
EVALUATION OF MASONRY GROUTING EFFECTIVENESS USING THERMOGRAPHY AND ULTRASONIC METHODS

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ABSTRACT

One of the frequently used methods of stabilization and reinforcement of historic masonry is grouting, especially grouting of cracks and voids in masonry structures. Determination of the properties of the injected structure, both in terms of physico-mechanical properties (with regard to the subsequent compatibility of the grouting mixture) and in terms of its condition and failures (cracks, voids, cavities), is a prerequisite for correct design and realization of reinforcement grouting. Minimization of interventions into the historic structure while performing surveys and the associated use of non-destructive diagnostic methods is one of the requirements for the remediation of listed buildings. Within the experimental research of reinforcement of historic masonry structures, the possibility of using thermography and ultrasound methods was evaluated and conditions and limitations for the use of these non-destructive methods were formulated.

KEYWORDS

Masonry grouting, Non-destructive testing, Ultrasound, Thermography

INTRODUCTION

Grouting of historic masonry structures is one of the frequently used methods of stabilization of damaged masonry. Reliable penetration of the grouting material into the masonry structure is a prerequisite for ensuring the desired reinforcement (stabilization) effect. However, it is very difficult to verify the rate of penetration of the grouting mixture into the masonry. Use of core samples and subsequent laboratory determination of chemical composition or total porosity to prove the presence of the grouting mixture is time-consuming and costly, but above all it is an intervention (albeit limited) into the historic structure. As such, it may not be, especially in case of buildings with heritage protection, possible.

The analysis of results of experimental research carried out within the project DG16P02M055 [1] showed the need for verification of the penetration of the grouting mixture into the masonry structures. Within this research, the possibilities of using two selected non-destructive diagnostic methods (NDT) for determination of the rate of injection of masonry structures were evaluated. Namely the method based on the infrared thermographic analysis of the temperature field on the surface of the injected structure (IRT) and the method based on the measurement of the velocity of the ultrasonic signal passing through the grouted structure (UST) were verified.

Among the various non-destructive diagnostic methods, acoustic methods (both ultrasonic - UST and sonic - ST) are often used to determine the internal layout of building structures, including structures being grouted [2]. Knowledge of the individual masonry components, the state of their failure by cracks and the percentage, size and distribution of voids or cavities are essential for the proper design and execution of reinforcing grouting [3-7]. Ultrasonic methods are also often used in laboratory verification of penetration of grouting mixtures into masonry structures (especially in the research of stabilization of multi-leaf masonry) [3, 7-10].

EXPERIMENTAL RESEARCH

Experimental research was carried out on test specimens consisting of stone blocks of approx. 250 x 250 x 250 mm of two types of sandstone (coarse-grained - Hořice quarry and fine-grained - Božanov quarry), marlstones and limestone, and mortar blocks of approx. 250 x 250 x 250 mm made of mortar 1: 3 and mortar 1: 5 (ratio of 5 years of slaked lime and sand fraction 0-4 mm). Nine test specimens were prepared from each material. One specimen was a reference (ungrouted), the other specimens were grouted in pairs (Figure 1, Table 1). In the middle of the upper wall, a grouting borehole Ø 18 mm ending 50 mm in front of the opposite side (borehole length 200 mm) was made. Grouting boreholes in experimental specimens designed for pressure grouting were equipped with grouting packers.

Grouting mixtures used for the experimental verification of the injectability can be divided into two groups according to the main base:

- **BV3** - 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.
- **BV7** - - mixture based on hydraulic lime and nanosuspension of calcium acetate Ca(OCOCH3)2 . H2O and magnesium acetate Mg (OCOCH3)2. 4H2O, which were dissolved in distilled water (this mixture was developed within the NAKI II DG16P02M055 [1] research project in cooperation with The Centre of Polymer Systems, Tomas Bata University in Zlín).
- **BP** - 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.
- **BK** – mixture 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.

A total of 4 grouting mixtures were used, of which 2 were based on hydraulic lime, 1 based on resins and 1 based on organosilicates. Hydraulic lime grouting mixtures were applied by low pressure grouting (LP) using a screw grouting pump (2-10 bar) and the grouting compositions based on resin and organosilicate were applied by non-pressure grouting (NP) by hydrostatic pressure (about 0.5 bar).

The total porosity and pore distribution were determined on test specimens. Laboratory research of porosity was carried out in cooperation with the Institute of Rock Structure and Mechanics of the Czech Academy of Sciences using the high-pressure mercury porosimetry method on samples (fragments) of 5 mm of materials used in test specimens. The measurement was carried out on a set of Pascal 140 + 240 fir thermo Electon - porotec.

Samples of the masonry for determining the porosity before and after grouting were, after the grouting mixture had cured, taken from the test specimens using a ø35 mm core borehole perpendicular to the grouting boreholes about 80 mm above the lower edge of the test specimen (Figure 2). Samples were taken from each core borehole at a distance of 5 mm from the grouting borehole (grouted sample) and at a distance of 100 mm from the injection well (ungrouted sample).

Tab. 1 - Overview of test specimens

Label	Material	Dimension [mm]	Grouting mixture
O1a	Marlstone	257x257x250	Hydraulic lime mixture BV3
O1b		253x251x250	
O2a		255x255x250	Hydraulic lime mixture BV7
O2b		254x254x250	
O3a		252x252x250	Epoxy resin BP
O3b		247x254x250	
O4a		252x255x250	Organosilicate BK
O4b		260x257x250	
OR		250x250x250	Reference sample (ungrouted)
B1a	Fine-grained sandstone (Božanov)	252x252x250	Vápenná směs BV3
B1b		252x252x250	
B2a		251x252x250	Vápenná směs BV7
B2b		251x251x250	
B3a		252x252x250	Epoxy resin BP
B3b		252x252x250	
B4a		252x252x250	Organosilicate BK
B4b		252x252x250	
BR		252x252x250	Reference sample (ungrouted)
H1a	Coarse-grained sandstone (Hořice)	249x249x250	Hydraulic lime mixture BV3
H1b		250x250x250	
H2a		251x253x250	Hydraulic lime mixture BV7
H2b		251x252x250	
H3a		252x251x250	Epoxy resin BP
H3b		252x252x250	
H4a		250x251x250	Organosilicate BK
H4b		251x252x250	
HR		248x248x250	Reference sample (ungrouted)
L1a	Limestone	254x255x250	Hydraulic lime mixture BV3
L1b		254x254x250	
L2a		253x253x250	Hydraulic lime mixture BV7
L2b		253x254x250	
L3a		253x251x250	Epoxy resin BP
L3b		254x253x250	
L4a		253x253x250	Organosilicate BK
L4b		253x259x250	
LR		252x252x250	Reference sample (ungrouted)
M3_1a	Mortar 1:3	248x250x250	Hydraulic lime mixture BV3
M3_1b		248x245x250	
M3_2a		250x245x250	Hydraulic lime mixture BV7
M3_2b		248x249x250	
M3_3a		250x245x250	Epoxy resin BP
M3_3b		249x250x250	
M3_3c		245x250x250	
M3_4a		250x250x250	Organosilicate BK
M3_R		250x248x250	Reference sample (ungrouted)
M5_1a	Mortar 1:5	251x248x250	Hydraulic lime mixture BV3
M5_1b		249x250x250	
M5_2a		251x248x250	Hydraulic lime mixture BV7
M5_2b		248x245x250	
M5_3a		248x252x250	Epoxy resin BP
M5_4a		246x252x250	Organosilicate BK
M5_4b		250x248x250	
M5_4c		248x245x250	
M5_R		245x250x250	Reference sample (ungrouted)

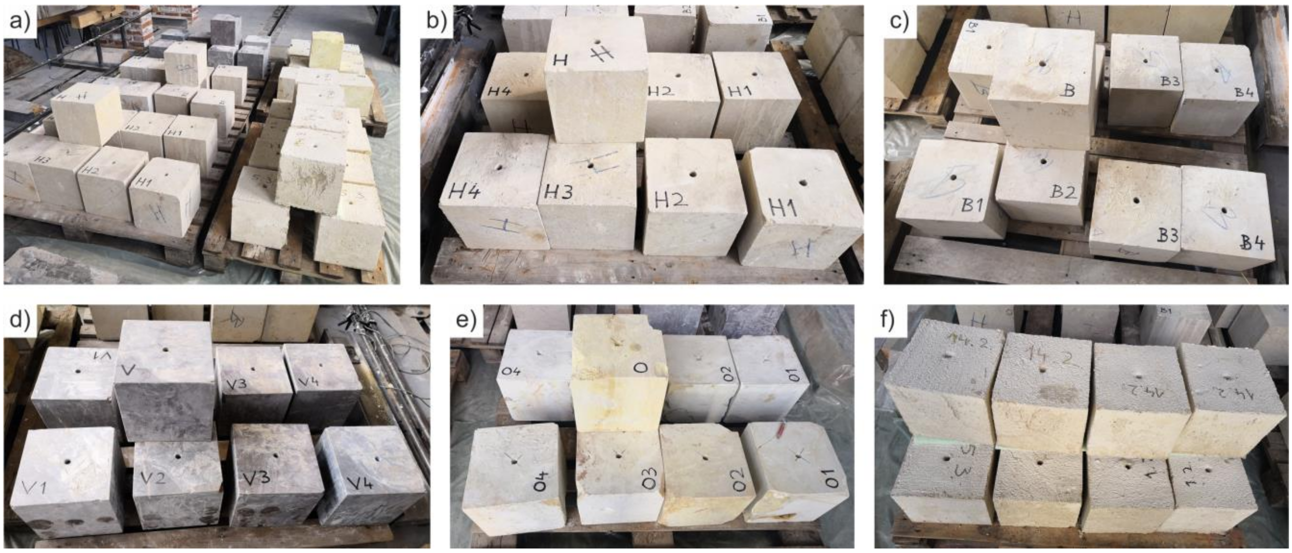

Fig. 1 – a) Stone a mortar test specimens, b) Coarse-grained sandstone test specimens (Hořice), c) Fine-grained sandstone (Božanov), d) Limestone test specimens, e) Marlstone test specimens, f) Mortar test specimens

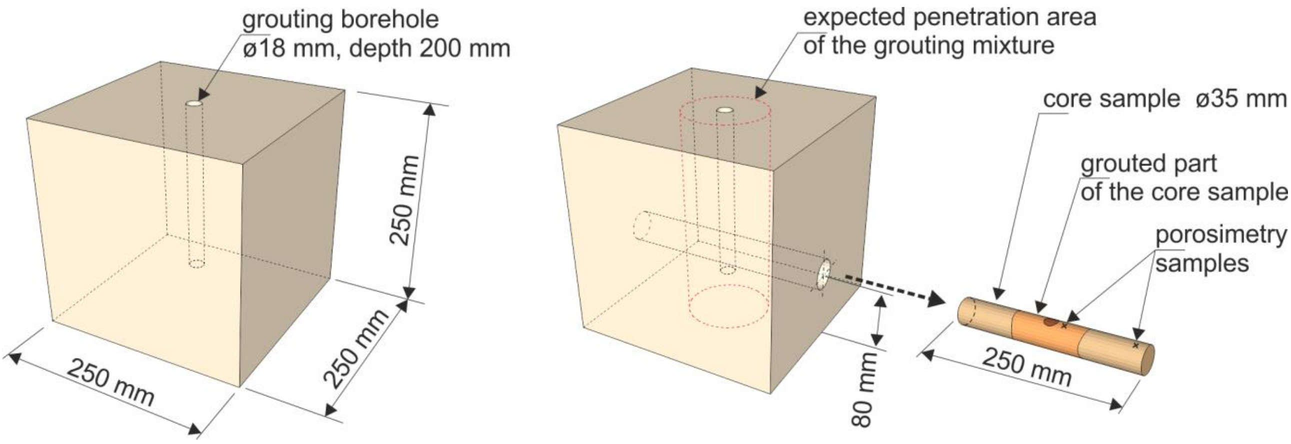

Fig. – 2 Test specimens' scheme

Based on the analysis of the total porosity (Figure 3), it can be concluded that the total porosity of the samples taken at a distance of 5 mm from the grouting borehole was in most cases lower than the total porosity of the samples taken at a distance of 100 mm from the grouting borehole.

In case of marlstone samples, the change in total porosity ranged from 2 to 15%, in case of coarse-grained sandstone samples between 8 and 20%, in case of fine-grained sandstone between 17 and 38% and in case of limestone between 1 and 35%. Thus, it is possible to assume that the test specimens are sufficiently grouted in their central part. On the other hand, extreme (or side) part of the test specimens can be labeled as grouted, because there was no decrease in the total porosity or a significant change in the distribution of individual pore groups.

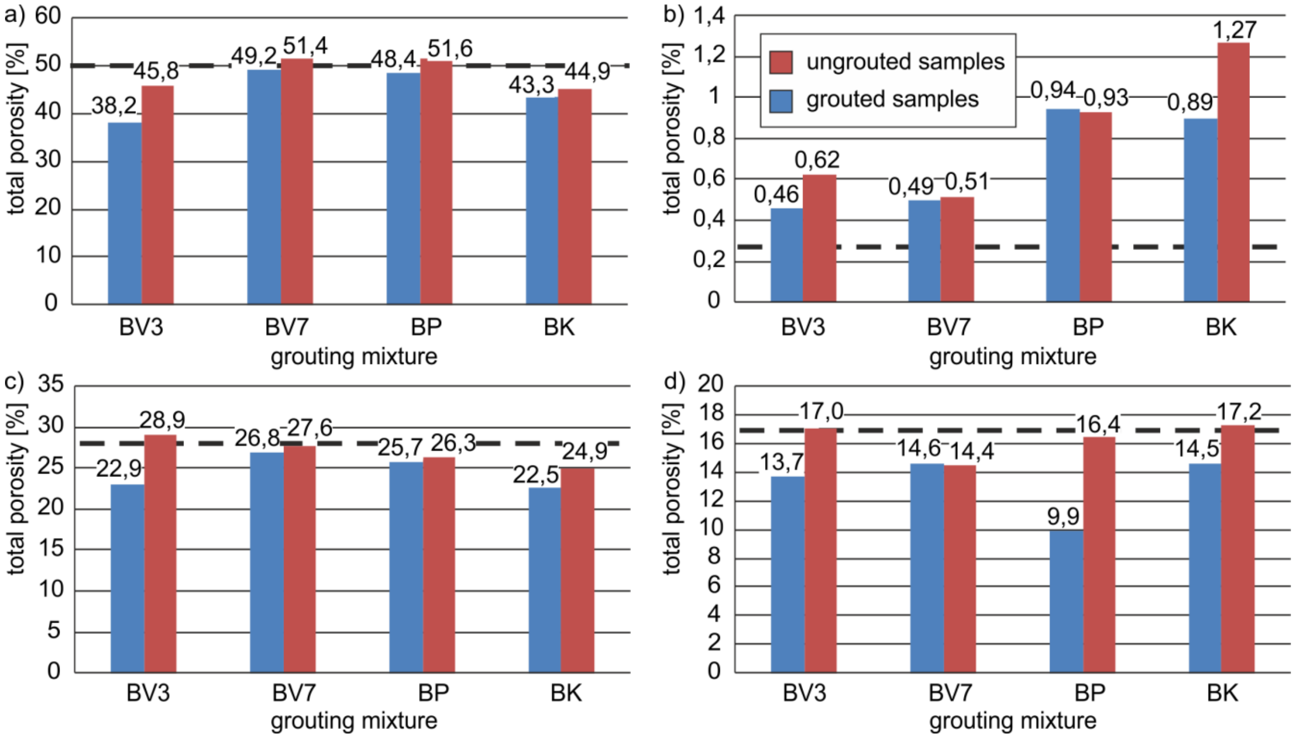

Fig. 3 – Comparison of total porosity of selected materials before and after grouting, a) Marlstone, b) Limestone, c) Coarse-grained sandstone (Hořice), d) Fine-grained sandstone (Božanov)

INFRARED THERMOGRAPHY

Thermal imaging (infrared thermography – IRT) is based on scanning and subsequent analysis of the distribution of the temperature field on the surface of the investigated body (structure). This temperature field is the result of the infrared radiation that each body emits. The accuracy of the measurement (resulting temperature field) is dependent on a number of parameters, in particular the emissivity of the surface and the apparent reflected temperature. Emissivity is a property of a material related to its ability to emit radiation and describes how much energy is emitted from a material relative to the amount emitted from an absolutely black body at the same temperature. The highest emissivity ($\varepsilon_T = 1$) therefore has an absolutely black body (it is an ideal absorber and at the same time an ideal emitter). Real material always has lower emissivity (ε_T <1). Emissivity of a body depends on a number of material properties, such as type of materials (metal, plastic, masonry, glass, etc.), chemical composition, structure and condition of its surface (roughness, degree of oxidation, soiling). The apparent reflected temperature is ambient thermal radiation, which is reflected by the surrounding (especially shiny) surfaces and is detected by a thermal imaging device (thermographic camera).

Evaluation of grouting mixture penetration into masonry specimens by thermal imaging was performed using the Flir One Pro thermovision set (sensor resolution 160 x 120 px, visual sensor resolution 1440 x 1080 px, temperature range -20 ° C to +400 ° C, spectral range 8 to 14 μm, temperature sensitivity 70 mK). Thermal imaging (static thermal imaging, thermal imaging videos) was performed during grouting of test specimens (Figure 4). The monitored parameter was the change of the surface temperature in the vicinity of the grouting borehole due to the penetration of the grouting mixture. Thermal imaging was performed for low-pressure (NT) and non-pressure (BT) grouting.

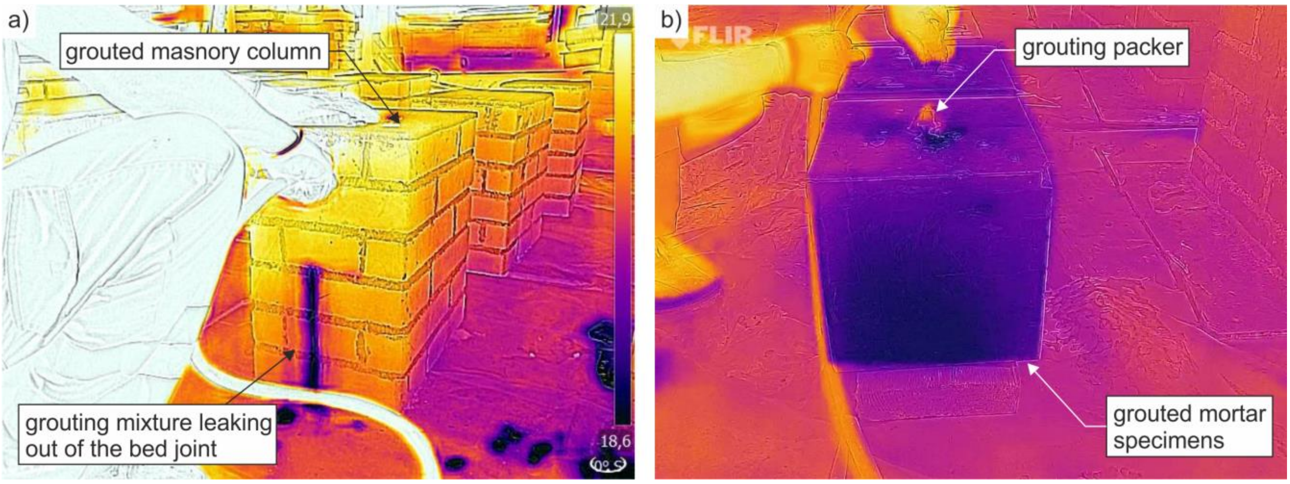

Fig. 4 – a) Thermovision image captured during grouting brick masnory test specimen with hydraulic lime based grouting mixture with nanosuspension labelled BV7, b) Thermovision image captured during grouting mortar test specimen with hydraulic lime based grouting mixture labelled BV3

Performed evaluation of the use of thermal imaging can be summarized as follows:

- monitoring of grouting mixture penetration is limited only to the surface of the grouted structure,
- grouting of the internal structure is manifested on the surface of the test specimens in a very limited extent,
- different properties of grouted masonry within the grouted structure (different emissivity and surface roughness of individual masonry elements and mortar) make it difficult to determine the appropriate parameters needed for thermal imaging,
- small temperature difference between the grouting mixture and the grouted masonry does not allow reliable monitoring of the penetration of the grouting mixture into the masonry,
- in the case of grouting of bodies damaged by a crack that extends to the masonry surface, it is possible, in some cases, to detect the grouting of the body (crack) by thermal imaging before it is visually observable.

ULTRASONIC MEASUREMENT

Ultrasonic testing methods (UST) are based on the determination of the speed of the acoustic signal passing through the investigated body (structure). The principle is based on sending repeated ultrasonic pulses into the material, their sensing and measuring the time of the front of the transmitted ultrasonic pulse through the material. From the known exciter – sensor distance (measuring base) and the measured pulse transit time, we can determine the ultrasonic propagation speed in the measured environment, which is the basic acoustic characteristic according to ČSN EN 12504-4 [11]. The value of the dynamic modulus of elasticity can be directly calculated from the measured speed and based on the statistically derived calibration relationships according to ČSN 73 1371 [12] some indicative properties of investigated material can be determined (e.g. compressive strength, modulus of elasticity, density etc.). The results can be refined by the methodology recommended by ČSN EN 13791 [13] for particular examined material. This method can also be used to detect various anomalies in the teste structure or material (cracks, voids, cavities etc.). Digital inspection ultrasonic flaw detectors operating at frequencies of 30 - 250 kHz are used for structural testing.

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Evaluation of grouting mixture penetration into masonry specimens using ultrasonic testing was performed using a Proceq Tico ultrasonic instrument (measuring range 15 to 6550 μs, resolution 0.1 μs, transmit and receive probe frequencies 54 kHz). The ultrasonic measurement of the acoustic signal velocity was performed by direct measurement on the specimens after curing of the grouting mixtures in 9 locations in the longitudinal direction and 9 locations in the transverse direction of the specimen (Figure 5 and Figure 6). The measurement locations included both theoretically grouted and ungrouted parts of the test specimens. In total 810 measurements on 45 test specimens was performed.

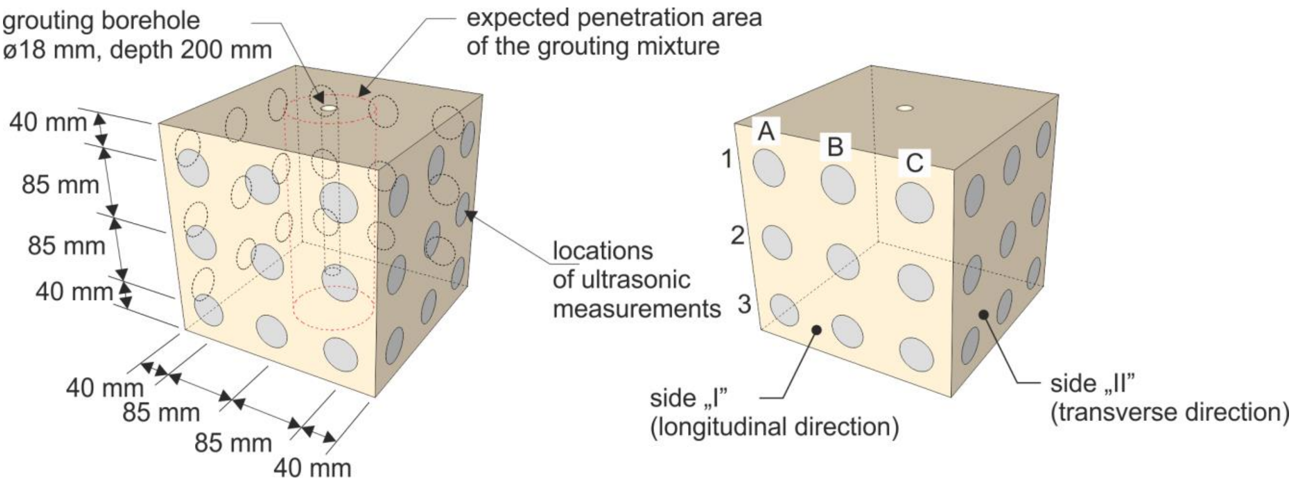

Fig. 5 – Ultrasonic testing scheme

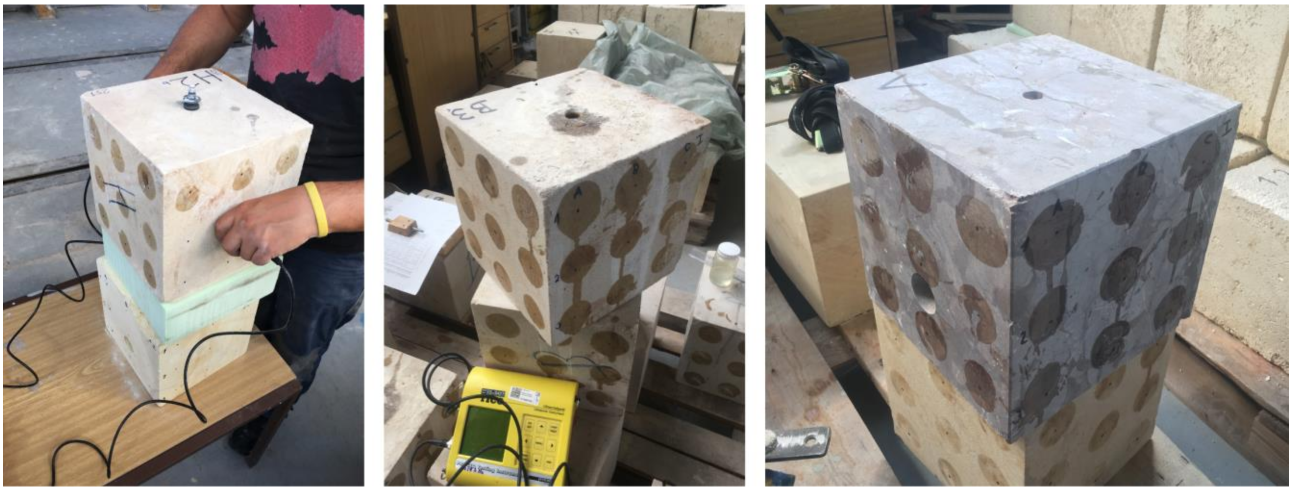

Fig. 6 – Ultrasonic testing

The recorded measurement results (ultrasonic signal velocity) were subsequently analyzed and statistically evaluated (Table 2 to Table 6). Due to the dispersion of the measured values of ungrouted samples of the same material, the grouting mixture penetration analysis was always performed within one or two test specimens.

Tab. 2 - Results of ultrasonic measurements (ultrasonic signal velocity) of reference (ungrouted) test specimens

Material	Average velocity [m/s]	Standard deviation [m/s]	Coefficient of variation
Fine-grained sandstone	3276,6	80,1	2,4%
Coarse-grained sandstone	2663,4	83,5	3,1%
Marlstone	1969,6	245,3	12,5%
Limestone	6137,3	338,4	5,5%
Mortar 1:5	1198,4	162,3	13,5%
Mortar 1:3	1247,8	131,0	10,5%

Tab. 3 - Results of ultrasonic measurements (ultrasonic signal velocity) of test specimens grouted with hydraulic lime based mixture labelled BV3

Material	Velocity in grouted part [m/s]	Velocity in ungrouted part [m/s]	Standard deviation in ungrouted part [m/s]	Velocity difference in grouted and ungrouted parts [m/s]
Fine-grained sandstone	3349,3	3331,5	44,1	17,8
Coarse-grained sandstone	3080,2	3121,0	105,9	40,7
Marlstone	1861,4	1928,5	191,4	67,2
Limestone	6511,9	6475,6	48,0	36,3
Mortar 1:5	1111,4	1236,0	31,1	124,6
Mortar 1:3	1229,8	1351,2	66,5	121,4

Tab. 4 - Results of ultrasonic measurements (ultrasonic signal velocity) of test specimens grouted with hydraulic lime based mixture with nanosuspension labelled BV7

Material	Velocity in grouted part [m/s]	Velocity in ungrouted part [m/s]	Standard deviation in ungrouted part [m/s]	Velocity difference in grouted and ungrouted parts [m/s]
Fine-grained sandstone	3197,1	3193,2	38,8	3,9
Coarse-grained sandstone	2557,7	2570,1	85,8	12,4
Marlstone	1737,7	1673,4	38,9	64,3
Limestone	6365,8	6387,6	153,3	21,8
Mortar 1:5	1093,4	1256,0	56,9	162,6
Mortar 1:3	1083,4	1188,1	67,7	104,8

Tab. 5 - Results of ultrasonic measurements (ultrasonic signal velocity) of test specimens grouted with epoxy resin based mixture labelled BP

Material	Velocity in grouted part [m/s]	Velocity in ungrouted part [m/s]	Standard deviation in ungrouted part [m/s]	Velocity difference in grouted and ungrouted parts [m/s]
Fine-grained sandstone	3436,0	3271,1	39,5	164,9
Coarse-grained sandstone	3094,6	3053,8	128,3	40,8
Marlstone	1819,7	1825,1	143,6	5,4
Limestone	6337,6	6349,8	143,6	12,2
Mortar 1:5	1184,1	1289,2	45,5	105,1
Mortar 1:3	1212,6	1248,3	100,3	35,7

Tab. 6 - Results of ultrasonic measurements (ultrasonic signal velocity) of test specimens grouted with organosilicate based mixture labelled BK

Material	Velocity in grouted part [m/s]	Velocity in ungrouted part [m/s]	Standard deviation in ungrouted part [m/s]	Velocity difference in grouted and ungrouted parts [m/s]
Fine-grained sandstone	3282,9	3120,5	166,1	162,3
Coarse-grained sandstone	2728,5	2675,2	42,7	53,3
Marlstone	2025,2	2016,5	175,4	8,7
Limestone	6377,0	6391,2	48,3	14,3
Mortar 1:5	863,3	1061,9	109,5	198,7
Mortar 1:3	1036,0	1086,8	115,1	50,8

Experimental evaluation of the use of ultrasonic methods based on comparison of ultrasonic signal transmission velocity in grouted and ungrouted test specimens showed:

- the penetration of lime-based grouting mixtures could be monitored especially in mortar test specimens and in the case of a mixture with nanosuspension also in the marl test specimens,
- the penetration of the epoxy-based grout can be monitored in fine-grained sandstone test specimens and mortar test specimens with a mixing ratio 1:5,
- the penetration of the grouting mixture based on organosilicate could be monitored in the test specimens of fine-grained and coarse-grained sandstone (however, in both cases the influence of the grouting on the velocity of the ultrasonic signal transmission was small) and further in the mortar test specimen with mixing ratio 1:3,
- there was a significant difference in the velocity of the ultrasonic signal passing through the monitored masonry materials and mortar mixtures. This difference is directly related to the material properties of the individual masonry components and can therefore be used to detect individual materials in a heterogeneous masonry structure. However, it also points out other possible obstacles in the use of ultrasound diagnostic methods.

Performed evaluation of the use of ultrasonic methods can be summarized as follows:

- the main prerequisite for the application of ultrasonic methods is to ensure perfect contact of the transducer with the investigated structure. In case of partial contact between the transducers and the masonry structure, the results may be subject to significant error,
- results may also be affected by the heterogeneity of the structure under investigation. Even specimens of the same material used in the experimental evaluation showed differences in measured values,
- differences in the measured values were observed even within one specimen due to internal inhomogeneities (especially cracks and microcavities).
- small differences in physico-mechanical properties of the grouting mixtures and the grouted structure (especially when using hydraulic lime based grouting mixtures) limits the possibility of reliable determination of the penetration of grouting mixture into the masonry structure.

CONCLUSION

Based on the experimental verification of the possibility of using non-destructive diagnostic thermovision and ultrasonic methods and subsequent evaluation of the obtained results, these methods cannot be unambiguously recommended as a reliable way of determining the penetration of the grouting mixtures into the masonry structure. In the case of infrared (thermal) imaging, apart from other parameters (surface properties of the injected structure, ambient temperature, etc.), the relatively small (difficult to measure) temperature difference of the grouting mixture and the grouted body appears to be the main obstacle. Ensuring bigger temperature difference is possible by heating the grouting mixture just prior to grouting. In such a case, penetration of the grouting mixture into the grouted masonry is detectable better. However, it is necessary to carefully consider the heating of the grouting mixture with regard to its composition so as not to affect its properties (especially in the case of epoxy resins and organosilicates). In case of ultrasonic methods it is necessary to ensure perfect contact of measuring probes (sending and receiving) with the surface of the measured structure. This can be rather complicated and sometimes even impossible, especially in case of historic masonry. The resulting measurements can be significantly influenced by this fact. The small difference in material properties of grout mixtures and grouted masonry structures, especially when taking into account the requirement to ensure their maximum compatibility in terms of heritage preservation (physico-mechanical and chemical compliance), also significantly limits the possibility of reliable detection of grouting penetration into masonry.

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