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Retrofitting and Strengthening Masonries of Heritage Structures: Materials Used

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Synonyms

Compatibility issues; Earthquake; Fiber reinforced polymers; Grouts; Masonry of heritage structure; Mortars; Preservation; Protection; Retrofitting; Selection

Introduction

Masonry heritage structures (MHS) constitute a countless number of different types of constructions dated from prehistory to present in which many "value contexts" (Lipe 1984) such as historic archaeological, aesthetic, symbolic, social, cultural, scientific/technological, and economic are included making them a real treasury of human civilization. According to Burman (Burman 2001), their survival is essential to the spiritual, emotional, and economic well-being of humans.

The preservation of these structures concerns both life expectancy and protection from collapse occurred from earthquakes in seismic regions or from other natural or anthropogenic disasters. The former is closely related to the conservation/consolidation from decay phenomena due to the ageing effects of the environment impact on the buildings. The collapse is mostly attributed to the inherent inadequacy of historical masonry structural systems to bear horizontal loads.

The great diversity in the typology of MHS due to the various components, techniques of construction, morphology, type of reinforcement, and functionality makes the study of it, in terms of time and cost, difficult.

Moreover, internationally accepted Charters and Documents (Venice Chapter 1964) (Nara Document on Authenticity 1994) recommend low invasive interventions for achieving a balance between keeping authentic characteristics and taking strengthening measures.

The peculiarity of the problems with MHS as well as some unforeseen failures after retrofitting in the past years led to the adoption of a step-by-step approach to strengthening, called observational method (Lowrenco 2006). By this way, a better compromise between traditional and innovative materials and techniques is achieved.

The society awareness about heritage structure preservation has globally increased internationally because of the higher recognition of the "values" associated with civilization of human genius and economy related to cultural tourism. The value of a monumental structure or area is increased after its preservation. Therefore, strategic policies of preserving built heritage have been promoted including: development of preventing seismic strengthening measures and establishing regulating frames and management systems. Technological advances in this field have fueled the market with many innovative materials and techniques or even new concepts of confronting seismic risk.

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The Ancient Masonry Structures

The ancient masonry structures are composed of load bearing horizontal and vertical masonry elements which often are inadequately connected to resist seismic actions. Besides, the flooring systems and roofing forms (arches, vaults, domes) do not always provide enough diaphragm stiffening. These features, as well as the type of masonry morphology (one, two, or three leaf rubble masonry), predetermine their respond to loading (monotonic or cyclic) and the type of failure.

The choice of an appropriate and reliable analytical model for the study and assessment of a masonry structure seismic capacity prerequisites a thorough knowledge of its characteristics and behavior, as well as its pathology and degree of degradation.

This knowledge acquisition is achieved by surveying the MHS and applying on site nondestructive measurements and other diagnostic tools of analysis at laboratory.

Masonry is a composite building material consisting of three discrete phases: units, joint mortar, and unit-mortar interface. The last is the weakest phase governing the behavior of masonry to horizontal loads.

As units may serve stone pieces shaped or irregularly cut, as well as mud bricks/earth blocks and fired bricks, or a combination of them. Successive courses of bricks are often found in stone masonry of city walls. It is also common, in large size piers or tower walls, a rubble material, or even mortar to have been used as infill.

The joint mortars are mainly lime-based mixtures of a binding system and aggregates with the following characteristics (Papayianni 2004):

- Apparent specific density 1.4–1.7
- High porosity 20–40 %
- Low strength (1–5 MPa)
- Low elastic modulus of elasticity (2–6 GPa)
- High deformability

They contain aggregates of small grains max size 4 or 8 mm not excluding greater sizes even pebbles of 16–30 mm, particularly in the cases of castle walls and churches with thick mortar joints of byzantine architecture. In earth block masonries of vernacular architecture, mud mortars are often used for jointing.

The strength capacity of the masonry depends on the strength of its components and their volume proportion in the masonry mass according to Eurocode 6, 1995. In some relevant equations found in literature (Tassios 1986), mortars' joint thickness is also taken into account for the estimation of masonry strength. Furthermore, the mortar strength is primarily influenced by the type of binding system.

Apart from the effect of masonry components on its strength, the type and morphology of the masonry (one or multiple leaf system) plays an important role to failure mechanism. For example, in three leaf masonry walls, separation of leaves is often observed (Binda et al. 2007). Moreover, if the unit-mortar interface has been weakened, shear or tensile type failure occurs easily.

In Table 1 some characteristics of often found components in ancient masonry are given for comparison with the modern materials used in construction (Papayianni and Tsolaki 1995). The structure of an ancient mortar and brick is shown in Fig. 1.

For the understanding of the behavior of an ancient masonry, the inside stress and stress-strain characteristics are measured on site by nondestructive test methods (NDT). Among the most widely used NDT are those of single and double flat jacks, sonic measurements, boroscoping, and active thermography.

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Table 1 Characteristics of components of ancient masonries

Monument	Historical period	Type of mortar	Binder	Lime content %	Ap. specific density	Strength in compression (MPa)	Brick plates (cm)	Absorption (%)	Strength in compression (MPa)
Galerius palace	Roman	Structural	Lime + pozzolan + soil	30	1.7	3.0–4.0	30 × 40 × 6	15.4	8.0–10.0
Acheiropoietos church	Middle Byzantine, seventh century	Structural	Lime + pozzolan + brick dust	35	1.55	3.0–3.5	30 × 40 × 5	17.5	5.0–9.0
Hagia Aikaterini Church	Late Byzantine thirteenth century	Structural	Lime + pozzolan + soil	20	1.65	2.0–2.5	30 × 30 × 4	14.5	10.0–12.0
Bezesteni	Ottoman, fifteenth century	Structural	Lime	40	1.70	1.0–1.5	30 × 30 × 4	20.0	10.0–14.0

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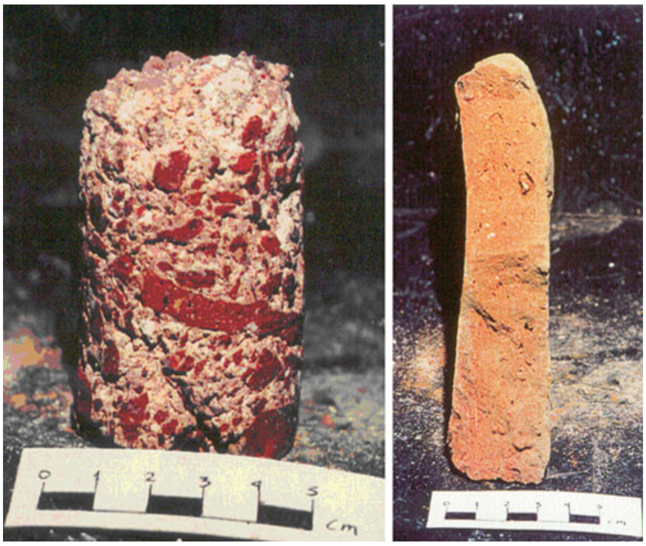

Fig. 1 Ancient mortar core and brick taken from Hagia Sophia in Thessaloniki (seventh century AD)

Table 2 Influence of the grade of deterioration on the bricks and mortars

Monument	Material	Absorption %	Salt content	Cracking	Strength in compression MPa
St. Panteleimon	Brick 1	14	Low	No	17.1
Fourteenth century AD	Brick 2	28	High	Yes	5.1
Hagia Aikaterini	Mortar 1	18	Medium	A few	2.5
Thirteenth century AD	Mortar 2	20	Medium	A few	1.9
Acheiropoietos	Mortar 1	20	Medium	No	3.3
Seventh century AD	Mortar 2	35	Medium	Yes	1.5

Moreover, long-term monitoring of deformations by establishing a proper system of gauges is essential for the estimation of the existing stresses. In addition, the determination of mechanical, chemical, and physical characteristics of the materials by applying test methods at laboratory allows the evaluation of residual strength and elasticity of masonry, as well as the diagnosis of the decay and the degree of degradation. This holistic process of studying heritage structures is necessary because apart from cracks, a "softening" of the masonry mass may occur due to ageing or chemical attack (sulfate attack, efflorescence) that leads to significant strength decrease of both components of the masonry. For example, the strength of mud bricks is strongly influenced by their moisture content. Relevant to the effect of degradation to the strength of mortars and brick is shown in Table 2 (Papayianni and Tsolaki 1995).

Then, an analytical model for the masonry structure is adopted to study the respond of it to different scenarios of loading. The kind of applied loads, the values for strength and elasticity of masonry components, the degree of stiffness, and the safety factors have to be decided for a realistic estimation of the degree of retrofitting and selection of remedial measures. This is a job of great responsibility since there are not adequate regulative frames and every monumental structure is a particular case study (Penelis 1996).

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Compatibility Issues

From experimental and analytical research works (Thomasen 2003), it is clear that the seismic capacity of masonry is inherently low and anti-seismic protection demands explicitly strengthening. Moreover, MHS materials suffer very often from decay, and consolidation of the masonry mass must precede before any strengthening.

The dilemma is how much strengthening is appropriate for the historic structures, which do not conform to modern seismic design codes, addressing concrete constructions. Internationally accepted documents (Venice Charter 1964, ICOMOS, (Burras Charter 1981, 1988), Nara Document on Authenticity 1994), require respect to the "values" of monumental character structures, including architectural integrity, authenticity of the materials, and their morphology. What is recommended in retrofitting is to use compatible to authentic materials and traditional skills for their appliance.

There are many poor examples of interventions on monuments with concrete, which was supposed to cooperate as repair material with the old masonry. The destructive consequences from the use of incompatible to authentic matrix repair materials are mostly related to different physicochemical characteristics of cement-based or polymeric matrix repair materials, which block the moisture movement, because of very low porosity and different porosity properties in comparison to old mortars. In addition, the aforementioned repair materials differ in elasticity from the existing old ones and consequently in deformability under the action of mechanical or hydrothermal loads.

However, for MHS in seismic regions, which are to be inhabited the value "safety" is of first priority. Therefore, strengthening methods are selected to be technical and cost-effective, as well as less invasive (Tassios and Mamillan 1985).

Homogenization and consolidation of the old masonry mass by inserting new repair materials is often applied with or without any reinforcement technique. It is worth mentioning how compatibility aspects could be interpreted in technical terms concerning their design (Papayianni 2004) (Van Balen et al. 2005). The most important characteristics or criteria by which compatibility is driven are:

– Surface features (color, texture, roughness)
– Composition (type of binder, granulometry of aggregate)
– Strength level (compressive, tensile)
– Elasticity (modulus of elasticity, deformability)
– Porosity (porosity, pore size distribution, capillarity)
– Coefficient of thermal dilation

These criteria have been applied in designing the repair mortars of a great number of interventions in Greece (Papayianni 2004), from 1990s to present, and proved very successful and long lasting. It must be pointed out that compatible repair material does not mean imitation of the authentic one. What is pursued is that having understood the functionality of the masonry, the repair material should not unsettle the long-term balance between local environment and structure and change its behavior. Based on experience from practice, it seems that by adopting mixed-type binding systems and suitable admixtures, the properties of repair materials may be adjusted to meet compatibility criteria.

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Materials and Techniques for Retrofitting and Strengthening Masonry Heritage Structures

Introduction

The increasing awareness of the society about safeguarding heritage buildings promotes strategies of preventing their seismic retrofit. Cracks and other damages must firstly be repaired for reintegrating the continuity of the masonry corpus and then proceed to strengthening alternatives. By this way, the resistance to earthquake and durability of MHS are globally improved. Of course, a thorough comprehension of the behavior of MHS must precede.

A solution of another concept to the problem is to reduce the seismic impact in the heritage structure by using a base isolation system (BIS) with supplementary viscous dampers at the base and the top of the building (Saito 2006). A successful example is the case of Los Angeles City Hall in which the BIS allows to remain stationary while the ground moves up to 500 mm in horizontal direction (Nabih 1996).

The methods of interventions are practically referred to materials and techniques. They are divided into irreversible methods, in which new materials are embodied in the masonry corpus and cannot be removed, and reversible ones, in which new materials are able to be activated on the surface or near the surface of the masonry undertaking local loads and can be replaced.

Irreversible Interventions

Irreversible interventions aim at consolidating the mass of the masonry, in particular when it suffers from softening due to intensive deterioration. The most common are:

– Grout injection
– Flowable mortar infills
– Deep repointing
– Reconstruction of masonry missing parts
– Punching steel bars (stainless steel) to saw cracks.

Of course, these interventions contribute to strengthening, but often additional techniques are applied to increase diaphragm stiffening and achieve adequate connection of horizontal and vertical structural elements of old masonry, aiming at increasing its seismic capacity. In the past, jacketing of piers with concrete, adding concrete beams as “chainage” or masonry confinement, has been widely used. They were characterized as invasive interventions altering the function and character of the old structure. Similarly, ferrocement surface coating or casting shotcrete over a steel mesh has been used for strengthening.

In irreversible interventions a major compromise between principles of restoration and safety and durability issues for the constructions is continuously under question. As declared in Nara Document (1994) “keeping the authenticity of heritage structures, materials and architecture is of great importance since all the values of a monumental or listed construction are transferred to future generation with materials.” However, as mentioned in the previous entry, in the case of inhabited historical buildings in urban areas which are to be preserved but also to be safe, authenticity issues are not of first priority.

Grouts and mortars are inserted into the masonry mass using different techniques to fill cracks, void in brick-mortar interfaces, and reduce the intrinsic heterogeneity and anisotropy of the masonry. After longtime and extensive research works and experience from field applications, some

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recommendations about designing grouts and mortars are found in literature (Tomazevic 1992). The conflicting aspects encountered in designing grout and mortar for repair of MHS make it an attractive research topic of paramount importance for the preservation of the heritage structures and their durability.

In most cases a tailored to the specific monumental structure grout/mortar mixture is proposed, taking into account the characteristics and pathology of the structure. Ready mixed grouts or mortars are not usually used since they do not often comply with specific requirements imposed by compatibility. Responsible for the design and application technique is the engineer who will select the binding system. This may be a combination of lime and pozzolan, with small quantities of cement, reactive silica, and admixtures, for rheology improvement, strength development, and volume stability. Commercial hydraulic lime is often used as an alternative binder. A series of tests are recommended for ensuring their quality (Toumbakari 2002).

Grouts

The technique of the consolidation with injection of grouts was at first well known in geotechnical and concrete engineering. Later, it was extended for the homogenization of the mass of heritage structure. From the 1970s onward, grout injections have been used in many historical buildings and monumental structures. Grouted anchors are often used when tierods are inserted into masonry to improve tensile strength capacity. In 1990–2000, a number of research works and PhD thesis (Miltiadou 1990) (Valluzzi 2000) (Toumbakari 2002) have contributed much to the evolution of materials and techniques improving the quality and performance of the grouts.

The grouts are slurries of hydraulic nature binding system with or without inert fines and admixtures. The water/binder ratio is usually around 1.0. To be efficient, grouts must present in fresh state adequate fluidity and consistence, penetrability, and volume stability. In addition, after hardening they must develop good bonding within old masonry microstructure and mechanical strength.

To keep compatibility principles in designing grouts for MHS implies the selection of inorganic and relatively low strength potential binders, such as lime-based binding systems, which are the constituents of the most joint mortars of ancient masonries. An exception is the earth block masonries, in which the soil is the main binder for blocks and mortars and grouts should be soil-based mixtures.

In the first grouting intervention on MHS, portland cement was used as binder, but gradually the cement was diluted with lime or replaced by hydraulic lime or ternary binding system of the lime-pozzolan-cement plus some additives. Based on experimental work some researchers suggested (Toumbakari 2002) that the grouts injection results in significant strengthening if its binding system contains at least 30 % of mass portland cement.

An example of application with mixed-type binding system constitutes the consolidation of masonry element of the Byzantine Church Acheiropoietos (dated from the seventh century AD) by grouting in the 1990s with the following mixture. The choice of the binding system was based on the experimental study of materials and trial mixtures.

Composition of grout used in Acheiropoietos:

Hydrated lime: 40 %
White cement: 30 %
Ground pozzolan: 15 %
Brick dust: 15 %

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Epoxy resin grouts which are widely used in filling cracks in concrete members are inappropriate in MHS grouting since the different nature of synthetic materials in terms of water and vapor impermeability makes moisture to be entrapped inside the MHS that is detrimental for old masonry. The ideal grout composition for MHS should present chemical and physical compatibility with the matrix of the MHS mortars like the transfused blood to human body.

The use of additives and admixtures in small quantities results in modifying grouts to develop the desirable properties. It should be pointed out that lime-based mixtures keep their fluidity for longer time than those of cement-based ones. This is a significant benefit for working in the field, especially in the summer period of Mediterranean climate.

Some lime-based grout mixtures with their characteristics in fresh and hardened state are shown in Table 3 (Papayianni and Pachta 2012).

In literature, there are recommendations (Papayianni 2004) about the selection of raw materials and methods of testing grout performance and checking the filling effect after hardening. Some of them are mentioned below:

– The hydrated lime powder must be reactive and its reactivity could be checked by measuring $Ca(OH)_2$ content by DTA-TG. Apart from lime hydroxide, hydraulic lime is also used in grouts because it hardens itself in humid environment and it is more convenient in the field work. However, there are differences between alternatives, concerning strength development and microstructure.
– Natural pozzolans are considerably activated if milled and contribute to earlier strength development, as well as to long-term strength.
– Sand or gravel of selected max size must present an even granulometry and be free of organic and soluble salts. Limestone dust or brick powder is also often added as fines.
– The salt content of all constituents of the grout mixture should be as low as possible. For example, efflorescence of sulfates is often observed due to sulfate content of brick powder. Even superplasticizers used to arrange fluidity must be free of sulfates.
– In case of cement addition it should be of low alkali and sulfate content.

Fluidity is commonly checked by Marsh cone (ASTM C939-87), while penetrability or injectability is tested by using the sand-column test (NORM NFP 18–891, 1986, EN 1771).

Table 3 Characteristics of lime-based grouts

Parts by weight						Fresh state properties			Compressive strength (MPa)	
Hydrated lime	Hydraulic lime	Natural pozzolan	White cement	Brick duct	W/B	Fluidity (sec)	Penetrability (sec)	Vol. stability (%)	28d	90d
1					1.06	10.8	3.15	1.5	–	0.69
	1				0.61	9.33	3.41	0.7	1.76	–
1		1			1.10	9.8	4.8	1.2	0.89	4.45
1		0.8	0.2		1.00	9.34	3.1	0.8	1.73	4.79
1		0.7	0.3		0.97	9.70	2.10	0.6	2.51	5.39
1		0.6		0.4	0.93	9.59	2.10	1.5	0.82	3.33
1		0.6	0.2	0.4	0.90	10.20	1.95	1.0	1.72	4.75

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For volume stability the test method according to DIN 4227 Teil 5 standards is used. Furthermore, other more specific tests may be used, such as water retentivity and drying shrinkage, according to ASTM C1506 and ASTM C474, respectively.

Cracks, voids, and other discontinuities inside the mass are detected by nondestructive methods, such those of ultrasonic sonometer, radar, and IR thermography before and after the grout hardening (Tomazevic 1992). A draft assessment of achieved filling is made by this way.

Flowable Mortars

In case of cracks of high opening (2–10 cm), it is preferable to use a flowable mortar instead of grout, because the sand content of greater grain max size (0–8 mm) contributes to volume stability reducing shrinkage cracking. If necessary, stainless steel rods are often inserted transversally to the crack in order to saw the separate parts of masonry. The binders of flowable mixtures may consist of hydrated lime powder, pozzolan, and fines, such as limestone powder added by superplasticizers and viscosity modifiers. The composition of the flowable mortar must be based on the analysis of the existing old mortar. It has also to be tested for adequate flowability, even one hour after making the mixture, following the known test methods for fluidity and robustness, in relevant European guidelines 2005, such as flow table and L-box.

A type of flowable mortar has been applied in filling cracks of a part of wall masonry in Galerius ensemble, by gravity or low pressure. The composition and mechanical characteristics are given in Table 4 and Fig. 2.

Deep Repointing Mortar

Retrofitting of masonry joints with mortar is a common intervention work of restoration projects. Before designing the mortar's composition, a systematic analysis of existing mortars is made to meet requirements for compatibility and a decision is made about strength demand and durability. The selected traditional type binding system, such as lime-pozzolan, may also include a small percentage of brick bust or cement and admixtures to meet the compatibility and durability requirement. Apart from binders, coarse aggregates are often used especially in thick mortar joints. Some examples of these mortars used in interventions are shown in Table 5.

Table 4 Composition and strength of a flowable mortar applied in parts of Galerius ensemble

Raw materials	Parts by mass
Hydrated lime powder	1
Ground pozzolan	1
Limestone filler	0.7
Sand (0–4 mm)	6.5
Water/binder ratio	0.61
Superplasticizer (% by mass of binder)	2.4
Retarder (% by mass of binder)	0.3
Porosity	20.8 %
Flexural strength (specimens: 4 × 4 × 16 cm)	2.65 MPa
Compressive strength (specimens: 4 × 4 × 16 cm)	6.5 MPa

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Fig. 2 Galerius palace ensemble, third century AD. Cracks filled with flowable lime-based mortar

Reversible Interventions

In general, they are considered low invasive and effective in terms of expectancy and resistance to environmental conditions. In most of this type of interventions, the materials are industrially manufactured, standardized, and commercially known with brand names. They are usually applied with specific technique. The problems presented in practice are rather related to technique than to materials.

An analytical assessment of how the MHS responds to earthquake is necessary, since the positions and the degree of retrofitting must be known before any type of reversible intervention.

A long list of this type of interventions could be mentioned since there are many technological advances in this field. Some of them are:

– Pre-stressed (stainless) steel cables offered many solutions in the last decades of previous century (Fig. 3; Ignatakis and Stylianidis 1989).
– Stainless steel bars or strips into bed joints repointing with lime-based repair mortars. Bars or strips could also be made of carbon fiber reinforced polymer (CFRP) covered with lime-based mortars (Modena and Valluzzi 2003).
– Metallic braces anchored on the masonry for confinement of the out of plane failure deformations (Fig. 4; Ignatakis and Stylianidis 1989).
– Bonded to surface fiber reinforcement with polymer or cementitious matrices (FRP or FRG).

  There is much progress in the materials and techniques of anchoring for FRP/FRG textiles, resulting in higher performance and cost-effectiveness, but still these types of interventions require special and expensive work. There are different types of advanced fiber reinforced sheets or grids of polymeric (FRP) or cement-based (FRG) matrix bonded on the surface of masonry elements. The use of this type of retrofit has impressively increased and continuously evolved. For example, tie bars are placed on the under strengthening areas of masonry with Shape Memory Alloy (SMA) devices by which recover from strain and relief of stress are achieved (Desroches and Smith 2004).

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Table 5 Proposal of deep repointing of Byzantine monuments

Monument: Saint Nicholaos Church, Aiges, Sparti (Post Byzantine period)							
Analysis of mortar samples							
Color: grayish white							
Stratigraphy: One layer							
Stereoscopic Observation: Compact paste with micropores, cracks with re-crystallized secondary material (photo) with concentration of calcite (photo). High content in aggregates, max size up to 8–10 mm, of mixed-type siliceous and calcitic origin							
Compressive strength: 14.1 kg/cm^2							
Porosity: 19.15 %							
Specific gravity: 1.74 g/cm^3							
Chemical composition %:							
Na_2O	K_2O	CaO	MgO	Fe_2O_3	Al_2O_3	SiO_2	L.I.
0.36	0.33	31.5	6.18	1.04	3.29	27.7	30.0
Content in anions:			Cl^-	NO_3^-	SO_4^{--}		
			0.17	0.12	0.19		
Insoluble residue: 48.8 % by mass							
Gradation curve: Max size of grains: 8 mm							
Proposal of repair mortar							
Constituents					**Parts by weight**		
Hydrated lime					1		
Pozzolan ground (milaiki gaia) (10 % residue on 45 μm sieve)					1		
River sand (0–1 mm)					0.2		
Local limestone crushed (2–4 mm)					1.6		
Coarse limestone (4–16 mm)					0.2		
Superplasticizer (free of sulfates) 1 % by mass of the binder							
Water required for 15 ± 1 cm expansion on the flow table							
The trial mixes showed that the achieved 28-days compressive strength ranges from 19 to 25 kg/cm^2 and the porosity from 17 % to 20 %.							

Fig. 3 St Panteleimon Church, Thessaloniki. Substitution of wooden tierods with stainless steel ones (Photograph courtesy of Prof. Ch. Ignatakis and Prof. K. Stylianidis)

Fig. 4 St Panteleimon Church, Thessaloniki. Metallic braces for confinements of small part of pier above the column capital (Photograph courtesy of Prof. Ch. Ignatakis and Prof. K. Stylianidis)

Table 6 Characteristics of fibers of FRP(s)

Type of fibers	Glass	Carbon	Aramid	Steel
Tensile strength (MPa)	1,300–3,400	2,000–5,600	2,500–3,620	1,500–3,500
Modulus of elasticity (GPa)	22–62	150–325	48–76	185–210
Ultimate strain (mm/mm)	0.03–0.05	0.01–0.015	0.02–0.036	0.04
Coefficient of thermal dilation (10^{-6} m/m/°K)	5.5	0.0	−0.5	6.5
Density (g/cm^3)	2.5–2.6	1.7	1.4	7.9
Melting point (°C)	1,100	310	420	1,300

Source: Based on ACI Manual of Concrete Practice ACI 544 1R-96 (2002)

Bonded to Surface- Reinforcement Techniques

These low invasive alternatives have started to be used in construction from the 1990s. They consist of a fibric system and a matrix system bonded in different forms, such as pultruded bars, sheet, or textiles and grids. The most known fibers are steel, carbon, aramid, glass and alkali-resisting glass (AR glass), basalt and biocomposites (flax, hemp), or recycled biopolymers based on lignin, cellulose, and pectin. Some characteristics of fibers are found in the literature in Table 6 (Meier 1995). Carbon fiber reinforced polymer sheets (CFRP) and steel fiber reinforced polymer sheets (SFRP) are the most widely used products in reinforcing constructions (Fig. 5). They undertake tensile stresses developed in parallel to fiber direction. The matrix in which fibers are embodied unidirectionally or bidirectionally is polymer, such as epoxy resins, polyester, and vinyl ester. In cement-based textiles or grids, a polymer-modified cement mortar with 1 % by volume long chopped AR glass fiber is used. Fibers could be categorized in three classes (Casadei and Agneloni 2009; Mitolidis 2009):

– Of high modulus of elasticity, such as different qualities of steel and carbon
– Of medium modulus of elasticity such as aramid, basalt, and glass

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Fig. 5 Commercial steel and carbon fiber polymer sheets (Photograph courtesy of G. Mitolidis)

– Of low modulus of elasticity such as Flax and Hemp

Indicative values for the characteristics of the epoxy resin matrices are:

– Density 1.1–1.7
– Modulus of elasticity 0.5–20GPa
– Flexural strength 9–30 MPa
– Ultimate strain 0.5–5 %

The main type of failure of surface bonded CFRP(s) concerns the development of considerable shear stresses on the surface leading to detachment. That is why the anchorage length must be estimated for each type of matrices and be based on reliable measurements of bonding.

The procedure of applying FRP includes:

– Check the bonding capacity of masonry substrate.
– Leveling the surface to succeed good bonding that is essential for transferring stresses in particular in the case of not strong anchorage.
– Apply FRP sheets on dry surface with good quality of adhesive material.
– Ensure sufficient anchorage. Metallic haunch connections are preferable for low invasive FRP.
– Use of proper dye for protection from UV radiation.

More details are available in literature (ACI 440 2R-08, 2008).

When retrofitting masonry walls or strengthening arches and domes, the values of practical interest in relation to FRP are:

– Ultimate tensile strength (i.e., 5–6 MPa)
– Ultimate elongation (i.e., 1.62 %)
– Transition zone tensile stress (i.e., 2.1 MPa)
– Tensile modulus of elasticity (i.e., 0.37GPa)

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As advantages of FRP are considered the following:

- The low weight or high strength to weight ratio
- The relatively easy installation and high productivity of the work
- The minimal dimensional change of the masonry elements
- The resistance to corrosion, chemical attack, and environmental impact

However, many disadvantages have also been noted mainly because of the polymer nature of the matrix, such as:

- Low resistance to fire
- Degradation of polymeric matrix by UV
- Application needs special equipment and specialized staff as well as dry surfaces and low temperatures
- The incompatibility of resins to masonry structure has an impact to the bond of FRP on masonry surface. Moreover, FRP may create secondary side effects that make the benefits of reversibility questionable. This occurs because of the lack of vapor permeability that leads to moisture accumulation inside the masonry mass which favors deterioration phenomena, particularly in the case of large masonry area rapping with FRP. Furthermore, FRP or AR fiber glass textiles exhibit brittle failure mechanism when their bonding is based on adhesion and friction. In fiber grids with cement-based matrix, these effects are mitigated.

Some outstanding examples of MHS strengthening with FRP mentioned in literature, such as the strengthening of the San Vitale Church in Parma, Italy, and the repair of the monastery of St Andreas, Mount Athos, 2011 (Figs. 6 and 7).

An interesting evolution in the field of reversible external intervention is SMA devices, which are systems of advanced technology applied in MHS for defending earthquake. The main materials of SMA are alloys of NiTi, which recover from large strain through heat action. They are considered superelastic and high damping systems so as by the removal of stress a recovery from strain occurs. The high cost, the difficulty in handling the material because of its hardness, and the welding deficiency are mentioned as disadvantages, as well as the dependency of the SMA properties from the temperature and their sensitivity to compositional changes of alloys. (MANSIDE Consortium 1998).

Fig. 6 The damages of the dome of the monastery at Andreas in Mount Athos before repair intervention (Photograph courtesy of G. Mitolidis)

Fig. 7 The use of CFRP for strengthening the base of the dome of St Andreas in Mount Athos, 2011 (Photograph courtesy of G. Mitolidis)

An example of SMA application, mentioned in literature, is the first application of these devices in S. Giorgio Church in Trigano, Italy, by Prof. Indirli (2001) (Indirli et al. 2001) and reinforcing of St. Francisco of Assisi Church by Professors Groci and Gastellano (Groci 2001).

Summary

Masonry Heritage Structures (MHS) have inherent weakness in carrying horizontal loads, and their preservation and protection in seismic areas require retrofitting and strengthening interventions. However, principles of philosophy of conservation about compatibility and keeping authenticity should be followed in parallel to safety and durability issues valid in any type of construction inhabited, according to modern codes and regulations for anti-seismic design of structures.

The nature of building materials of old masonries which are porous and of low strength capacity is different from modern compact cement-based building materials (reinforced with steel bars) and of low porosity, high bearing capacity in compression, and bending and tensile loads. Similarly, materials of organic polymer-based matrix are impermeable and hardly cooperating with inorganic matrix materials. These contradictions introduce particular difficulties in retrofitting and strengthening heritage masonries enhanced by the fact of the great variety of masonry types, in terms of their components, way of constructing, functionalism in the structural ensemble, and various loading conditions.

After earthquakes of the last three decades of the twentieth century in Italy and Greece, countries with a tremendous heritage building asset, the MHS “de facto” separation in historical masonry buildings of urban areas and monumental buildings was followed for emergency repairs. This temporary separation allowed more freedom in compromising safety and compatibility issues in the case of historical buildings of old urban centers, while compatibility and authenticity issues prevailed in the case of monumental buildings. This option was also suggested by distinguished scientists (Tassios and Mamillan 1985), because it helps decision makers about the degree of strengthening.

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Addressing properly the aforementioned issues in lifesaving interventions on MHS prerequisites the consideration of a holistic approach of analysis of existing structures. This involves using measurements on site and at laboratory, as well as assessment of MHS behavior by adequate models. In this manner, a thorough understanding of the structure can be obtained before deciding about repair materials and techniques.

In the past, many failures occurred concerning mainly side effects due to invasive retrofitting interventions on the MHS ensembles. The current evolution in this field focuses on the development of compatible grouts, flowable mortars, and repointing mortars for irreversible type consolidation of the mass of the masonry corpus. Besides, steel and other fiber reinforcement bonded on the surface of masonry with materials of polymeric- or cement-based matrix are used as reversible interventions.

Advances in the field of irreversible interventions could be considered the use of upgraded lime-based grouts and mortars, i.e., with addition of new generation admixtures prolonging fluidity and increasing volume stability, or by using nano-modified slurries for the enhancement of bonding of interfaces between old and new materials.

Furthermore, new types of reinforcement are expected, which would be light and resistant to environmental influences, providing a high deformability capacity with strong and yet less harmful anchorage, and meet aesthetic and compatibility requirements are some expectations in reversible strengthening of HMS.

Moreover, the quality of materials and intervention works is of primary importance for the longevity and economy of interventions. However, the system of regulations, recommendations, proper test methods, and specific standards has not been fully developed, in spite of continuous efforts of the last decade on national and European level. There is still a gap between knowledge and practice, but undoubtedly the continuous education and joint research efforts, as well as the awareness of the society about safeguarding cultural patrimony, have resulted in significant improvement of consolidation and strengthening works.

Cross-References

► Ancient Monuments Under Seismic Actions: Modeling and Analysis
► Damage to Ancient Buildings from Earthquakes
► Masonry Components
► Seismic Behavior of Ancient Monuments: from Collapse Observation to Permanent Monitoring
► Seismic Strengthening Strategies for Heritage Structures
► Strengthening Techniques: Masonry and Heritage Structures

References

Binda L, Gardani G, Cantini L, Tirabischi C (2007) On site and laboratory detection of the quality of masonry in historic buildings. In: Arun G (ed) Proceeding of the international symposium studies on historical heritage, Antalya Turkey, pp 667–682)

Burman PATI (2001) What is cultural heritage? In: Baer NS, Snickars F (eds) Rational decision-making in the presentation of cultural property. Dahlem University Press, Berlin

Casadei P, Agneloni E, (2009) Advanced composite materials for strengthening, blast protection and seismic protection. EC-COST ACTION C26 urban habit constructions under catastrophic events. http://www.tecinn.com

DOI 10.1007/978-3-642-36197-5_203-1

Desroches R, Smith B (2004) Shape memory alloys in seismic resistant design and retrofit: a critical review of their potential and limitations. J Earthq Eng 3(8):415–429

Groci G (2001) Strengthening of the Basilica of St. Francis of Assisi after the September 1997 Earthquake. Struct Eng Int 11:207–210

Ignatakis C, Stylianidis K (1989) Criteria for the substitution of wooden tierods in Byzantine Churches- St. Panteleimon Church of Thessaloniki. In: Brebbia CA (ed) Proceedings of the 1st international conference on structural studies, repairs and maintenance of historical buildings, Florence, pp 385–393

Indirli M, Castellano M, Clemente P, Martelli A (2001) Demo application of SMA devices. The rehabilitation of the St. Giorgio Church bell tower. In: Proceedings of the SPIE, Smart Systems for Bridges, Structures and Highway, New port Beach, California (US) March, 2001

Lipe WD (1984) Value and meaning in cultural resources. In: Cleeve H (ed) Approaches to the archaeological heritage: a comparative study of world cultural resource management system. Cambridge University Press, Cambridge

Lowrenco PB (2006) Structural restoration of monuments: recommendations and advances in research and practice. In: Proceedings of the 1st international conference restoration of heritage masonry structures, Minho Portugal, KP05 01–16

MANSIDE Consortium (1998) Guidelines for the passive seismic protection of structures using shape alloy based devices. Report of the Brite/Euram, Brusselles project BE 95–2168

Meier U (1995) Strengthening of structures using carbon fibre/epoxy composites. Constr Build Mater 6(9):341–351. Elsevier Science, London

Miltiadou A (1990) Contribution a l' etude des coulis hydrauliques pour la reparation et le reinforcement des structures et des monuments historique en masonnerie. PhD thesis, ENPC, Paris

Mitolidis G (2009) Experimental investigation of concrete beams behaviour with carbon or steel fibre reinforced polymers. PhD thesis, AUTH, Thessaloniki

Modena C, Valluzzi MR (2003) Repair techniques for creep and long- term damage of massive structures. In: Brebbia CA (ed) Proceedings of the conference structural studies, repairs and maintenance of heritage architecture VII. WIT Press, pp 141–150

Nabih Y (1996) Application on hybrid damping system with base isolation for the seismic retrofit of Los Angeles City Hall. www.cctk.ac.in/nicee/wcee/article/n_2090.pdf

Papayianni I (2004) Design of compatible repair materials for the restoration of monuments. Int J Restor 10(6):623–636

Papayianni I, Pachta V (2012) High performance lime based grouts for repair of historic masonries. In: Jasienko J (ed) Proceedings of the SAHC 2012 conference structural analysis of historical constructions, pp 1897–1904)

Papayianni I, Tsolaki A (1995) Microstructural and mechanical strength of ancient mortars. In: Papayianni I, Astrinidou P (eds) Proceedings of the NATO SFS workshop on materials for restoration, Thessaloniki Greece, pp 35–48

Penelis G (1996) Techniques and materials for structural restoration. In: Proceedings of the 14th WCEE, Acapulco

Saito T (2006) Basic concept of base isolation system for buildings. Japan Society of Seismic Isolation. http://www.cibw114.net/report/Japan02.pdf

Tassios TP (1986) Mechanics of masonry. Edition of National Technical University of Athens, Athens, pp 6–13 (in greek and italian)

Tassios TP, Mamillan M (1985) Structural investigation of ancient monuments. Valutazione Structurale dei Monumenti antichi. Ed. Kappa, Rome

DOI 10.1007/978-3-642-36197-5_203-1

Thomasen SE (2003) Performance- based seismic design criteria for historic buildings. In: Brebbia CA (ed) Structural study, repairs and maintenance of heritage architecture VII. WIT Press, Southampton, pp 507–512

Tomazevic M (1992) Laboratory and in sites test of the efficacy of grouting and tying of stone masonry. In: Binda L (ed) Proceedings of the international work CNR-ENDT effectiveness of injection techniques of retrofitting of stone and brick masonry walls in seismic areas, Milan, pp 95–117

Toumbakari E (2002) Lime-pozzolan-cement grouts and their structural effects on composite masonry walls. PhD thesis, K.U. Leuven

Valluzzi MR (2000) Mechanical behaviour of masonry strengthened by lime-based materials and techniques. PhD thesis, University of Padua

Van Balen K, Papayianni I, Van Hess R, Binda L, Waldum A (2005) Introduction to requirements for functions and properties of repair mortars. Mater Struct/Materiaux et Constr 38(282):781–785