ECCOMAS Congress 2016
VII European Congress on Computational Methods in Applied Sciences and Engineering
M. Papadrakakis, V. Papadopoulos, G. Stefanou, V. Plevris (eds.)
Crete Island, Greece, 5–10 June 2016

THE ROLE OF RESTORATION MORTARS IN THE EARTHQUAKE PROTECTION OF THE KAISARIANI MONASTERY

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Keywords: *mortar compatibility, mortar serviceability, restoration mortars, historical structures, fragility curves, masonry retrofitting*

Abstract. *Monuments and historical buildings are degraded as time passes due to natural ageing, environmental factors, as well as natural phenomena such as earthquakes. Their conservation and restoration thus becomes crucial in order to preserve our cultural heritage. Repointing of monuments and historical buildings is perhaps the most usual conservation action, as it restores and ensures masonry continuity in a reversible manner. However, this is accomplished only if the restoration mortar applied fulfills compatibility and serviceability criteria. In the current study, the characterization of the historical mortars of the Kaisariani monastery was undertaken and six restoration mortars were selected from literature and examined in order to assess their compatibility with the historical structure of the Kaisariani Monastery in Greece. The restoration mortars were assessed regarding their compatibility with the structural materials of the Kaisariani Monastery, as well as their impact on the earthquake resistance of the structure. A new stochastic computational framework for earthquake resistant design of masonry structural systems, based on fragility analysis and artificial neural networks was applied for the assessment of the seismic vulnerability of the Kaisariani Monastery, for three different repairing scenarios, utilizing the results of the examined restoration mortars. The results showed that a variety of restoration mortar characteristics can be achieved, an important feature, which coupled with the results of the fragility analysis for the repairing scenarios, can be utilized for the selection of the optimum restoration mortar in terms of compatibility and serviceability.*

1. INTRODUCTION

Monuments and historical buildings are degraded as time passes due to natural ageing, environmental factors, as well as natural phenomena such as earthquakes [1]. Their conservation and restoration thus becomes crucial in order to preserve our cultural heritage. **Repointing** of monuments and historical buildings is perhaps the most usual conservation action, as it restores and ensures masonry continuity in a reversible manner. However, this is accomplished only if the restoration mortar applied fulfills **compatibility** and **serviceability** criteria.

The need for knowledge of the traditional mortars has recently arisen from an increased interest in the techniques and materials used in the past. Negative results in recently restored buildings due to the use of improper materials have created a growing demand for research into the field of the traditional ones. Traditional building materials, such as joint mortars, plasters, waterproofing mortars etc., have exhibited remarkable longevity throughout time, however their production technology has been lost, as traditional materials have been replaced due to the extensive use of common contemporary materials, like cement and polymers, materials highly incompatible with the authentic building materials, resulting in extensive and irreversible damage to many cultural heritage monuments [2, 3, 4].

A methodology which has proved helpful in this procedure is reverse engineering [1, 5, 6]. Thus, by discovering the ancient technology employed for the production of the original mortars, new, compatible restoration mortars can be designed. The researcher however cannot rely solely on the results of the analysis of the historical mortar; one must examine the other building materials as well, such as stones and bricks, in order to assess whether the new restoration mortar is compatible with these materials as well. Furthermore, one must always take into consideration the specific environment of the monument, as environmental factors, such as excessive humidity or atmosphere pollution also affect the longevity of the materials [7, 8]. The most important steps that must be followed, are i) sampling of representative mortar samples, selecting the mortars that exhibit the least possible decay (environmental, physical, mechanical), ii) characterization of the historical mortar through various techniques, classification in order to determine the range of acceptability values, as well as analysis of specific considerations, deriving from the in situ analysis of the structure, the restrictions accompanying the other building materials and the study of the materials decay and iii) production of proper restoration mortars or selection of restoration mortars available in literature and compatibility and serviceability assessment [6].

In the current study a number of historical samples deriving from the Kaisariani monastery masonries were studied through *Fiber Optic Microscopy (FOM), Sieve analysis, Differential Thermal and Thermo-Gravimetric Analysis (DTA-TG), Mercury Intrusion Porosimetry (MIP)* and *Total Soluble Salts Measurements.* Several compatibility and serveacability criteria were set during this process, in order to then evaluate the selected restoration mortars and concretes. Six restoration mortars were selected from existing literature and the results of their analysis were examined in order to assess their compatibility with the historical structure of the Kaisariani Monastery in Greece. The restoration mortars examined were two lime-metakaolin mortars and one hydraulic lime mortar, and two lime-metakaolin concretes and one hydraulic lime concrete (thick joint mortars) [9, 10]. The concretes were designed with the addition of crushed bricks, in order to simulate historical mortars of byzantine monuments that have shown excellent performance in earthquakes [11]. The restoration mortars were examined by DTA/TG, in order to assess their physicochemical characteristics and MIP in order to study their microstructural characteristics. These results were crucial in the assessment of compatibility. Finally, the mechanical strength of the restoration mortars was examined. Thus, the restoration mortars were assessed regarding their compatibility with the structural materials of the Kaisariani Monastery, as well as their impact on the earthquake resistance of the structure through the use of fragility analysis for different repairing scenarios, thus accomplishing the selection of the optimum restoration mortar in terms of compatibility and serviceability.

The Catholicon of the Kaisariani Monastery is a typical mid-byzantine Athenian church structure (11th or 12th century), its main building elements consisting of carved stones, bricks and mortars. The monastery has a rich history, and subsequently many construction phases throughout the centuries. The original building was a complex cross-in-square four-column domed church, without a narthex; the domed narthex was added to the west of the original structure in the early 17th century, and the barrel-vaulted chapel dedicated to Aghios Antonios positioned at the southwest of the Catholicon was added in the late 17th century (Fig. 1), thus comprising the present structure. The monastery complex has undergone many conservation treatments, which are not fully documented; however two important reconstruction projects took place in the complex in the beginning and the middle of the 20th century [12-14].

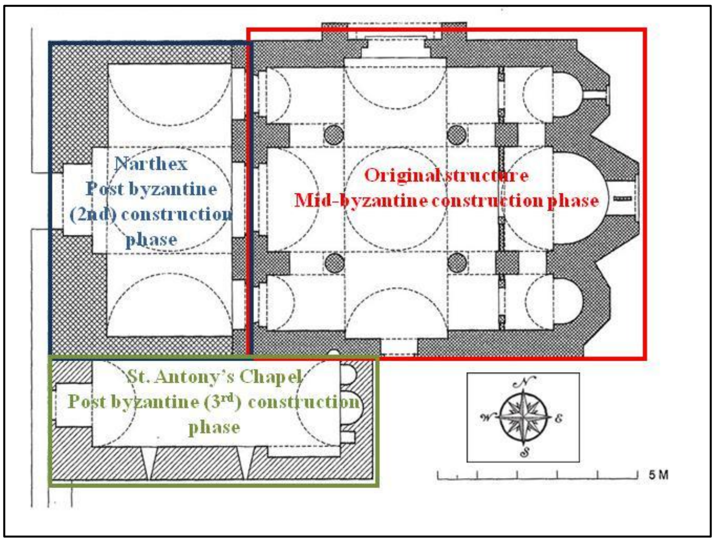


Figure 1: Ground plan of the church [15], with probable construction phases

2. SAMPLING

A number of historical mortar samples deriving from the historic masonry of the original Catholicon structure were examined (Table 1, Figure 2), as well as two brick samples. The samples were obtained internally and externally of the main temple, from different sides and depths of the walls.

Sample Code	Sampling Location	Sample Description
MK1	East wall of the Catholicon, in depth of the exterior masonry leaf. Position from ground level 1.4 m	Whitish mortar with the addition of straw, aggregates not discernible
MK2	East wall of the Catholicon, in depth of the exterior masonry leaf. Position from ground level 1.4 m	Mortar with evident lime lumps and the addition of straw, presence of dark-colored aggregates

MK2b	East wall of the Catholicon, exterior. Position from ground level 1.4 m	Whitish joint mortar, deriving from the joint of the cloisonné, presence of straw in matrix. Very low cohesion between mortar constituents
BR3a	East wall of the Catholicon, exterior. Position from ground level 0.4 m	Detached ceramic, evident biodegradation
BR3b	East wall of the Catholicon, exterior. Position from ground level 0.4 m	Whole piece of ceramic brick deriving from the cloisonné masonry. Mortar with straw adhered on the surface
MK4	North wall of the Catholicon, masonry left of the entrance, in depth of the exterior masonry leaf. Position from ground level 3.1 m	Whitish mortar straw additives, presence of dark-colored aggregates
MK5	North wall of the Catholicon, masonry right of the entrance, exterior. Position from ground level 3.5 m	Mortar, deriving from the joint of the cloisonné. Two layers visible: Exterior layer is pink hued and appears as 1mm thick (MK5a). Interior layer is (MK5b).
MK6	North wall of the Catholicon, masonry left of the entrance, in depth of the interior masonry leaf. Position from ground level 3 m	Whitish mortar with the presence of discernible dark-colored and light grey colored aggregates
MK7	Interior west wall of the Catholicon, joining with the Narthex Position from ground level 2.1 m	Whitish mortar. Presence of lime lumps. Presence of dark-grey colored aggregates, presenting a wide grain size distribution.
MK8	South wall of the Catholicon, in depth of the exterior masonry leaf. Position from ground level 3.6 m	Whitish mortar with dark-colored aggregates.

Table 1 Description of samples

3. METHODS AND TECHNIQUES

Various lab techniques were applied in order to characterize and study the samples taken from the Catholicon. *Fiber Optic Microscopy (FOM)* was employed in order to examine the samples microscopically, using a PICO SCOPEMAN-MORITEX and x50 magnification. *Sieve analysis* was performed according to Normal 27/88 [16] in order to analyze the mortar aggregates grain size distribution and to calculate the binder aggregate ratio. The sieves used were according to ISO 565. *Differential Thermal and Thermo-Gravimetric Analysis (DTA-TG)* provides qualitative and quantitative information regarding the composition of the samples (Mettler Toledo 651e). The temperature range applied was 25-1000^{o}C and the heating rate was selected at 10^{o}C/min [17]. X-ray diffraction (XRD) provides information regarding the mineralogical composition of the materials (Advance D8 Diffractometer of Bruker Corporation) [16-18]. The microstructural characteristics of the samples were studied through the use of *Mercury Intrusion Porosimetry (MIP)* with the use of a Pascal 400 Thermo-Electronics-Corporation [16, 19]. Taking into consideration the high water content of the masonries as well as the efflorescence of salts on the interior walls of the church [20], *Total Soluble Salts Measurements* were conducted, in accordance to the guidelines of Normal 13/83 [21], as well as spot tests in order to identify the salts present [22]. Finally, Water Absorption by Capillarity test was conducted in accordance to Normal 11/85, in order to estimate the capillarity absorption coefficient of the brick sample [23].

The restoration mortars were selected through extensive research of available literature [9, 10]. The selected mortars were all designed for use in historical buildings through the reverse engineering methodology. Furthermore, it was a prerequisite that the restoration mortars were examined with the same techniques as the historical samples, in order to assist the examination of their compatibility. The compatibility of the selected mortars was examined through the evaluation of their physicochemical and mechanical characteristics in relation to the historic mortars of the original structure, as well as the criteria arising from the study of the materials decay and the environmental factors affecting the monument. Finally, the use of the restoration mortars is evaluated as far as serviceability through the use of fragility curves.

4. RESULTS AND DISCUSSION

4.1 Characterization and classification of historical mortars

Fiber Optic Microscopy (FOM) results indicated that all samples are in a bad state of preservation, presenting low adhesion between binder and aggregates. Lime lumps are present in all samples, except for MK5a (the final mortar layer of the cloisonné). The presence of straw additives is detected in samples MK1, MK2, MK2b and MK4, whereas no straw is detected in samples MK5b, MK6, MK7, MK8. Furthermore, extensive biodeterioration is evident on the surface of brick sample BR3a (Fig. 2).

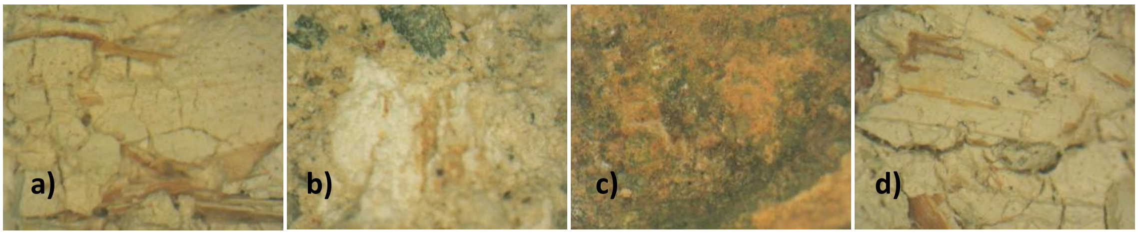
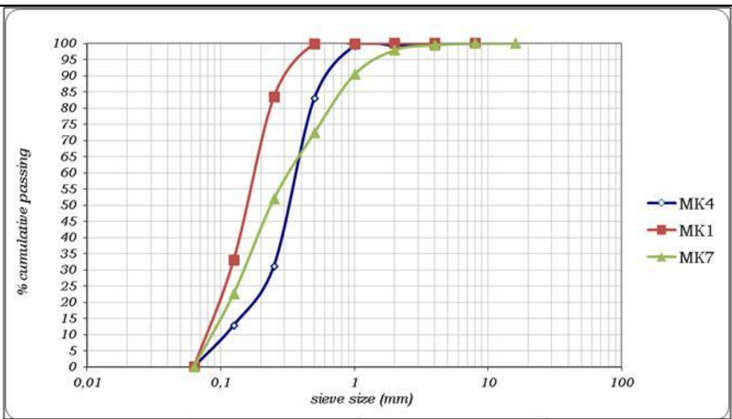


Figure 2: Selected FOM images of samples, a) MK2 – evident straw addition, b) MK2b – evident lime lumps, c) BR3a – Evident bio deterioration, d) Mortar attached on BR3b – evident straw hay addition

The grain size distribution analysis showed a good sorting of aggregates. MK1 and MK4, deriving from the exterior wall of the Catholicon present a greater similarity in comparison to sample MK7, the mortar of the interior wall joining the main temple and the Narthex (Fig. 3). The binder to aggregate ratio differs between samples.



Sample Code	MK1	MK4	MK7
B/A ratio	0,41	0,65	0,22

Figure 3: Grain size distribution analysis results

The results from the historical mortar sieve analysis act as a guide for the selection of the aggregates for the restoration mortar. Taking into consideration that the gradation curves of the historical mortars are only indicative of the original aggregates' gradation curve, as after many centuries the material has deteriorated and altered, the gradation curve of the restoration mortar aggregates must be as close as possible to that of the historical mortars, thus fulfilling compatibility criteria, but at the same time it must present a normal distribution, in order to fulfill serviceability criteria.

Thermal analysis was conducted on all mortar samples, as well as on the binder parts of the mortars separated through sieve analysis. The results show two types of mortars. The first type (samples MK1, MK2, MK2b, MK6) presents a curve as seen in Figure 4a, and the second type (samples MK4, MK5a, MK5b, MK7 and MK8), which presents an exothermal peak at 420-480^oC, corresponds to a curve as seen in Fig. 4b. The values of physically bound water, which is connected to weight loss observed in the temperature range <120 ^oC, are very low, corresponding to lime mortars [1]. In the temperature 120-200 ^oC weight loss is attributed to the dehydration of hydrated salts. The weight loss in the temperature range 200-600^oC is attributed to the dehydration of water chemically bound to hydraulic compounds, however in the case of samples MK4, MK5a, MK5b, MK7 and MK8 the exact amount cannot be calculated, as an exothermal peak connected to the presence of organic matter, probably due to the addition of plant-based natural fibers, is also observed within this range (420-480^oC). Therefore the reversed hydraulicity index cannot be calculated for the aforementioned samples. The endothermal peak at 580^o C, not accompanied by any mass loss, is attributed to the transition of quartz-a to quartz-b. The high values of CO_2 loss (>600 ^oC), corresponding to the decomposition of calcium carbonate, in combination to the high reverse hydraulicity index calculated in the cases where no decomposition of organic matter was noticed, further confirms the classification of the mortars as lime mortars (Table 2, Fig.5) [24]. Furthermore, the mortar aggregates are solely calcitic in the case of samples MK1, MK2,MK2b, MK4, whereas in the rest of the samples, aggregates are a mix of calcitic and silicate nature. Thermal analysis results can be utilized to correlate physicochemical values to mortar tensile strength (Fig.6) [1].

Sample	**Mass loss for each temperature range (%)**				**$CO_2/H_2O_{ch.b}$**	**$CaCO_3$**
	<120	**120-200**	**200-600**	**>600**		
	$H_2O_{ph.b}$	**H_2O_{salts}**	**$H_2O_{ch.b.}$**	**CO_2**		
MK1	1,06	1,83	2,14	39,30	18,36	89,21
$MK1_{binder}$	0,85	2,02	2,33	39,22	16,83	89,03
MK2	1,21	2,34	2,03	31,43	15,48	71,35
MK2b	0,42	0,50	3,6	28,39	9,28	64,44
MK4	0,50	0,52	5,12**	39,25	7,67**	89,10
$MK4_{binder}$	0,52	0,45	3,82	40,00	10,47	90,80
MK5a	0,95	2,05	7,36**	27,50	3,74**	62,42
MK5b	0,68	0,90	6,05**	24,55	4,06**	55,73
MK6	0,38	0,54	2,76	20,35	7,37	46,19
MK7	0,50	0,57	5,93**	29,87	5,04**	67,80
$MK7_{binder}$	1,09	0,20	3,14	36,80	11,71	83,54
MK8	0,69	0,96	7,7**	26,48	3,44**	60,11

* $H_2O_{ph.b}$: *physically bound water,* $H_2O_{ch.b.}$: *chemically bound water*

***Samples with the presence of organic matter – the exact amount attributed to chemically bound water cannot be calculated and therefore the reverse hydraulicity index calculated is not indicative*

Table 2: Thermal Analysis Results

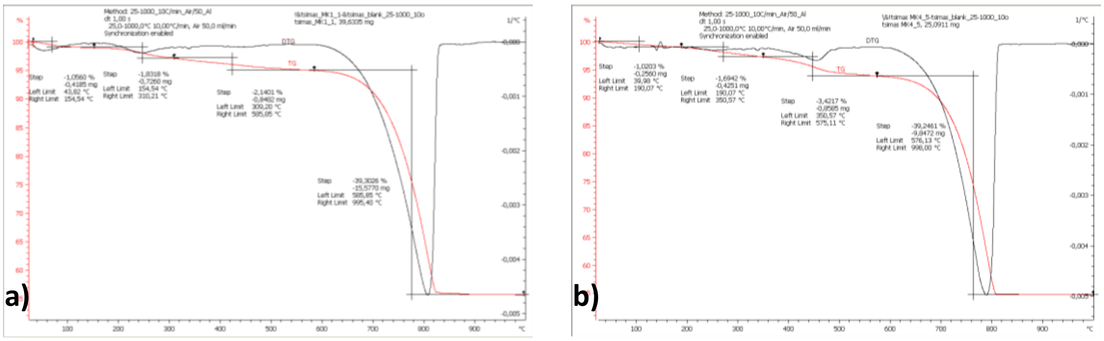


Figure 4: Selected thermal analysis diagrams a)MK1 – mortar with the addition of straw, b)MK4 – mortar with the addition of organic additive

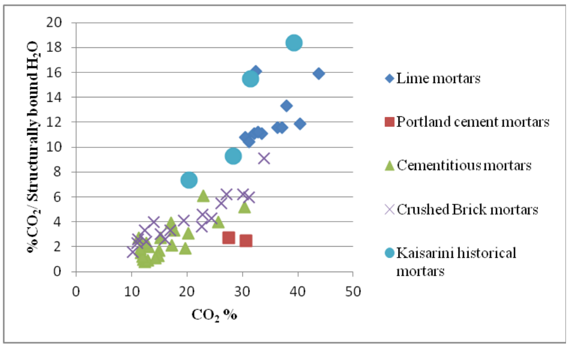


Figure 5: Grouping of the Kaisariani mortars according to thermal analysis results

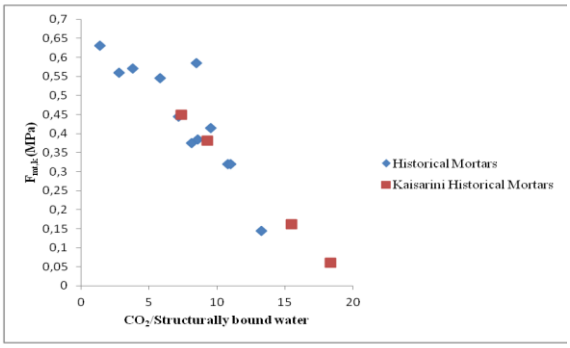


Figure 6: Correlation of tensile strength and inverse hydraulicity index

Thermal analysis results can be further utilized in the selection of the proper restoration mortars, as the restoration mortar selected must be compatible with the historical mortars, regarding its physicochemical characteristics, and in particular in terms of reverse hydraulicity index and CO_2 % loss.

X-ray diffraction analysis of mortar samples, showed the mineralogical compositions (Table 3 and Fig. 7). The principal mineralogical phase of all examined mortars is calcite. Quartz is detected in all samples, muscovite is detected in almost all samples.

X-ray diffraction results	
Sample	**Mineralogical Composition**
MK1	Calcite, quartz
MK2	Calcite, muscovite, quartz, albite, chlinochlore
MK2b	Calcite, quartz, muscovite, chlinochlore
MK4	Calcite, quartz
MK5a	Calcite, quartz, muscovite, hornblende, chlinochlore
MK5b	Calcite, muscovite, quartz
MK6	Calcite, quartz, muscovite, albite, chlinochlore, vaterite
MK7	Calcite, quartz, muscovite, chlinochlore, albite
MK8	Calcite, quartz, muscovite, albite, chlinochlore

Table 3: X-ray diffraction results

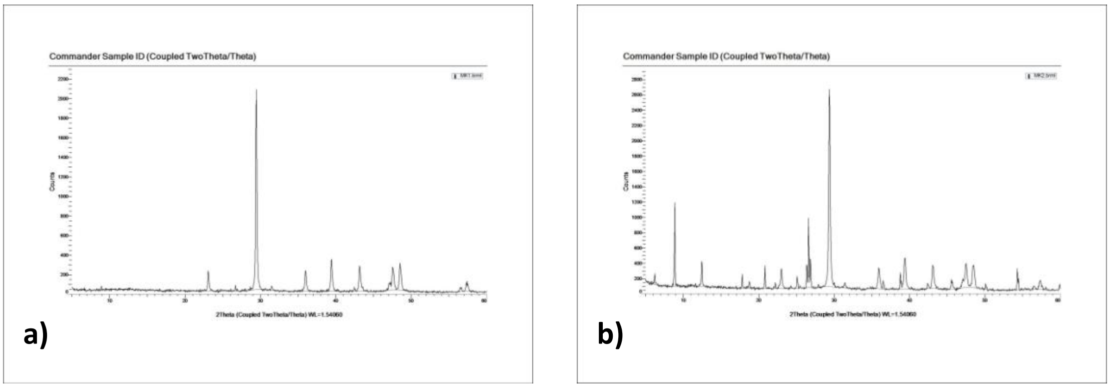


Figure 7: Selected X-ray diffraction diagrams, a)MK1, b)MK2

The microstructural characteristics of selected samples were examined through mercury intrusion porosimetry (Table 4, Fig.8). The brick samples present characteristics similar to handmade byzantine bricks, as found in literature [25, 26]. The mortars examined through MIP were MK6 deriving from the north wall and selected from the interior, MK7, from the interior west wall of the Catholicon, in joint with the Narthex wall and MK8, selected from the South Wall of the Catholicon. All samples present relatively high total cumulative volume values (MK7 total cumulative value is much higher than the other two). MK7 also presents a very low bulk density value, whereas MK6 and MK8 present similar values. MK6 and MK8 present similar average pore radius, total porosity and specific surface area values, whereas MK7 presents a much higher total porosity, as well as a lower average pore radius and higher specific area. The examination of the mortars microstructure confirms them as lime mortars [27].

Sample	***Total Cumulative Volume (mm³/g)***	***Bulk Density (g/cm³)***	***Total Porosity(%)***	***Average pore radius (μm)***	***Specific Surface Area (m²/g)***
BR3a	131,24	1,89	24,85	0,81	5,82
BR3b	167,68	1,82	30,54	0,85	1,03
MK6	233,75	1,61	37,70	0,44	3,27
MK7	337,86	1,37	46,47	0,33	5,64
MK8	255,81	1,62	36,55	0,47	3,40

Table 4: Mercury Intrusion Porosimetry results

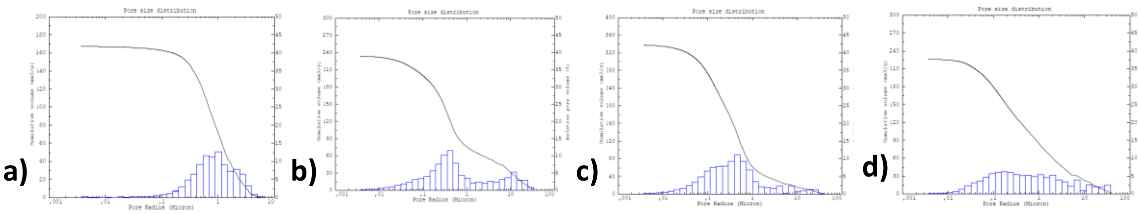


Figure 8: Pore size distribution for a)BR3b, b)MK6, c)MK7, d)MK8

The microstructural characteristics of the historical mortars, serve as a tool in the selection of the optimum restoration mortar, as it must present compatibility regarding microstructural characteristics. A study by Moropoulou & Bakolas 1998 assists in this task as it states the acceptability limits for restoration mortars for different mortar categories [27].

The presence of soluble salts in the church masonries was then assessed through the examination of the samples with Total Soluble Salts Measurements. The percentage of soluble salts is calculated through the following equation:

$$SST\% = (C \times 6{,}88) / M, \qquad (1)$$

where C is the measured conductivity in μS and M is the mass of the sample undergoing the measurement. Following the Total Soluble Salts Measurements, the results of which are presented below, spot tests were conducted in order to identify the salts present. The detection of chloride (Cl.), sulphate (SO_4^{-2}) and nitrate (NO_2^{--}) salts was possible through the use of $AgNO_3$, $BaCI_2$ and diphenylamine respectively.

Sample	Conductivity	TSS	Cl^-	SO_4^{3-}	NO^{2--}
MK1	72,2	4,84	-	-	+
MK2	83,3	5,54	-	-	+
MK2b	65,7	4,38	-	+	-
BR3b	53,8	3,57	-	-	-
MK4	97,1	6,53	+	-	++
MK5	122,1	8,28	-	-	+++
MK6	48,3	3,2	-	-	-
MK7	61,4	4,09	+	-	-
MK8	87,7	5,91	-	-	+

*Very high content (+++++), high content (++++), medium content (+++), low content (++), extremely low content (+), traces (tr).

Table 5: Total Soluble Salts measurements results and spot test results

All examined samples present high soluble salts contents, above the limit of 3%. A very high content of nitrates was detected in the mortar samples of the North wall, attributed to the more intense biodeterioration on this side, the transportation of fertilizers through rising damp into the masonries, as well as the presence of an underground ossuary at close proximity to the north wall of the church. The high amount of soluble salts must be taken into account when selecting the proper restoration mortars, as the presence of salts, as well as the movement of salts through water transportation phenomena, creates various problems to masonries.

Finally, the capillary rise coefficient of the brick sample (BR3b) was estimated through the Water Absorption by Capillarity test. The experiment was conducted at 15 ^oC and 70% RH. The capillary rise coefficient (C.R.C.) is calculated as:

$$C.R.C.=\Delta B/(S*t^{1/2}) \qquad (2)$$

Where, S is the surface of the sample in contact with the water and ΔB is the amount of water absorbed at a chosen time t(s). The above results where then designed in the following diagram, selecting the experimental results up to the time of $\sqrt{t}$ = 30 which corresponds to the linear part of the experimental curve, in order to estimate the trend line, and calculate the coefficient which is equal to the trend line slope. The trend line shows a very good R-squared value of 0.9948. The capillary rise coefficient value was thus calculated as $C.R.C._{MK3b}$=16.5 mg/($cm^2 \cdot s^{1/2}$) (Fig.9). The restoration mortars must present a capillary rise coefficient equal or higher than this value in order to avoid moisture concentration in the brick elements.

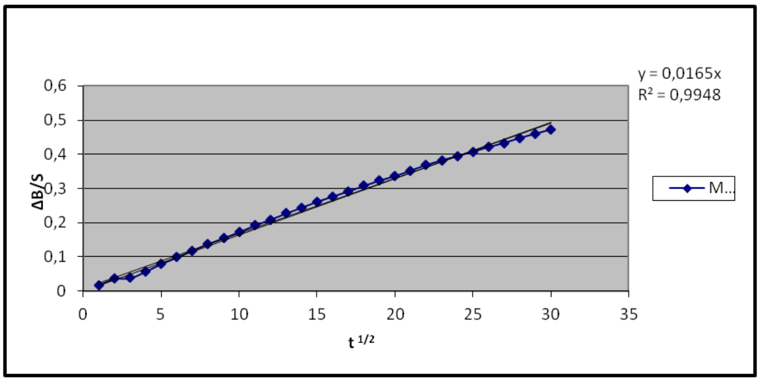


Figure 9: Plot of selected water absorption by capillary test results in order to estimate the capillary rise coefficient

4.2 Determination of decay factors, restriction arising from other building materials and earthquake behavior

An important degradation factor of the structure is the high water content of the structure, as revealed by non-destructive techniques in a previous study [20]. The high humidity content of the structural materials is attributed to rising damp, low sun radiation on all sides except for the south, as well as intense vegetation at a close proximity to the masonries of the structure and is further aggravated by problems in the roof system. The restoration mortars must be hydraulic in order to harden in high humidity conditions, as well as to serve adequately in this environment.

Furthermore, the detection of soluble salts above the acceptable limit of 3% for building materials dictates the use of a hydraulic mortar, either lime-pozzolan, either natural hydraulic lime, either a lime crushed brick restoration mortar, as these mortars exhibit a better behavior in the presence of soluble salts [8].

Although no stone samples were permitted, a previous study managed to categorize the building stones of the historical masonries of the Kaisariani Monastery and to estimate the compressive strength of the most common stone (fossiliferous) appearing in the structure. The compressive strength of the fossiliferous stone was estimated through a Schmidt hammer rebound test and the average value was estimated at 8.2 MPa with a standard deviation of 1.72 [20]. As the fossiliferous stone is the weakest building stone in the masonry, this values must act as a limit as far as the restoration mortar compressive strength is concerned, in order to avoid compatibility problems.

As the region of Greece is in constant danger from a potential earthquake, it is important to examine the structural system in earthquake stresses. Due to the thickness of the joint mortar in the Catholicon masonries, the restoration mortar is an important element contributing to the mechanical properties of the structure; the restoration mortar will inevitably affect the behavior of the structure to earthquake stresses. Therefore an important serviceability criterion must be the results of the fragility analysis for different repairing scenarios; the fragility analysis results can be utilized for the selection of the optimum restoration mortar.

Another important factor is the use of the monument; if a monument is in use or even only accessible to visitors as a cultural site, it is important that the restoration mortars used present high values of early strength. Therefore another serviceability criteria arises, namely the restoration mortar must present adequate early strength values.

4.3 Evaluation of selected restoration mortars

The goal in selecting the optimum restoration mortar is the compromise between all compatibility and serviceability requirements. The restoration mortars selected exhibit adequate hydraulicity, so as to ensure hardening in high humidity conditions and resilience in the presence of salts. Specifically, two lime-metakaolin and one hydraulic lime mortar, and two lime-metakaolin and one hydraulic lime concrete were selected (Table 6). The concretes were designed with the addition of crushed bricks, in order to simulate historical mortars of byzantine monuments that have shown excellent performance in earthquakes [11]. The raw materials used fulfilled all criteria in order to be acceptable for use in a historical masonry [6]. The selected aggregates presented a good agreement with the historical mortars' gradation curve, as well as a good sorting and normal distribution.

Sample Code	**Lime powder**	**Meta kaolin**	**NHL3,5**	**Silicate Sand (0-2 mm)**	**Silicate Sand (0-6 mm)**	**Crushed brick (0-16 mm)**
LM_1	27,5	2,5	-	70	-	-
LM_5	25	5	-	70	-	-
NHL	-	-	25	-	75	-
$LM_{C5.}$	27,5	2,5	-	-	35	35
NHL_{C10}	-	-	30	-	35	35
LM_{C15}	20	10	-	-	35	35

Table 6: Synthesis of selected restoration mortars [9, 10]

The thermal analysis results are stated for all selected restoration mortars (Table 7, 8). Furthermore, the resulting data is compared with the historical mortars thermal analysis results in order to assess compatibility (Fig.10); it is clear that they fulfill compatibility requirements, especially the lime-metakaolin mortars.

Restoration mortar	**Curing time (months)**	**$(H)_{t.ch.b.}$**	**H-CH**	**CH**	**$(CH)_{react.}$ (%)**	**CO_2**	**$CaCO_3$**	**$CO_2/(H)_{t.ch.b.}$**
LM_1	**0**	0,16	4,73	19,44	0	1,40	3,18	8,75
	1	2,44	3,06	12,58	35	3,91	8,88	1,60
	3	2,44	2,22	9,12	53	6,90	15,68	2,83
	6	2,20	1,30	5,34	73	8,50	19,31	3,86
	12	1,91	0,00	0,00	100	12,38	28,13	6,48
LM_5	**0**	0,23	4,70	19,33	0	1,85	4,21	8,04
	1	6,85	2,80	11,51	40	2,81	6,38	0,41
	3	3,24	2,50	10,28	47	2,88	6,54	0,89
	6	3,67	2,19	9,00	53	7,67	17,43	2,09
	12	3,60	0,00	0,00	100	10,70	24,31	2,97
NHL	**0**	0,00	0,83	3,41	0,00	9,82	22,30	9820
	1	1,15	0,18	0,74	10,84	17,43	39,57	15.16
	3	1,88	0,12	0,49	40,96	13,38	30,37	7.12
	6	1,83	0,00	0,00	100	12,40	28,15	6.78
	9	1,90	0,00	0,00	100	16,47	37,39	8.67

**$(H)_{t.ch.b.}$: total chemically bound water, H-CH: water chemically bound to $Ca(OH)_2$, CH: $Ca(OH)_2$, $(CH)_{react.}$(%): percentage of consumed CH*

Table 7 Mass loss percentages for restoration mortars in relation to curing time [9, 10]

Sample Code	CH (%) in relation to curing time				
	0 months	1 month	3 months	6 months	12 months
LM_{C5}	23,5	18,3	16,4	10,2	3,8
NHL_{C10}	12,5	12,1	14,1	11,7	4,1
LM_{C15}	16,5	3,2	0,0	0,0	0,0

**CH(%): percentage of $Ca(OH)_2$ not yet consumed at testing date*

Table 8 Mass loss percentages for restoration mortars in relation to curing time [9]

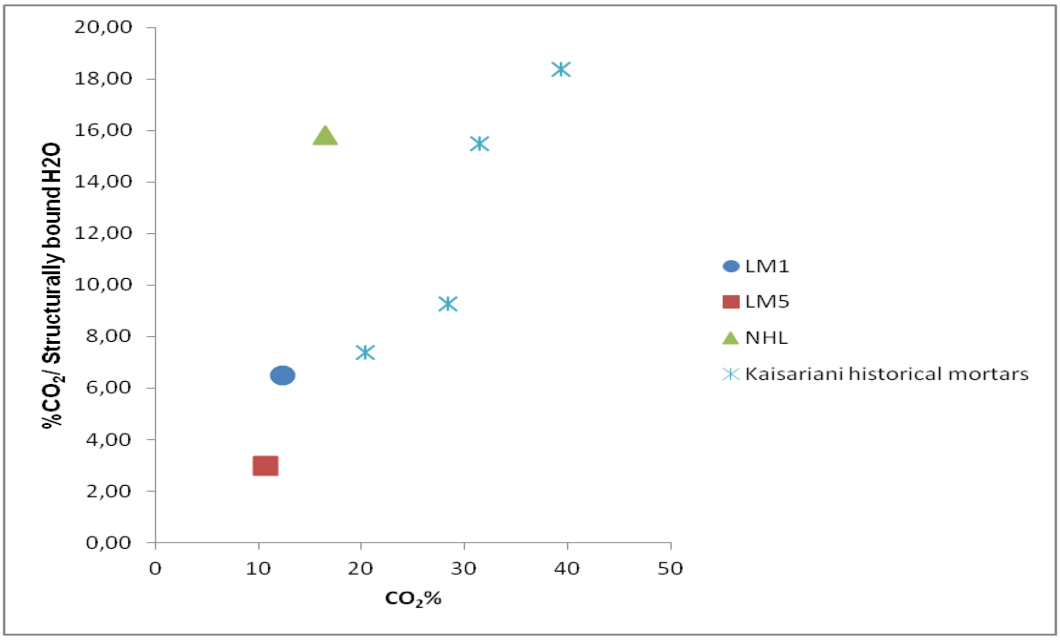


Figure 10: Correlation of $\%CO_2$ loss with inverse hydraulicity index

The microstructural characteristics of the selected mortars are presented in the following table. The concretes, due to the large size of the aggregates were only analyzed regarding their apparent density.

Sample code	T.C.V. (mm^3/g)	S.S.A. (m^2/g)	Por. Rad. Av. (μm)	d_{bulk} (g/cm^3)	$d_{corr.}$ (g/cm^3)	Total Porosity (%)
LM_1	198,78	4,15	0,32	1,73	2,63	34,30
LM_5	191,63	5,56	0,29	1,75	2,64	33,57
NHL	151,1	4,24	0,28	1,90	2,67	28,7
LM_{C5}	-	-	-	1,62	-	-
NHL_{C10}	-	-	-	1,85	-	-
LM_{C15}	-	-	-	1,69	-	-

**T.C.V.: Total Cumulative Volume, S.S.A.: Specific Surface Area, Por.Rad.Av.: Average Pore Radius, d_{bulk}: apparent density, $d_{corr.}$: corrected density, Total Porosity (%)*

Table 9 MIP results – Hardened restoration mortar characteristics [9, 10]

Regarding the thermal analysis results, at the end of twelve months the entire $Ca(OH)_2$ has reacted, except for concretes LM_{C5} and NHL_{C10}, where a very small amount remains. Regarding the microstructural characteristics of the selected mortars, all lime-metakaolin mortars, as well as the lime-metakaolin concretes, are within the range of acceptability limits [27]. Therefore, regarding physicochemical and microstructure compatibility, LM_1, LM_5, LM_{C5} and LM_{C15} are all deemed as acceptable and exhibit adequate hydraulicity, thus fulfilling serviceability criteria.

The average values of flexural and compressive strength measured for the examined mortars is listed in Table 10. The flexural strength values result as the average of the value measured for three different prismatic samples for each mortar mix, while the compressive strength values result as the average of the value measured for six different cubic samples for each mortar mix.

Sample Code	Curing time	F_f (MPa)	St.Dev.	F_c (MPa)	St.Dev.	Ed (MPa)
LM_1	**12 months**	1,59	0,34	3,92	1,40	6532
LM_5	**12 months**	1,51	0,46	5,88	0,88	6641
NHL	**12 months**	1,00	-	4,50	-	-
LM_{C5}	**12 months**	1,50	0,25	8,4	0,36	6981
NHL_{C10}	**12 months**	2,22	0,27	18,7	0,50	18547
LM_{C15}	**12 months**	2,40	0,35	21,4	1,26	13334

**Ff: Flexural strength (MPa), Fc: Compressive strength (MPa), St.Dev.: standard deviation, Ed:Dynamic elasticity modulus*

Table 10 Flexural and Compressive strength values for examined mortar and concrete mixes – Dynamic elasticity modulus [9, 10]

In the case of the lime-metakaolin mortar mixes, LM_1 και LM_5, it is concluded that the early acquirement in compressive strength noticed is enhanced due to the use of metakaolin (Fig.11). Furthermore, the results show that by increasing the percentage of metakaolin in relation to the lime powder, the compressive strength also increases. Regarding the gain in flexural strength with hardening, it is concluded that both lime-metakaolin mortar mixes present similar final values, however not the same trend in the progression of hardening in time. In the case of the hydraulic lime mortar, the highest compressive strength value is measured at 6 months of curing, while it has already acquired 66% of its final mechanical strength values already from the first month of hardening. The final compressive strength value measured for the hydraulic lime mortar is between the compressive strength values of LM_1 and LM_5. The flexural strength of the hydraulic mortar is relatively lower than the lime-metakaolin mortar mixes. The concretes examined present a large range of compressive and flexural strength values (Table 10). As expected the concretes mixes examined presented much higher modulus of elasticity values in comparison to the mortar mixes. Amongst the concretes, the lowest values of dynamic elasticity modulus are exhibited by concrete LM_{C5}, which also presented the lowest values of flexural and compressive strength; the highest dynamic modulus of elasticity values by far is exhibited by the hydraulic lime concrete, although it exhibited lower compressive and flexural strength values than LM_{C15}. The mortar containing the highest amount of metakaolin p.w., presented the highest compressive strength values, and also the highest modulus of elasticity value, however near the value exhibited by LM_1.

In Fig.11 compressive strength values are presented in relation to curing time. The results show that a large range of mechanical properties can be achieved with small variations to the mortar mixes and furthermore the use of the selected mortars fulfills the serviceability criteria set, namely the early acquirement of compressive strength.

The optimum selection in order to ensure a good behavior under seismic action is the compromise of a high compressive strength and low dynamic elasticity modulus. In Fig.12 these values are correlated for the selected restoration syntheses.

The selected lime-metakaolin mortars present C.R.C. values between 17-25 $mm^3/g.s^{1/2}$, and are therefore compatible with the original brisk elements of the historical masonry [9].

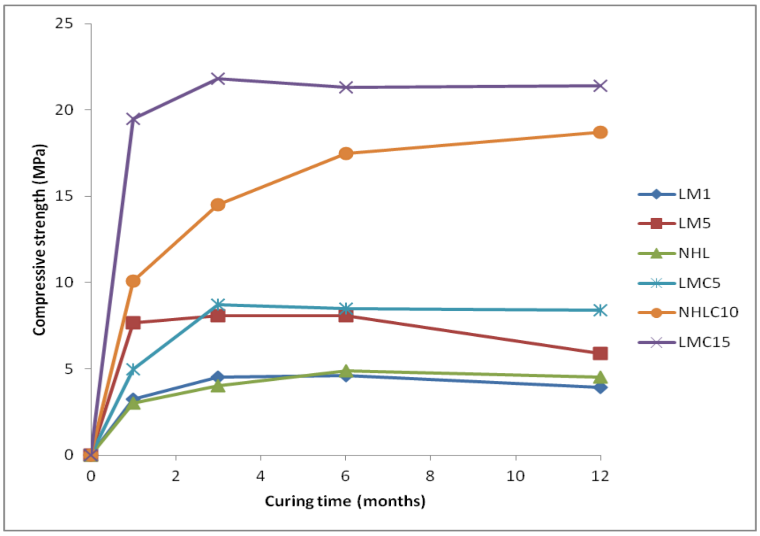


Figure 11: Compressive strength values (MPa) in relation to curing time (months)

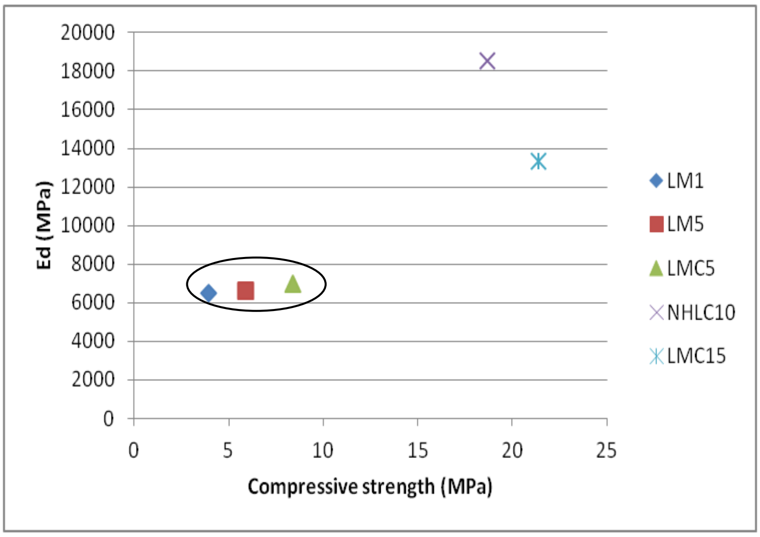


Figure 12: Correlation of compressive strength and dynamic elasticity modulus for selected restoration mortars and concretes

Fragility analysis was conducted for the case of the Catholicon of the Kaisariani monastery, for different repairing scenarios, in accordance to the analysis of the selected restoration mortars [28-36]. The entry values selected for the original materials was an average values of 12 MPa compressive strength for the building stones, taking available literature into account, and 1 MPa for the original mortars, as correlated through the analysis of the physic-chemical properties [20]. Specifically, the probability of damage occurring under the effect of different ground accelerations was estimated for a) the original structural materials, b) repointing of joints with restoration mortar exhibiting 5 MPa compressive strength, c) repointing of joints with restoration mortar exhibiting 10 MPa compressive strength. The fragility analysis concerned the probability of appearance of insignificant, moderate and heavy damage (Fig.13-15) for the different repairing scenarios.

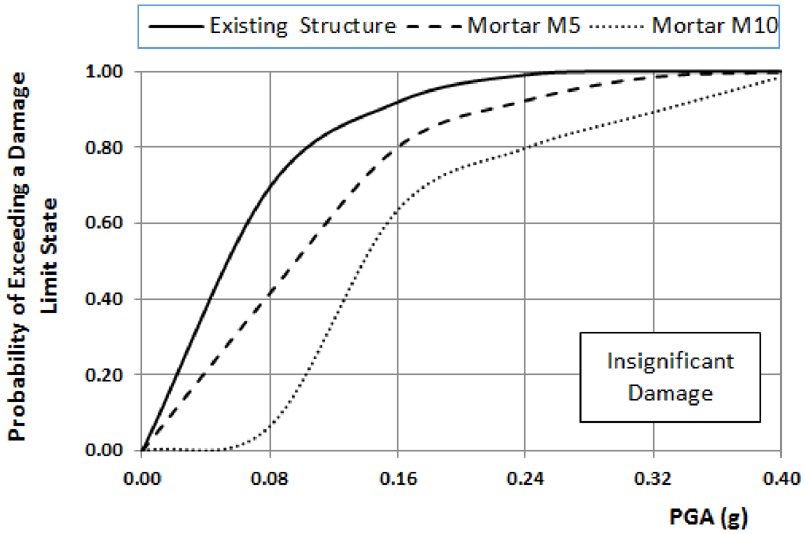


Figure 13: Probability of insignificant damages occurring for different ground accelerations

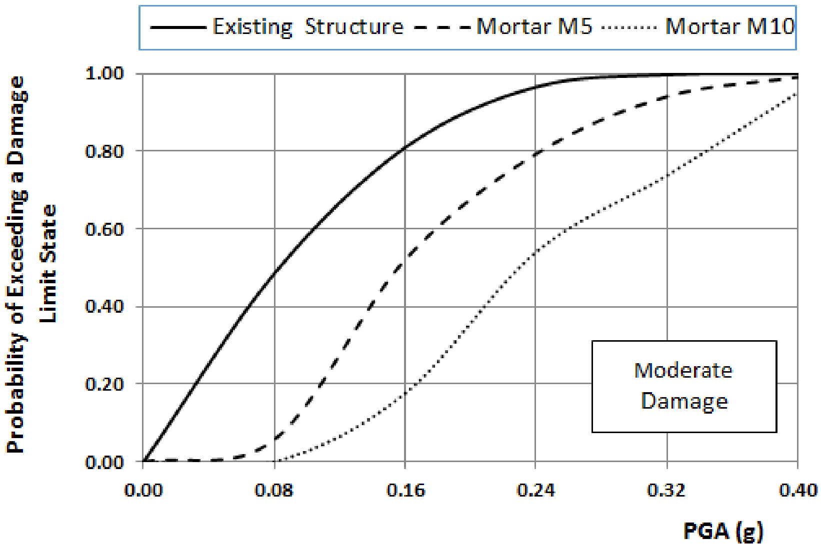


Figure 14: Probability of moderate damages occurring for different ground accelerations

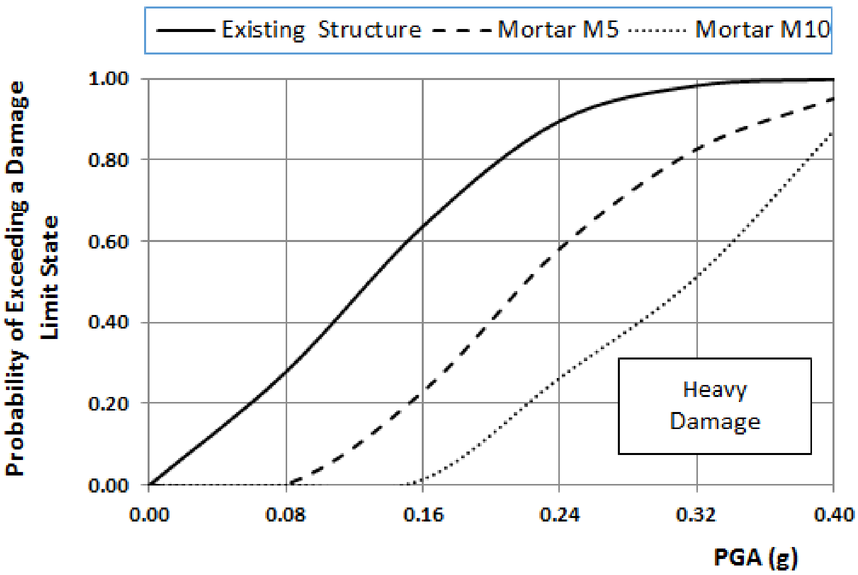


Figure 15: Probability of heavy damages occurring for different ground accelerations

The results show that even the use of a restoration mortar exhibiting compressive strength 5 MPa, can achieve an improvement in terms of damage in the case of an earthquake; the improvement is greater as the damage severity increases. At this point, the restriction deriving from the low compressive strength of the fossiliferous stone must be taken into consideration; NHL_{C10} and LM_{C15} are therefore rejected as possible restoration mortars, in order to ensure compatibility with the original structural materials. Thus, restoration mortar LM_5 and LM_{C5} can be selected in order to use according to the joint thickness, as these restoration mortars exhibit compatibility with the original structure and serviceability in the environment of the Kaisariani monastery, at the same time contributing to the mechanical performance of the structure under earthquake stresses.

5. CONCLUSIONS

- The mortars of the Kaisariani Monastery Catholicon are typical lime mortars mixed with calcite and aluminosilicate aggregates, with high porosity values and occasionally the addition of straw or fiber admixtures
- Tensile strength can be estimated for historical mortars, through correlation with physicochemical properties; this is only an estimation, but can be indicative and assist in the assessment of the seismic behavior of the masonry
- The microstructural characteristics of the examined bricks are typical for handmade bricks of the byzantine period
- By setting requirements during the characterization of the historical materials and the in situ investigation of the monument, the selection of the optimum mortar, complying with the set compatibility and serviceability requirements can be accomplished
- Lime-metakaolin mortars present similar physicochemical and microstructural characteristics with the examined historical mortars, at the same time contributing in a decisive manner to the behavior of the masonry under earthquake stress
- The role of restoration mortars is crucial in the earthquake protection of thick joint masonries
- Fragility analysis is a valuable tool that can be utilized for the selection of the optimum restoration mortar in terms of compatibility and serviceability amongst different repairing scenarios

ACKNOWLEDGEMENTS

Part of this investigation was performed within the research project “Seismic Protection of Monuments and Historic Structures - SEISMO” which is co-financed by the Greek Ministry of Education and Religions and the European Union under the action “Thales” within the context of the Operational Programme - Education and Lifelong Learning, NSRF 2007-2013. The authors would like to thank the employees of the 1st Ephorate of Byzantine Antiquities for their cooperation.

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