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A COMPARISON OF THE EFFECTIVENESS OF GROUTING METHODS, PENETRATION AND SURFACE APPLICATION OF GELS IN INCREASING THE STRENGTH OF HISTORIC MASONRY

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ABSTRACT

This article focuses on the verification of the effect of selected grouting agents on historic brick masonry with different degrees of weathering using different techniques of grouting application. The effectiveness of grouting was verified by changes in the masonry strength. Experimental research also verified the effectiveness of the penetration of grouting agents as bonding primers on the surface of selected materials often found in historic buildings.

KEYWORDS

Masonry, Grouting, Brick, Mortar, Experimental research

INTRODUCTION

The grouting of historic masonry with degraded binders is a method frequently applied in the rehabilitation of historic masonry. Historic masonry is most often treated with grouting agents based on minerals, mostly lime or its modifications, or with admixtures. In the case of the requirement for a significant improvement of mechanical characteristics, resin-based substances are used in justified cases.

The experimental and theoretical research into the effect of grouting on the physical and mechanical characteristics of historic masonry carried out within the NAKI II research project (DG16P02M055 project "Research and development of materials, processes and techniques for restoration, preservation and strengthening of historic masonry structures and surfaces and systems for preventive protection of historic and listed buildings threatened by anthropogenic and natural risks") [1] includes the verification of the effect of the grouting method (pressure and pressureless grouting), the type of grouting agent (grouts based on minerals, resins and silicates) on the major physical (pore system) and mechanical (strength, deformation characteristics) properties of masonry [2, 3]. The objective of Phase I and Phase II of the research also covered the investigation of the effect of grouting on degraded masonry.

OBJECTIVE AND SUBJECT OF RESEARCH

The objective of experimental research was to verify the strengthening of degraded masonry or surface and near-surface layers of masonry, with selected grouting agents and techniques.

Selected historic brick masonry with a lime binder, or a lime binder with a 2.5% admixture of cement, was the subject of monitoring the strengthening effect of grouting on historic masonry for different types of grouts and different grouting techniques. The application of different types of mortar in the brick masonry allowed the verification of the effect of brick masonry strengthening by grouting in relation to the degradation rate of the masonry, primarily mortar.

METHODOLOGY OF EXPERIMENTAL VERIFICATION

Experimental research into the verification of the effect of grouting agents and techniques was conducted on brick masonry segments made up of solid burnt bricks on different types of lime mortar, or lime mortar with a 2.5% admixture of cement. Individual types of mortar differed in the amounts of binder and filler – ratios of 1:3, 1:5 and 1:7 were used. In this way, the degradation of the binder – masonry was simulated.

The subject of the research focusing on the verification of the effectiveness of grouting on the major mechanical characteristics was to identify the strength (load-bearing capacity) of masonry test pieces treated by pressure and pressureless grouting. The results were analysed on a limited number of masonry test pieces, which did not allow statistical evaluation. With a view to this fact and considering the dispersion of the physical and mechanical properties of the masonry, the results of the analysis must be interpreted with sensitivity.

The brick pillars for the experimental research were made up of CP 20 bricks on lime mortar with the binder: filler ratio of 1:3 or 1:5. The binder was five-year-old aged slaked lime, and the filler sand with a grains size of 0-4 mm. A part of the pillars with the above types of mortar was fitted with artificially made voids in the bed joints. Another part of the experimental pieces were brick pillars from CP20 bricks on lime mortar with a 5% admixture of MV 1 cement mixed in a 1:1 ratio with sand 0-2 mm with a resulting strength corresponding to the 1:7 ratio. The walling was executed under stabilized conditions of a testing laboratory – with the air temperature ranging from 15 to 20°C, and the relative humidity of ca. 30 to 40%.

The grouting agents selected for the experimental research were based on lime (V1, V3), on a mixture of hydraulic lime and lime nanoparticles (V5), on silicates (K1, for the penetration test) and on epoxy resin (P2). The V5 grouting agent based on hydraulic lime and lime nanoparticles had been developed within the NAKI II DG16P02M055 research project, in which the research workplace cooperated with the Centre of Polymer Systems (Tomas Bata University in Zlín).

The characteristics of masonry units, mortar and grouting agents are presented in Table 1.

The dimensions of the brick masonry test pieces were 300 x 450 x 420 to 450 mm, or 300 x 600 x 420 to 450 mm. After walling, the pillars were left for 28 days to mature, and, afterwards, grout holes Ø18 mm, at an angle of inclination of 30° were made in all pillars ca. 90 mm below the pillar upper edge, terminated ca. 50 mm from the opposite masonry face. The next step was the mounting of grout packers and low-pressure (3 to 10 bars using a low-pressure screw pump for suspension grouting) or pressureless (hydrostatic pressure) grouting. After grouting, the grout holes were filled with a low-shrinkage mix (Oxal VP TK2). The length of the technological break depended on the grouting agent used – for grouting agents based on minerals or organosilicates, the technological break necessary for hardening was 28 days, and for epoxy-based substances from several hours to several (three) days. Individual sets of test pieces contained a so-called reference pillar, in which all preparatory phases had been performed identically to the grouted pillars. The tests of the grouted pillars and the reference pillar were carried out ca. 3 to 4 weeks after the grouting and filling in the grout holes (Figure 1).

Tab. 1 - Characteristics of masonry units, mortar, grouting agents – compressive and tensile strength

Label	Mortar - ratio	Mortar – $f_{compr,m}$/ $f_{tension,m}$	Brick - $f_{compr,b}$	Grouting mixture	Grouting mixture – f_{compr} /$f_{tension}$
	-	MPa	MPa	-	MPa
CP01-1:7-P2	1:7	0,50/0,21	22,01	P2	64,6/43,3
CP02-1:7-P2	1:7				
CP03-1:3-P2	1:3	1,03/0,59	22,23		
CP04-1:3-P2	1:3				
CP05-1:5-P2	1:5	0,67/0,28	21,11		
CP06-1:3-V5	1:3	0,96/0,59	22,23	V5	0,88/0,53
CP07-1:3-V5	1:3				
CP08-1:5-V5	1:5	0,67/0,25	21,11		
CP09-1:5-V5	1:5				
CP10-1:7-V3	1:7	0,50/0,21	22,01	V3	1,26/0,11
CP11-1:7-V3	1:7				
CP12-1:3-V3	1:3	0,96/0,59	22,23		
CP13-1:3-V3	1:3				
CP14-1:5-V3	1:5	0,67/0,25	21,11		
CP15-1:5-V3	1:5				
CP16-1:7-V1	1:7	0,48/0,16	22,01	V1	2,500/-
CP17-1:7-V1	1:7				
CP18-1:3-V1	1:3	1,03/0,59	22,23		
CP19-1:3-V1	1:3				
CP20-1:5-V1	1:5	0,67/0,28	21,11		
CP21-1:5-V1	1:5				

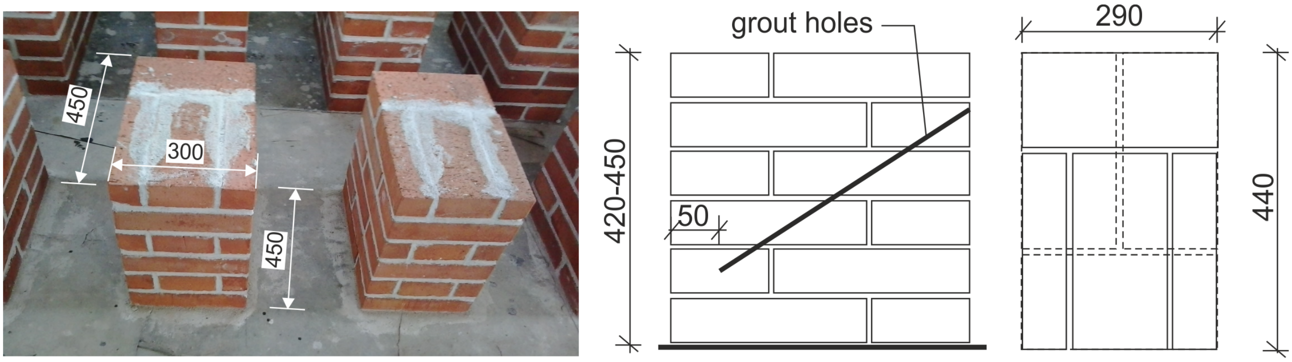

Fig. 1 - Photo and diagram of the test pieces

Considering the attributes of the grouting mixes, the propagation of the grouting agent through the masonry units and the binder was first verified on the brick pillars by pressure and pressureless grouting. Based on the experimentally obtained results and information, the grouting agents to be used as the bonding primer were selected and applied.

The grouting technique was chosen with a view to the attributes of the grouting agents and the brickwork pillars to avoid any damage to the experimental pieces during grouting. The epoxy-based substance was applied by a pressureless technique, while the substances based on lime or a mixture of lime and lime nanoparticles were applied by low-pressure grouting.

Verification of grouting effectiveness

Load tests under concentric compression until failure were performed in an actuator with a digital data logger for reading compression manufactured by the German MFL Company – (range of 0 to 10 000 kN, operational accuracy of ±0.1 kN). The deformations in the vertical and horizontal directions were measured by LVDT strain gauges (6 pieces). The monotonously rising loading of the pillars under concentric compression was exerted by steps of 50 to 75 kN, i.e. ca. 10 to 15 % of the theoretically identified ultimate loading of pillar masonry under ČSN EN 1996 (EC6).

Fig. 2 - a) Test piece during the load test with mounted strain gauges, b) Test piece after the completed load test

Verification of penetration effectiveness

The penetration abilities of selected grouting agents were verified by the depth of their penetration into selected materials after the application of repeated coatings on the vertical surface (the number of repetitions differed for individual substances due to their characteristics). All grouting agents were applied as the bonding primer, and epoxy-based substances were successively only used for a second coating, while the other grouting agents were applied for another 11 coatings following the bonding primer. The grouting agents were coloured to allow the visual observation of the penetration depth and to avoid changes in the properties of the grouts. The grout coatings were gradually applied on the surface of bricks, sandy marlstone, sandstone and limestone, see Figure 3.

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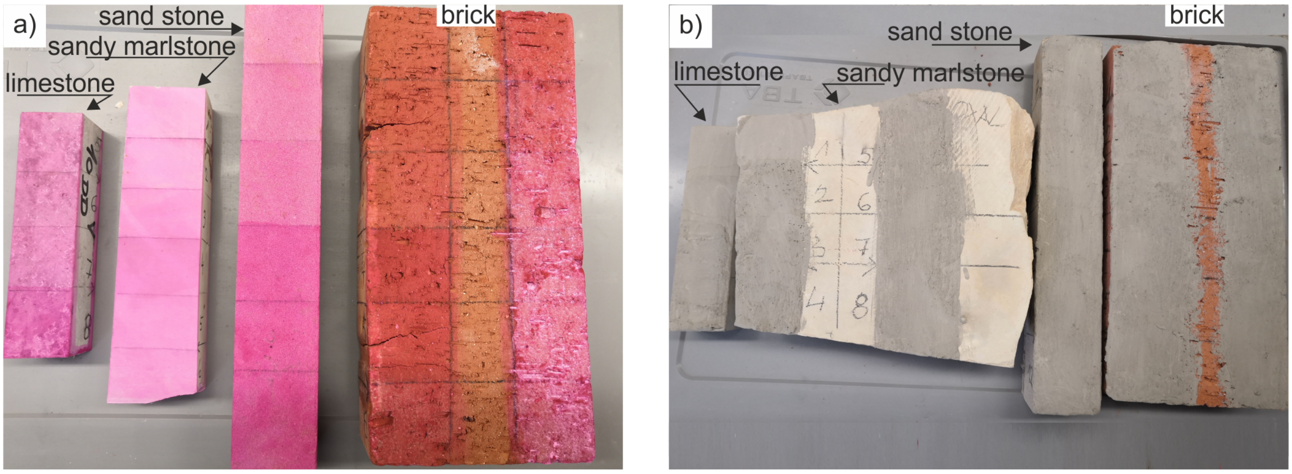

Fig. 3 - Example of test pieces with a bonding primer a) using V5, b) using V3

EVALUATION OF PARTIAL RESULTS OF EXPERIMENTAL VERIFICATION OF METHODS

Evaluation of grouting

The results of the load tests of masonry pillars under concentric compression – strength in concentric compression, the values of experimentally identified vertical and horizontal deformations, modulus of elasticity, or the ratio of vertical and horizontal strain, were processed graphically and in tables for successive analysis for individual sets of test pieces after the grout application. Due to large amounts of obtained data, the sections below present partial results of this analysis aimed at the evaluation of the grouting effectiveness measured by the strength of the grouted masonry in compression, the effect of the grouting technique, the effect of the pore system and the grouting agent's particle size, and potential changes in the pore system of the grouted material as compared to ungrouted material.

Partial results of the experimentally identified parameters of the masonry of test pieces are presented in Table 2.

Based on the comparison of the experimentally identified ultimate strength in concentric compression of brick masonry, including both pillars with voids and reference pillars (mortar 1:3 and 1:5) and pillars without voids with reference pillars (mortar 1:7), we may draw the following conclusions (ungrouted masonry f_{exp} = 100%):

In pressureless grouting applying the P2 epoxy-based agent, the ultimate strength of the pillars in compression $f_{exp,epox}$ = 217% for the mortar of the pillars with a mixing ratio of 1:3, and 197% for the mortar of the pillars with a mixing ratio of 1:5. The P2 epoxy-based grout applied on the pillars with mortar with a mixing ratio of 1:7 increased strength on average to 116% of the reference pillars.

Note: The ultimate strength of masonry was averaged for the whole pillar area. Due to high strength of the grouted masonry zone, the differences in average strength are small for both types of mortar.

In low-pressure grouting applying the V1 lime-based grouting agent, the ultimate strength of the pillars in compression $f_{exp,epox}$ = 196% for the mortar of the pillars with a mixing ratio of 1:3, and 165% for the mortar of the pillars with a mixing ratio of 1:5. In low-pressure grouting applying the V1 lime-based grouting agent on the pillars with mortar with a mixing ratio of 1:7, the compressive strength of the masonry ranged from 96 to 107% of the reference pillars.

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Tab. 2 - Experimentally identified parameters of test piece masonry

Label	Compressive strength	Modulus of elasticity	Hor. def. δ_x at 50% N_{um}	Vert. def. δ_y at 50% N_{um}	Hor. def. δ_x at 500 kN	Vert. def. δ_y at 500 kN	Ratio ε_X / ε_Y at 50% Num	Ratio ε_X / ε_Y at 500 kN
	MPa	GPa	mm	mm	mm	mm	(-)	(-)
CP01-1:7-P2	6,00	0,26	0,51	-4,14	1,06	-5,21	0,15	0,25
CP02-1:7-P2	5,62	0,36	0,52	-2,60	0,52	-2,60	0,24	0,24
CP03-1:3-P2	7,46	0,87	0,38	-1,63	0,38	-1,63	0,30	0,30
CP04-1:3-P2	6,67	0,76	0,10	-1,70	0,16	-1,89	0,08	0,11
CP05-1:5-P2	3,61	0,52	-0,07	-1,26	X	X	-0,07	X
CP06-1:3-V5	6,59	1,21	0,00	-0,90	0,01	-1,19	0,00	0,01
CP07-1:3-V5	6,28	1,41	0,15	-0,70	0,29	-1,02	0,27	0,36
CP08-1:5-V5	4,87	0,44	0,02	-1,98	0,39	-3,04	0,01	0,16
CP09-1:5-V5	5,84	0,83	0,05	-1,17	0,44	-1,83	0,05	0,31
CP10-1:7-V3	4,79	0,22	0,94	-3,42	4,56	-6,345	0,33	0,87
CP11-1:7-V3	5,44	0,28	1,45	-3,385	1,45	-3,385	0,52	0,52
CP12-1:3-V3	6,27	0,74	0,21	-1,55	0,43	-1,895	0,17	0,29
CP13-1:3-V3	6,66	1,22	0,12	-0,96	0,17	-1,14	0,16	0,19
CP14-1:5-V3	4,40	0,50	2	-2,895	2	-2,895	0,88	0,88
CP15-1:5-V3	5,82	0,67	0,01	-1,45	0,31	-2,195	0,01	0,18
CP16-1:7-V1	4,70	0,25	X	-2,9	X	-6,1	X	X
CP17-1:7-V1	5,53	0,75	X	-1,04	X	-1,04	X	X
CP18-1:3-V1	7,46	0,87	0,38	-1,625	0,38	-1,625	0,30	0,30
CP19-1:3-V1	6,67	0,76	0,1	-1,695	0,16	-1,89	0,08	0,11
CP21-1:5-V1	5,42	0,47	0,24	-2,165	1,08	-2,715	0,14	0,51

Note: X - values not measured

In low-pressure grouting applying the V3 lime-based grouting agent, the ultimate strength of the pillars in compression $f_{exp,epox}$ = 179% for the mortar of the pillars with a mixing ratio of 1:3, and 141% for the mortar of the pillars with a mixing ratio of 1:5. In low-pressure grouting applying the V3 lime-based grouting agent on the pillars with mortar with a mixing ratio of 1:7, the compressive strength of the masonry ranged from 94 to 111% of the reference pillars.

In low-pressure grouting applying the V5 grouting agent based on a mixture of hydraulic lime and lime nanoparticles, the ultimate strength of the pillars in compression $f_{exp,epox}$ = 178% for the mortar of the pillars with a mixing ratio of 1:3, and 148% for the mortar of the pillars with a mixing ratio of 1:5.

Figure 4 shows the relationship of the strength of brick masonry pillars on mortar with mixing ratios of 1:3, 1:5 and 1:7 to the used grouting agent, and the comparison with the strength values theoretically identified under ČSN EN 1996-1-1.

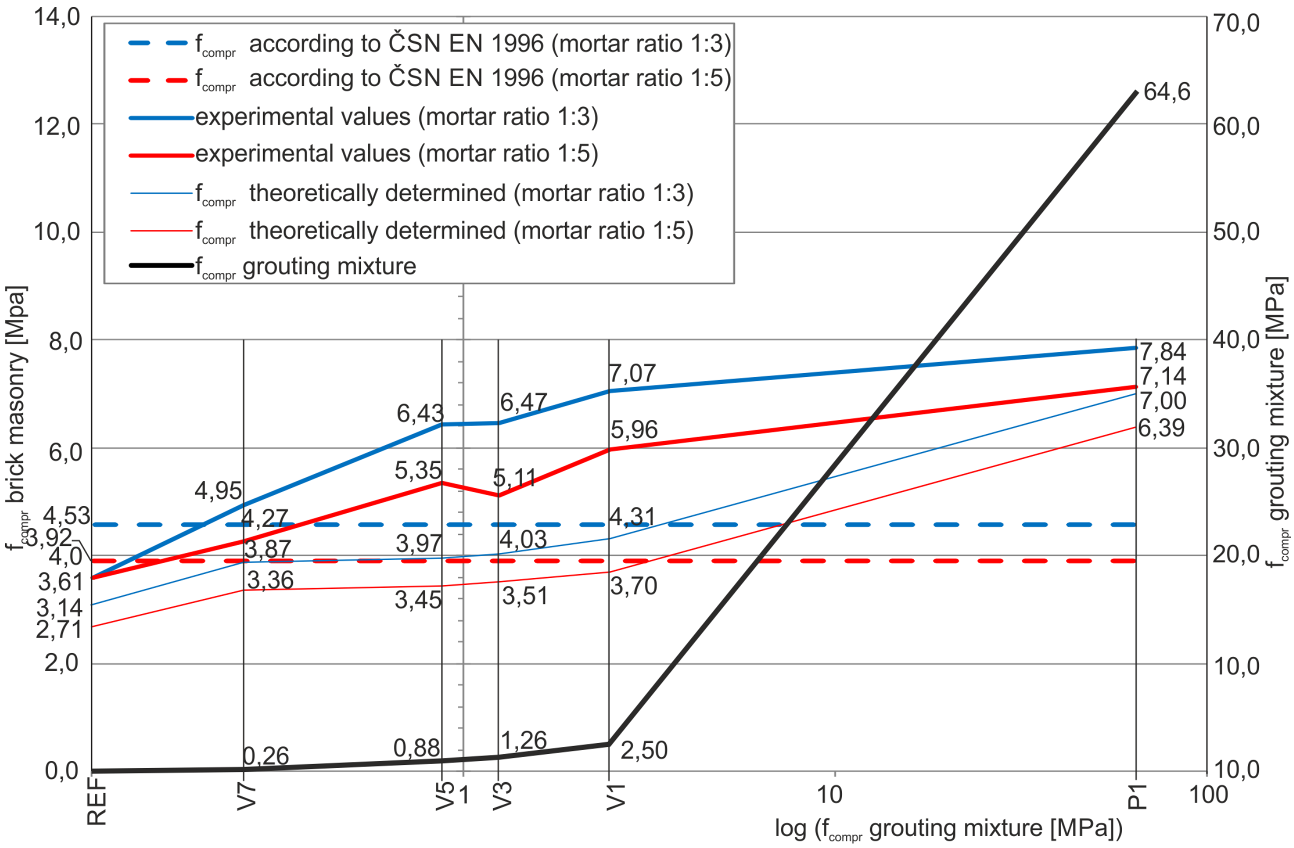

Fig. 4 - Relationship of the strength of brick masonry pillars on mortar 1:3, 1:5 to grouting agents used

Summary of grouting results

The experimentally identified compressive strength values indicate that the ultimate strength of the masonry in compression grew in the verified cases of brick masonry pillars with mortar with a mixing ratio of 1:3 and 1:5 after grouting with the above agents. The increase in strength ranged from 41% to 117% of the strength of ungrouted masonry. In the pillars with mortar with a mixing ratio of 1:7, the identified strength values ranged from only 94 to 111% of the strength of ungrouted masonry.

The load tests of masonry pillars have manifested the relationship of the strength of grouted brick pillar masonry to the strength of the grouting agents filling in the voids and penetrating into the masonry around the voids and the borehole. The effect of grouting on the masonry strength is gradually falling with the decreasing strength and penetration abilities of the grouting agent, or due to imperfect filling of the voids and cavities with the grout.

The experimentally identified strength values of grouted masonry for mortar with a mixing ratio of 1:3 and 1:5 are mutually roughly affine, and the comparison of experimental values for both types of mortar with the values calculated for the respective material characteristics under ČSN EN 1996-1-1 has brought similar results, too (see Figure 4).

The experimental verification did not prove a greater effect of low-pressure grouting in terms of compressive strength as compared to pressureless grouting.

Evaluation of penetration

As the number of coatings with the “grouting” substances increased, they penetrated into the near-surface layers. The penetration depth differed for different materials and grouting agents (Table 3).

Tab. 3 - Penetration depth of “grouting” substances

Label - Penetration substance	Penetrated material	Penetration depth [mm]	Note
P2	Brick CP 20	≤ 1	Only 3 coats, then epoxy sealed the surface forming glass-like film
	Sandy marlstone	max 0.1 mm	
	Sandstone	up to 1 mm	
	Limestone	up to 0.05 mm	
V3	Brick CP 20	up to 0.05 mm	Filled uneven surface spots, on the surface
	Sandy marlstone	---	Only on the surface
	Sandstone	up to 0.1 mm	Filled uneven surface spots, on the surface
	Limestone	---	Only on the surface
V5	Brick CP 20	up to 0.1 mm	From 8th coating white lime film on the surface
	Sandy marlstone	up to 0.05 mm	
	Sandstone	0,1 to 0.5 mm	Up to 5th coating - depth of ca. 0.1 mm, 6th to 12th coating – depth of 0.1 to 0.5 mm
	Limestone	---	In places of microcracks up to 0.01 mm, only on the surface
K1	Brick CP 20	up to 0.15 mm	Up to 6th coating 0.1 mm, 7th – 12th coating up to 0.15 mm, from 9th coating shiny sealed surface
	Sandy marlstone	up to 0.01 mm	
	Sandstone	up to 0.1 mm	From 7th coating shiny sealed surface
	Limestone	---	In places of microcracks up to 0.01 mm, only on the surface

Summary of penetration results

In limestone samples, all the grouting agents remained only on the surface. The best results (greatest penetration depths) were reached with the P2 epoxy-based agent, whose three coatings penetrated to a depth of ca. 1 mm in the case of bricks and sandstone, and to a depth of 0.1 mm in sandy marlstone. The V3 lime-based agent remained only on the surface in limestone and sandy marlstone samples, and in the case of sandstone and bricks it penetrated to a depth of ca. 0.1 mm. The K1 silicate-based grouting agent penetrated to a depth of ca. 0.2 mm in bricks, to 0.1 mm in sandstone and 0.02 mm in sandy marlstone. The V5 agent based on hydraulic lime and nanolime penetrated to a depth of ca. 0.1 to 0.5 mm in bricks and sandstone, and to 0.05 mm in sandy marlstone.

Regardless of the base of the grouting agents applied on the surface, the greatest penetration depth was reached in sandstone and bricks, while, on the contrary, all grouting agents applied on limestone remained only on the surface. Partial results of the experimental research manifested low penetration abilities of the verified grouting agents and excessive dependence of the penetration on the pore system of penetrated materials.

CONCLUSION

Due to the dispersion of the monitored parameters of grouted and ungrouted brick masonry and a limited number of samples, statistical data analysis allowing the formulation of unambiguous conclusions is impossible. The presented evaluation was made on the basis of the results of experimental research into the effect of grouting on major physical and mechanical characteristics of undamaged and compact brick masonry (Phase I) and brick masonry damaged by an artificial cavity (Phase II).

Partial results of experimental research into the effect of grouting on the strength of degraded brick masonry have manifested a positive effect of grouting on increasing the masonry strength. The effect of selected grouting agents on the strength of masonry with mortar with a mixing ratio of 1:3 and 1:5 was analogous. The partial experimental results obtained do not allow an unambiguous manifestation of a higher effectiveness of the pressure or pressureless grouting technique.

Partial results of experimental research into the penetration of selected grouting agents applied on the surface of materials often found in historic buildings have pointed out a possibility of using this technology for the strengthening and improving the adhesion of mainly the surface and near-surface layers of masonry structures of historic buildings.

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