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THE EFFECT OF PORE DISTRIBUTION IN HISTORIC MASONRY ON THE GROUTING METHOD AND GROUTING MIX SELECTION

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ABSTRACT

The NAKI II DG16P02M055 research project incorporates extensive experimental and theoretical research into the effect of grouting on the physical and mechanical characteristics of brick, stone and mixed masonry. The focus of the research is on the verification of particularly the reinforcing effect of selected grouting agents based on hydraulic lime (nanolime), resins and silicates. Selected materials are used for the monitoring of the effect of grouting on changes in the porosity, pore distribution, absorption capacity as compared to ungrouted masonry, and the reinforcing effect of grouting on historic brick, sandy marlstone, sandstone, trachyte, limestone and mixed masonry with a lime binder for different types of grouting agents as compared to ungrouted masonry.

KEYWORDS

Masonry, Grouting, Pore distribution, Stone, Brick, Experimental campaign

INTRODUCTION

The grouting of historic masonry with a degraded binder, damaged by cracks, or with high void contents and cavities represents a frequently applied rehabilitation method of historic masonry. Despite this, no objective background materials and procedures for the selection of the grouting method and mixture and the quantitative assessment of the grouting effect in terms of the physical and mechanical characteristics of the masonry have been elaborated to become a basis for the design and evaluation of the grouting effectiveness depending on the used grouting agent, grouting method and the properties of grouted masonry. The experimental verification of reinforcing grouting procedures abroad is primarily focused on multi-leaf masonry or masonry damaged by cracks. In [1], an empirical formula for the calculation of compressive strength of three-leaf masonry is derived as

$$f_{wc,i} = f_{wc,0}\left(1 + 1.25\frac{V_i \cdot \sqrt{f_{gr,c}}}{V_w \cdot f_{wc,0}}\right) \qquad (1)$$

where, $f_{wc,0}$ and $f_{wc,i}$ denote the compressive strength of the masonry before and after grouting; V_i and V_w the volume of the filling material and of the whole wall, respectively; and $f_{gr,c}$ is the compressive strength of the grout.

In [2], Valluzi used a formula for the calculation of the compressive strength of grouted masonry where the compressive strength of the grouted (filling) material is calculated as the function of the compressive strength of the grouting mix

$$f_{wc,i} = f_{wc,0}\left(1 + \frac{V_i \cdot f_{i,s}}{V_w \cdot f_{wc,0}}\right) \quad (2)$$

$$f_{i,s} = 0.31 \cdot f_{gr,c}^{1.18} \quad (3)$$

where, $f_{i,s}$ denotes the compressive strength of the grouted filling material.

The authors [1] conclude that the compressive strength of the mixture is not the crucial characteristic for the grouting effectiveness in the respective case of the filling material. Likewise, study [3] based on tests whose objective was to specify the mechanical properties of three-leaf stone masonry concluded that although the strength of ternary grouts is nearly twice the strength of the hydraulic lime-based grout, the strength of the grouting mixture does not principally affect the final compressive strength of the grouted wall. Due to the homogenization of multi-leaf masonry, improved mechanical characteristics of the masonry are achieved even in the case of a mixture that does not contain cement.

Based on observations, study [1] claims that the compressive strength of the grouted masonry also depends on the tensile strength of the grouting mix. The formula designed for the prediction of the compressive strength of the grouted filling material in [1] reads

$$f_{i,s} = 1.60 + 0.50 f_{gr,t} \quad (4)$$

where, $f_{gr,t}$ the bending tensile strength of the grout.

Mixtures based on hydraulic lime modified with admixtures are most commonly applied for historic masonry. In [4], experimental tests and in-situ applications (Crete) were performed with a mortar based on natural hydraulic lime (as a binding material), siliceous sand and crushed brick. Based on the results of the tests and measurements done three years later, further use of hydraulic lime mortars is recommended in [4].

In justified cases, a grouting mixture with small amounts of cement (5 to 10%), or with substances based on resins is also applied. In a similar way, study [5] verified lime-based grouts in several series with gradual additions of other components (pozzolan, clay, brick dust and their combinations). On the basis of the results of testing, a grouting mixture with the following composition: lime : brick dust : pozzolan, is, among others, recommended, which is effective in terms of strength development (measured at 28 and 90 days).

Modified admixtures of grouting mixes based on hydraulic lime such as pozzolan, lime, clay and brick dust are effective in modifying the rheological, volume changes and strength of the grouted masonry. The resulting properties of the grouted masonry may be, to some extent, affected by the non-compatibility of the original mortar and the grouting mix (different porosity, chemism, mineralogical and chemical characteristics). Adding pozzolan, lime or cement admixtures can affect both the tensile and shear strength, the bonding of the original binder and the grouting mix (new binder). Grouting agents based on minerals and hydraulic lime are suitable for the masonry of historic and particularly heritage buildings.

Local strengthening of material by modifying the masonry pore system's properties can be achieved by using mixes based on silicates. Like resin-based mixes, these mixes penetrate inside the pore system to a depth of 50 to 60 mm from the grouting borehole.

As part of the NAKI II research project (DG16P02M055 project "Research and development of materials, processes and techniques for the restoration, preservation and strengthening of historic masonry structures and surfaces and systems for preventive protection of historic and listed buildings threatened by anthropogenic effects"), extensive experimental and theoretic research is conducted investigating the effect of grouting on the physical and mechanical characteristics of the brick, stone and mixed masonry most commonly used in historic buildings. The analysis of the experimental and laboratory research is focused on the verification of the effect of the grouting method used (pressure and pressureless), the grouting agent type (agents based on minerals, resins and silicates) on the principal physical (pore system) and mechanical characteristics (strength, deformation characteristics) of the masonry. In the first research phase, test pieces of brick, stone and mixed masonry without an initial crack were tested (except for microcracks and structural cracks caused by volume changes of the binder, or by handling). In the second phase, the research will cover masonry columns with an initial crack and masonry columns with cavities.

The following parts present partial results of the first research phase investigating the effect of the grouting method, the masonry pore system, grouting agent's particle size, porosity on strength in concentric compression of the grouted masonry.

EXPERIMENTAL AND LABORATORY RESEARCH OF THE EFFECT OF GROUTING ON THE PHYSICAL AND MECHANICAL CHARACTERISTICS OF BRICK, STONE AND MIXED MASONRY

The subject of the experimental research into the effect of grouting on the principal physical characteristics of individual components of historic masonry was the identification of total porosity, pore distribution and integral pore system curves. The research focused on the principal mechanical characteristics included the identification of the strength characteristics of individual components of historic masonry, the strength (load-bearing capacity) of test pieces of ungrouted masonry and test pieces of grouted masonry. The analysis of the results was carried out on the basis of a limited number of masonry test pieces, which did not allow statistical analysis. With a view to this fact and considering the scattering of the physical and mechanical characteristics of the masonry, the results of this analysis need interpretation.

Research into the effectiveness of grouting involved masonry test pieces with dimensions of 300 x 450 x 420 to 450 mm, or 300 x 600 x 420 to 450 mm (brickwork columns) and 500 to 550 x 600 to 650 x 700 to 750 mm (stonework and mixed columns). The brickwork columns were walled with P20 solid burnt bricks on a lime mortar with a 5% admixture of MV 1 cement mixed in a 1:1 ratio with sand with a grain size of 0-2 mm. The stonework columns were built as irregular masonry of quarried stone – sandy marlstone, sandstone, limestone, trachyte, or as mixed masonry with sandy marlstone, limestone and bricks. The test pieces of stone masonry were walled on mortar with a lime binder (lime mortar 1:3 made from 5-year aged slaked lime and sand with a grain size of 0-4 mm).

The test pieces of brick, stone and mixed masonry are listed in Table 1 and Table 2 and displayed in Figure 1 and Figure 2.

After reaching the required mortar strength, all masonry columns were fitted with drilled holes 18 mm in diameter for pressure grouting and 22 mm in diameter for pressureless grouting inclined at ca 37° (27°) from the horizontal in the brickwork columns and running to a depth of 450 (600) mm, and at 30° from the horizontal in the stonework columns and terminated ca 50 mm from the masonry edge. The grout was applied as low-pressure (LP) using a low-pressure membrane pump for grouting suspensions and a piston grout pump for grouting resins, or as pressureless (PL) where the grout was applied by hydrostatic pressure. After the grouting procedure was completed, the grout holes were filled with a mix with very low shrinkage (Oxal VP TK2). Individual sets of the test pieces included a so-called reference column, which had gone through all the preparatory phases in the same way as the grouted columns, i.e. drilling a grout hole and its filling with a mix with very low shrinkage (Oxal VP TK2). The tests of the grouted columns and the reference column were performed ca 3 to 4 weeks after the grouting procedure and filling the grout hole.

Tab. 1 - Overview of test pieces – brick masonry

Label	Dimensions width/ thick./height			Mortar	$f_{tension,\,m}$	$f_{compr,m}$	$f_{compr,b}$	$f_{k,masonry}$ accord. EC6	grouting mixture	grouting method
	mm	mm	mm		MPa	MPa	MPa	MPa		
CP01.45-P3	300	450	450	Mortar 1:1	0.21	0.50	22.01	3.89	P3	low-pressure
CP02.45-V4									V4	low-pressure
CP03.45-V3									V3	low-pressure
CP04.45-P2									P2	low-pressure
CP05.45-P2									P2	pressureless
CP06.45									-	-
CP07.45-K1	300	450	450		0.16	0.48	22.01	3.83	K1	pressureless
CP08.45-V2									V2	low-pressure
CP09.45-K1									K1	low-pressure
CP10.45-V1									V1	low-pressure
CP11.45-P1									P1	low-pressure
CP12.45									-	-
CP01.60-P3	300	600	450		0.20	0.46	22.01	3.8	P3	low-pressure
CP02.60-V4									V4	low-pressure
CP03.60-V3									V3	low-pressure
CP04.60-P2									P2	low-pressure
CP05.60-P2									P2	pressureless
CP06.6									-	-
CP07.60-K1	300	600	450		0.18	0.46	22.01	3.79	K1	pressureless
CP08.60-V2									V2	low-pressure
CP09.60-K1									K1	low-pressure
CP10.60-V1									V1	low-pressure
CP11.60-P1									P1	low-pressure
CP12.60									-	-

Note:
Mortar 1:1 – common lime mortar with 5% cement admixture diluted with sand in the 1:1 ratio, experimentally determined compressive strength 0,45 - 0,55 MPa

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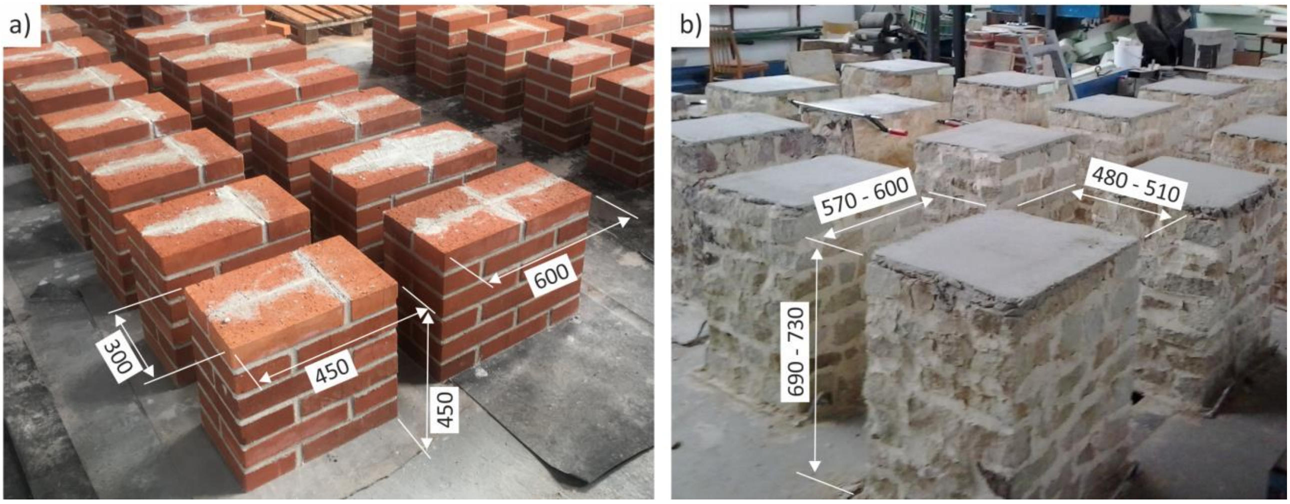

Fig. 1 - Experimental test pieces of brick masonry (a) and stone masonry (b)

Tab. 2 - Overview of test pieces – stone masonry

Label	Dimensions width/thick./height			Mortar	$f_{tension,\,m}$	$f_{compr,m}$	$f_{compr,b}$	$f_{k,masonry}$ accord. EC6	grouting mixture	grouting method
	mm	mm	mm		MPa	MPa	MPa	MPa		
KP.ON01-V3	490	570	690	lime mortar 1:3	0.20	0.80	15.17	0.35	V3	low-pressure
KP.ON02-K1	510	600	715		0.20	0.80	15.17	0.35	K1	low-pressure
KP.ON03-P1	490	580	700		0.20	0.80	15.17	0.35	P1	low-pressure
KP.ON04-V6	500	580	710		0.32	0.83	15.17	0.34	V6	low-pressure
KP.ON05	500	595	710		0.32	0.83	15.17	0.34	-	-
KP.PN01-V3	495	590	700		0.32	0.83	46.35	0.49	V3	low-pressure
KP.PN02-K1	505	585	705		0.30	0.83	46.35	0.49	K1	low-pressure
KP.PN03-P1	475	600	720		0.30	0.83	46.35	0.49	P1	low-pressure
KP.PN04-V7	490	600	730		0.30	0.83	46.35	0.49	V7	low-pressure
KP.PN05	485	595	730		0.32	1.01	46.35	0.52	-	-
KP.TN01-K1	495	595	700		0.32	1.01	63.58	0.56	K1	low-pressure
KP.TN02-P1	500	600	715		0.32	1.01	63.58	0.56	P1	low-pressure
KP.TN03-V5	495	600	700		0.32	0.79	63.58	0.52	V5	low-pressure
KP.TN04	480	595	695		0.32	0.79	63.58	0.52	-	-
KP.VN01-K1	480	590	740		0.28	0.83	111.13	0.64	K1	low-pressure
KP.VN02-P1	480	590	710		0.28	0.98	111.13	0.70	P1	low-pressure
KP.VN03	480	595	715		0.28	0.98	111.13	0.70	-	-

Note:
Lime mortar 1:3 – lime mortar without cement, 5 years old slaked lime, diluted with sand in the 1:3 ratio, experimentally determined compressive strength 0,8 - 1,01 MPa

Fig. 2 - Experimental test pieces of brick (a) and stone (b) masonry during compressive tests

Experimentally verified grouting agents

According to the main base, the grouting agents were divided into 3 basic groups:

- Hydraulic lime-based grouts
- Resin-based grouts
- Silicate-based grouts

Within experimental research, a total of 11 different grouts were applied, of them 7 based on hydraulic lime, 3 based on resins and 1 grout based on silicates:

- **Lime-based grouts**

V1 Mixture of natural hydraulic lime and mineral admixtures without cement with good fluidity, filling ability and with no shrinkage after adding water, high resistance to water-soluble sulphates, bending strength at 28 days of ca 0.6 N/mm2, compressive strength of ca 2.5 N/mm2, dynamic modulus of elasticity of 2.5kN/mm2. Filling and shaping joints, small cavities, cracks from 2 to 10 mm

V2 Two-component suspension from ultrafine hydraulic binder and a liquid grouting admixture resistant to sulphates, high initial strength (compressive strength at 7 days > 5 N/mm2, at 28 days > 20 N/mm2), water impermeable. Filling cracks and cavities in concrete, mortar, brick and stone masonry, strengthening and increasing the load-bearing capacity of foundations

V3 Mixture based on hydraulic lime and mineral admixtures without cement, resistant to sulphates, with very low modulus of elasticity, low viscosity and good fluidity, mechanical characteristics at 28 days: bending strength of ca 3.3 N/mm2, compressive strength of ca 16 N/mm2, dynamic modulus of elasticity of 9.6 kN/mm2. Filling and shaping joints, cavities, small cracks, sealing, stabilization and strengthening of stone, mixed and multi-leaf masonry which is not exposed to permanent (long-term) loading with water (moisture)

V4 Trass-lime-based mixture resistant to sulphates, with very low modulus of elasticity, low viscosity, good fluidity and very low shrinkage, compressive strength at 28 days > 5 N/mm2. Filling and shaping joints, cavities, small cracks, sealing, stabilization and strengthening of stone, mixed and multi-leaf masonry which is not exposed to permanent (long-term) loading with water (moisture)

V5 Calcium lime test portion was dispersed in ethanol and distilled water was added. The mixture was left in the magnetic stirrer for 24 hours. The resulting suspension was made by filling the reaction mix to a volume of 1 litre. The $Ca(OH)_2$ concentration is 5 g/l. Larger particles and lower viscosity than Ca4. Strengthening, sealing concrete and brick, stone and mixed masonry

V6 Calcium methoxide test portion was dispersed in isopropyl alcohol and distilled water was added. The mixture was left in the magnetic stirrer for 24 hours. The resulting suspension was made by filling the reaction mix to a volume of 1 litre. The $Ca(OH)_2$ concentration is 5 g/l. Strengthening, sealing concrete and brick, stone and mixed masonry

V7 Test portions of calcium acetate $Ca(OCOCH_3)_2$ H_2O and magnesium acetate $Mg(OCOCH_3)_2 . 4H_2O$, which were dissolved in distilled water. Strengthening, sealing concrete and brick, stone and mixed masonry

- **Resin-based grouts**

P1 Two-component epoxy resin with low viscosity of 100 mPa*s, mechanical characteristics at 7 days – tensile strength of 51 N/mm2, bond strength of 7.4 N/mm2, friction of 16.8 N/mm2. Filling cracks and cavities in concrete

P2 Acrylate-based low-viscosity (ca 5 mPa*s) resin with very good penetration into fine-grained conglomerates, allowing grouting into dry, moist as well as water soaked environments, watertight, resistant to compression, compressive strength of 12.5 N/mm2. Strengthening, sealing concrete and masonry, strengthening, sealing and improving cohesion of rocks and fine-grained soils

P3 Epoxy-based two-component duromer resin with high penetration activity, allowing grouting into moist environments as well, with fast increase in strength, hardening even under dynamic loading, tensile strength of ca 45.7 N/mm2, compressive strength of ca 60 N/mm2, modulus of elasticity of 2.6kN/mm2. Strengthening, filling cracks, cavities, joints

- **Silicate-based grout**

K1 Based on silicic acid ethyl ester with no content of solvents with gel separated amounts greater than 40%, with deep penetration and high resistance to weathering and UV radiation, colourless to slightly yellowish. Strengthening of porous, moisture-absorbing, mineral building material (mainly sandstones, weathered bricks, mortar)

The grouts labelled V5, V6 a V7 based on nanoparticles were developed within the NAKI II DG16P02M055 research project in cooperation with The Centre of Polymer Systems, Tomas Bata University in Zlín [6], [7] and [8].

Table 3 presents the main characteristics of the grouting agents, including the spectrum and the particle proportion contained in the grout.

Tab. 3 - Main characteristics of grouting agents

Label	Characteristic	Strength	Particle size (diameter)
V1	Mixture of natural hydraulic lime and mineral admixtures without cement	at 28 days bending strength ca 0.6 N/mm2, compressive strength ca 2.5 N/mm2	*1000 – 4000 nm*
V2	Two-component suspension from ultrafine hydraulic binder and a liquid grouting admixture	compressive strength at 7 days > 5 N/mm2, at 28 days > 20 N/mm2	*500 – 2500 nm*
V3	Mixture based on hydraulic lime and mineral admixtures without cement	at 28 days: bending strength ca 3.3 N/mm2, compressive strength ca 16 N/mm2	160 – 2000 nm
V4	Trass-lime-based mixture	compressive strength at 28 days > 5 N/mm2	1500 – 4000 nm
V5	Calcium lime test portion dispersed in ethanol	n/a	1330 – 1770 nm
V6	Calcium methoxide test portion dispersed in isopropyl alcohol	n/a	220 – 360 nm
V7	Test portions of calcium acetate and magnesium acetate dissolved in distilled water	n/a	35 – 835 nm
P1	Two-component epoxy resin	at 7 days - tensile strength 51 N/mm2, bond strength 7.4 N/mm2, friction 16.8 N/mm2	n/a
P2	Acrylate-based low-viscosity resin	compressive strength 12.5 N/mm2	n/a
P3	Epoxy-based two-component duromer resin	tensile strength ca 45.7 N/mm2, compressive strength ca 60 N/mm2	n/a
K1	Based on silicic acid ethyl ester with no content of solvents with gel separated amounts greater than 40%	n/a	n/a

Laboratory research into porosity

The laboratory research into porosity was carried out in cooperation with the Institute of Rock Structure and Mechanics of the Academy of Sciences CR using the high-pressure mercury method on specimens of solid burnt bricks, sandy marlstone, sandstone, limestone, trachyte and lime mortar. The measurement was performed on specimen chippings sized 5 mm of the materials used in the test columns. The measurement was made on a set of Pascal 140 + 240 fir Thermo Electon – Porotec porosimeters. Based on the results of mercury porosimetry, the distribution and integral curves of the pore system of individual materials (masonry units) were drawn before and after grouting. The specimens of masonry units for porosity detection after grouting were sampled from the masonry columns after the load test from places in the vicinity of the grouting borehole (ca within a distance of 40 to 60 mm), from the grout hole and from places close to the masonry unit edge (ca 50 mm from the unit edge).

Table 4 and Table 5 list the characteristic values of the pore system of the masonry units and mortar detected by mercury porosimetry from the sampled specimens before and after the grout application. Figure 3 displays the time patterns of the distribution and integral curves illustrating the pore distribution in the selected materials from a radius of 0 to 10 nm up to a size of 30 000 to 50 000 nm.

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Tab. 4 - Pore distribution in bricks and mortar

Material – brick masonry	Total porosity (%)	Pore radius (nm)							
		0 - 10	10 - 25	25 - 150	150 - 600	600 - 2000	2000 - 7500	7500 - 30000	30000 - 50000
brick P20	32.85	0.48	2.08	10.15	19.57	42.58	18.38	4.56	2.24
brick P20 + V3	29.56	0.55	0.84	5.41	13.3	35.41	32.15	10.28	2.08
brick P20 + K1	31.46	0.65	1.45	5.4	10.99	35.34	34.33	8.51	3.34
brick P20 + V1	29.32	1.16	2.56	12.94	21.85	35.88	13.45	8.84	3.33
mortar 1:1	32.35	0.32	2.46	6.8	7.22	14.11	17.97	28.79	22.32
mortar 1:1 + V3	31.69	1.81	4.66	7.51	8	11.62	12.3	47.01	7.09
mortar 1:1 + K1	31.25	2.46	3.76	8.62	10.25	14.23	22.29	29.14	9.24
mortar 1:1 + V1	30.05	1.98	4.08	8.62	10.17	15.26	21.36	28.06	10.47

Note:

- dominant pores

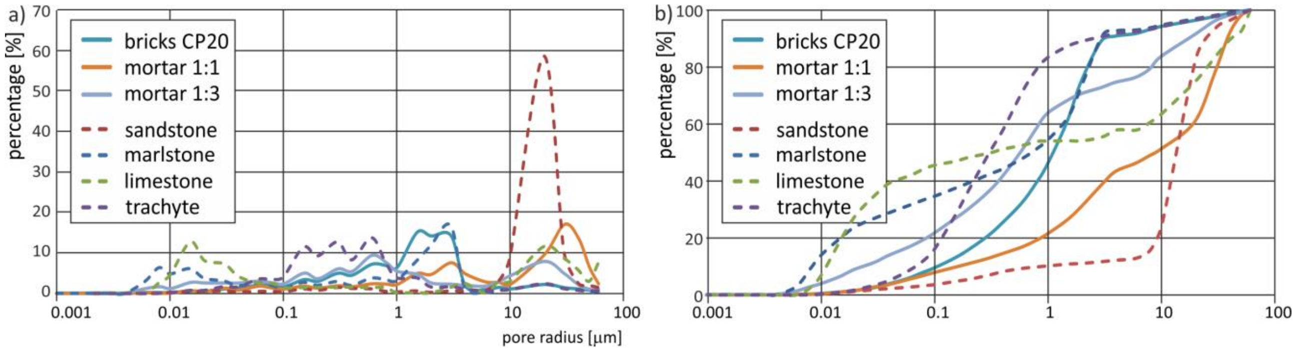

Fig. 3 - Distribution (a) and integral (b) curves of pore representation in bricks, mortar and stone units

Tab. 5 - Pore distribution in stone units and mortar

Material – stone masonry	Total porosity (%)	Pore radius (nm)							
		0 - 10	10 - 25	25 - 150	150 - 600	600 - 2000	2000 - 7500	7500 - 30000	30000 - 50000
marlstone + V3	21.47	20.13	10.44	6.85	8.97	22.77	25.28	3.79	1.79
marlstone + K1	29	11.78	10.88	8.11	9.67	26.78	29.11	2.22	1.44
marlstone + P1	26.53	14.35	11.1	9.08	9.98	24.77	23.64	4.71	2.35
marlstone + V6	26.49	17.4	17.8	7.9	7.5	17.41	26.78	3.61	1.62
marlstone	26.4	14.11	12.94	10.35	10.7	26.35	19.41	4.36	1.77
sandstone + V3	15.74	0	2.52	4.09	3.31	1.45	11.39	74.3	2.91
sandstone + K1	15.83	0.28	2.82	2.82	2.54	2.53	9.59	71.56	7.89
sandstone + P1	15.48	0.2	1.37	3.05	2.85	1.48	10.13	78.05	2.85
sandstone + V7	15.18	0.17	2.55	4.76	5.61	1.19	10.19	70.29	5.27
sandstone	18.92	0.25	1.16	2.86	4.61	1.74	4.98	77.83	6.1
trachyte + K1	6.79	0.48	10.2	16.47	29.35	19.58	11.7	8.59	3.81
trachyte + P1	7.32	1.54	9.53	17.84	20	30.16	6.16	9.85	4.93
trachyte	11.76	0.26	3.3	24.31	44.18	17.11	4.17	4.6	2.08
limestone + K1	1.17	4.93	18.52	11.1	6.16	9.88	14.81	22.22	12.34
limestone + P1	1.50	1.47	27.93	16.17	7.35	1.47	8.82	26.47	10.29
limestone	2.1	7.15	28.11	11.65	5.65	1.55	6.7	23.19	15.95
mortar 1:3 + V3	16.96	2.4	9.45	14.25	19.29	15.14	9.71	23.83	5.93
mortar 1:3 + K1	20.97	4.17	7.22	11.72	19.95	13.19	7.1	27.06	9.59
mortar 1:3 + P1	19.76	3.36	7.31	10.37	19.3	16.08	15.5	24.13	3.94
mortar 1:3 + V7	19.45	4.57	7.53	14.29	21.93	15.18	12.79	20.04	3.37
mortar 1:3 + V6	21.77	3.93	5.1	13.17	22.59	12.18	12.38	23.19	7.46
mortar 1:3	26.23	3.82	6.32	13.37	25.11	23.49	11.16	14.24	2.49

Note:

- dominant pores

Mechanical tests of masonry short columns

The load tests in concentric compression until failure were performed in an actuator with a digital central processing unit for reading compression manufactured by MFL – Germany (range of 0 to 10 000 kN, accuracy of 0.01 kN). The monotonously rising loading of the columns with concentric compression was performed in steps, amounting in the case of brick columns to 50 to 100 kN, and, in the case of stone columns to 30 to 60 kN, i.e. ca 10 to 15 % of the theoretically established ultimate load of column masonry pursuant to ČSN EN 1996 (EC6) in the case of brick columns and ČSN 731101 in the case of stone columns.

The results of the load tests of the masonry columns in concentric compression – strength in concentric compression, values of experimentally identified vertical and horizontal deformations, modulus of elasticity or lateral strain coefficient for individual sets of the test pieces after the grout application were summarized for subsequent analysis in a graphical form and in tables. Due to a large amount of these data, the section below presents partial results of this analysis focused on the assessment of the effectiveness of grouting on the compressive strength of the grouted masonry, on the effect of the grouting method, on the effect of the pore system and the grout particle size and on potential changes in the pore system of the grouted material as compared to ungrouted material. Table 6 and 7 present and Figure 4 to 7 graphically illustrate selected experimentally obtained values, which are proportionally compared to the respective values of the ungrouted, so-called reference masonry test piece.

Tab. 6 - Results of experimental loading - brick masonry columns

Label	Compressive strength	Hor. def. at 50% N_{um}	Vert. def. at 50% N_{um}	Hor. def. at 500 kN	Vert. def. at 500 kN	coefficient of lateral strain at 50% N_{um}	coefficient of lateral strain at 500kN
	MPa	$\delta_{x,1/2}$ (mm)	$\delta_{y,50\%}$ (mm)	$\delta_{x,500}$ (mm)	$\delta_{y,500}$ (mm)	(-)	(-)
CP02.45-V4	5.65	0.98	-3.50	2.33	-5.13	0.34	0.55
CP03.45-V3	4.79	0.94	-3.42	4.56	-6.35	0.33	0.87
CP04.45-P2	5.45	1.03	-3.86	2.89	-5.48	0.32	0.64
CP05.45-P2	6.00	0.51	-4.14	1.06	-5.21	0.15	0.25
CP06.45	5.10	0.38	-2.49	1.93	-4.45	0.18	0.52
CP02.60-V4	5.38	X	-2.54	X	-2.54	X	0.00
CP03.60-V3	5.44	1.45	-3.39	1.45	-3.39	0.52	0.52
CP04.60-P2	5.53	0.45	-2.94	0.45	-2.94	0.18	0.18
CP05.60-P2	5.62	0.52	-2.60	0.52	-2.60	0.24	0.24
CP06.60	4.92	0.95	-2.10	0.95	-2.60	0.55	0.44
CP07.45-K1	5.09	X	-2.76	X	-4.80	X	X
CP08.45-V2	4.95	X	-2.90	X	-4.79	X	X
CP09.45-K1	4.71	X	-2.36	X	-4.97	X	X
CP10.45-V1	4.70	X	-2.90	X	-6.10	X	X
CP11.45-P1	4.44	X	-2.26	X	-5.40	X	X
CP12.45	4.40	X	-4.53	X	-7.76	X	X
CP07.60-K1	4.67	X	-1.10	X	-1.66	X	X
CP08.60-V2	5.09	X	-1.00	X	-1.42	X	X
CP09.60-K1	5.00	X	-1.08	X	-1.71	X	X
CP10.60-V1	5.53	X	-1.04	X	-1.04	X	X
CP11.60-P1	5.70	X	-1.09	X	-1.09	X	X
CP12.60	5.76	X	-1.31	X	-1.31	X	X

Note:
X – values not measured

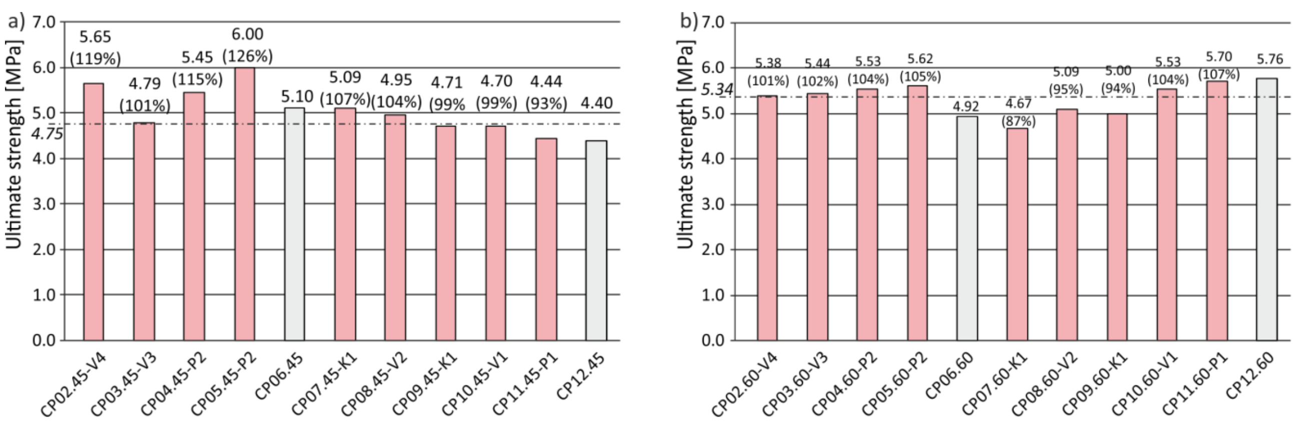

Fig. 4 - Experimentally obtained ultimate strengths of brick masonry columns

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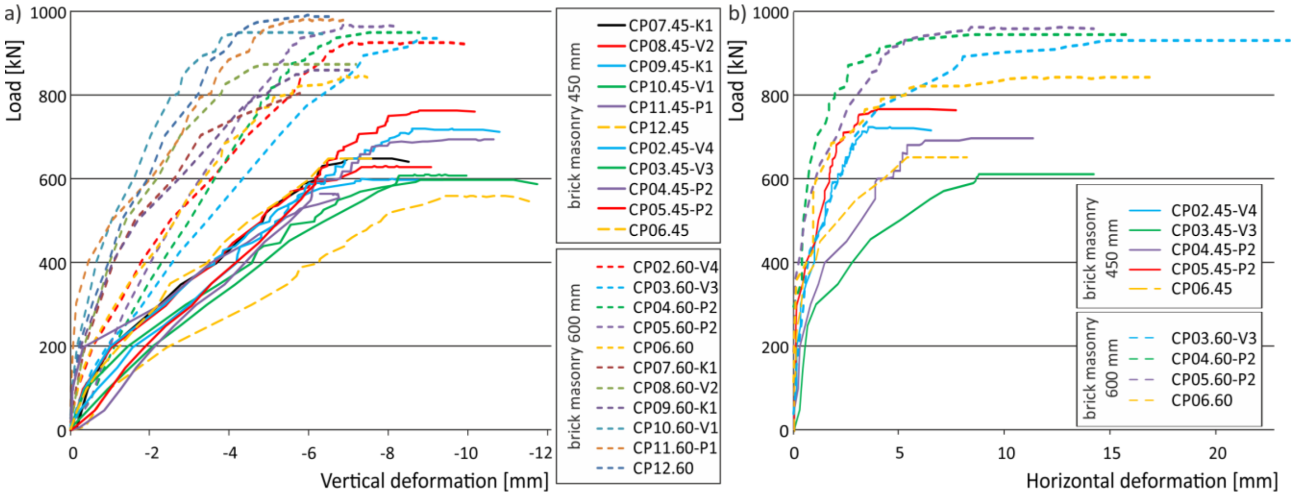

Fig. 5 - a) Vertical deformations of brick masonry with thickness of 450 mm and 600 mm, b) Horizontal deformations of brick masonry with thickness of 450 mm and 600 mm

Tab. 6 - Results of experimental loading – stone masonry columns

Label	Compressive strength	Vertical deformation δ_y (mm)			Horizontal deformation δx (mm)			Ratio $\varepsilon_x/\varepsilon_y$ at 200 kN	Ratio $\varepsilon_x/\varepsilon_y$ at 50% N_{um}	Ratio $\varepsilon_x/\varepsilon_y$ at N_{um}
	MPa	~ 200 kN*	50% N_{um}	ultimate**	~ 200 kN*	50% N_{um}	ultimate**	(-)	(-)	(-)
KP.ON01-V3	0.77	-2.06	-0.70	-2.58	4.87	0.16	6.06	2.18	0.21	2.16
KP.ON02-K1	0.82	-1.24	-0.48	-2.36	2.05	0.89	3.90	1.60	1.79	1.60
KP.ON03-P1	0.78	-5.22	-1.96	-5.91	5.90	0.84	8.53	1.11	0.42	1.42
KP.ON04-V6	0.86	-1.36	-0.60	-2.32	3.71	1.55	6.75	2.67	2.52	2.83
KP.ON05	0.96	-0.81	-0.44	-2.16	3.68	1.49	10.70	4.43	3.34	4.84
KP.PN01-V3	2.71	-0.52	-1.57	-6.65	0.56	1.93	11.81	1.03	1.17	1.69
KP.PN02-K1	3.29	-0.24	-1.62	-8.03	0.54	0.98	9.23	2.23	0.59	1.12
KP.PN03-P1	3.53	-0.93	-2.38	-7.28	0.22	0.86	10.71	0.23	0.35	1.44
KP.PN04-V7	2.15	-0.55	-1.57	-6.26	0.89	1.73	7.68	1.61	1.08	1.21
KP.PN05	2.89	-0.76	-2.05	-6.60	0.50	1.72	10.08	0.68	0.86	1.56
KP.TN01-K1	2.73	-1.39	-3.07	-7.77	0.20	0.44	5.76	0.14	0.14	0.70
KP.TN02-P1	2.35	-0.91	-1.76	-8.54	0.23	1.64	19.93	0.24	0.90	2.25
KP.TN04	2.33	-0.73	-1.68	-7.08	1.08	1.68	13.32	1.45	0.97	1.84
KP.VN01-K1	1.75	-0.43	-0.80	-3.49	1.21	1.80	6.96	2.64	2.09	1.85
KP.VN02-P1	1.71	-0.96	-1.29	-6.85	1.31	1.71	12.11	1.19	1.16	1.54
KP.VN03	2.31	-1.41	-2.59	-8.35	1.05	1.83	13.46	0.66	0.63	1.43

Note:
** last measured value at 200 kN*
*** first measured value when reaching the ultimate load*

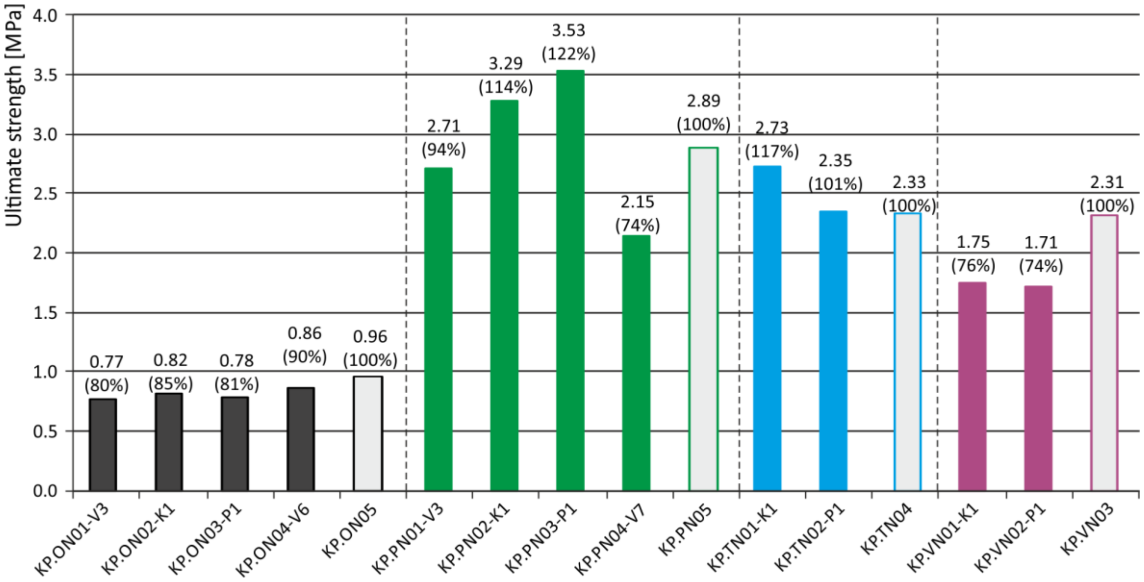

Fig. 6 - Experimentally obtained ultimate strengths of stone masonry columns

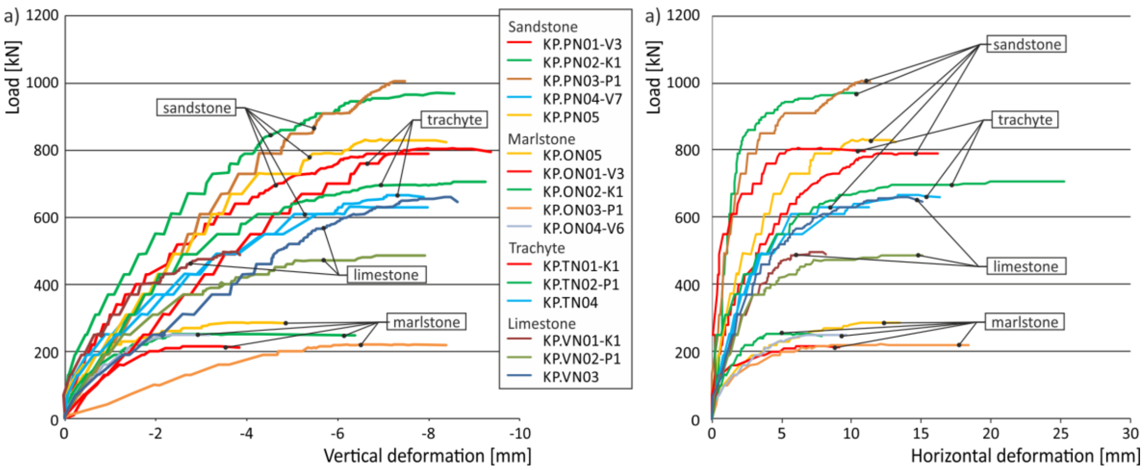

Fig. 7 - Vertical (a) and horizontal (b) deformations of stone masonry

DISCUSSION OVER THE RESULTS OF EXPERIMENTAL AND LABORATORY RESEARCH

Experimental verification of the effectiveness of low-pressure and pressureless grouting

The efficiency of the grouting method was verified for both the case of brick masonry – test pieces CP04.45 and CP05.45 for the resin-based grout P2, test pieces CP07.45 and CP09.45 for the silicate-based grout K1. In the case of stonework columns KP.PN02 and KP.VN01, for the silicate-based grout K1, and test pieces KP.PN03 and KP.VN02 for the resin-based grout P2.

The pressureless grouting was applied at an operating pressure range of 0.5 to 1 bar, while the low-pressure grouting was applied at a pressure range of 6 to 7 bars.

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- **Assessment of the efficiency of grouting agents in terms of the implementation method** (Figure 8)
  - The experimentally identified ultimate strengths in concentric compression of the brick masonry 450 mm or 600 mm thick, using a resin-based grout applied by low-pressure grouting reached values f_{exp} = 107%, or 112% respectively, and applied by pressureless grouting f_{exp} = 118%, or 114% respectively, as compared to the experimentally identified ultimate compressive strength of the reference, i.e. ungrouted masonry of the corresponding group of test pieces (f_{exp} = 100%). The highest ultimate strength value was reached in the case of the masonry grouted with the resin-based agent labelled P2.
  - The experimentally identified ultimate strengths in concentric compression of the brick masonry 450 mm or 600 mm thick, using a silicate-based grout applied by low-pressure grouting reached values f_{exp} = 107%, or 87% respectively, and applied by pressureless grouting f_{exp} = 116%, or 81% respectively, as compared to the experimentally identified ultimate compressive strength of the reference, i.e. ungrouted masonry of the corresponding group of test pieces (f_{exp} = 100%). The highest ultimate strength value was reached in the case of the masonry grouted with the silicate-based agent labelled K1.

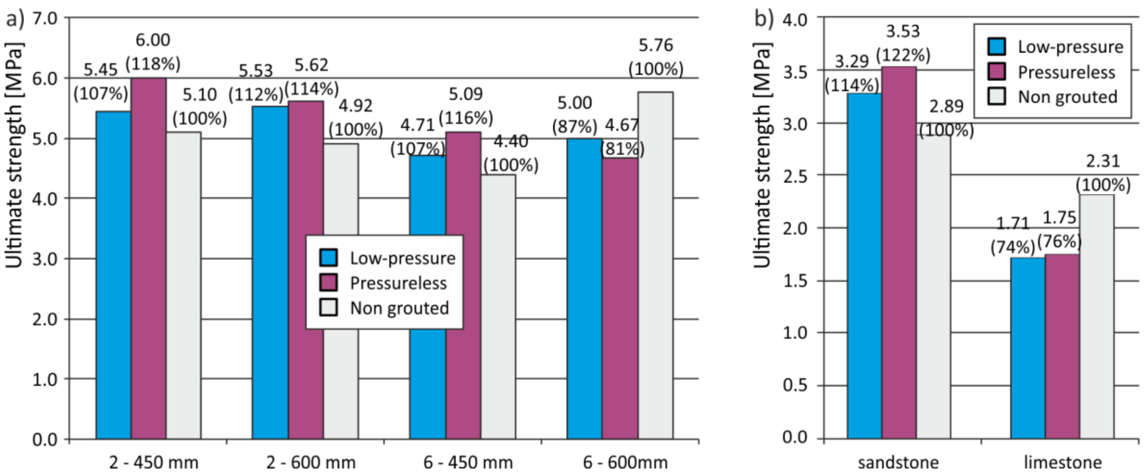

Fig. 8 - Comparison of ultimate strengths of brick (a) and stone (b) masonry grouted with pressureless and low-pressure technology

  - The experimentally identified ultimate strengths in concentric compression of the limestone stonework using a resin-based grout applied by low-pressure grouting reached values f_{exp} = 74%, and applied by pressureless grouting f_{exp} = 122% as compared to the experimentally identified ultimate compressive strength of the reference, i.e. ungrouted masonry of the corresponding group of test pieces (f_{exp} = 100%). The highest ultimate strength value was reached in the case of pressureless masonry grouting with the resin-based agent labelled P2.
  - The experimentally identified ultimate strengths in concentric compression of the sandstone stonework using a silicate-based grout applied by low-pressure grouting reached values f_{exp} = 114%, and applied by pressureless grouting f_{exp} = 76% as compared to the experimentally identified ultimate compressive strength of the reference, i.e. ungrouted masonry of the corresponding group of test pieces (f_{exp} = 100%). The highest ultimate strength value was reached in the case of pressureless masonry grouting with the silicate-based agent labelled K1.

Laboratory verification of porosity of masonry units and mortar

The objective of the investigation of porosity – distribution and integral curves and total porosity – was to obtain information allowing the assessment of the effect of the pore system – prevailing pore proportion – and the effect of the particle size of the grout on the grouting effectiveness. The proportion of prevailing pores of a certain size for individual types of the evaluated materials within the total porosity ranged ca from 25% to 80%.

- **Assessment of the effectiveness of grouting agents in terms of pore distribution** (Figure 9 to Figure 12)
  - The ultimate strength values of the brick masonry in concentric compression in relation to the particle (nanoparticle) size of the grout and the prevailing pore size of the bricks (600 to 2000 nm) and lime mortar (7500 to 30000 nm) ranged within $f_{exp} \in$ (94%, 112%) in the case of the brick masonry 450 mm thick grouted with the agents labelled V3, V2 and V4, and within $f_{exp} \in$ (88%, 111%) in the case of the grouting agents labelled V1 and V2 and the brick masonry thickness of 600 mm as compared to the ultimate strength of the ungrouted masonry. In the case of all the above grouts applied on the brick masonry, the particle size of the grouts was lower than the prevailing size of the pore radii r $\in$ (600 - 2000) nm of the bricks and mortar.

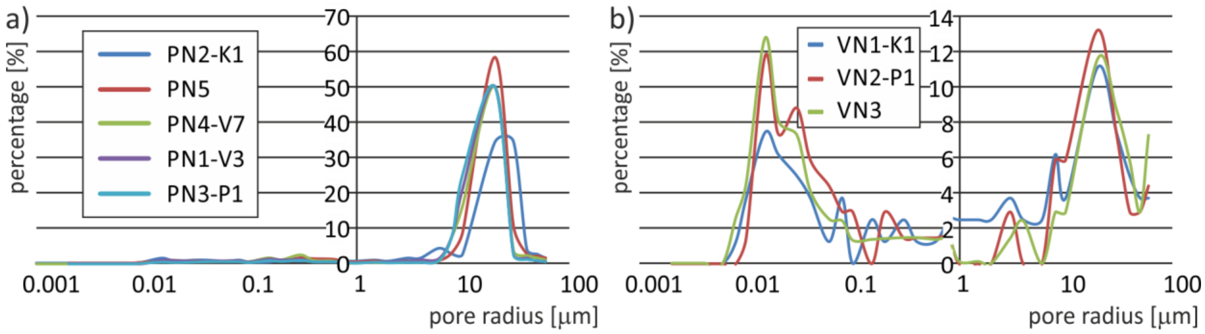

Fig. 9 Examples of distribution curves of the pore system of the masonry units before and after grouting – a) sandstone, b) limestone

  - The ultimate strength values of the stone masonry in concentric compression in relation to the particle (nanoparticle) size of the grout and the prevailing pore size ranged within $f_{exp} \in$ (74%, 147%), in the case of the sandstone stonework grouted with the calcium-hydroxide-based agents labelled V7 and V3 within $f_{exp} \in$ (74%, 94%), in the case of the sandy marlstone stonework grouted with the calcium-hydroxide-based agents labelled V3 and V6 within $f_{exp} \in$ (80%, 90%), in the case of the limestone stonework grouted with the resin- and silicate-based agents labelled P1 and K1 within $f_{exp} \in$ (74%, 147%), in the case of the trachyte stonework grouted with the resin- and silicate-based agents labelled P1 and K1 within $f_{exp} \in$ (101%, 117%) as compared to the ultimate strength of the ungrouted reference masonry. In the case of all the grouting agents above applied on stone masonry, the particle size of the grouts was lower than the prevailing size of the pore radii of the masonry units and mortar.
  - The experimental research into the effect of grouting on the total porosity pointed out a change in the total porosity due to grouting. In all the grouted materials used, the total porosity had decreased in a range of 1% - 9.5% of the total material volume and in a range of 20% - 50% of the total pore volume. In the case of the brick masonry, the porosity of the masonry units (bricks) decreased by 1% - 3% and of the binder (lime mortar 1:1) by 1% - 2% as compared to the ungrouted materials. In the case of the stone masonry, the total porosity of sandy marlstone decreased by 3% - 5%, sandstone by 3.5%, trachyte by 4% – 5%, limestone by 1%

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and lime mortar by 5% - 9.5% as compared to the ungrouted materials. The greatest change in the overall pore volume was detected in the stone masonry units. In the case of the grouting agents based on lime and lime mortar, there was a drop by ca 40% and in sandy marlstone by ca 20%, in the case of the silicate-based grouts in limestone there was a drop by 50% and in trachyte by 45%. In the case of the resin-based grouts, the greatest drop in the total porosity recorded was in trachyte by 35% and in the lime mortar by 20%.

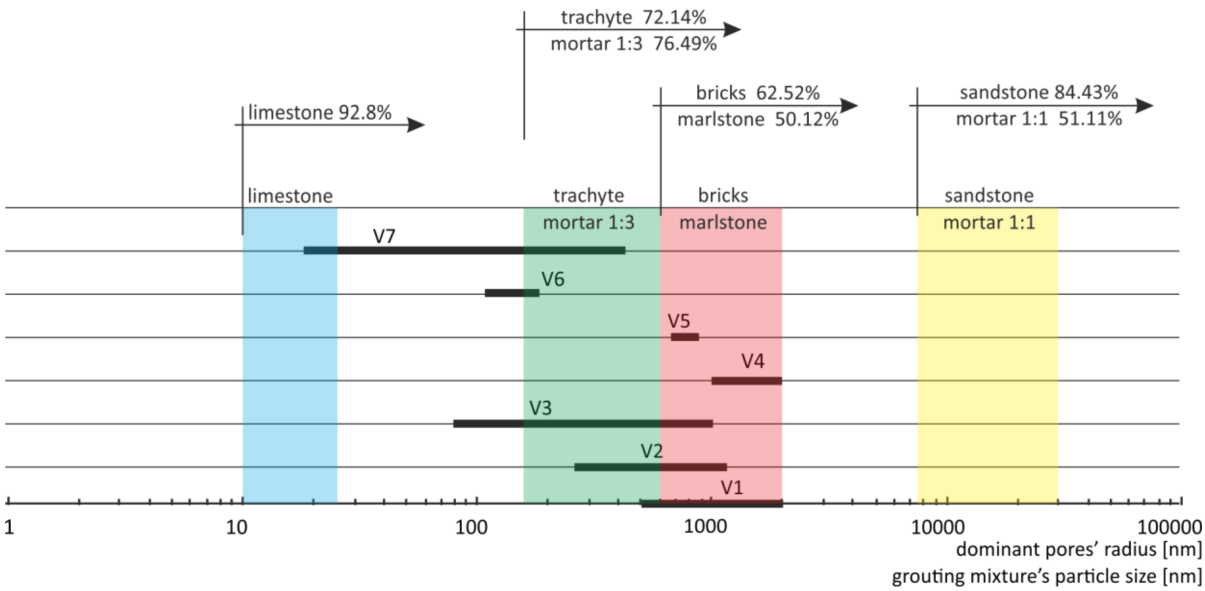

Fig. 10 - Comparison of the radius of the predominant pores of the masonry elements and mortar and particle size of the grouting materials

- A component part of the research was also the verification of the grout penetration into the pore system of the masonry units (sandstone). Partial results of the research that will need further attention in the next research phase are graphically presented in Figure 11 and Figure 12b, which display the total porosity of an ungrouted specimen and grouted specimens sampled from a distance of ca 1 cm and ca 15 cm from the grouting borehole. Figure 12b shows the little difference between the total porosity of the grouted specimens (sandstone) sampled from a distance of ca 15 cm (89% - 99%) as compared to the ungrouted specimen (100 %). Despite the small number of tests that cannot be subjected to statistical analysis, it is evident from the results that the penetration of the grout greatly depends on the mixture, as the K1 mixture shows better penetration (89% at 15 cm distance) than the V3 and V7 mixtures (96% - 99% at 15 cm distance).

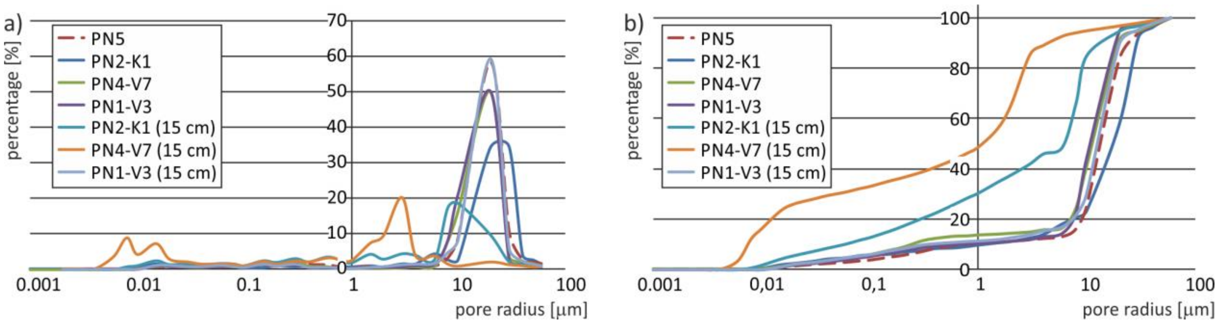

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Fig. 11 - Comparison of distribution (a) and integral (b) curves of the pore system of the masonry units depending on the distance from grouting borehole.

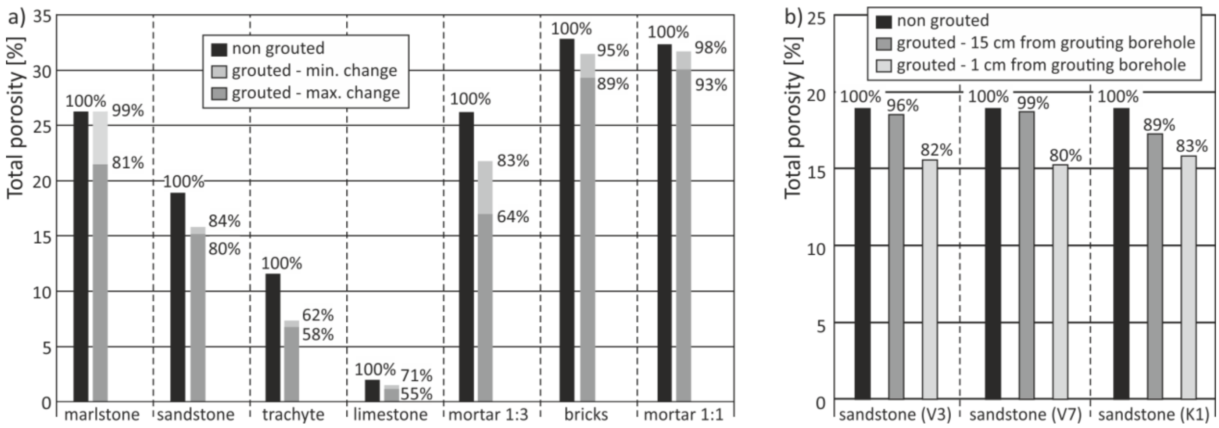

Fig. 12 - a) Comparison of the influence of grouting on the overall porosity of building materials, b) Comparison of the influence of distance from grouting borehole on the overall porosity

Experimental research into the effectiveness of grouting agents in terms of masonry strength in concentric compression

- **Assessment of the effectiveness of grouting agents in terms of brick masonry strength** (see Figure 4 and Figure 5)

  - Lime (mineral)-based grouts:
    The experimentally identified ultimate strengths in concentric compression of the brick masonry grouted with a calcium-hydroxide-based mixture reached values within a range of f_{exp} ϵ (88%, 112%) as compared to the experimentally identified ultimate strength in compression of the ungrouted masonry (100%). The highest ultimate strength value f_{exp} ϵ (110%, 112%) was reached in the case of the masonry grouted with the calcium-hydroxide-based agents labelled V2, V3 and V4.

  - Low-viscosity-resin-based grouts:
    The experimentally identified ultimate strengths in concentric compression of the brick masonry grouted with a low-viscosity-resin-based mixture reached values within a range of f_{exp} ϵ (99%, 118%) as compared to the experimentally identified ultimate strength in compression of the ungrouted masonry (100%). The highest ultimate strength value f_{exp} ϵ (112%, 118%) was reached in the case of the masonry grouted with the low-viscosity-resin-based agent labelled P2.

  - Silicate-based grouts:
    The experimentally identified ultimate strengths in concentric compression of the brick masonry grouted with a silicate-based mixture reached values within a range of f_{exp} ϵ (81%, 116%) as compared to the experimentally identified ultimate strength in compression of the ungrouted masonry (100%). The highest ultimate strength value f_{exp} ϵ (107%, 116%) was reached in the case of the masonry grouted with the silicate-based agent labelled K1.

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- **Assessment of the effectiveness of grouting agents in terms of stone masonry strength in concentric compression** (see Figure 6 and Figure 7)
  - Lime- (mineral-) based grouts:
    The experimentally identified ultimate strengths in concentric compression of the stone masonry grouted with a lime-based mixture reached in the case of sandstone values f_{exp} ϵ (74% of grout V7 to 94% of grout V3), in the case of sandy marlstone values f_{exp} ϵ (80% of grout V3 to 90% of grout V6) as compared to the experimentally identified ultimate strength in concentric compression of the ungrouted masonry (100%). The highest ultimate strength value f_{exp} = 94% was reached in the case of sandstone and 90% in the case of sandy marlstone using the lime-based agents labelled V3 and V6.
  - Low-viscosity-resin-based grouts:
    The experimentally identified ultimate strengths in concentric compression of the stone masonry grouted with a low-viscosity-resin-based mixture reached in the case of sandstone values f_{exp} = 122% of grout P1, in the case of trachyte 101% of grout P1, in the case of sandy marlstone 81% of grout P1 and in the case of limestone 74% of grout P1 as compared to the experimentally identified ultimate strength in concentric compression of the ungrouted masonry (100%). The highest ultimate strength value f_{exp} = 122% in the case of sandstone was reached using the low-viscosity-resin-based agent labelled P1.
  - Silicate-based grouts:
    The experimentally identified ultimate strengths in concentric compression of the stone masonry grouted with a silicate-based mixture reached in the case of sandstone values f_{exp} = 114% of grout K1, in the case of sandy marlstone 86%, limestone 74%, trachyte 117% as compared to the experimentally identified ultimate strength in concentric compression of the ungrouted masonry (100%). The highest ultimate strength value f_{exp} = 117% was reached in the case of trachyte and 114% in the case of sandstone using the silicate-based agent labelled K1.

Probability assessment and statistical analysis of test results

The statistical analysis of the effectiveness of **brick masonry** grouting was based on the results of mechanical tests in concentric compression for 22 test pieces of brick masonry, ungrouted and grouted with the agents specified in previous parts. The average value of strength in concentric compression of the ungrouted (reference) brickwork test pieces was 5.04 MPa (100%) with a standard deviation of the set of values of the reference columns of 0.49 MPa (9.7%). The values of strength in concentric compression of the grouted masonry expressed in % lying within the scattering range of the strength values in concentric compression of the ungrouted brick masonry must be assessed as values that can be significantly affected by the strength scattering of the ungrouted masonry. The values whose percentage exceeds the scattering range limits of strength in concentric compression of the ungrouted masonry, on the other hand, can be more significantly affected by the grouting agent applied (Figure 13a).

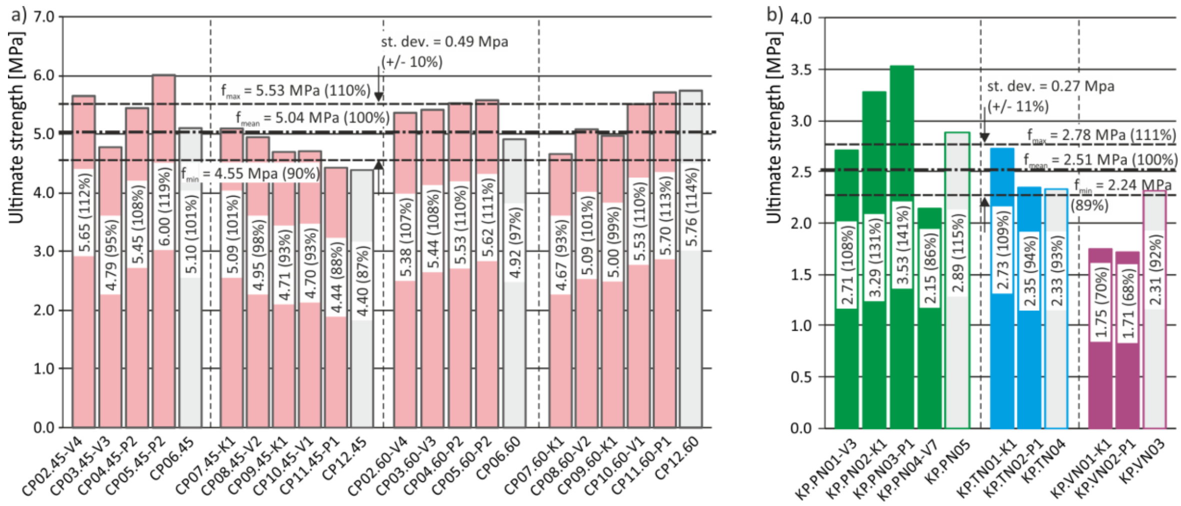

Fig. 13 - Evaluation of the grouting effectiveness of brick (a) and stone (b) masonry

From this perspective, more significant effects on the strength of brick masonry in concentric compression were reached by applying particularly the resin-based grouts labelled P1 and P2, and the lime-based grouts labelled V1 and V4. The probability assessment of the effect of grouting on the brick masonry strength is based on a set of four strength measurements of the ungrouted masonry, which shows an average of 5.04 MPa and a standard deviation of 0.49 MPa. The coefficient of variation is relatively low, 0.111. Figure 1 captures the strength probability density of the ungrouted masonry assuming the normal (red curve) and the lognormal (blue curve) distribution, together with marked values of the quantiles corresponding to probabilities of 5 and 95 %. The following pairs (or tetrads) of the identified strength values of the grouted masonry for different grouting agents indicate that the average value of these measurements is mostly slightly higher than the strength of the ungrouted masonry. It is, however, apparent that none of the measurements of the two (or four) strength values available of the grouted masonry is situated outside the quantile limits for probabilities of 5 and 95 % marked in Figure 14a. It may, therefore, be said that the average strength of the grouted masonry, for the most part, cannot be considered significantly greater than the average strength of the ungrouted masonry. The exception is grouting with agent P2 (Figure 14b), which significantly increases both the average and the characteristic strength (quantile with a probability of 5 %) of the grouted brick masonry.

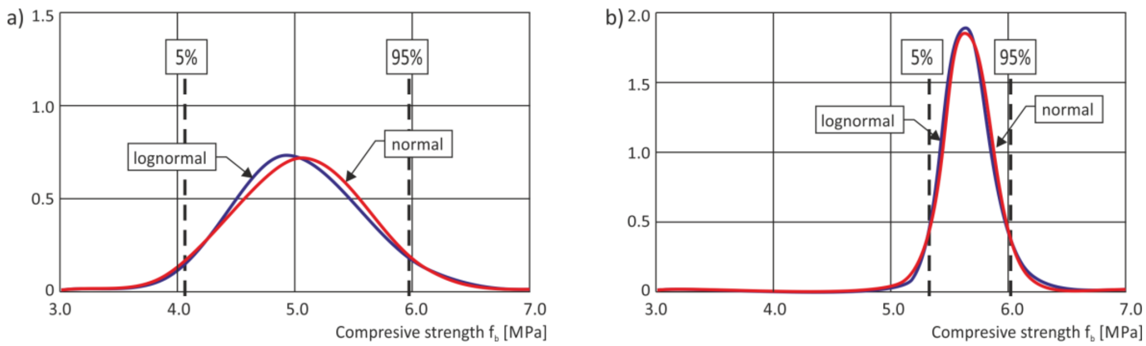

Fig 14 - a) Strength probability density of ungrouted brick masonry (a) and brick masonry grouted with agent P2 (b) assuming the normal and lognormal distribution with marked quantiles for probabilities of 5 and 95 %.

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The statistical analysis of the effectiveness of **stone masonry** grouting was based on the results of mechanical tests in concentric compression for 11 test pieces of stone masonry, ungrouted and grouted with the agents specified in part 2. The average value of strength in concentric compression of the ungrouted (reference) stonework test pieces was 2.51 MPa (100%) with a standard deviation of the set of values of the reference columns of 0.27 MPa (11%). The values of strength in concentric compression of the grouted stone masonry expressed in % lying within the scattering range of the strength values in concentric compression of the ungrouted stone masonry must be assessed as values that can be significantly affected by the strength scattering of the ungrouted stone masonry. The values whose percentage exceeds the scattering range limits of strength in concentric compression of the ungrouted masonry, on the other hand, can be more significantly affected by the grouting agent applied (Figure 13b).

From this perspective, more significant effects on the strength of stone masonry in concentric compression were reached by applying particularly the resin-based grouting agent labelled P1 and the silicate-based agent labelled K1. The probability assessment of the effect of the grouting agents and the type of stone in stone masonry is less credible than the analysis of the masonry made up of bricks. It is based on a set of four strength values of stone masonry whose average value is 2.12 MPa and a standard deviation 0.8203 MPa. This is reflected by a high coefficient of variation of 0.39. The strength probability density of the ungrouted stone masonry assuming the normal and lognormal distribution with marked quantiles for probabilities of 5 a 95 % is presented in Figure 15.

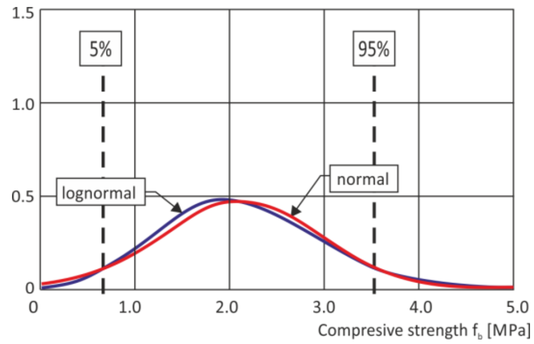

Fig. 15 - Strength probability density of ungrouted stone masonry assuming the normal and lognormal distribution with marked quantiles for probabilities of 5 and 95 %.

The experimental research into the strength of ungrouted stone masonry is followed by a limited number of strength measurements for different grouting agents and aggregate types. The high variability in the strength of the initial ungrouted stone masonry and the limited numbers of follow-up measurements do not allow sufficient confidence of the analysis of the effect of grouting agents and aggregate types. All the measurements available in both cases range within the quantile limits for probabilities of 5 and 95 % marked in Figure 14b. For this reason, it may be said again that (analogically to the brick masonry) the average strength of the ungrouted masonry in general cannot be considered significantly greater than the average strength of the ungrouted masonry. Despite this fact it seems that the grouting agents V7 and K1 provide slightly elevated masonry strengths, whereas the effect of the other grouting agents is highly uncertain. Figure 16a captures the probability density of the stone masonry grouted with agent K1. The lognormal distribution in this case differs considerably from the normal distribution due to the high variability of the grouted stone masonry. The analysis of the effect of the type of used aggregates indicates that the grouting has a positive effect in the case of sandstone and trachyte. The grouting of sandy marlstone masonry, on the other hand, seems to be the least favourable. Figure 16b captures the probability density of the stone masonry of sandstone. Figure 15 and 16 clearly show that the effect of grouting on the strength of masonry made up of different materials is highly variable and requires further research. More accurate findings can only be obtained with a larger number of measurements for individual grouting agents and different types of materials.

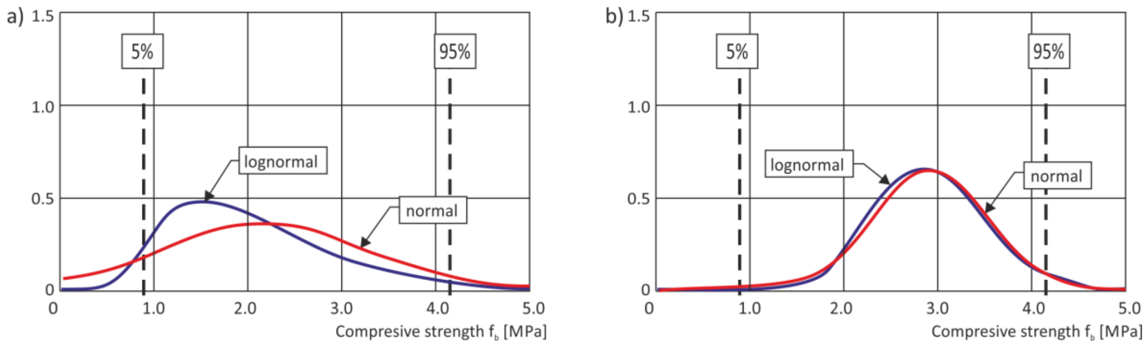

Fig. 16 - Strength probability density of stone masonry grouted with agent K1 (a) and V7 (b) assuming the normal and lognormal distribution with marked quantiles for probabilities of 5 and 95 %.

SUMMARY OF THE RESULTS OF EXPERIMENTAL AND LABORATORY RESEARCH

- Based on the values obtained by the experimental research into the effect of the grouting method we can say that in the case of brick masonry no significant effect of low-pressure grouting in terms of strength in concentric compression was manifested as compared to the strength in concentric compression of the brick masonry where the grout had been applied without grouting pressure. In the case of stone masonry, a demonstrably positive effect of a low-pressure application of the grout on the strength of the stone masonry in concentric compression was reached as compared to the strength of the stone masonry in concentric compression with a pressureless application of the grout.
  The cause of the different result of the grouting method effect can primarily be seen in the difference in the pore system of the mortar used in the brickwork columns and the mortar used in the stonework columns. In the brickwork columns, the proportion of coarse pores sized 7500 to 30000 nm amounts to ca 30% of the total porosity, whereas the mortar of the stonework columns, which participates to a considerably greater extent in the strength of the stonework masonry of irregular quarried stone, has a prevailing proportion (ca 25%) of macropores sized 150 to 600 nm in which the low-pressure application of the grouts contributes to better "grouting through".
- The experimentally identified values of the ultimate strength in concentric compression of the brick and stone masonry indicate a correlation between the grouting agents' effectiveness in relation to the particle size (nanoparticles) of the grouting agent and the prevailing pore size. The experimental values of the ultimate strength identified also indicate that the assessment of the grouting agents' penetration mechanism into the pore system is governed not only by the extent of the prevailing agreement of the pore size and the grouting agents' nanoparticles, but also by other mechanisms like e.g. surface stress, the spectrum and nature of pores, viscosity and stability of the grouting agent, chemism, etc. The clarification of these mechanisms requires further experimental and theoretical research.
- Based on the values obtained through the experimental research into the effectiveness of grouting in terms of the strength of brick or stone masonry, based on the assessment and taking into account the strength scattering of the masonry itself (see Figure 13), we can say that a demonstrable increase in the load-bearing capacity of the masonry in concentric compression (exceeding the strength scattering of the ungrouted masonry) was reached in the

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case of brick masonry by the application of the resin-based grouts labelled P1 and P2 and the lime-based grouts labelled V1 and V4, and in the case of stone masonry by the application of the resin-based grout labelled P1 and the silicate-based grout labelled K1. The identified values of an increased or decreased load-bearing capacity of the masonry in concentric compression reached by the application of the grouts labelled V2, V3, V5, V6 and P3 can be assessed as non-conclusive and unreliable, and, in general, they cannot be recommended as methods for the strengthening of undamaged masonry

CONCLUSION

The scattering of the monitored values of the physical and mechanical characteristics of grouted and ungrouted brick or stone masonry and the limited number of specimens do not allow statistical analysis as a basis for the formulation of unambiguous conclusions. The above assessment was performed on the basis of the results of the experimental research into the effect of grouting on the principal physical and mechanical characteristics of undamaged and compact brick and stone masonry, carried out as part of research phase 1. Phase 2 will include experimental research into the effect of grouting on the principal physical and mechanical characteristics of brick and stone masonry with increased void contents, damaged by an artificial crack and cavity. Based on the experimental research into the effectiveness of grouting on the physical and mechanical characteristics of undamaged masonry completed to-date, we may state that the effectiveness of individual types of grouting agents must be assessed in terms of the mutual relationship between the properties of the grouted masonry and the grouting agent. The grouting of undamaged brick masonry can be assessed as insufficiently effective in terms of increasing the ultimate strength in compression.

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