Structural Analysis of Historical Constructions – Jerzy Jasieńko (ed)
© 2012 DWE, Wrocław, Poland, ISSN 0860-2395, ISBN 978-83-7125-216-7

HIGH PERFORMANCE LIME BASED GROUTS FOR REPAIR OF HISTORIC MASONRIES

Ioanna Papayianni[1], *Vasiliki Pachta*[2]

ABSTRACT

Grouting is a widely used repair technique for consolidating and strengthening historic structures. Since '80s, when grouting techniques started to be systematically used, they have been improved by establishing criteria for their design and application. The first applied grouts were rather cement-based and presented different physico-chemical and mechanical properties from the existing historic building materials. Following compatibility issues, many efforts have been made in order to develop softer grouts, more compatible to the authentic old structures. The improvement of their properties through the use of additives and admixtures so as to make these grouts more effective is still an open field.
In this paper a high number of grout compositions based on lime are comparatively studied. In order to improve their performance, other traditional binders have been added (pozzolan, clay, brick dust) while in some cases a small quantity of white cement (10-15% p.w.) was included to improve early strength development. Additives and admixtures were also used. Grout performance was checked in liquid state and hardened state by testing Fluidity, Penetrability and Volume Stability, as well as physico-mechanical properties (Dynamic Modulus of Elasticity, flexural and Compressive strength). Results showed that lime-based grouts could be of high performance, regarding rheological properties and strength capacity if they are properly designed. By this way, a compatible consolidation of historic constructions could be achieved.

Keywords: *Grouts, Lime, Consolidation, Historic masonry*

1. INTRODUCTION

As is known, grouts are basically mixtures of a binder or a system of binders with water and admixtures, in some cases with fine inert material, which present low viscosity and high penetrability. The use of grouting as an irreversible intervention to consolidate and strengthen historic masonries is a widely applied technique, since the 80's [1-3]. During the past decades, a lot of research has been realized in order to establish criteria for the design and testing the properties of grouts, as well as on the effectiveness of grouting techniques [3-13].
Because of the demand for high fluidity and penetrability, grouts are designed with a high Water/Binder (W/B) ratio, which inevitably leads to problems related to the volume stability and early strength development of the grout mixtures [11]. In the past, these problems enhanced the use of cement based grouts, which however presented different physico-mechanical character and behaviour than that of the old building materials and therefore created secondary problems to the historic structures. In order to produce 'softer' grouts, the use of cement was gradually replaced by traditional binders (lime, pozzolana) that were more compatible to the historic materials.
Nowadays, research results have proved [7, 10, 11, 13, 14] that the proper combination of traditional binders, as well as the use of modern advanced additives and admixtures can lead to the design of effective grouts that retain the physico-chemical properties of old materials.

[1] Professor, Laboratory of Building Materials, Dept. of Civil Engineering, Aristotle University of Thessaloniki, PO Box: 482, 54124, Thessaloniki, Greece, papayian@civil.auth.gr
[2] Dr. Architect, Conservator, Laboratory of Building Materials, Dept. of Civil Engineering, Aristotle University of Thessaloniki, PO Box: 482, 54124, Thessaloniki, Greece, vpachta@civil.auth.gr

In the present study, 4 series of totally 29 grout compositions were designed, manufactured and tested, in order to evaluate their effectiveness and properties in fresh and hardened state. Test results were evaluated and comparatively studied so as to proceed to conclusions about the influence of the binding system and of the use of additives and admixtures in the final characteristics of grouts.

2. MATERIALS AND METHODS

2.1. Raw materials and proportions

The selection of binders for the manufacture of grout compositions was based on the principle of compatibility [2, 4, 7, 11, 13]. Since the majority of old mortars found in monuments and historic buildings of Greece constitute of lime+pozzolan [15-17], grout compositions were also based in lime+pozzolan. Powder hydrated lime and lime putty were used, while other traditional binders such as clay and brick dust were also tested.

For comparison reasons and for testing their efficacy, hydraulic lime and white cement were used, as well as specific additives such as limestone filler and diatomite. White cement was added in a low percentage, in order to increase the early strength development and stability of the mixtures. To reduce the water demand, a superplasticizer of polycarboxilic basis (1% by mass of binders) was added to all mixtures. The superplasticizer was firstly mixed in a small quantity of water, which was part of the total quantity.

The proportioning of raw materials was based on the knowledge concerning the binding systems of the historic mortars, as well as on the properties of nowadays available traditional materials. The quantity of water was adjusted to keep flow time 9-11 sec (measured by Marsh cone, ASTM C939-87). This was previously defined (through former experimental laboratory and insitu work) as adequate parameter for maintaining the optimum fluidity of grouts in fresh state and at the same time the higher possible strength in hardened state.

Two types of hydrated lime were used (powder and putty), as well as two natural pozzolanic materials (milled to increase fineness), including a volcanic material from the island of Milos and a diatomite. Brick dust from modern fired bricks was also added as pozzolanic or inert material. Some of the characteristics of the binders and additions used are shown in Table 1.

Table 1 Characteristics of grouts' constituents

Constituents	**App. Specific density**	**Specific surface area** (m^2/g)	**Pozzolanicity index ASTMC311:77** (MPa)
Lime powder	2.471	2.250	–
Milos pozzolan	2.403	1.820	10.5
Diatomite	2.425	1.070	9.0
White Cement	3.100	1.030	–
Brick dust	2.851	0.225	2.5
Limestone filler	2.846	0.408	–

The grout compositions were divided, according to the traditional binders used, in four series of totally 29 mixtures. The binding system of each series is shown in Table 2, while in Table 3 the raw materials and proportions of all compositions are presented.

Table 2 Series of compositions according to the type of traditional binders

Series	**Traditional binders**			
	Lime	**Natural Pozzolan (Milos island)**	**Brick duct**	**Clay**
L	✓			
LP	✓	✓		
LPB	✓	✓	✓	
LPC	✓	✓		✓

Table 3 Constituents and proportions of grout compositions

Series	Code Nr	Parts by weight									W/B
		Hydrated lime		Hydraulic lime	Natural Pozzolan	White Cement	Brick duct	Clay	Diato-mite	Limestone filler	
		powder	putty								
L	L1	1									1.06
	L2	1				0.2					0.93
	L3	1				0.3					0.83
	L4		1								2.52
	L5		1			0.2					2.28
	L6		1			0.3					2.11
	L7	1							1		0.86
	L8	1							1	0.5	0.71
	L9			1							0.61
	L10			1						0.5	0.42
LP	LP1	1			1						1.10
	LP2	1			0.8	0.2					1.00
	LP3	1			0.7	0.3					0.97
	LP4		1		1						1.34
	LP5		1		0.8	0.2					1.02
	LP6	1			1					0.5	0.86
	LP7	1			0.7	0.3				0.5	0.83
LPB	LPB1	1			0.6		0.4				0.93
	LPB2	1			0.6	0.2	0.4				0.90
	LPB3	1			0.6	0.3	0.4				0.98
	LPB4	1			0.5		0.5				1.00
	LPB5	1			0.5	0.2	0.5				0.96
	LPB6	1			0.5	0.3	0.5				0.93
LPC	LPC1	1			0.8			0.2			1.17
	LPC2	1			0.8	0.2		0.2			1.12
	LPC3	1			0.8			0.4			1.14
	LPC4	1			0.8	0.2		0.4			0.89
	LPC5	0.5			0.5			1			1.25
	LPC6	0.5				0.5		1			1.11

2.2. Manufacture and testing procedure

For mixing all constituents, a high speed mixer (up to 8000 rpm) was used, for a total period of 5 minutes. It started with low speed, which was gradually increased up to 8000 rpm. Three triplets of 4 × 4 × 16 cm steel moulds were sealed and filled with fresh grouts and cured at climatic chamber of 90% RH and 20°C, up to the testing dates.

In order to evaluate their performance, grout mixtures were tested at fresh and hardened state. During their fresh state, three properties were measured:

- Flow time measured by Marsh cone (ASTM C939-87)
- Penetrability by using sand-column test (NORM NFP 18-891, 1986) filled with sand 2-4 mm.
- Volume stability was tested 24 hours after mixing, by using filled with grouts cylindrical containers (DIN 4227 Teil 5 standards).

Tests at hardened state (28 days after their manufacture) consisted of:

- Determination of Dynamic Modulus of Elasticity (ASTM C597-71)
- Determination of Flexural and Compressive strength (ASTM C191-81)

3. RESULTS AND DISCUSSION

3.1. Fresh state properties results

The test results concerning fluidity, penetrability and volume stability are presented in Table 4.

Table 4 Fresh state properties of grout mixtures

Series	Code Nr	Flow time (sec)	Penetrability (sec)	Volume stability (%)
L	L1	10.8	3.15	1.5
	L2	9.9	2.5	0.65
	L3	10.0	1.62	0.55
	L4	10.2	1.9	1
	L5	9.5	1.5	0.5
	L6	9.8	0.8	0.4
	L7	9.48	2.86	11.9
	L8	9.94	2.47	13.9
	L9	9.33	3.41	0.7
	L10	10.04	8.50	0.8
LP	LP1	9.8	4.8	1.2
	LP2	9.34	3.1	0.8
	LP3	9.70	2.10	0.6
	LP4	9.78	2.5	1.1
	LP5	9.38	2.3	0.7
	LP6	10.55	7.5	1.3
	LP7	9.61	1.52	1.3
LPB	LPB1	9.59	2.10	1.5
	LPB2	10.20	1.95	1.0
	LPB3	9.9	2.67	1.1
	LPB4	9.9	3.80	1.5
	LPB5	10.15	3.20	1.1
	LPB6	9.60	4.20	1.1
LPC	LPC1	9.50	7.50	1.8
	LPC2	9.09	6.40	1.2
	LPC3	9.17	2.30	1.7
	LPC4	9.70	2.00	1.1
	LPC5	10.05	3.32	6.95
	LPC6	10.81	2.5	5.93

3.2. Hardened state properties results

The test results concerning Dynamic Modulus of Elasticity, Flexural and Compressive strength are presented in Table 5 and Figures 1-3.

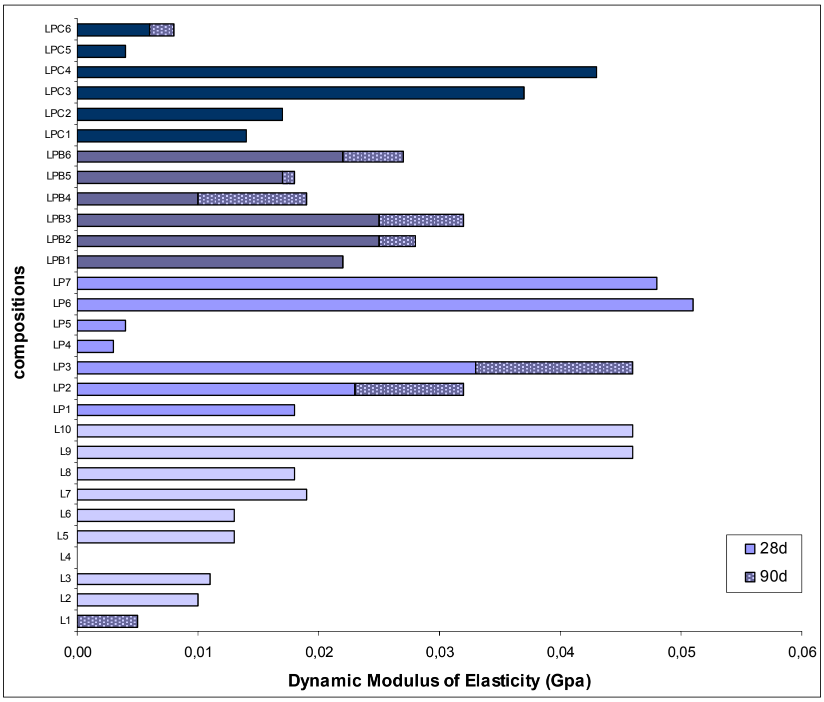

Fig. 1 Dynamic Modulus of Elasticity results of grout mixtures in 28 and 90 days

Table 5 Hardened state properties of grout compositions

Series	Code Nr	Dyn. Modulus of Elasticity (GPa)		Flexural strength (MPa)		Compressive strength (MPa)	
		28d	90d	28d	90d	28d	90d
L	L1	-	0.005	-	0.21	-	0.69
	L2	0.01	0.009	0.25	0.29	0.29	0.75
	L3	0.011	0.009	0.29	0.44	0.47	1.06
	L4	-	-	-	-	-	-
	L5	0.013	-	0.08	-	0.12	-
	L6	0.013	0.003	0.12	0.38	0.24	0.67
	L7	0.019	-	0.58	-	1.17	-
	L8	0.018	-	0.46	-	0.87	-
	L9	0.046	-	1.15	-	1.76	-
	L10	0.046	-	1.18	-	2.17	-
LP	LP1	0.018	-	0.57	0.22	0.89	4.45
	LP2	0.023	0.032	0.75	0.3	1.73	4.79
	LP3	0.033	0.046	1.04	1.24	2.51	5.39
	LP4	0.003	-	0.01	-	0.26	-
	LP5	0.004	-	0.06	-	0.85	-
	LP6	0.051	-	1.03	-	2.49	-
	LP7	0.048	-	0.97	-	2.34	-
LPB	LPB1	0.022	0.018	0.54	-	0.82	3.33
	LPB2	0.025	0.028	0.84	1.18	1.72	4.75
	LPB3	0.025	0.032	0.87	1.3	1.75	4.27
	LPB4	0.01	0.019	0.41	0.55	0.88	4.16
	LPB5	0.017	0.018	0.54	0.6	1.46	3.06
	LPB6	0.022	0.027	0.77	2.13	1.84	5.05
LPC	LPC1	0.014	0.014	0.27	0.38	0.46	2.17
	LPC2	0.017	0.017	0.55	0.68	0.88	2.89
	LPC3	0.037	0.028	0.28	0.63	0.29	3.34
	LPC4	0.043	0.031	0.94	0.71	1.52	3.57
	LPC5	0.004	-	0.13	-	0.55	-
	LPC6	0.006	0.008	0.23	0.28	0.66	1.22

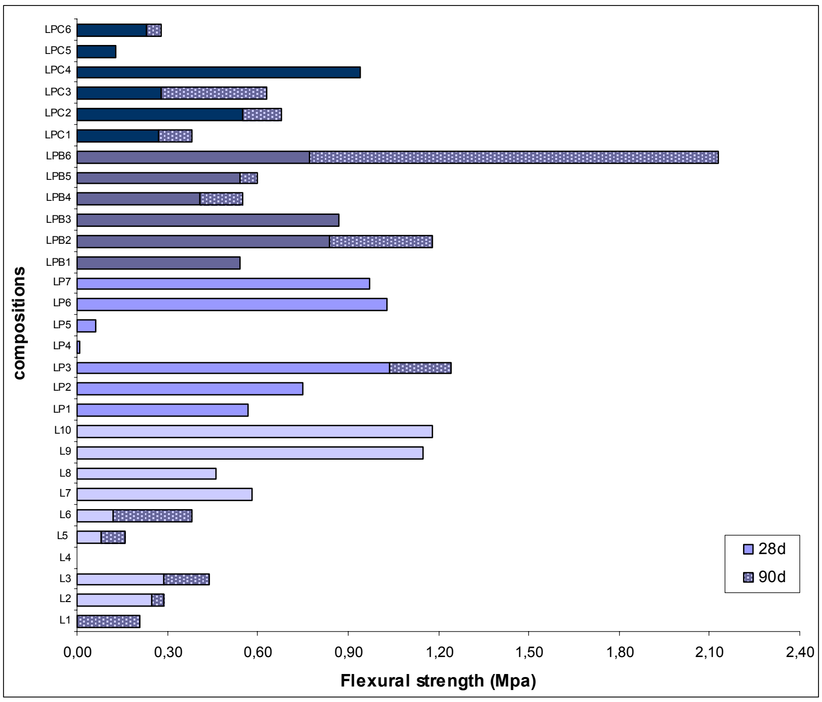

Fig. 2 Flexural strength results of grout mixtures in 28 and 90 days

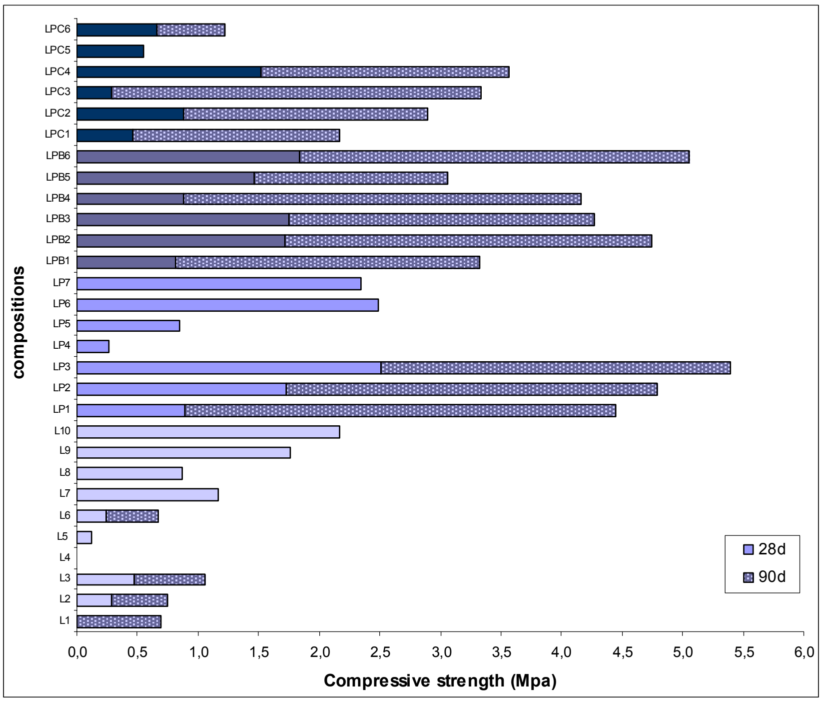

Fig. 3 Compressive strength results of grout mixtures in 28 and 90 days

3.3. Evaluation of results

In general, it can be said that with proper curing the 28d mechanical strength of grout mixtures corresponds to the 30-50% of the 90d mechanical strength. According to binding system used, the most important remarks can be synopsised as following:

3.3.1. L (Lime) series

When 20% and 30% of white cement is added both in hydrated lime powder (mixtures L1-L2-L3) and hydrated lime putty (mixtures L4-L5-L6), similar results can be foreseen:

- For keeping a stable flow time (around 10sec) the W/B ratio is reduced in a percentage of 10% with a 20% white cement addition and 20% with a 30% white cement addition. Penetration time reduces around 20% and 50% respectively, while volume stability is also reduced in a percentage of 50% and 60% respectively.
- Hardened state characteristics are significantly increased, since at 28days the pure lime mixtures have not been completely hardened and therefore did not show any results. Comparing the addition of 20% and 30% white cement, Dynamic Modulus of Elasticity is stable, Flexural strength is increased (around 20%), while compressive strength is almost doubled. In 90 days the results are similar. Therefore, it seems that low addition of cement is beneficial.

When diatomite (mixture L7) and especially when limestone filler is added (mixture L8), volume stability is increased (11.9 and 13.9sec respectively), and overcomes the accepted limit of 5%. However, mechanical strength is significantly increased (slightly decreased by the addition of limestone filler).

With the use of hydraulic lime (mixtures L9-L10), different results are appeared. While penetration time is increased, especially in the case of the addition of limestone filler (3.41sec and 8.5sec), volume stability is kept low (0.7-0.8%). The 28d flexural and compressive strength is high and is increased when limestone filler is added.

3.3.2. LP (Lime+Pozzolan) series

When 20% and 30% of pozzolan (10 and 15% by mass of binders) is replaced by white cement (mixtures LP1, LP2, LP3), W/B ratio is reduced (around 10%). Penetration time and volume stability are also reduced (around 30% for 10% replacement and 50% for 15% replacement). Mechanical characteristics are significantly increased and are almost double when 15% of pozzolan is replaced by white cement.

Similarly, in lime putty+pozzolan mixtures, when 10% of pozzolan is replaced by white cement (mixtures LP4-LP5), penetrability and volume stability is decreased (10 and 35%), while mechanical characteristics are almost tripled.

When limestone filler is added (mixtures LP6), W/B ratio is decreased, while penetrability is increased and volume stability slightly decreases. Dynamic modulus of Elasticity and Flexural strength is doubled and Compressive strength is tripled. In the same matrix, when 30% of pozzolan (15% by mass of binders) is replaced by white cement (mixtures LP7), penetrability is significantly decreased, while mechanical characteristics remain stable.

3.3.3. LPB (Lime+Pozzolan+Brick dust) series

When 10% (by mass of binders) of white cement is added in the system lime+pozzolan+brick dust (1:0.6:0.4) (mixture LPB2), penetrability and volume stability decrease, while mechanical characteristics are significantly increased. When 15% (by mass of binders) of white cement is added (mixture LPB3), properties in fresh and hardened state remain similar with that of 10% addition.

When the proportion of brick dust increases (mixture LPB4, LPB5, LPB6), penetration time increases (60-80%), while mechanical characteristics remain stable with some fluctuations.

3.3.4. LPC (Lime+Pozzolan+Clay) series

When 10% (by mass of binders) of white cement is added in the system lime+pozzolan+clay (1:0.8:0.2) (mixture LPC2), penetrability and volume stability decrease and mechanical characteristics are significantly increased. When 10% (by mass of binders) of white cement is added in the system lime+pozzolan+clay (1:0.8:0.4) (mixture LPC2), the properties in fresh and hardened state are even better.

When the proportion of clay is increased (0.5:0.5:1) (mixtures LPC5, LPC6) volume stability significantly increases (6-7%). Mechanical properties are also decreased.

4. CONCLUSIONS

Since grouting is an irreversible restoration technique which can often lead to secondary undesirable effects, the proper design and testing of grout mixtures is essential. According to the principle of compatibility, the grout mixture's constituents should be in accordance with the building materials found in historic masonries, so as the same physico-mechanical behaviour to be maintained. Since old mortars are usually lime-based, properly modified lime based grouts can be used for the consolidation of historic structures.

From the evaluation of the results it is concluded that according to their binding system, lime based grouts can provide efficient properties both in fresh and hardened state. In order to reduce W/B ratio, penetrability, volume stability and increase mechanical properties a sulphate free white cement can be added in a percentage of 10% by mass of binders, either as an additional binder or as a replacement of pozzolan. From the comparative study of the results it seems that the replacement of pozzolan is more effective.

Regarding the type of hydrated lime used (powder or putty) it seems that lime putty gives better results related to the fresh properties of grouts (penetrability, volume stability), while lime powder gives better mechanical characteristics. With the addition of diatomite the volume stability exceeds the accepted limit of 5% and therefore its use should be further studied, while the addition of limestone filler seems to have a positive effect on the fresh and hardened properties.

In any case, it can be concluded that the effectiveness of lime-based grouts depends on the proper selection and proportion of the binding system and can be only recorded by trial testing of properties in fresh and hardened state. Only by this way, the long-term performance of grouts can be envisaged and positively evaluated.

REFERENCES

[1] Ferragni D., Forti M., Malliet J., Teutonico J.M, Torraca G. (1985) In situ consolidation of wall and floor mosaics by means of injection grouting techniques. *Conservation in Situ Mosaics*, ICCROM Edition. 3:83-101.

[2] Penelis G., Karaveziroglou M., Papayianni I. (1988) Grouts for Repairing and Strengthening Old Masonry Structures., In: *Proc. International Conference on Structural Repair and Maintenance of Historic Buildings STREMAH*, Brebbia C. edition 179-188.

[3] Miltiadou A (1990) Contribution à l'étude des coulis hydraulique pour la réparation et le renforcement des structures et des monuments historiques en maçonnerie. PhD thesis ENPC Paris

[4] Binda L, Modena C, Baronio G, Gelmi A (1994) Experimental qualification of Injection Admixtures used for Repair and Strengthening of Stone Masonry Walls. In: Proc. 10th International Brick and Block Masonry Conference, Calgary Canada, 539-548.
[5] Binda L., Modena C., Baronio G., Abbaneo S. (1997) Repair and investigation techniques for stone masonry walls. *Construction and Building Marerials* 11(3):133-142.
[6] Lawrence J., Li L., Spencer J.T. (1998) A two-stage ceramic tile grout sealing process using a high power diode laser-II. Mechanical, chemical and physical properties. *Optics & Laser Technology* 30: 215-223.
[7] Toubakari E (2002) Lime-Pozzolan – Cement grouts and their Structural Effects on Composite Masonry Walls. PhD thesis Katholieke Uneversiteit Leuven.
[8] Toumbakari E.E., Van Gemert D., Tassios T.P., Tenoutasse N. (1999) Effect of mixing procedure on injectability of cementitious grouts. *Cement and Concrete Research* 29: 867-872.
[9] Eriksson M., Friedrich M., Vorschulze C. (2004) Variations in the rheology and penetrability of cement-based grouts – an experimental study. *Cement and Concrete Research* 34: 1111-1119.
[10] Vintzileou E., Miltiadou-Fezans A. (2008) Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime-based grouts. *Engineering Structures* 30: 2265-2276.
[11] Papayianni I., Stefanidou M., Pachta V. (2010) Grouts for Injection of Historical Masonries: Influence of the Binding System and other Additions on the Properties of the Matrix. In: *Proc. 2nd Historic Mortars Conference & Rilem TC 203-RHM 'Repair Mortars For Historic Masonry' Final Workshop* Prague, RILEM, 1123-1134.
[12] Bras A., Fernando M.A. Henriques F. (2012) Natural hydraulic lime based grouts – The selection of grout injection parameters for masonry consolidation. *Construction and Building Materials* 26: 135-144.
[13] Papayianni I., Argiropoulos M., Pachta V. (2009) Consolidation of earth block buildings with clay grouts. Materials and application. In: Proc. 2^{nd} Conference on Restoration Athens, ETEPAM, Proc in cd (in Greek).
[14] Gaitero J.J, Campillo J, Guerrero A (2008) Reduction of the calcium leaching rate of cement paste by addition of silica nanoparticles. *Cement and Concrete Research* 28: 1112-1118
[15] Papayianni I. (2004) Design of Compatible Repair Materials for the Restoration of Monuments. *Int. Journal for Restoration* 1(6): 623-636.
[16] Pachta V. (2011) Study of the technological evolution of mortars. PhD Thesis, Dept. of Civil Engineering, Aristotle University of Thessaloniki.
[17] Papayianni I. (2006) The longevity of old mortars. *Applied Physics A, Materials Science & Processing* 83: 685-688.