Article no. 51

THE CIVIL ENGINEERING JOURNAL 4-2020

MATERIALS AND TECHNOLOGIES FOR THE STRENGTHENING OF HISTORIC MASONRY BY THE DEEP GROUT INJECTION AND SURFACE PENETRATION METHOD

Jiří Witzany[1], Radek Zigler[1], Klára Kroftová[2], Tomáš Čejka[1], Jan Kubát[1]

1. *CTU in Prague, Faculty of Civil Engineering, Deparment of Building Structures, Prague, Thákurova 7, Czech Republic; wizany@fsv.cvut.cz, zigler@fsv.cvut.cz, cejka@fsv.cvut.cz, jan.kubat.2@fsv.cvut.cz*
2. *CTU in Prague, Faculty of Civil Engineering, Deparment of Architecture, Prague, Thákurova 7, Czech Republic; klara.kroftova@seznam.cz*

ABSTRACT

The grouting of historic masonry with degraded binders or masonry units, masonry with insufficient load-bearing capacity, masonry damaged by cracks, with a high void content and cavities and multi-leaf masonry is one of the rehabilitation methods of masonry frequently applied in practice, restoring its integrity and increasing its load-bearing capacity.

KEYWORDS

Masonry, Grouting, Cracks, Cavities, Brick, Stone, Experimental campaign

INTRODUCTION

The methodology for the design of the grout injection technique for masonry structures that would become the basis for the design and assessment of the grouting effectiveness in terms of the grouting agent, the grout injection method used and the grouted masonry properties have not been developed yet, and nor has the procedure for the selection of the technique, a suitable grouting mixture and the calculation procedure for the assessment of the effect on the pore system of the binder or masonry units (pore distribution, total porosity, pore type), verification of the masonry moisture content and chemism (pH, salt content and type).

The design of a grouting technique involves the specification of the purpose of grouting (grouting masonry as a whole, grouting of a binder or masonry units, reducing the void content, filling in cavities and voids, grouting cracks, strengthening surface and subsurface layers, etc.). A reliable grouting technique performed to the required extent requires the verification of the pore system, injectability and the penetration of the grouting mixture into the pore system for the selected grouting mixture and technology (optimum distance, diameter and depth of grouting boreholes, grout stability, setting and curing time, grout shrinkage, grout-masonry mutual reactivity). In this perspective, we must evaluate the total porosity, pore size and distribution and, on this basis, design the grouting mixture and the expected amount of applied grout penetrated into the grouting boreholes in relation to the total porosity. An integral part is the design of the grouting substance (based on hydraulic lime, silicates, resins, with a filler or without a filler, grout consistency), the injection technology and procedure (pressure, pressure less, single or multiphase grouting, overall grouting or in grouting strips, impregnation grouting).

The infusion and injection of substances with defined properties, usually in the liquid phase, into the pore structure is one of the methods of active modification of the physical and mechanical characteristics of porous materials, such as strength, static and dynamic elastic modulus, hardness, resistance (mainly frost resistance), moisture absorption and others.

The building materials – natural and anthropogenic - used in the present-day civil engineering practice are characterised by a pore structure generally comprising the entire pore size spectrum, from nanopores to macropores. The effectiveness of grouting relies on numerous factors, particularly the transport of the injected substance through the pore structure. The transport is affected by the properties of the injected substance, the pore structure type of the injected material and, last but not least, by the application method of the injected substance. The issues related to the transport of injected substances in relation to the type of pores and the pore system (pore distribution, pore shape and surface, their mutual communication, etc.), in relation to the specific properties and composition of the injected substance and its irreversible changes during its transport through the pore system (viscosity, etc.), and the physical, chemical and mineralogical properties of porous materials and their stability in the stage of the injected mix application have not been satisfactorily solved so far.

The design and application procedures of grouting methods in building materials prevailing to-date resemble, in individual solved cases, a largely unreliable process based on insufficiently precise knowledge and empirical data (trial and error method). Due to the lack of expertise in this field, grout injection can be classified as a less reliable and, in many cases, insufficiently effective method.

The expected effect of grouting is achieved by both the required modification of the pore system and pore properties (total porosity, pore distribution, pore shape and interconnection, etc.) and the modification of the solid phase material characteristics by a chemical, or physical-chemical and mineralogical reaction of the grout and the solid material phase (binder component strengthening by a predictable crystallization of secondary minerals, stabilization of soluble substances).

Achieving the optimum conditions for the “injected substance - injected material” mutual interaction resulting in the required/modified properties and parameters of the injected material, requires a reliable transport of the injected substance into the pore structure in the contact area between individual components of the composite material (masonry, concrete etc.) and its optimum distribution within the pore structure. In this case, the desired change in the properties of the injected material is achieved by the “modification” of the pore system.

The effective reaction of the injected substance with the injected composite material (masonry units, aggregate, binder) solid phase requires the transport of the injected substance into the secondary system of individual solid phase components as well. In this case, the desired changes in the properties of the injected material are achieved not only by changing the pore system, but also by changing the properties of individual solid phase components.

GROUTING SUBSTANCES, MIXTURES AND GELS

The choice of the grouting substance relies, above all, on the masonry (masonry components) pore system, the mineralogical and chemical composition of masonry units and the binder, the void content, crack width and the extent of masonry disintegration and the degree of weathering, the type of masonry and the required effect of grout injection, in particular:

- improvement in binder properties (mechanical, chemical, etc.),
- improvement in properties of masonry units (mechanical, chemical, etc.),
- reduction of total porosity,
- reduction of the void content,
- filling in cracks and regaining integrity,
- filling in cavities,
- modification of chemical and physical characteristics (moisture absorption, resistance to aggressive substances).

The main properties of the **grouting mixture** include the rate of solidification and hardening (stability in the injection phase, thixotropy, consistency), particle size, viscosity, strength, physical and mechanical properties and durability. Experimental research has pointed out a significant effect of the compressive strength of the grouting mixture on an increase in the compressive strength of injected masonry.

Note: The pore size and distribution in individual components of the composite material - brick and stone masonry - is non-uniform and, as a result, the same applies to the penetration of the grouting mixture into the masonry pore structure after the grout injection. It is, above all, hydraulic lime-based grouts that are susceptible to premature setting, hardening thus reducing the pore permeability. In the case of an insufficient and non-uniform penetration of the grout into the masonry structure (pore system and voids), the masonry heterogeneity in terms of masonry strength and stiffness is increasing, which unfavourably affects the masonry failure mechanism (non-uniform distribution of normal stresses) reducing the ultimate compressive strength of masonry (Figure 1).

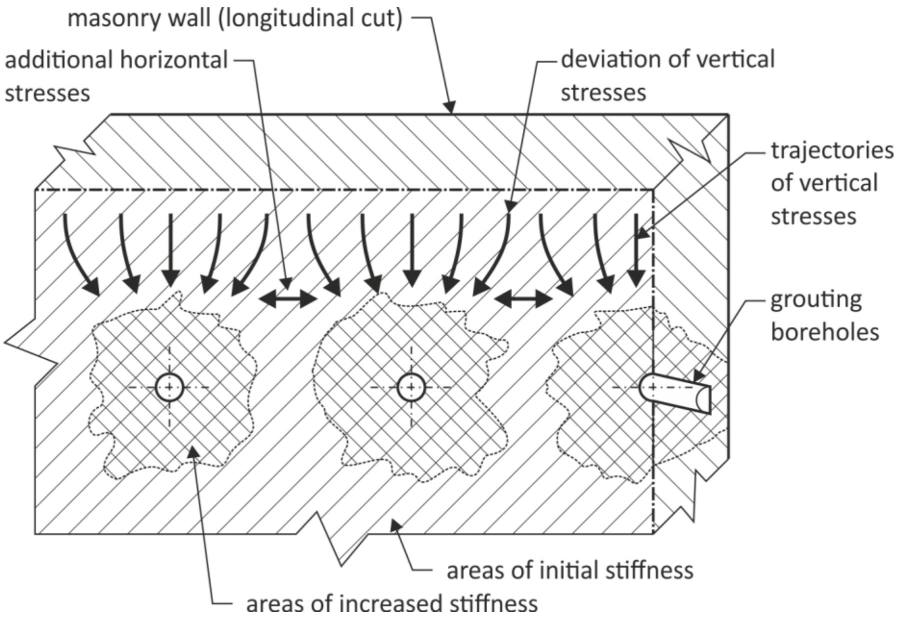

Fig. 1 - Increase of masonry stiffness due to the non-uniform penetration of the grout into the masonry structure

The design of a static grouting technique of masonry can be based on the WTA 4-3-98 guideline [1]. The principal properties of the grouting mixture include the rate of solidification and hardening, low viscosity, strength, stability in the injection phase, thixotropy, consistency, physical and mechanical properties, durability. The grouting mixtures can be divided into:

- **lime suspensions** which are characterized by good fluidity and filling ability without shrinkage after the addition of water, without the separation of excess water, high resistance to sulphates, but may have higher porosity,
- **lime-cement suspensions** are suitable for injecting masonry with a high void content and cavities, masonry damaged by a system of cracks (2 - 3 mm in width), disintegrated masonry and for grouting larger local cracks in historic brick or stone masonry,
- **cement suspensions** are less suitable due to their high viscosity and low stability – rapid sedimentation and premature clogging of cracks of smaller widths occurs during injection,

DOI 10.14311/CEJ.2020.04.0051

due to their relatively low tensile strength after hardening, low adhesion and greater shrinkage (failure of adhesion or the cement filling of cracks occurs), they are not suitable for application to heritage buildings,

- **acrylate mixtures** have low viscosity (approaching water viscosity), they can maintain permanent flexibility even under water, have high reversibility,
- **epoxy resins** achieve the required properties by the selection of suitable monomers, hardeners and the curing regime, accelerating additives, internal plasticizers, modifiers, fillers and extenders, they are among the most effective grouts for the remediation of damaged masonry and concrete structures,
- **polyester resins** have low viscosity and relatively simple curing reactions, their disadvantage is greater shrinkage (ca 5% by volume) and lower adhesion to some building materials,
- **polyurethane resins** have a high penetration capacity and are primarily used for reinforcing mortar in masonry joints to increase the load-bearing capacity of masonry.

The research project [2] addressed the development of consolidation agents based on lime nanoparticles not exceeding 1µm in size, labelled CA-Mg, Ca4 and Ca4O, characterized by a high penetration capacity into the material structure [3-5].

Note: Grouting agents developed within the research project [2]:

Ca4 *The test portion of calcium methoxide was dispersed in isopropyl alcohol and distilled water was added. The mixture was left in a magnetic stirrer for 24 hours. The resulting suspension was produced by supplying the reaction mixture to a volume of 1 litre. The concentration of* $Ca(OH)_2$ *is 5 g/l. Strengthening, sealing of concrete and brick, stone and mixed masonry, particle diameter of 220-360 nm*

Ca4O *The test portion of calcium oxide was dispersed in ethanol and distilled water was added. The mixture was left in a magnetic stirrer for 24 hours. The resulting suspension was produced by supplying the reaction mixture to a volume of 1 litre. The concentration of* $Ca(OH)_2$ *is 5 g/l. Larger particles and lower viscosity than in Ca4. Strengthening, sealing of concrete and brick, stone and mixed masonry, particle diameter of 1330 – 1770 nm*

Ca-Mg *Test portions of calcium acetate* $Ca(OCOCH_3)_2 \cdot H_2O$ *and magnesium acetate* $Mg(OCOCH_3)_2 \cdot 4H_2O$*, which was dissolved in distilled water. Strengthening, sealing of concrete and brick, stone and mixed masonry, particle diameter of 35-835nm*

Compared to conventional lime macroparticles, lime nanoparticles finely dispersed in the nanosuspension have many times higher performance, high chemical performance, excellent plastic, consolidation and diffusion properties, low sintering temperature, cleaning abilities, etc. At the same time, lime nanoparticles are a material highly compatible with historical lime-based materials. The lime nanosuspension returns the missing binder to the masonry and plaster on the principle of carbonation, where the reaction with atmospheric CO_2 *produces calcium carbonate* $CaCO_3$*.*

In addition to the stabilization, conservation and consolidation of degraded historic masonry, lime nanosuspensions also ensure a combination of deep consolidation of masonry by grouting and surface strengthening of preserved historically valuable, usually multi-layer plasters.

Historic masonry grouting aimed at improving its physical and mechanical characteristics can be performed with agents based on mineral substances, e.g. hydraulic lime with additives (brick dust, pozzolans, clays, etc.), which regulate the setting and hardening process, viscosity, etc., with agents based on lime and cement (e.g. trass lime and cement), or resin-based agents with suitable fillers (e.g. quartz sand with a maximum grain size of 1 mm).

In justified cases, a grouting mixture with a small amount of cement (5 to 10%), Roman cement, or with resin-based substances can also be applied. In exceptional cases where the

DOI 10.14311/CEJ.2020.04.0051

masonry reinforcement with a lime-based grout is insufficient, resin-based grouting agents may be used. Lime-based grouts fill up "free" spaces and minimally penetrate into the pore structure of masonry units and the binder.

Modified admixtures added to grouts based on hydraulic lime, such as pozzolan, lime, or clay and brick dust, are effective in modifying the rheological properties, volume changes and strength of the injected masonry. By adding pozzolan, lime and cement, the tensile and shear strength of masonry, the bonding of the original binder and the grout (new binder) can be affected. The grouting agents based on minerals and hydraulic lime are suitable for the masonry of historic and mainly heritage buildings.

Improved properties are achieved with suspensions of quick-setting cements with a larger proportion of solid gypsum-free clinker (suitable for the rehabilitation of historic buildings with a high moisture content).

Research into the effectiveness of cement suspensions for grouting masonry with poor load-bearing capacity has shown that the injected cementitious material fills in the cracks and cavities in the masonry, increases the contact between the masonry units and mortar and thus significantly improves its strength.

Silicate-based mixtures can be used to locally strengthen the material by modifying the properties of the masonry pore system. These mixtures, like resin-based mixtures, penetrate into the pore system to a depth of 50 to 60 mm from the grouting borehole. Grouting mixtures based on hydraulic lime with additives and silicate-based mixtures are applied for the strengthening of historic or heritage masonry.

The filling of cavities and cracks after grouting can be investigated with radar or ultrasonic devices.

Note: Mortars based on natural hydraulic lime, silica sand and crushed bricks can also be used for grouting [6]. Pozzolan, clay, brick dust admixtures and their combinations were also added to lime-based grouts to modify their strength development [7]. In justified cases, a grouting mixture with a small amount of cement (5 to 10%) can be applied.

Experiments [8] were also conducted to verify the use of a grout with Sporosarcina Pasteurii bacteria, which modify the masonry pore system properties thus affecting the carbonation process, setting and hardening of lime in degraded masonry. The method was applied by low-pressure micro-grouting during the repair of soiled masonry achieving a compressive strength of microbial mortar of up to 55 MPa.

GROUT INJECTION TECHNOLOGIES AND METHODS

Masonry grout injection can be performed as pressure or pressureless, single or multiphase, deep, surface or combined grouting.

Pressure grouting of masonry applies a pressure from 3 to 10 bar depending on the pore system, the tensile strength of injected materials and masonry, the type of grout and the purpose of grouting. Only such masonry (binder, masonry units) which has the necessary tensile strength to transfer the internal tensile stresses caused by pressure grouting can be injected under pressure. The used pressure is based on the requirement to achieve a reliable filling of the pores with the grout.

Pressureless grouting using hydrostatic pressure usually up to 3 bar requires good masonry permeability, low consistency and slow solidification of the grout.

The basic precondition for achieving the required effect of grouting in historic masonry is:

- evaluation of the masonry pore structure (pore distribution, pore size with the maximum proportion in total porosity), chemism (salt content and type, pH), masonry moisture content, masonry condition (disintegration, cavities, cracks, degree of weathering),

- grout design, its properties, composition or particle size allow a reliable filling of the pore structure, including cavities and cracks,
- verification of the grout penetration radius (distance from the grouting borehole),
- overall evaluation and design of the grout, grout injection technology and distance of boreholes.

The grouting aimed at improving mechanical or other properties of individual components of masonry is carried out by means of injection pipes, so-called packers, with a diameter of 20 to 30 mm, fitted into drilled holes sealed with gypsum or fast-setting mortar. The injection pipes (packers) can be made of plastic (working on the principle of a dowel and requiring a “stronger” material) or metal with a free-floating or fixed ball. Metal packers are anchored in the masonry by a ring seal in the lower part, which expands by screwing. For grouting degraded mortar, it is advisable to use metal packers with a free-floating ball.

The selected distance of boreholes is usually ca 0.2 m, max. 0.3 m (exceptionally, in justified cases, even larger) so that the pores, voids, cracks and cavities are properly filled. The grouting design includes the design of grouting packers and pumps, the distribution of packers, the distance, diameter and depth of the boreholes and the grouting technique. Only structures that are permeable can be injected - they have an open pore system composed of mutually interconnected pores - so that air can escape during grouting and the grout can penetrate into the masonry structure.

The depth of single-sided boreholes is 3/4 to 4/5 of the masonry thickness, in double-sided boreholes usually 1/3 to 2/3 of the wall thickness. The depth of the boreholes, the grouting procedure (singlephase, multiphase) and the grouting pressure must be determined with a view to the material and the masonry condition. The achieved compressive strength of grouted masonry depends on the amount and quality of the grout penetrated into the masonry.

With the use of individual boreholes, masonry grouting can be performed as overall grouting or grouting in strips, always proceeding from the lower section to the higher one. The density and distance of boreholes are specified as described above. Larger cracks (above 2 mm) must be cleaned, damaged parts removed, wedged and sealed before grouting.

The research project [2] addressed the design and laboratory verification of a special method – overall surface pressure grouting for the strengthening of mainly surface and subsurface masonry layers and a combined electrophysical method for high-volume grouting.

The method of strengthening materials by overall surface pressure grouting employs additional mechanical supply of substances based on Ca_2^+, or based on silicates into the material structure and the activation of unreacted substances based on Ca_2^+ contained in the structure of injected materials to achieve an increase in strength, cohesion, or adhesion to the substrate. In overall surface pressure grouting, the injected solution is “pushed” into the pore system of (injectable) masonry so that the required gradual saturation of masonry pores occurs. The main advantage of this method is its high effectiveness and uniformity in terms of strengthening the plaster and increasing its adhesion to the substrate. With good injectability and an open pore system of masonry, this method may also enable a partial penetration of the grout into the subsurface layers of masonry, which usually show the highest degree of weathering and disintegration (deposition of leached salts). It is commonly assumed that masonry is weathered to a depth of ca 10 - 20 cm, and the remaining part of masonry is usually not affected by degradation processes.

The grouting agent must not contain particles that settle rapidly in surface layers (filling the pore system) and thus form a layer impermeable for further penetration of the grout. The surface and subsurface masonry layers of the grouted structure must not have a moisture content higher than 7% by weight (under ČSN P 730610 [9] – increased moisture content), and the total amount of salts must not exceed 1% by weight. There must be no surface crust on the surface of the grouted structure that would prevent the grout penetration into the pore system of the structure, and the masonry surface must be free of major uneven spots, dirt and deposits. Overall surface pressure grouting is not suitable for reinforcing of masonry degraded by cracks or cavities.

During combined pressure and electrophysical grouting, the hydrostatically applied grouting substance penetrates into the structure through the action of an electrostatic field. Combined electrophysical grouting is based on the principle of active electroosmosis using the electrical potential to propagate the injected grout through a porous material with a pore distribution with radii in the range of r ϵ (10^{-7}; 10^{-10}) m, and pressureless or low pressure grouting uses hydrostatic pressure for the primary “impregnation” of the grouted structure with the grout.

Combined electrophysical grouting is based on the principle of a closed DC circuit composed of a low voltage source (≤30 V) and a connection between wall strip electrodes (cathodes – negative electrodes) located on opposite surfaces of masonry and anode (positive electrode) at the end of the injection tube inserted into a borehole reaching to the middle part of the masonry (Figure 2). The electric field that is created between the electrodes causes a directed accelerated movement of ions, e.g. Ca_2^+ present in the grouting mixture. The positive cations move towards the negative electrode (cathode), while the negative anions move towards the positive electrode (anode).

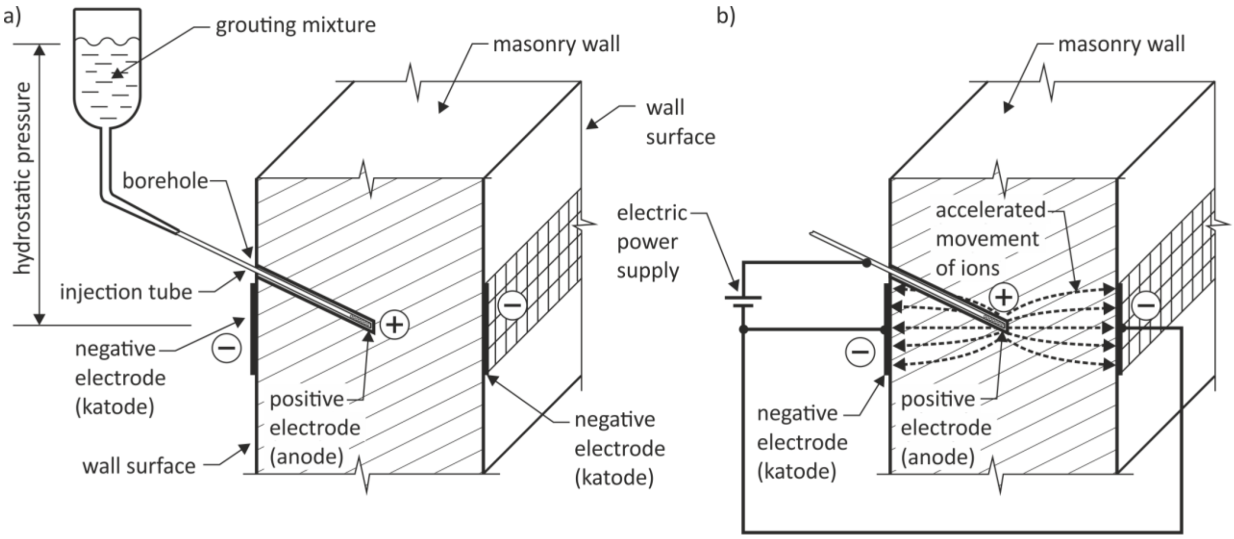

Fig. 2 - Combined electrophysical grouting of masonry structures; a) Grouting of masonry setup, b) Application of electrostatic field for propagation of grouting mixture through masonry

The depth and penetration rate of the grout into the structure varies depending on the pore system, the size and intensity of the electric field, the moisture content of the structure, the grout viscosity and the particle size in the grout. The uniformity of reinforcement depends on the electrodes used and the pore distribution. If strip electrodes are used, we may expect that the narrower the pore distribution range, the more uniformly the grout will be distributed across the cross-section of the structure. With an increasing proportion of pores with a radius greater than 10^{-4} m in the total porosity of the material, the effectiveness of combined electrophysical grouting decreases.

The combined electrophysical grouting method is not suitable for use in cases with too low pH (pH > 6), which often occurs in older historic buildings. To ensure its effectiveness in masonry with high salinity a voltage of up to 50 V is required compared to the commonly used voltage of 6 V. The effectiveness of combined electrophysical grouting also decreases with an increasing proportion of pores with a radius r > 10^{-8} m, especially if r > 10^{-4} m and larger. The proportion of

DOI 10.14311/CEJ.2020.04.0051

pores with a radius r > 10^{-4} m and larger should not be greater than 10%, and the proportion of pores with a radius r > 10^{-8} m should not exceed 30%. The combined electrophysical grouting method is not suitable for masonry with ≥ 1% wt. salts and chloride contents ≥ 0.3% by weight. The combined electrophysical grouting method is applicable to structures with a moisture content of 4% to 5% by weight so that there is enough space remaining in the pore system for the grouting substance propagation.

EXPERIMENTAL RESEARCH

The experimental research into the effect of grouting on the restoration of integrity and strength of historic brick and stone masonry degraded by cracks or by cavities located inside columns was conducted on experimental specimens with dimensions of 290 x 440 x 420 to 450 mm (brick masonry) and 500 x 600 x 720 to 750 mm (stone masonry). Five grouting agents were used in the research, of them 4 based on hydraulic lime mixtures and 1 resin-based mixture. The lime-based grouting agents were applied by low-pressure grouting using a screw grout pump (2 - 10 bar), and the resin-based grout was applied by pressureless grouting using hydrostatic pressure (ca 0.5 bar).

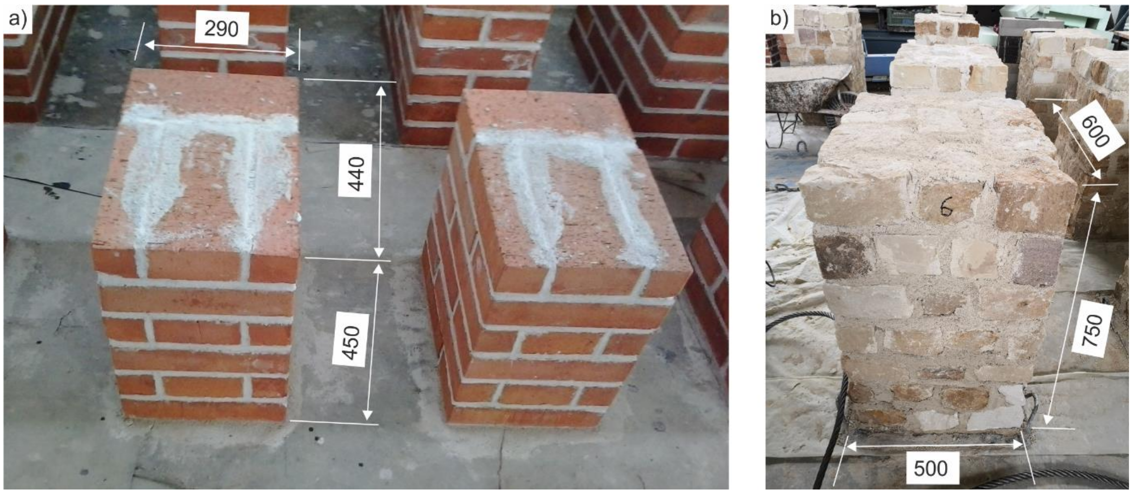

Fig. 3 Experimental specimens with aritificial crack and cavities;
a) Brick masonry, b) Stone masonry

The total porosity of bricks ranged within 29.3 - 32.9% with a prevailing pore radius of 600-2000nm (42%), of sandy marlstone within 21.5 – 29% with a prevailing pore radius of 600-2000nm (25%), sandstone within 15.2 – 18.9% with a prevailing pore radius of 7500-30000nm (72%), trachyte within 6.8 - 11.8% with a prevailing pore radius of 150-600nm (35%), limestone within 1.2 - 2.1% with a prevailing pore radius of 10-25nm (25%) and mortars from 16.5 to 26.2% with a prevailing pore radius of 150-600nm (25%), (Figure 4).

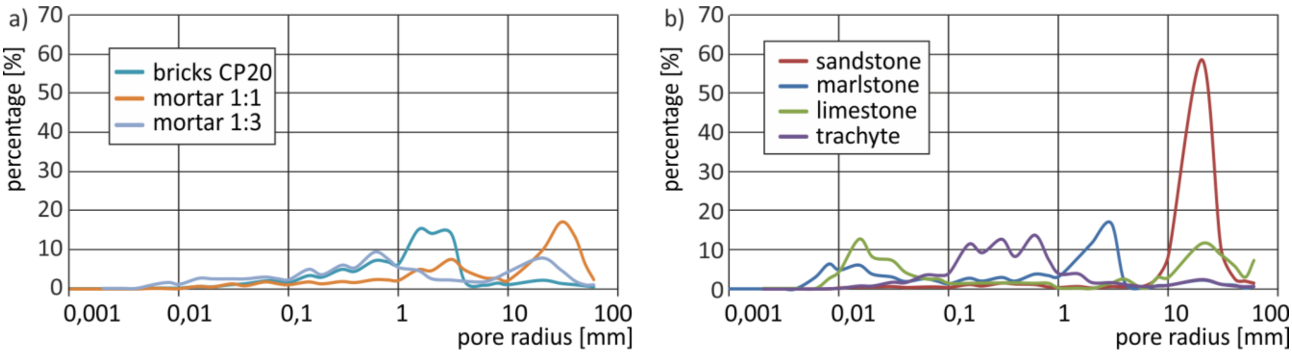

Fig. 4 - Distribution curves of pore representation in bricks and mortar (a) and stone masonry units (b)

The effectiveness of grouting in terms of the experimentally identified ultimate bearing capacity values of grouted brick and stone masonry columns with an artificial crack and an artificial cavity under concentric compression varies. In the case of columns with **an artificial cavity**, a demonstrable increase in the load-bearing capacity of the grouted column under concentric compression was manifested as a result of filling up the artificially created cavity with the grout. However, stone masonry columns showed greater variation in obtained results, due to their greater heterogeneity. In the case of grouted columns with **an artificial crack**, the grouting effectiveness in terms of increasing the load-bearing capacity of masonry under concentric compression was not manifested to the extent expected. In the case of masonry with an artificial crack, a partial increase in the load-bearing capacity of the masonry was achieved by grouting with the agent based on hydraulic lime nanoparticles, low viscosity resins and silicates. In the case of masonry with an artificial cavity, an increase in the load-bearing capacity of the masonry was achieved by grouting with all cases of the verified grouting agents. The basic precondition for achieving the required effectiveness of grouting is a perfect filling of the crack or cavity with the grout.

The relatively low effectiveness of grouting of masonry columns with an artificial crack, manifested during the dismantling of the columns after the test, is caused by insufficient filling of the cracks located in the vicinity of the grouting borehole due to premature grout settling or due to inadequate consistency of the grout:

- the ultimate bearing capacity of grouted brick masonry columns with **an artificial crack** under concentric compression (Figure 5a) ranges within 85 to 145 % of the ultimate bearing capacity mean value of reference columns under concentric compression (masonry columns with an unfilled artificial crack),
- the ultimate bearing capacity of grouted brick masonry columns with **an artificial cavity** under concentric compression (Figure 5b) ranges within 85 to 172 % of the ultimate bearing capacity mean value of reference columns under concentric compression (masonry columns with an unfilled artificial cavity),
- the ultimate bearing capacity of grouted stone masonry columns with **an artificial crack** under concentric compression (Figure 6b) ranges within 80 to 175 % of the ultimate bearing capacity mean value of reference columns under concentric compression (masonry columns with an unfilled artificial crack),
- the ultimate bearing capacity of grouted stone masonry columns with **an artificial cavity** under concentric compression (Figure 6a) ranges within 61 to 132 % of the ultimate bearing capacity mean value of reference columns under concentric compression (masonry columns with an unfilled artificial cavity).

DOI 10.14311/CEJ.2020.04.0051

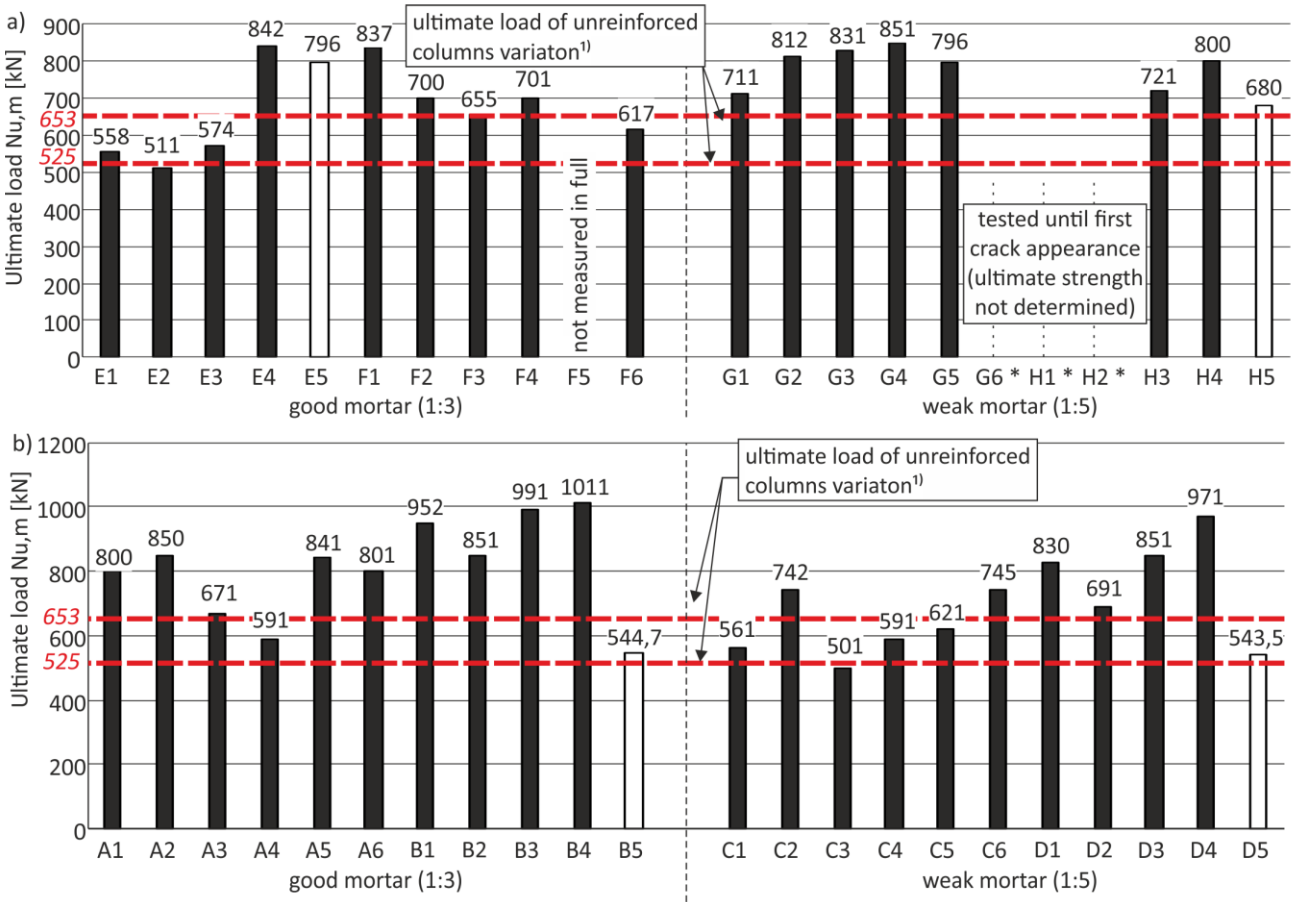

Fig. 5 - Comparison of experimentally determined ultimate strength in concentric compression of grouted brick columns with an artificial crack (a) and with an artificial cavity (b)

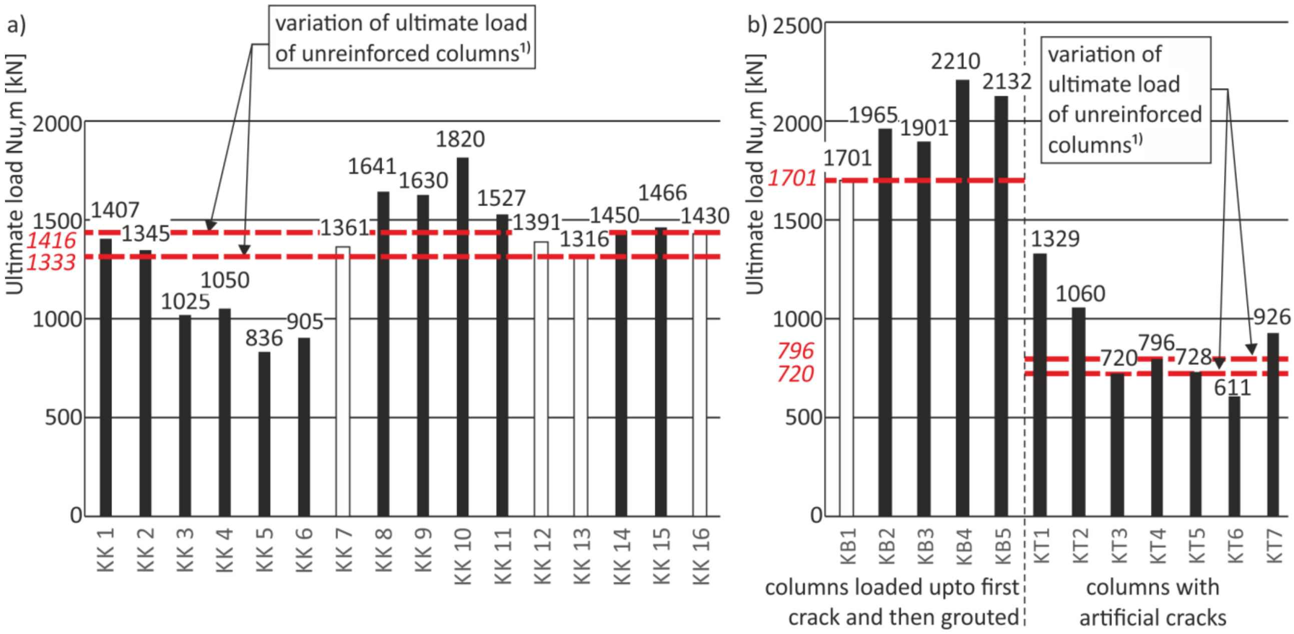

Fig. 5 - Comparison of experimentally determined ultimate strength in concentric compression of grouted stone columns with an artificial cavity (a) and with an artificial crack (b)

The experimental research has revealed a relatively significant effect of the mechanical properties of grouting agents (adhesion, compressive strength) on the effectiveness of grouting [10].

CONCLUSION

The experimental research [2] aimed at gaining new knowledge for the design of brick and stone masonry grouting techniques in terms of the stabilization and increase in the strength of masonry damaged by cracks, masonry with cavities and masonry with a high void content by applying grouting agents based on lime, resins and silicates has pointed out a considerable variability of the resulting grouting effectiveness. To achieve the required properties of grouted masonry the masonry must be diagnosed and the above grouting design procedure must be observed.

ACKNOWLEDGEMENTS

The article was written with support from the NAKI DG16P02M055 project "Development and Research into Materials, Procedures and Technologies for Restoration, Conservation and Strengthening of Historic Masonry Structures and Surfaces and Systems of Preventive Care of Historic and Heritage Buildings Threatened by Anthropogenic and Natural Risks".

REFERENCES

[1] WTA 4-3-98 Masonry repairs - stability and load capacity (WTA guideline). WTA, 2004

[2] NAKI II DG16P02M055 research project (Ministry of Culture of Czech Republic) "Development and Research into Materials, Procedures and Technologies for Restoration, Conservation and Strengthening of Historic Masonry Structures and Surfaces and Systems of Preventive Care of Historic and Heritage Buildings Threatened by Anthropogenic and Natural Risks", 2016-2020, lead researcher prof. Ing. Jiří Witzany, DrSc.

[3] Škoda, D., Kuřitka, I., Kroftová, K., Kubát, J., 2019. Technology of preparation of barium and magnesium hydroxide nanodispersion and possibilities of their use in monument care. In: *Contemporary materials and technologies in civil engineering 2018*. Praha: Czech Technical University in Prague. Acta Polytechnica CTU Proceedings. vol. 21.

[4] Kroftová, K., Kuřitka, I., Škoda, D., Šmidtová, M., Masař, M., 2017. *Synthesis of nanolime suspension and their potential use in cultural heritage preservation* In. EASEC 15 – The Fifteenth East Asia – Pacific Conference on Structural Engineering and Construction.

[5] Kroftová, K., Kubát, J., Škoda, D., 2018. *Possibilities of Consolidation of Historical Materials with Selected Nanodispersions - Results of Experimental Research of the Strength Degree on Reference Formulas*, In. NaNs: Moderní materiály a technologie ve stavebnictví.

[6] Maravelaki-Kalaitzaki, P., Bakolas, A., Karatasios, I., Kilikoglou, V., 2005. Hydraulic lime mortars for the restoration of historic masonry in Crete, *Cement and Concrete Research*, 35, pp. 1577-1586, DOI 10.1016/j.cemconres.2004.09.001

[7] Papayianni, I., Pachta, V., 2015. Experimental study on the performance of lime-based grouts used in consolidating historic masonries. *Materials and Structures*, 48, pp. 2111-2121, DOI 10.1617/s11527-014-0296-5

[8] Yang, Z., Xiaohui Ch., 2013. A performance study of high-strength microbial mortar produced by low pressure grouting for the reinforcement of deteriorated masonry structures. *Construction and Building Materials*, 41, pp. 505-515. ISSN 09500618. DOI: 10.1016/j.conbuildmat.2012.12.055

[9] ČSN P 730610 Waterproofing of buildings - The rehabilitation of damp masonry and additional protection of buildings against ground moisture and against atmospheric water - Basic provision, UNMZ, 2000

[10] Witzany, J.; Zigler, R.; Kroftová, K.; Čejka, T.; Kubát, J.; Holický, M.; Karas, J., 2018. The Effect of Pore Distribution in Historic Masonry on the Grouting Method and Grouting Mix Selection, *The Civil Engineering Journal*, 3(10), 307-329. ISSN 1805-2576, DOI: 10.14311/CEJ.2018.03.0025