grout	Composition [%-wt]			
	Cement	Lime	Metakaolin	Pozzolan from Milos island
G1	80	20	–	–
G2	30	35	35	–
G3	30	47	23	–
G4	30	50	–	20

Table 3 Compressive and flexural strength of grouts [MPa]

Age (days)	G1		G2		G3		G4	
	f_c	f_t	f_c	f_t	f_c	f_t	f_c	f_t
7	13.3	3.7	5.1	1.3	3.5	0.7	1.0	0.6
28	14.6	3.4	9.9	2.0	7.3	2.3	3.3	1.7
90	17.9	4.5	13.6	1.0	7.9	1.9	7.6	1.9
230	–	–	17.9	3.3	9.9	2.2	7.3	1.7

both the pozzolanic reaction and the fineness of the pozzolan. Ambroise et al. [26] have demonstrated the positive effect on the microstructure (rich in CSH) and the pore size distribution (which is displaced toward smaller values) of cement-metakaolin based mortars when they are adequately proportioned. The smaller but stabilizing with time flexural strength of grout G4 shows a less dense microstructure, which nevertheless is resistant to microcracking.

3.2 Testing program and investigated parameters

In order to examine the in-time development of the bond strength of grout-to-substrate interfaces, tension and shear tests were carried out at ages of 28, 60, 90 and 180 days. Among the four grouts mentioned in the previous section, grouts G1, G2 and G4 were retained for further investigation. Grout G3 is not investigated, since preliminary tests have shown that the pozzolan to lime ratio was not optimum. In case of shear tests, an additional parameter was considered, namely the value of the normal compressive stress, σ, on the interface. Three values of this parameter were considered, namely: 0.1, 0.3, and 0.6 MPa. The first two values correspond to stresses frequently developed in masonry walls due to vertical loads (mainly self weight). The unusually high value of ($\sigma = 0.60$ MPa was adopted to complete the picture on the effect of this parameter on the behaviour of interfaces.

The selection of combinations of parameters to be investigated was based on the following criteria: (1) The tests to be carried out should be limited to a sensibly large number that (2) would provide an as clear as possible picture of the effect of all investigated parameters. Thus, all mixes were tested at the age of 28 and 90 days. Nevertheless, the ages of 60 and 180 days are also examined for the mixes that contain pozzolan, since the pozzolanic reaction is mobilized with some delay and it is active for longer. The value $\sigma = 0.3$ *N*Pa is adopted as the main normal stress value. Thus, all combinations of substrates and mixes are tested for this normal stress value. Some selected combinations of substrates and mixes are tested for $\sigma = 0.1$ and 0.6 MPa as well. Thus, 111 composite specimens were prepared and tested in direct tension, whereas the shear test program includes 144 specimens. Tension tests are completed; shear tests for the ages of 28, 60, and 90 days are carried out to date.

3.3 Construction of specimens

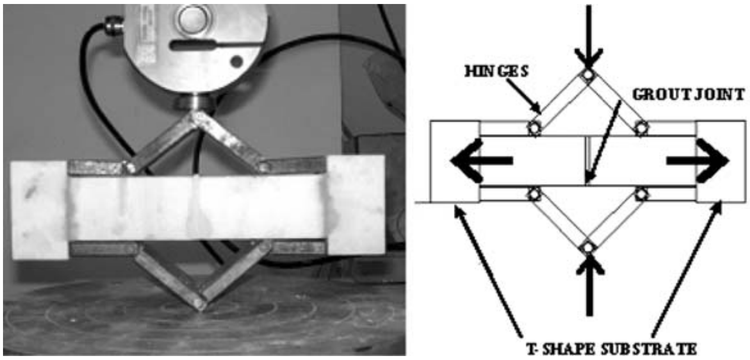
The specimens were prepared as follows: (a) Dionysos marble, travertine and brick prisms were cut in dimensions: $40 \times 40 \times 65$ [mm] or $40 \times 40 \times 80$ [mm] (for tension tests) or $40 \times 40 \times 20$ [mm] (for shear tests). (b) The prism faces to be bonded with a grout were mechanically chiseled, in order to simulate the roughness of the inner layers of multi-leaf masonries. (c) The surface to be connected with grout was cleaned using high-pressure air and, then, the substrate specimens were stored for at least two weeks in the humidity chamber at 95% R.H. and 20°C. (d) The injection of the grout that followed was carried out in two phases: In a first step, half of the quantity of the grout was injected and compacted using of a metal wire. In a second step, the rest of the grout was poured following the same procedure. For the injection of the grout in the (3 mm thick) joint of the composite specimen, a disposable syringe without the needle (10 ml capacity) or a 20 ml capacity syringe with 1 mm vent needle was used. Special care was taken, to avoid air penetration in the grout layer. During the whole procedure of injection and curing, the composite specimens were in horizontal position. In order to keep the width of the vertical grout joint constant, a system of steel plates and rods was used. (e) The composite specimens were covered with a wet hessian cloth for one week. Then, in order to limit the carbonation of the grout, the joint was covered with an adhesive tape and then the specimens were cured at 95% R.H. and 20°C until the day of testing.

Three identical specimens were tested for each combination of parameters.

3.4 Experimental setup

The fragment-test method [27] was used to measure the tensile strength of the interfaces. For this purpose, further preparation of the

Fig. 1 Experimental set up for direct tension tests



specimens was needed. As shown in Fig. 1, each composite specimen, prepared as described in Sect. 3.3, was glued (using epoxy resin) with transverse pieces of the same substrate material, to give it the form required by the applied testing method. The forces were applied by a hydraulic press (max capacity: 300 kN). A load cell (max capacity of 10 kN) was placed between the piston and the specimen; it was connected to a computer, where load measurements were transferred and stored.

The shear tests were performed using a shear box device (Fig. 2), designed for this purpose. Displacement-controlled tests were carried out at a speed of 0.5 mm/min. Displacements were imposed at mid grout joint level (with zero eccentricity), whereas the normal stress was imposed by means of hanging weights and it was kept constant throughout testing. Horizontal displacement, lateral dilatancy and the corresponding resisting shear stress were automatically recorded and stored.

Fig. 2 Experimental set up for shear tests

4 Experimental results

4.1 Failure modes of the composite specimens

4.1.1 Direct tension test

Four modes of failure were observed (Fig. 3):

i. Mode ITZ (Interface zone): Tensile failure of the interface. The grout detaches from the substrate along one interface.
ii. Mode Z: Similar to failure mode ITZ. In this case, however, practically half of the grout joint remains attached to the one substrate prism, whereas the other half remains attached to the second prism.
iii. Mode G: Failure within the grout (tensile failure of the grout).
iv. Mode S: Failure of the substrate.

4.1.2 Shear tests

As shown in Fig. 4, specimens subjected to shear exhibited one of the failure modes (i), (ii) or (iv), as described in the previous paragraph for tension tests.

4.2 Results and discussion

In this section, the main experimental findings are presented and commented upon. It should be noted that some of the test results were rejected

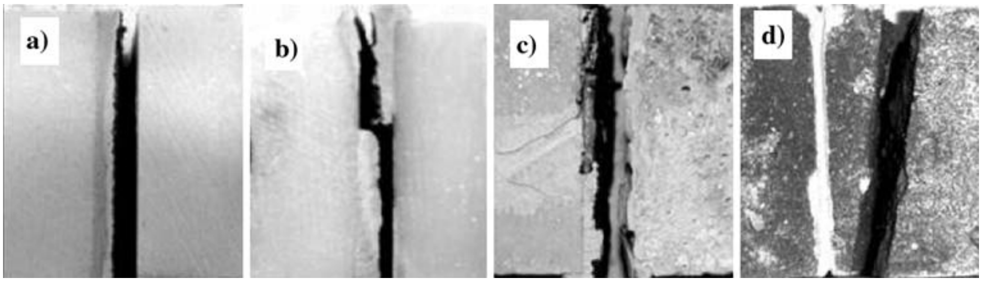
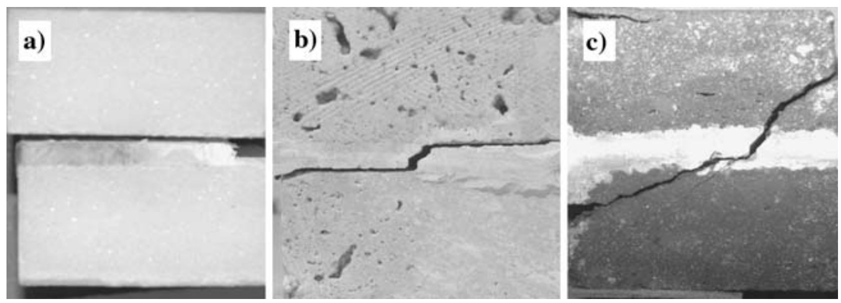


Fig. 3 Failure modes: (**a**) ITZ, (**b**) Z, (**c**) G, (**d**) S

Fig. 4 Failure modes: (**a**) ITZ, (**b**) Z, (**c**) S



and, therefore, they were not evaluated: (a) Defectively constructed specimens (either those with a grout joint not fully filled or those with a large amount of air in the joint) were discarded; (b) Specimens that failed in the substrate away from the interface are excluded as well. Finally, (c) in some specimens, carbonation of the grout in the joint was observed. Since this situation is not representative of the grout condition in the interior of a masonry wall, where carbonation is not expected to occur, the respective specimens were not taken into account.

4.2.1 *Direct tension test*

- Marble-to-grout interfaces:

In Fig. 5, bond strength of marble-to-grout interfaces is plotted against the age at testing for the three alternative grout mixes. It is observed that the lowest tensile strengths were measured for the tripartite grout G4 (with pozzolan from Milos Island), whereas the highest tensile strength values were reached in specimens with the metakaolin-based grout G2.

As for the in-time development of interface strength, the following can be observed: (i) For grout G1(C = 80%, L = 20%), the tensile strength was more or less stabilized after the age of one month. The observed slight reduction of tensile strength (from 0.93 to 0.85 MPa) between the 28th and the 90th day lies within the acceptable margins of scatter of experimental results, related to a very sensitive property like tensile strength. (ii) For grout G2 (C = 30%,

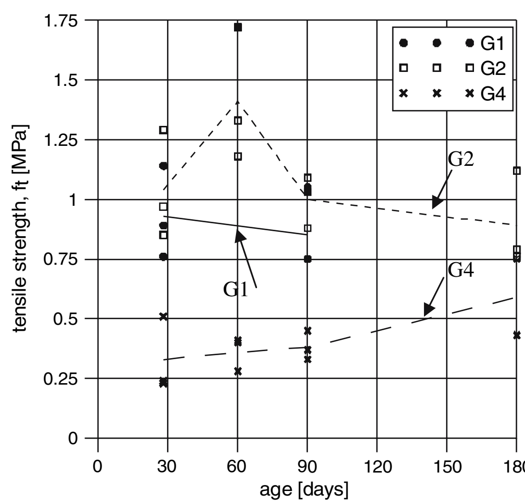


Fig. 5 In-time development of marble-to-grout bond tensile strength

L:MK = 1:1), it is assumed (on the basis of XRD observations [28]) that the consumption of portandite crystals and the early formation (at 28th day) of the C-S-H gel, provided the mechanical interlock between marble and grout and thus led to tensile bond strengths close to (or even larger than) those ensured by the reference grout G1. It is very important to observe that (as shown in Table 3) both the compressive and the tensile strength of grout G2 are substantially smaller than those of the reference grout G1. On the other hand, after the age of 60 days, the tensile bond strength of G2 to marble interfaces exhibited a reduction (with subsequent stabilization though). This reduction may be related to a similar reduction of the tensile strength of the grout G2 itself (see Table 3). However, until more detailed study of this phenomenon is available, no interpretation of this drop in bond strength is attempted. (iii) For grout G4, a continuous increase of the tensile bond strength was recorded between the 28th day and the 180th day (from 0.33 to 0.59 MPa). Based on available data from the literature (see for example the comparative results of short and long term bond tensile strength and the respective SEM observations of new-to-old concrete with fly ash mortar as a binder [29]), this behaviour is attributed to the densification of the interface due to the pozzolanic reaction, which is slower with the coarser pozzolan from Milos Island. In contrast to what happens in interfaces with G1 or G2, the in-time development of strength for grout G4 follows an ascending branch even after 180 days. This trend, most probably due to the slowly developing pozzolanic reaction allows for further increase of the bond strength to be expected.

It should be mentioned that the better behaviour exhibited by joints with grout G2 is also evidenced by the observed failure modes of the specimens. In fact, all specimens with grouts G1 and G4 failed along the interface (Mode ITZ). For grout G2, some specimens failed in Mode ITZ (27%). However, Modes Z and G were also observed (in 46 and 27% of the cases respectively). Needless to say that the observed failure modes Z and G characterize improved interface properties possibly attributed to the fine metakaolin particles.

- Travertine-to-grout interfaces:

In Fig. 6, bond strength of travertine-to-grout interfaces is plotted against the age at testing for the three alternative grout mixes. One may observe the larger scatter of experimental strength values as compared to the results regarding marble. It is to be reminded that the porosity and the mechanical properties of the travertine itself are very scattered (see Table 1). In general, the values of tensile bond strength for grout to travertine interfaces are by more than 50% higher than those obtained for marble interfaces. Since bond is partly due to mechanical interlock (see i.a. Lawrence and Cao [30] quoted in Hendry [31]), the improved performance of travertine-to-grout interfaces may be explained by the higher porosity and surface absorption of the travertine substrate, which led to a better interlocking of the binders to the substrate, as well as to a reduction of the water at the interface. It should be noted that, since high injectability grouts contain a large amount of water, this local water reduction does not influence adversely the hydration process of the binder. On the contrary, it results to grout/travertine interface zone that is denser and less porous. The higher values for the tensile bond strength could possibly be explained also by the reduced wall effect due to higher natural surface roughness of this travertine, as compared to

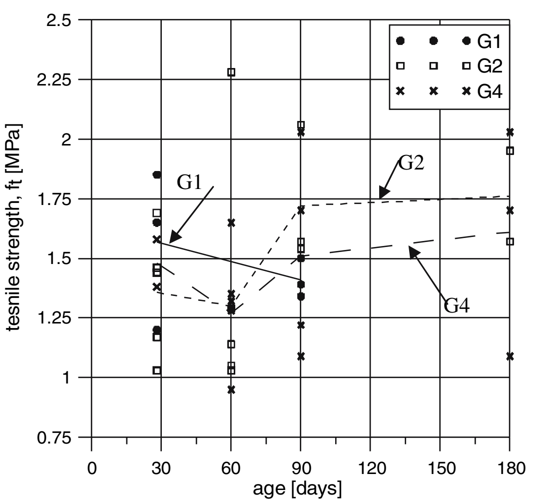


Fig. 6 In-time development of travertine-to-grout bond tensile strength

marble. If the fact that grouts G1 and G4 develop their bond strength in different rate is disregarded, it is observed that their ''final'' bond strength is not substantially different, although the mechanical properties of grout G1 are significantly higher than those of grout G4 (see Table 3). The similar behaviour of travertine to G1 or G4 interfaces seems to be confirmed by the fact that failure modes type Z or ITZ (i.e. failure plane along an interface) are typically observed. Although grout G2 exhibits for all examined ages higher bond properties than grouts G1 and G4 (the main observed failure mode is of type G), this difference is not as pronounced as in case of interfaces with marble. This result suggests that the properties of the travertine are governing the behaviour of the interfaces.

- Brick-to-grout interfaces:

In all composite specimens with brick as a substrate, the failure occurred in the brick, irrespectively of the grout composition and the age of the specimen. The mean tensile strength obtained by the specimens is equal to 0.80 MPa. This value can be therefore taken as a measure of the tensile strength of the bricks. As for the bond tensile strength of the interfaces, it can only be said that (for the brick and for the grouts tested within this program) it is higher than 0.80 MPa.

4.2.2 Shear tests

This section summarizes the experimental results obtained from shear tests. Although this part of the program is still in progress, the available results allow for several key features to be discussed. They also allow for comparison with the results obtained from tension tests.

Figure 7 presents some diagrams of shear stress (τ) versus shear slip (s) and transverse dilatancy (w) for marble-to-grout G2 specimens (age 90 days at σ = 0.30 MPa). The shape of the curves is typical for all stones-to-grout specimens independently of the binder and the limestone type. It is observed that the relationship between imposed slip and shear resistance is practically linear until the maximum resistance is reached. A steep falling branch follows, whereas subsequently, the shear resistance is stabilized to a

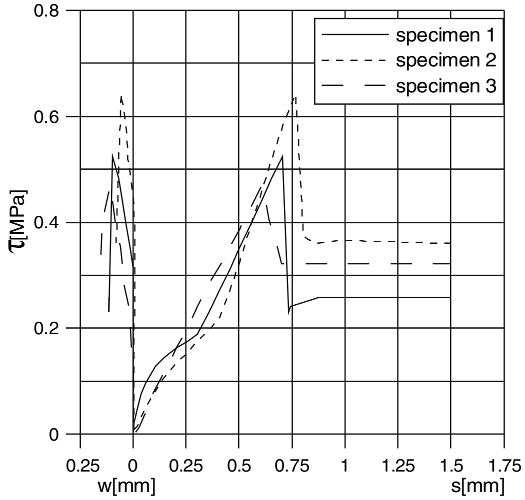


Fig. 7 Shear stress (τ) versus shear slip (s) and lateral dilatancy (w) for marble-to-grout G2 specimens (age 90 days at σ = 0.30 MPa)

residual value depending on the grout mix, as discussed in the following paragraphs. In a similar way, lateral dilatancy is increasing with increasing imposed slip, whereas after stabilization of the shear resistance, τ_{res}, lateral dilatancy stabilizes as well.

- Marble-to-grout interfaces:

All specimens, independently of the grout mix, failed along the grout/substrate interface (Mode ITZ).

Regarding the maximum shear stress mobilized along interfaces, the results (summarized in Table 4) seem to be in accordance with the results of direct tension. In fact, the maximum shear resistance of marble to G1 interfaces exhibits a slight increase (from 0.47 to 0.64 MPa). On the contrary, marble to G2 interfaces that exhibited a mean value of the maximum shear resistance equal to 0.82 MPa at the age of one month, are less resistant at the age of 90 days. In fact, the shear resistance of the interfaces is reduced by 30% approximately, following the similar in-time reduction of the tensile strength of grout G2. In case of grout G4, the maximum shear resistance of the interfaces is continuously increasing with time.

It has to be noted, however, that although with increasing age, the maximum mobilized shear resistances seem to be quite similar for the three

Table 4 Summary of shear test results (mean values of two or three specimens per combination of parameters)

Days	Substrate type	Ref. No of the grout	τ_u[MPa]			μ_{max}			s_u[mm]			w_u[mm]		
			σ = 0.1	σ = 0.3	σ = 0.6	σ = 0.1	σ = 0.3	σ = 0.6	σ = 0.1	σ = 0.3	σ = 0.6	σ = 0.1	σ = 0.3	σ = 0.6
28	Marble	G1		0.47			1.57			0.687			0.288	
		G2		0.82			2.73			0.693			0.466	
		G4		0.26			0.87			0.537			0.238	
	Travertine	G1	[a]	1	1.14	[a]	3.33	1.9	[a]	1.274	1.132	[a]	0.644	0.662
		G2	1.05	1.1	1.12	10.5	3.67	1.87	0.926	1.6	1.316	0.161	0.725	0.472
		G4	0.66	0.45	0.8	6.6	1.5	1.33	0.877	0.843	1.104	0.25	0.063	0.172
60	Travertine	G2		1.37			4.56			1.39			0.494	
		G4		0.64			2.13			0.86			0.265	
90	Marble	G1		0.61			2.03			0.712			0.057	
		G2		0.54			1.8			0.693			0.087	
		G4		0.5			1.67			0.642			0.002	
	Travertine	G1	0.61	0.7	0.88	6.1	2.33	1.47	0.586	0.798	0.558	0.098	0.776	0.036
		G2	0.99	0.93	1.14	9.9	3.1	1.9	1.02	1.181	0.919	0.041	0.435	0.21
		G4	1.02	0.95	1.14	10.2	3.2	1.9	0.842	1.025	0.638	0.307	0.486	0.001

[a] Unreliable test results

grout mixes, the behaviour of marble to G2 and G4 interfaces is considered to be better than marble to G1 interfaces taking into account the higher mechanical properties of the cement grout G1 (Table 3).

Regarding the mean values of the residual shear strength at the age of three months, it is observed that for grouts G1 and G4, τ_{res} is approximately equal to 0.20 MPa, while it is somehow higher for grout G2 (equal to 0.30 MPa). It is interesting to observe that independently of the bonding material (i.e. for G1, G2 and G4) and the age at testing, the shear slip corresponding to the maximum shear resistance is approximately equal to 0.7 mm. On the contrary, the lateral dilatancy at maximum shear resistance exhibits a substantial reduction between the age of 30 and 90 days.

- Travertine-to-grout interfaces:

The general behaviour of travertine to grout interfaces seems to be in accordance with test results of shear along cracks in concrete (see i.a. Tassios et al. [32]). In fact, as shown in Table 4, the maximum mobilized shear resistance increases for increasing normal compressive stress on the interface, whereas the friction coefficient (expressed as the ratio between maximum shear resistance and corresponding shear slip) is decreasing with increasing normal compressive stress (Fig. 8).

Furthermore, the results obtained from shear tests seem to confirm the improved bonding properties of travertine-to-grout interfaces as compared with those between grout and marble: As shown in Table 4, the maximum shear resistances obtained for travertine are systematically higher than those recorded for marble. The improved bonding properties of tripartite grouts G2 and G4 are also confirmed, since they ensure higher shear resistances although they are of lower mechanical properties than the reference grout G1. This is shown also in Fig. 9, where the values of friction coefficient are plotted against the applied normal stress normalized to the compressive strength of the respective grout. One may observe that, for the same σ/f_c ratio, grouts G2 and G4 ensure substantially higher

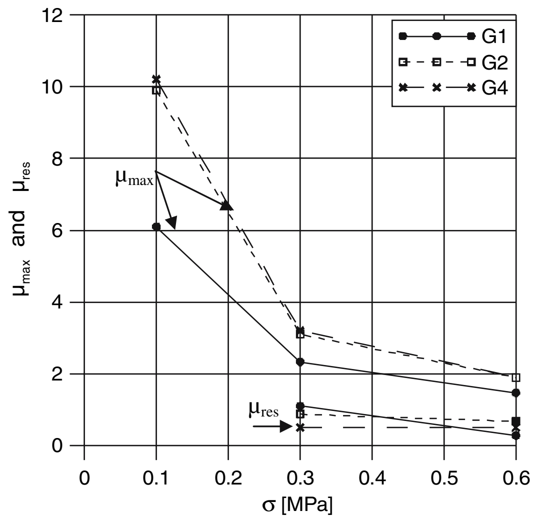


Fig. 8 Effect of the applied normal stress on the friction coefficient along travertine-to-grout interfaces (age 90 days)

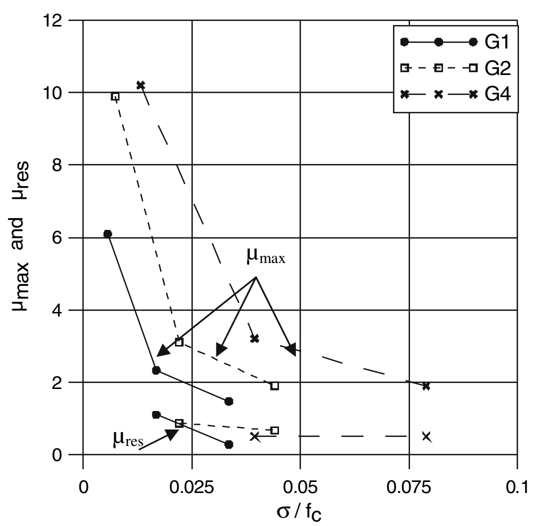


Fig. 9 Effect of the applied normal stress-to-grout compressive strength ratio on the travertine-to-grouts friction coefficient (age 90 days)

friction coefficients μ_{max}. This is more so for the residual friction coefficient, μ_{res} (Fig. 9). Thus, the potential of high injectability tripartite grouts as repair/strengthening materials is proven. Regarding the in-time development of shear strength of interfaces, the general trend observed in case of direct tension tests is observed in case of shear tests as well.

It has to be mentioned that the strong dependence of the behaviour of travertine-to-grout interfaces on the (quite variable) properties of the substrate is illustrated by the substantially larger scatter of the measured maximum shear resistance, of the respective shear slip value, as well as of the lateral dilatancy (see Table 4). Last but not least, this dependence becomes apparent when the failure mode of the specimens is examined. Thus, composite specimens with grout G1 failed in mode ITZ at early ages, while at the age of three months failed in mode Z. Specimens with grout G2 failed mainly (67%) in mode Z at higher values of the normal stress level and older ages.

Finally, travertine to grout G4 interfaces failed mostly in mode ITZ (83%).

- Brick-to-grout interfaces:

The experimental results available to date show that specimens with joints filled either with G2 or with G4 fail due to shear failure of the substrate (at a shear stress approximately equal to 0.85 MPa for σ = 0.3 MPa). Thus, similar to the case of direct tension, one may say that the two grouts provide a shear resistance along the interface larger than 0.85 MPa. This is not the case for specimens where the reference grout G1 is used: A mixed failure mode is observed, mainly an ITZ mode combined in some cases with partial failure of the substrate. In this case, the mean value of the measured shear resistance of the interface is approximately equal to 0.90 MPa (at σ = 0.3 MPa). Thus, it is legitimate to assume that, in this case too, the bond ensured by the tripartite grouts is higher than that of the cement grout.

5 Conclusions

1. The bonding properties of tripartite grouts with reduced cement content (30%-wt) were proven to be satisfactory. In fact, both in direct tension and in shear tests the bond strength exhibited by tripartite grouts to substrate interfaces were equal or higher than the bond strength reached by cement grout to

substrate interfaces, although the mechanical properties of the cement grout itself are higher.

2. As expected, the three grouts considered within the program exhibited differences in their in-time behaviour. Thus, grouts containing metakaolin or pozzolan from Milos island need a longer period for the development of their strengths.
3. Both tension and shear tests proved the dependence of the bond properties of the interfaces on the characteristics of the substrate. Thus, for the same grout mix, low porosity marble exhibited in general lower bond strength values than the higher porosity travertine.
4. Interfaces between bricks and the grouts examined in this work were in general stronger than the substrate itself. Thus, failure did in most cases occur within the substrate.
5. Interfaces subjected to shear have exhibited similar behaviour with interfaces within concrete. Thus, the beneficial effect of normal compressive stress on the interface was confirmed. Furthermore, it was shown that both for marble and for travertine even after attainment of the maximum resistance, the interfaces are able to sustain larger displacements under a residual shear resistance of the order of 0.20–0.30 MPa.
6. These results are in accordance with results from testing grouted three-leaf masonry wallets. In fact, tests have shown that masonry grouted with low to medium compressive strength grouts (5.0–10.0 MPa) may reach compressive strengths equal to or higher than those obtained by masonries grouted with cement based grouts.
7. It is believed that the test results presented in this work may encourage further the use of ternary grouts with reduced cement content to inject historic masonries, thus ensuring a durable and mechanically efficient intervention.

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References

1. Binda L, Baronio G, Tiraboschi C (1993) Repair of brick masonries by injection of grouts: experimental research. J Struct Eng 20(1):29–44
2. Laefer D, Baronio G, Anzani A, Binda L (1996) Measurement of grout efficacy for stone masonry walls. Proc 7th NAMC, Indiana, USA, 484–496
3. Vintzileou E, Tassios TP (1995) Three-leaf stone masonry strengthened by injecting cement grouts. J Struct Eng ASCE 121(5):848–856
4. Toumbakari E-E (2002) Lime-pozzolan-cement grouts and their structural effects on composite masonry walls. Doctor Thesis, Katholieke Univ. Leuven
5. Valuzzi M-R (2004) Consolidamento e recupero delle murature, Coolana Scientifica 'REFICERE', 96
6. Vintzileou E, Miltiadou-Fezans A, Vrouva A, Anagnostopoulou S (2006) Mechanical properties of three-leaf stone masonry. In: Lourenço PB, Roca P, Modena C, Agrawal S (eds) Proc 5th Struct Analysis of Historical Constructions, New Delhi, 2006, 777–784
7. Miltiadou-Fezans A, Vintzileou E, Papadopoulou E, Kalagri A (2006) Mechanical properties of three-leaf stone masonry after grouting. In: Lourenço PB, Roca P, Modena C, Agrawal S (eds) Proc 5th Struct Analysis of Historical Constructions, New Delhi, 2006, 785–792
8. Farran J (1956) Contribution minéralogique à l'étude de l'adhérence entre les constituants hydratés des ciments et les matériaux enrobés. Revue des Matériaux de Construction et Travaux Publics 490–491:155–172
9. Lyubimova TYu, Pinus ER (1962) Crystallization structure in the contact zone between aggregate and cement in concrete. Colloid J USSR 24(5):491–498
10. Maso JC (1980) The bond between aggregates and hydrated cement pastes. Proc 7th Int Cong on the Chem of Cement, Paris, (Septima Editions) 3–15
11. Xiong G, Liu J, Li G, Xie H (2002) A way for improving interfacial transition zone between concrete substrate and repair materials. Cem Concr Res 32(12):1877–1881
12. Lange D, Deford HD, Werner AM (1999) Microstructural investigation of mortar/unit interaction. J Masonry Soc 17(1):31–42
13. Reda Taha MM, Shrive NG (2001) The use of pozzolans to improve bond and bond strength. Proc 9th Canadian Masonry Symposium, Canada
14. Ray I, Davalos J, Luo S (2005) Interface evaluations of overlay-concrete bi-layer composites by a direct shear test method. Cem Concr Composites 27(3):339–347
15. Momayez A, Ehsani MR, Ramezanianpour AA, Rajaie H (2005) Comparison of methods for evaluating bond strength between concrete substrate and repair materials. Cem Concr Res. 35(4):748–757

16. Minoru K, Toshiro K, Yuichi U, Keitetsu R (2001) Evaluation of bond properties in concrete repair materials. J Mat Civil Eng 13(2):98–105
17. Rao G, Prasad BK (2002) Influence of the roughness of aggregate surface on the interface bond strength. Cem Concr Res 32(2):253–257
18. Jiang L (1999) The interfacial zone and bond strength between aggregates and cement pastes incorporating high volumes fly ash. Cem Concr Composites 21(4):313–316
19. Groot C (1993) Effects of water on mortar-brick bond. Thesis, Technical University Delft
20. Grandet J, Farran J, Maso JC (1970) Variations des concentrations de portlandite et d'ettringite dans les pâtes de ciment Portland au contact des terres cuites poreuses. Comptes Rendus, Acad.Sc.Paris, serie D, 4–7
21. Bei G, Papayianni I (2004) Experimental study of shear bond strength of traditional masonry. 13th Int Brick and Block Masonry Conf, Amsterdam, 181–190
22. Miltiadou A (1990) Etude des coulis hydrauliques pour la réparation et le renforcement des structures et des monuments historiques en maçonnerie. Doctor Thesis, Ecole Nationale des Ponts et Chaussées, Paris
23. Papayianni I (1998) A diachronic principle in construction: the use of mixed type binders–Durability aspects. In: Swamy RN (ed) Proc JCCabrera Symp.Durability of Building Materials, Bangkok, 115–129
24. Vardoulakis I, Kourkoulis SK (1997) Mechanical properties of Dionysos marble. Final Report of the Environment Project EV5V-CT93-0300 Monuments under seismic action (Nat. Tech. Univ. of Athens)
25. Vardoulakis I, Stavropoulou M, Papadopoulos Ch. (2000) Direct tension tests on Dionysos marble. EU DG XII SMT Programme No SMT4-CT96-2130, Final Report
26. Ambroise J, Maximilien S, Pera J (1994) Properties of metakaolin blended cements. Adv Cem Based Materials 1(4):161–168
27. Tassios TP, Vachliotis C, Spanos C (1989) In-situ strength measurement of masonry mortars. Int Technical Conf in Structural Conservation of Stone Masonry, Athens, (ICCROM, 1989)
28. Toumbakari E-E, Adami Ch.-E, Vintzileou E (2005) Properties and performance of tripartite lime-natural pozzolan-cement based grouts with the use of artificial pozzolans. Proc 1st Hellenic Conf the Utilization of By-Products in Constructions, Thessaloniki, November, 141–150 (in Greek)
29. Li G (2003) A new way to increase the long-term bond strength of new-to-old concrete by the use of fly ash. Cem Concr Res 33(6):799–806
30. Lawrence S, Cao TH (1987) An experimental study of the interface between clay and cement. Proc 4th North American masonry Conf, Los Angeles, 1–14
31. Hendry AW (1998) Structural masonry, 2nd edn. Macmillan Pub Ltd
32. Tassios TP, Vintzileou E (1987) Concrete to concrete friction. J Struct Eng ASCE 113(4):832–849