

GROUTING METHODS FOR THE REHABILITATION AND REINFORCEMENT OF MASONRY STRUCTURES DAMAGED BY CRACKS

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ABSTRACT

The article sums up the requirements for historic masonry structures whose reinforcement is based on the grouting technology application, the grouting implementation procedure in relation to the extent, type and size of masonry damage. Special focus is put on grouting agents and requirements for their characteristics.

KEYWORDS

masonry structure, historic structure, grouting, requirements

INTRODUCTION

The restoration, reconstruction and rehabilitation of historic and heritage buildings presently put great emphasis on such conservation and restoration methods which are not associated with significant damage and irreversible interventions in the historical matter. These requirements can be, to a certain extent, met by reinforcement methods using composites based on high-strength carbon or aramid and glass fibres and resin, or polymer-modified cement mixes (for specially modified fabrics) applied usually on the surface or in layers close to the surface. Another group of methods meeting the requirements above are grouting methods, which preserve or restore the original, i.e. initial characteristics of historical materials and structures. By the application of these methods, the structure - damaged by degradation processes of mostly chemical nature (at elevated moisture contents) or mechanical effects causing cracks and degrading the structure of historical materials and structures - is stabilized (its structural integrity regained).

MASONRY GROUTING METHODS, REQUIREMENTS FOR GROUTING AGENTS AND MIXES

Composites based on high-strength fibres (carbon, aramid, glass) and suitable adhesives (resin, special polymer-modified cement mixes) can be applied in the form of all-surface fabrics placed on cleaned surfaces of masonry structures damaged by tensile or shear cracks. Another option, mainly for local cracks, is the application of partial composite strips covering tensile or shear cracks in the appropriate direction. These issues have been the subject of extensive research and its results have been published e.g. [1 - 5] (Figure 1).

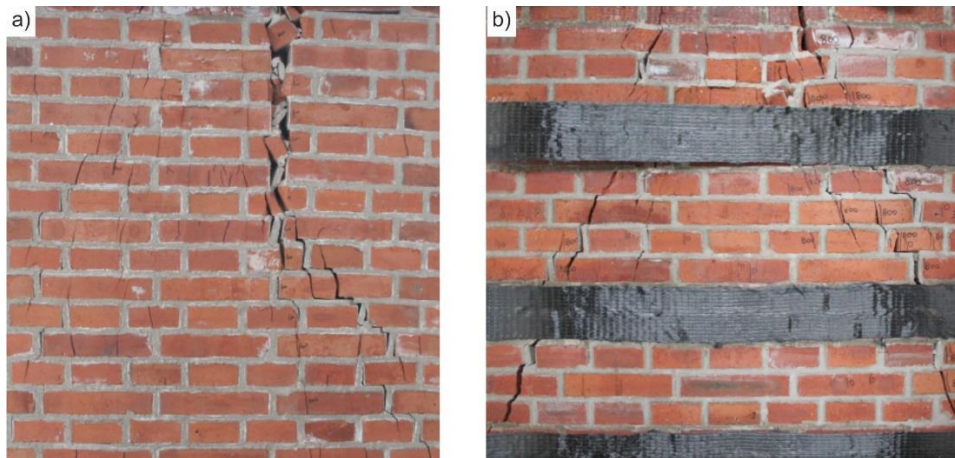


Fig. 1. - a) damaged masonry, b) masonry with carbon strips

The damage of compressed masonry pillars and walls is usually manifested by the appearance of tensile cracks whose direction corresponds to the pattern of compression trajectories and is the consequence of the low strength of masonry and its components in tension, ranging in the interval of 5 to 12 % of the strength of the masonry and its components in compression. The rehabilitation of masonry, in these cases, mostly consists of the prevention of the development of tensile cracks by the application of transverse masonry reinforcement or pre-stress. In the case of totally insufficient load-bearing capacity of masonry in compression, the masonry load-bearing capacity in compression is increased by adding a reinforcing (additional) construction. The extent and the method of masonry rehabilitation depend on the condition, type and extent of masonry damage.

The grouting of primarily multi-layer masonry for the purpose of improving its physical and mechanical characteristics is a relatively old and widely used irreversible method of masonry rehabilitation [6, 7].

The type and dimensions of cracks (inclined and vertical cracks to a width of ca 20 mm) which can be grouted, the position of grouting and inspection holes (the distance of verification holes from the crack being 150 – 300 mm), the composition of grouting mixes and grouting pressures for brick masonry damaged by earthquakes are prescribed in [8]. The verification of the masonry grouting quality is described in [9, 10]. Depending on changes in surface emissivity and potential changes in the temperature field (during the chemical reaction of grouting mixes with masonry components), thermal imaging can be used for the verification of grouting depths [9]. Ultrasound tomography helps to verify the grouting effectiveness (grouting depth) based on changes in density [10].

Masonry damaged by degradation processes can be reinforced by suitable grouting (using epoxy resin, cement, lime suspension, etc.) depending on the extent and type of masonry damage. Damaged surface layers or plasters can be reinforced by repetitive multiple coatings (sprayed) of lime water (in the case of less damaged masonry). The respective masonry rehabilitation must be assessed in terms of water vapour diffusion to avoid moisture entrapping in the masonry.

The basic grouting substances are mixes based on cement or hydraulic lime with additives such as brick dust, pozzolana, clays, etc. [6, 7, 11 - 14]. The additives are used to reduce the necessary amounts of cement, modify the major characteristics of grouting substances – rheological, volume changes, strength, grout ability [6, 7, 11, 12, 14 - 17]. An important and demanding step is the design of the grouting mix with high grout ability at low pressures to allow the penetration of the mix into the masonry, filling all cracks, caverns, cavities and filling or partially filling the pore system of original materials, forming a bond between the original materials and grouted mortar and taking into account the “roughness” effect of masonry units’ surfaces [12, 14, 15, 18].

Special emphasis in the restoration and reconstruction of historic and heritage buildings has been recently put on the usage of traditional materials based e.g. on lime, pozzolana, metakaolin.

Experimental research has pointed out that the usage of metakaolin or pozzolana led to the extension of the hardening time; after reducing the cement amount by 30% the bond between the masonry units and the grouting mix shows satisfactory characteristics [16] and low-strength masonry manifests a relatively higher increase in strength than high-strength masonry after grouting [16]. Experimental research [7] compared commercially available lime-based grouting agents. The growth in resistance and mechanical characteristics of masonry depends on the strength of the bond between the grouting mix and masonry.

The masonry made up of high-quality masonry units with insufficiently load-bearing mortar can be strengthened by pressure grouting, so-called micro grouting using epoxy- or polyurethane resin-based mortar injected through boreholes into each bed joint (under a pressure of ca 0.5 MPa). Prior to grouting, pillars may e.g. be fitted with temporary formwork of hardened paper impregnated repeatedly with alkali silicate.

Local cracks (active, passive), both tensile and shear, require securing to prevent their further development and propagation. Provided the masonry in the vicinity of local cracks is not damaged or poor-quality, so-called “**stitching**” can be performed using e.g. steel ties of round bars with higher-quality periodic surfaces (\varnothing 14 mm to \varnothing 18 mm), or ties of specially profiled high-strength steel (e.g. Helifix), properly anchored to the load-bearing masonry. When applying this method, the possibility of the appearance of new cracks must be carefully considered, particularly in the places of tie anchorage. The ties must be arranged perpendicularly to the passing crack with a sufficient overlap of e.g. min. 0.5 m on each side. The distance between the ties, which usually ranges from 0.3 to 0.6 m, will decrease to prevent further crack propagation at both ends and in the area of the largest crack width. Progressive and, at the same time, non-invasive methods include the stitching of cracks with composite strips based on high-strength fibres (carbon, aramid, glass) and suitable adhesives (resins, special polymer-modified cement mixes) (Figure 2).

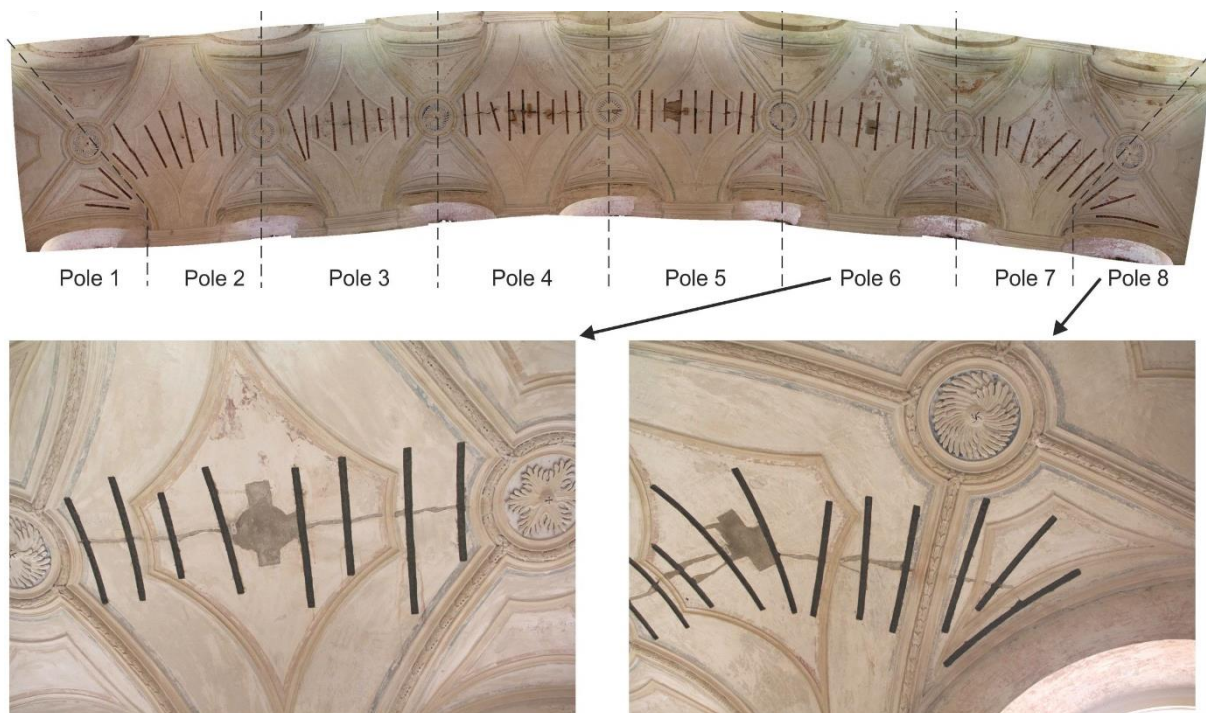


Fig. 2. - Stitching cracks on a barrel vault

After the mounting of ties in grooves and cleaning the crack with compressed air, pressure grouting is performed or deep cementing of the crack with an expansive cement mix or mortar is done. The ties must be protected from corrosion by proper backfilling of the groove and covered by

a layer of polymer-modified cement mortar sufficient in thickness and successively overlaid with a mesh and plaster.

Masonry damaged by a cluster of active cracks can be rehabilitated by overall crack grouting, preceded by deep cementing of cracks with larger width with a pressure caulking gun. The grouting of cracks up to the width of 2 mm is performed with low viscosity resins under the pressure of minimally 20 to 40 kPa. The grouting of cracks 2 to 4 mm in width is performed after their previous wedging with a mixture of resin with a filler (fine silica sand) at the pressure of 20 to 60 kPa. Cracks wider than 4 mm are filled with cement mortar, or two-stage grouting with cement mortar and resin is performed. Active cracks must be clamped with ties or pins of stainless steel before grouting, or in the case of large-scale cracking the masonry structure must be braced by steel tie rods of reinforcing steel or hoop steel embedded in bed joints, by prestressing cables embedded and anchored in a continuous groove min. 50 mm in depth, or by prestressed carbon lamellae. The cluster of active cracks rehabilitated in this way is successively covered over the whole surface with a composite based on the special fabrics and a polymer-modified cement mix.

Masonry damaged by tensile or shear cracks can be reinforced after previous wedging and local grouting of cracks wider than 2 mm by inserting steel rods (e.g. helibar) or carbon composite strips anchored by a special polymer-modified cement mix and, after flushing joints and cracks, by overall micro grouting of the masonry. To ensure the effectiveness, steel sections or composite strips based on high-strength fibers 50-60 mm in width, must be embedded deeper, and, as appropriate and depending on the extent of masonry damage, reinforced on both sides.

Masonry grouting is performed down under the protection of hardened, sufficiently compact, properly anchored and strong sheathing. Grouting pipes (packers) mounted in drilled holes are sealed by gypsum or rapid-setting mortar. The selected distance of boreholes is usually from 0.5m to 1m (exceptionally up to 2m) so that all cracks are properly filled depending on the permeability of the damaged structure and the extent of damage. Grouting can be applied only to structures which have sufficient tensile strength and are permeable (in relation to the pore system and grouting pressure) to carry the internal tensile stress induced by grouting and let the grouting agent penetrate into the masonry structure.

Prior to masonry grouting, damaged surface layers must be removed. To avoid the bleeding of suspension on the surface of a rehabilitated wall the wall surface must be properly sealed or a new sheathing plaster must be put on before grouting. The choice of the grouting procedure (single-phase, multiple-stage), the grouting agent composition and consistency depend on the masonry condition. Grouting can be complemented by e.g. reinforced plaster (gunite) anchored to the masonry by reinforcing ties, pins, etc. In numerous cases, grouting mostly helps to restore damaged masonry by filling in cavities, voids and joints between masonry units and thus to increase its load-bearing capacity. Grouting of little damaged, compact masonry, as a rule, does not significantly increase its load-bearing capacity (having relatively little effectiveness). The design of static masonry grouting can be based on the WTA 4-3-98 directive.

Cracks to a width of 1 mm are rehabilitated by epoxy resins without fillers. The temperature of the structure must be minimally +5 °C (varying for different manufacturers, but +5°C is the minimum). The cracks must be cleared of impurities, grease, dust and damaged parts. The grouting agent must comply with the requirements for low viscosity (being applicable at a grouting pressure of 20 ÷ 40 kPa), long-time workability in liquid state and fast hardening to prevent the infiltration of the grouting agent into the structure, low shrinkage, low dependence on moisture and alkalinity of the environment. The holes for grouting ca Ø 10 to 15 mm are 500 mm apart for crack widths of up to 1 mm. Other requirements include limited reactivity with metals, absence of health hazards, good adhesion, high tensile strength, potential modification of the modulus of elasticity, non-permeability, durability and dilatometric properties similar to the grouted masonry.

Cracks over 1 mm are grouted with a mixture of resin and a filler (e.g. silica flour with a max. grain size of 0.1 mm in amounts of 20 to 40 %). Prior to grouting, cracks must be wedged, sealed on the surface and grouting packers mounted. The holes for grouting ca Ø 10 to 15 mm are 600 ÷

1000 mm apart for crack widths of over 1 mm. The grouting pressure is ca 20 ÷ 60 kPa, the grouting time of one borehole is usually shorter than 20 minutes.

Cement suspensions (paste, cement milk, cement mortars with lime addition for grouting cavities, or with an admixture lowering viscosity and retarding hardening) can be used for cracks larger than 2 mm.

Density of boreholes: 2 ÷ 4 boreholes \varnothing 20 ÷ 30 mm/m², borehole depth 2/3 to 4/5 of masonry thickness, grouting pressure 50 ÷ 150 kPa. Larger cracks (over 2 mm) must be jointed on the surface before grouting. The grouting time of one borehole at a masonry thickness of 0.9 ÷ 1.2 m is approx. 30 minutes.

The rehabilitation of heritage buildings can be performed with so-called grouting anchors consisting of a steel pin of adequate length of stainless steel with a periodic surface (e.g. 2 m in length, \varnothing 12 mm, in a hole \varnothing 36 mm) mounted in bored holes and grouted with cement suspension (of e.g. Portland cement, w/c = 0.7) or special mixes based on polymers, resins, etc.

Prior to masonry **grouting**, damaged surface layers must be removed. To avoid the bleeding of suspension on the surface of a rehabilitated wall the wall surface must be properly sealed or a new sheathing plaster must be put on before grouting. The choice of the grouting procedure (single-phase, multiple-stage), the grouting agent composition and consistency depend on the masonry condition. Grouting can be complemented by e.g. reinforced plaster (gunite) anchored to the masonry by reinforcing ties, pins, etc.

Stone masonry of historic buildings of less massive and water-absorbing stones can be rehabilitated by micro grouting using epoxy resin (e.g. CHS EPOXY 1000 and 2000, or their 1:1 mixes). Prior to **overall grouting**, the masonry surface is sealed with e.g. a sheathing plaster. The grouting mix is injected into the masonry at a pressure of ca 0.2 MPa by grouting pipes 12 to 15 mm in diameter distributed in a checkerboard pattern over the whole surface of the rehabilitated masonry or divided into sections (where you always proceed from the lower section to the upper one) 0.5 m to 1.0 m apart. The grouting mix must fill in all cavities, cracks and also penetrate into the structure of porous masonry units and mortar.

In **strip grouting**, the grouting boreholes are distributed in vertical and horizontal strips approx. 1 m in width, at a mutual axial distance of 4 to 6 m. The boreholes in the strips are arranged in a checkerboard pattern, 0.5 m to 1.0 m apart. The depth of single-sided boreholes is 2/3 to 3/4 of the masonry thickness, in double-sided boreholes usually 1/3 of the wall thickness. The depth of the boreholes, the grouting procedure (single-phase, multiple-stage) and the grouting pressure must be specified based on the material and masonry condition.

The compressive strength of grouted masonry depends on the amount and quality of the grouting mix penetrated into the masonry.

The choice of the **grouting agent**, its consistency and composition depend on the width of cracks, porosity, mineralogical and chemical composition of the binder or masonry units and the degree of overall masonry degradation. Grouting can only be applied to stabilised masonry and cracks (passive cracks, cracks secured by reinforcement, braced or clamped masonry). The principal characteristics of the grouting agent include rapid setting and hardening, viscosity, strength, stability in the grouting phase, thixotropy, consistency, physical and mechanical properties and durability. A high-quality grouting design further includes the design of grouting packers and pumps, packer distribution and the depth of holes. Structures with higher moisture contents can be grouted with cement milk (mixture) or epoxy resin, while polyurethane and acrylic resin substances (gels) are used for the grouting of cracks which allow undesirable water condensation.

- **Cement suspensions** are less suitable due to their high viscosity (low stability during grouting – fast sedimentation and premature clogging of cracks smaller in width occurs), low tensile strength after hardening, low adhesion and greater shrinkage (adhesion or the cement filling in the cracks fails). Improved characteristics are added by suspensions of fast-bonding cements with a greater proportion of solid gypsum-free clinker (suitable for the rehabilitation of historic buildings with high moisture contents). The grouting cement

mix ($w : c = 1 : 1$ up to $3 : 1$) is injected into boreholes $\varnothing 30$ to 40 mm to the depth of ca $2/3$ of the masonry wall at the pressure of 0.5 to 1.2 MPa. The grouting mortar used for filling larger cracks ($c : p = 1 : 3$ up to $1 : 5$, $w = 0.5$ to 0.8) hardens in 5 to 15 hours, or in 3 to 5 hours when hardening accelerators are used.

Research into the effectiveness of cement suspensions used for the grouting of masonry with poor load-bearing capacity has manifested that the grouting cement substance fills the cracks and cavities in the masonry, improves the masonry unit's contact with mortar and thus produces a visible improvement of its strength. The investigation of cavity and crack filling after grouting can be made with radar or ultrasonic devices.

- **Epoxy resins** reach the required characteristics by the right selection of monomers, setting agents and the hardening procedure, accelerating admixtures, internal plasticisers, modifiers, fillers and extenders. They belong to the most suitable grouting mixes for the rehabilitation of damaged masonry and concrete structures.
- **Polyester resins** are characterised by low viscosity and relatively easy hardening reactions. Their disadvantage is greater shrinkage (ca 5 % of volume) and lower adhesion to concrete and other building materials.
- **Polyurethane resins** possess high penetration abilities and are mostly used for the reinforcement of mortar in masonry joints, for increasing the load-bearing capacity of masonry.

STRENGTHENING OF MULTI-LAYER HISTORICAL MASONRY BY GROUTING

Grouting is often used for the reinforcement of multi-layer (three-layer) historical masonry composed of two "sheathings" and an inner core. The failure of multi-layer masonry in compression occurs by increasing the distance of layers in the transverse masonry section [11]. Using a grouting mix based on hydraulic lime does not cause layer separation under loading as this mix homogenises the masonry. Using a grouting mix based on hydraulic lime or cement and hydraulic lime increases the tensile strength of masonry [11]. The experimental verification of the reinforcement of multi-layer (three-layer) masonry by grouting manifested that by adding little amounts of cement to the grouting mix a significant increase in the strength of the fresh mix is produced. The grouting mix of hydraulic lime – pozzolana – cement in a 1:0.7:0.3 ratio developed a strength twice higher compared to the grouting mix based on lime [6, 15]. The replacement of cement by brick dust has a positive effect on rheological properties, volume changes and strength [6]. Based on experimental verifications, empirical formulae for the prediction of grouted masonry strength were prepared [15]. At the same time, the effect of the water-cement ratio on strength for mixes based on cement and hydraulic lime was verified. After 6 months, the specimens composed of cement – lime – pozzolana with a w/c ratio of 0.8 showed the highest strength, while lower strength was found in the specimens based on hydraulic lime with a w/c ratio of 0.8 and the lowest strength in specimens on the same basis with a w/c ratio of 0.7 [15].

SPECIAL GROUTING MIXES FOR GROUTING DEGRADED MASONRY

Special grouting mixes with *Sporosarcina Pasteurii* bacteria, which positively affect the setting and hardening process of lime in degraded masonry were verified in China [19]. Modified mortar shows higher tensile strength and higher resistance to cyclic loading than traditional mortar. According to [13], the differences in compressive strength after multi-layer masonry grouting are not that significant if a grouting mix based on hydraulic lime or cement is used. Experimental research [14] confirmed the positive effect of grouting based on cement and hydraulic lime on the compressive strength of masonry, diagonal (transverse) compressive strength of masonry, the modulus of elasticity in compression (E) and in shear (G) of masonry with the growth of the above characteristics

of up to 10 % pointing out the effect of the quality of the bond between the grouting agent and original masonry units on the mechanical and physical characteristics of masonry.

Research into the rehabilitation and reinforcement of multi-layer masonry [20] revealed that masonry reinforcement with GFRP tie rods passing through the entire wall thickness in combination with masonry grouting with a mix based on lime had the greatest effectiveness with an average increase in the masonry compressive strength by up to 71%. The research also verified the failure mechanism when a displacement occurs between the outer and the inner masonry layer and a dominant vertical tensile and shear crack gradually arises.

EXPERIMENTAL RESEARCH

The NAKI DG16P02M055 project is presently in the preparation phase of research into the strengthening of historical brick, stone and mixed masonry using the grouting technology with a special focus on the reinforcement of masonry damaged by cracks due to seismic effects, including the reinforcement of masonry by grouting and by composites based on high-strength fibres and adhesives. Figure 3 presents the scheme of a masonry test piece and the designed grouting procedure. The test pieces will be “wrapped” in sealing sludge to prevent the grouting agent from escaping. The grouting boreholes are designed to pass through the maximum number of bed joints.

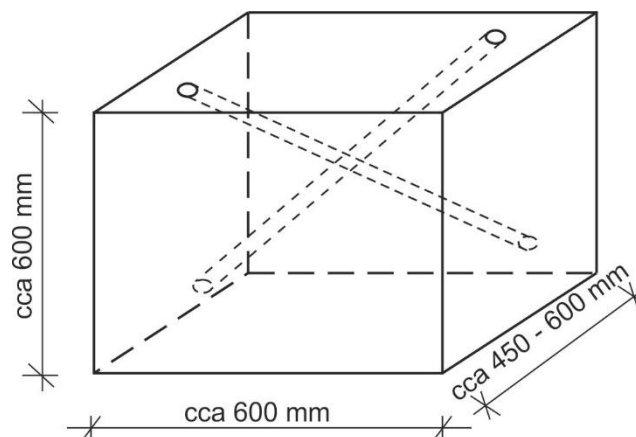


Fig. 3. - Scheme of experimental masonry specimen and proposed method of consolidation grouting

CONCLUSION

Based on a literature search study, the article sums up some principles for the grouting procedure, the grouting agents used, including some limiting and recommended requirements.

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REFERENCES

- [1] Witzany, J., et al. Strength Assessment of Historic Brick Masonry. *Journal of Civil Engineering and Management*. 2016, 22(2), s. 224-233. ISSN 1392-3730.

- [2] Witzany, J., Zigler, R. a Kroftová, K. Strengthening of compressed brick masonry walls with carbon composites. *Construction and Building Materials*. 2016, 112s. 1066-1079. ISSN 0950-0618. Dostupné z: <http://www.sciencedirect.com/science/article/pii/S0950061816303130>
- [3] Witzany, J. a Zigler, R. Stress State Analysis and Failure Mechanisms of Masonry Columns Reinforced with FRP under Concentric Compressive Load [online]. *Polymers*. 2016, 8(5), s. 1-25. ISSN 2073-4360. Dostupné z: <http://www.mdpi.com/2073-4360/8/5/176>
- [4] Witzany, J. a Zigler, R. Failure mechanism of compressed reinforced and non-reinforced stone columns. *Materials and Structures*. 2015, 48(5), s. 1603-1613. ISSN 1359-5997. Dostupné z: <http://link.springer.com/article/10.1617%2Fs11527-014-0257-z>
- [5] Witzany, J., et al. The application of carbon composites in the rehabilitation of historic baroque vaults [online]. *Polymers*. 2015, 7(12), s. 2670-2689. ISSN 2073-4360. Dostupné z: <http://www.mdpi.com/2073-4360/7/12/1540>
- [6] Papayianni, Ioanna a Vasiliki Pachta. Experimental study on the performance of lime-based grouts used in consolidating historic masonries. *Materials and Structures* [online]. 2015, 48(7), 2111-2121 [cit. 2016-04-18]. DOI: 10.1617/s11527-014-0296-5. ISSN 1359-5997.
- [7] Luso, Eduarda a Paulo B. Lourenco. Experimental characterization of commercial lime based grouts for stone masonry consolidation. *Construction and Building Materials* [online]. 2016, 102, 216-225 [cit. 2016-04-18]. DOI: 10.1016/j.conbuildmat.2015.10.096. ISSN 09500618.
- [8] City LA DBS. Crack repair of unreinforced masonry walls with grout injection. Information bulletin/ Public – building code reference NO.: Effective: 01-01-2014, DOCUMENT NO.: P/BC 2014-056
- [9] Peřina, Zdeněk, Boris Plšek a Marie Wolfová. Verification of Range of Chemical Grouting of Masonry by Non-Destructive Method Using Infrared Thermography. *Advanced Materials Research* [online]. 2014, 923, 191-194 [cit. 2016-04-18]. DOI: 10.4028/www.scientific.net/AMR.923.191. ISSN 1662-8985.
- [10] Jorne, Fernando, Fernando M.A. Henriques a Luis G. Baltazar. Evaluation of consolidation of grout injection with ultrasonic tomography. *Construction and Building Materials* [online]. 2014, 66, 494-506 [cit. 2016-04-18]. DOI: 10.1016/j.conbuildmat.2014.05.095. ISSN 09500618.
- [11] Vintzileou, Elizabeth a Androniki Miltiadou-Fezans. Mechanical properties of three-leaf stone masonry grouted with ternary or hydraulic lime-based grouts. *Engineering Structures* [online]. 2008, 30(8), 2265-2276 [cit. 2016-04-18]. DOI: 10.1016/j.engstruct.2007.11.003. ISSN 01410296.
- [12] André Filipe Melo de Almeida Figueiredo. Injection grouts for ancient masonry – adherence study. Extended abstract
- [13] Sayed Hemeda. Grouting of multiple leaf-masonry walls: Application on some islamic historical monuments in Cairo, Egypt. Article in *International Journal of conservation Science*, Volume 3, Issue 4, October-December 2012: 275-288, ISSN: 2067-533X
- [14] Mojmir Uranjek, Roko Žarnić, Violeta Bokan-Bosiljkov, Vlatko Bosiljkov. Seismic resistance of stone masonry building and effect of grouting. *GRAĐEVINAR 66 (2014) 8, 715-726*, DOI: 10.14256/JCE.1031.2014
- [15] Kalagri, A., A. Miltiadou-Fezans a E. Vintzileou. Design and evaluation of hydraulic lime grouts for the strengthening of stone masonry historic structures. *Materials and Structures* [online]. 2010, 43(8), 1135-1146 [cit. 2016-04-18]. DOI: 10.1617/s11527-009-9572-1. ISSN 1359-5997.
- [16] Adami, Chryssi-Elpida a Elizabeth Vintzileou. Interventions to historic masonries: Investigation of the bond mechanism between stones or bricks and grouts. *Materials and Structures* [online]. 2008, 41(2), 255-267 [cit. 2016-04-18]. DOI: 10.1617/s11527-007-9235-z. ISSN 1359-5997.

- [17] Sepulcre-Aguilar, Alberto a Francisco Hernández-Olivares. Assessment of phase formation in lime-based mortars with added metakaolin, Portland cement and sepiolite, for grouting of historic masonry. *Cement and Concrete Research* [online]. 2010, 40(1), 66-76 [cit. 2016-04-18]. DOI: 10.1016/j.cemconres.2009.08.028. ISSN 00088846.
- [18] L. Binda, C. Modena, G. Baronial, S. Abbaneo. Repair and investigation techniques for stone masonry walls. *Construction and Building Materials*, Vol. 11, No. 3, pp. 133-142, 1997. PII: SO950-0618(97)00031-7
- [19] Yang, Zuan a Xiaohui Chenh. A performance study of high-strength microbial mortar produced by low pressure grouting for the reinforcement of deteriorated masonry structures. *Construction and Building Materials* [online]. 2013, 41, 505-515 [cit. 2016-04-18]. DOI: 10.1016/j.conbuildmat.2012.12.055. ISSN 09500618.
- [20] D.V. Oliveira, P.B. Lourenço, E. Garbin, M.R. Valluzzi, C. Modena. Experimental Investigation on the Structural Behaviour and Strengthening of Three-Leaf Stone Masonry Walls. *Structural Analysis of Historical Constructions*, New Delhi 2006.