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THE EFFECT OF MOISTURE ON SIGNIFICANT MECHANICAL CHARACTERISTICS OF MASONRY

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Abstract. Experimental and laboratory research into residual physical and mechanical characteristics of historical masonry structures (GAČR 2008; Witzany *et al.* 2008), in particular the determination of residual strength and modulus of elasticity in compression, included research oriented towards the effect of moisture and porosity on the respective characteristics of masonry units – bricks, sandstone and arenaceous marl. Partial results published in (Witzany *et al.* 2008) and in this paper testify to the need for further research into the effects of porosity, moisture and chemism on the development of characteristics of building materials applied on historical structures.

Keywords: masonry structures, moisture, porosity, chemism, residual strength in compression, modulus of elasticity in compression, bricks, sandstone, arenaceous marl.

1. Introduction

Despite a relatively extensive research into masonry structures, the issue of a reliable determination of the load-bearing capacity of existing, particularly historical masonry structures is still waiting for solutions with adequately satisfactory results. The decreasing reliability of the determination of physical and mechanical characteristics of historical masonry must be accompanied by a growing difference between the experimentally specified ultimate strength and the actual loading of the masonry structure. The determination of residual mechanical characteristics of historical, mainly composite and stone, masonry provides results that are mostly of informative value only – due to the heterogeneity of masonry, the variability of the properties of its different components, irregularity of walling, the distribution of moisture content and low reliability of the results obtained by non-destructive methods of the determination of compressive strength of masonry units and mortars and it is applicable only in cases of sufficient reserves in the load-bearing capacity of masonry in relation to its actual loading (which, because of the scatter of the respective characteristics, the workmanship of walling and the degree of masonry disintegration, should not exceed 30% of the ultimate strength of masonry as determined by non-destructive methods).

Of special notice are, in particular, masonry constructions with a high percentage of building-stone blocks of sedimentary rock (Kotlík *et al.* 2000; Pavlík *et al.* 2007; Šrámek 1992). Moisture content in the porous system of these materials is the subject of numerous studies (Hall, Hoff 2002; Nwaubani *et al.* 2000; Kutílek 1984; Půbal, Myška 2008). Distribution and integral curves of pores are often a basis for the analysis of moisture content in relation to significant mechanical characteristics. Like building-stone blocks of sedimentary rock, burnt bricks are also characterized by changes in their physical and mechanical properties due to moisture effects depending on their pore distribution and production technology (Kotlík *et al.* 2000; Hanykýř *et al.* 2009). Due to moisture effects, apart from damage caused by e.g. salt crystallization, freeze-thaw cycles, bricks are also exposed to hydrolysis of the glass phase of the matrix. The hydrolysis process is very slow and continuous in moist masonry.

2. The effect of moisture, porosity and chemism on compressive strength and modulus of elasticity of masonry units

The research of the effect of moisture on the values of the compressive strength f_b of masonry units has manifested a significant influence of moisture on the compressive strength and modulus of elasticity of porous building materials.

Fig. 1 displays experimentally determined relationships of the compressive strength f_b, the modulus of elasticity E for bricks obtained from core boreholes sampled from historical masonry in the pore saturation state. Fig. 2 shows diagrams expressing the number, distribution and size of pores for individual types of bricks determined by means of mercury porosimetry.

Based on the analysis of the results of experimental research, with regards to the limited number of samples, we may state that the effect of moisture content expressed by the saturation degree of the porous system on the compressive strength fb and the modulus of elasticity E of bricks ranging in the interval from 0% to 100% of saturation is a variable depending, apart from the saturation degree, also on the size and frequency of occurrence of individual pores. The results of research indicate that the effect of moisture on the investigated characteristics of bricks (f_b, E) is more prominent in bricks with a porous system with a significant proportion of pores sized d∈ (0.01–1) µm as compared to bricks with a porous system containing a significant proportion of pores sized d∈ (1.0–10) µm.

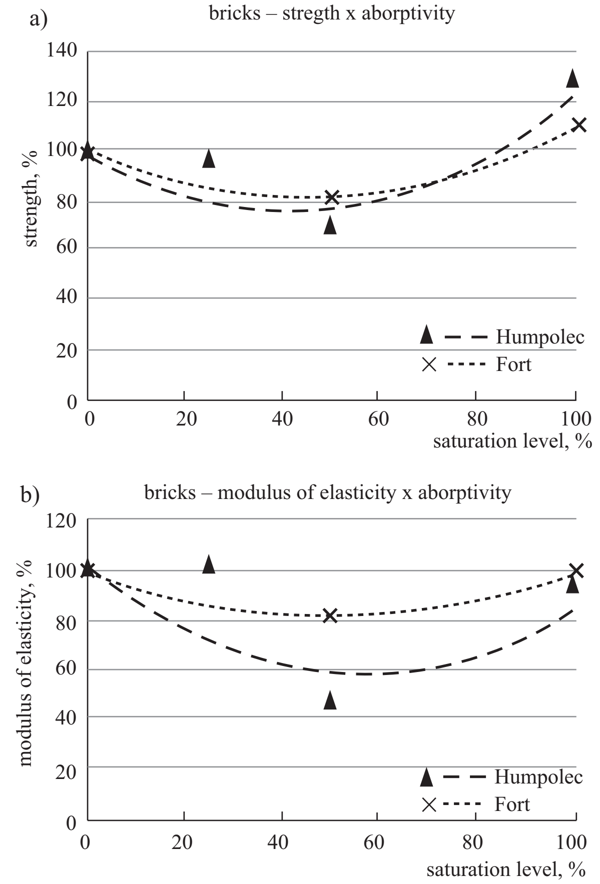

Fig. 1. Relationship of compressive strength f_b and modulus of elasticity E on saturation degree determined from core boreholes Ø 35 mm and ca 70 mm in length

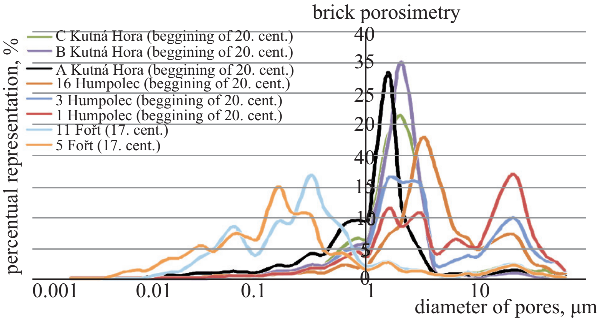

Fig. 2. Size and distribution of pores – bricks specified by mercury porosimetry

Fig. 3 displays experimentally obtained charts of f_b x w and E x w relationships for sandstone and arenaceous marl. Fig. 4 displays the pore distribution in sandstone and arenaceous marl. In the case of sandstone, the respective relationships clearly show that sandstones with a greater proportion of pores sized d∈(10–100) mm react more vividly, showing a more progressive drop in the compressive strength f_b and the modulus of elasticity E with the growing pore saturation degree, as compared to the sandstone with a greater proportion of pores sized d∈ (0.1–1) mm. This different effect of the pore saturation degree by the liquid phase of moisture in bricks and sandstone is, among other things, caused by a different structure of both masonry units. Whereas the brick structure created by burnt brick clay is relatively compact, the sandstone structure is predominantly composed of two phases – individual grain types creating a matrix whose gaps are filled up with a binder as the second phase. Together with the original structure, the liquid phase of moisture creates a multi-phase structure (system) in which the mutual interaction of individual phases affects the resultant compressive strength and modulus of elasticity (compressibility). The understanding of this mechanism of the mutual interaction of a multi-phase structure with a sudden change in characteristics at the interface of individual phases requires relatively demanding mathematical modelling.

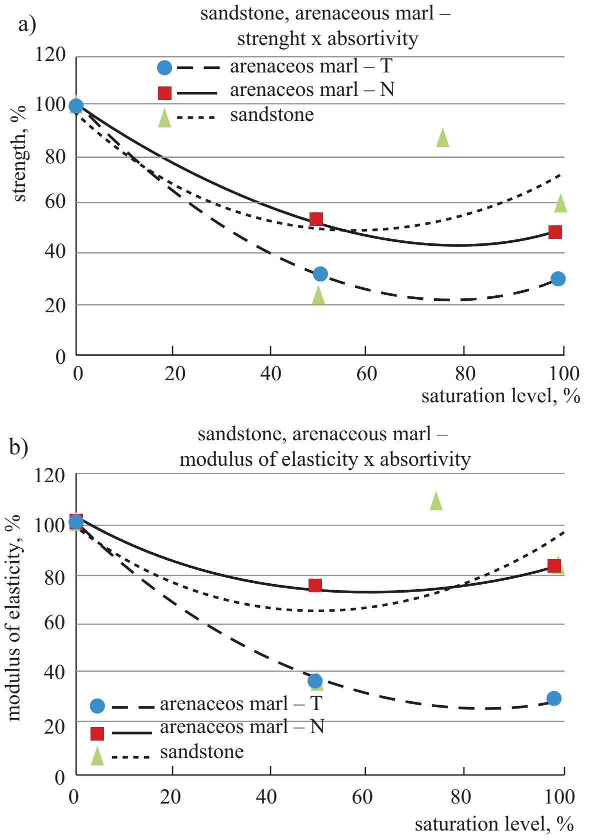

Fig. 3. Relationship of compressive strength f_b and modulus of elasticity E of sandstone and arenaceous marl on saturation degree determined from core boreholes Ø 35 mm and ca 70 mm in length

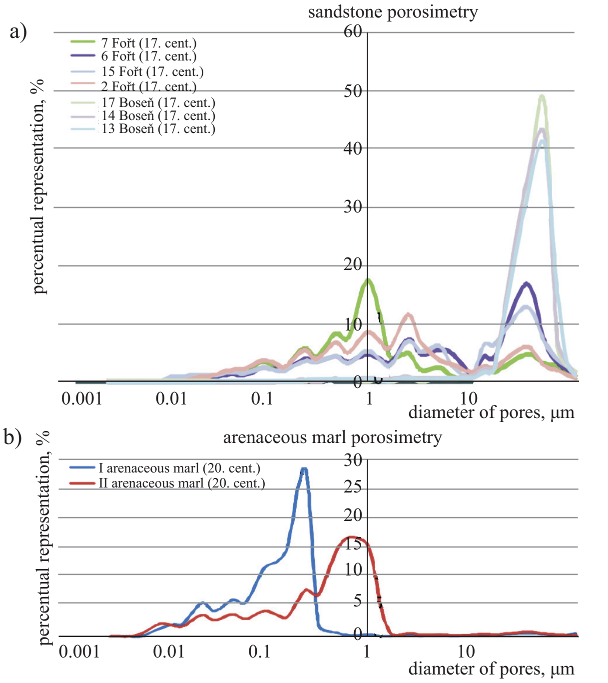

Fig. 4. Pore size and distribution – sandstone, arenaceous marl specified by mercury porosimetry (Weishauptová 2008)

The facts above are in accordance with the results of experimental and laboratory research performed on materials sampled from historical structures (Witzany *et al.* 2008), which are illustrated in Fig. 5 and Fig. 6, manifesting, unlike bricks, a significant drop in the compressive strength f_b and the modulus of elasticity E of sandstone with growing porosity (Witzany, Čejka 2008). A similar drop in the respective parameters was also monitored in arenaceous marl.

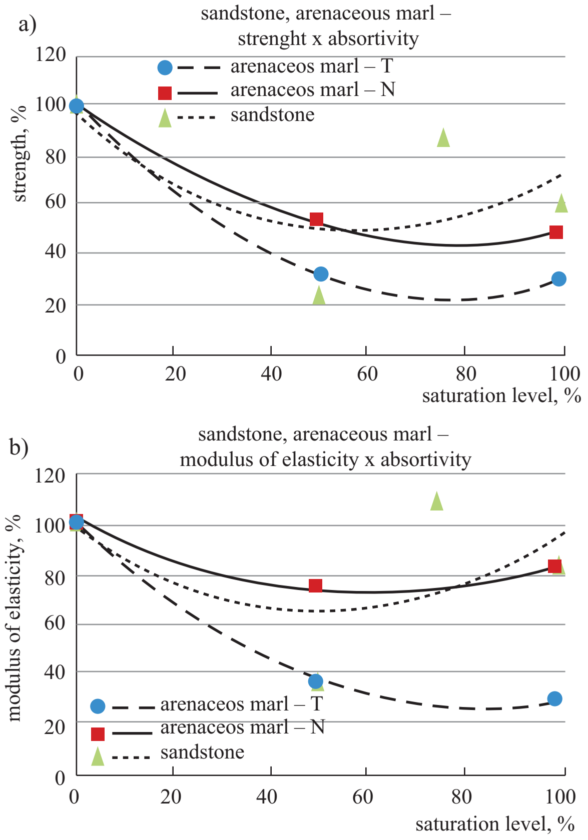

Fig. 5. Relationship of modulus of elasticity in compression E and compressive strength f_b on porosity (brick, sandstone, arenaceous marl)

The relationship pattern of the modulus of elasticity in compression E and the compressive strength f_b on the total proportion of pores sized 25–7500 nm and pores greater than 7500 nm clearly shows differences in the respective relationships for bricks, sandstone and arenaceous marl. The patterns of the respective relationships in particular manifest a dramatic effect of the size and proportion of macropores and coarse pores on the strength f_b and the modulus of elasticity E.

The partial results of the effect of salinity (salt contents in pores) obtained to-date show that the salts contained in the porous system not only cause chemical degradation processes, resulting, in a longer time

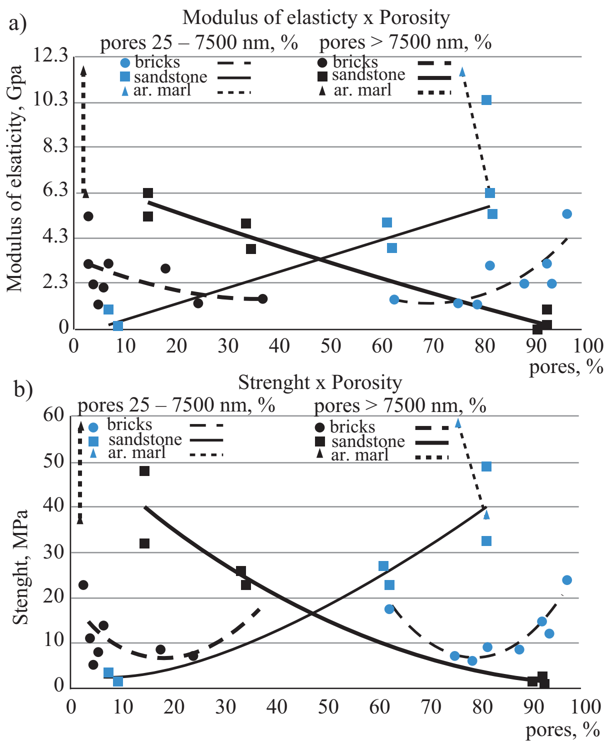

Fig. 6. Relationship of modulus of elasticity in compression E and compressive strength f_b on pore sizes and their proportion on total porosity

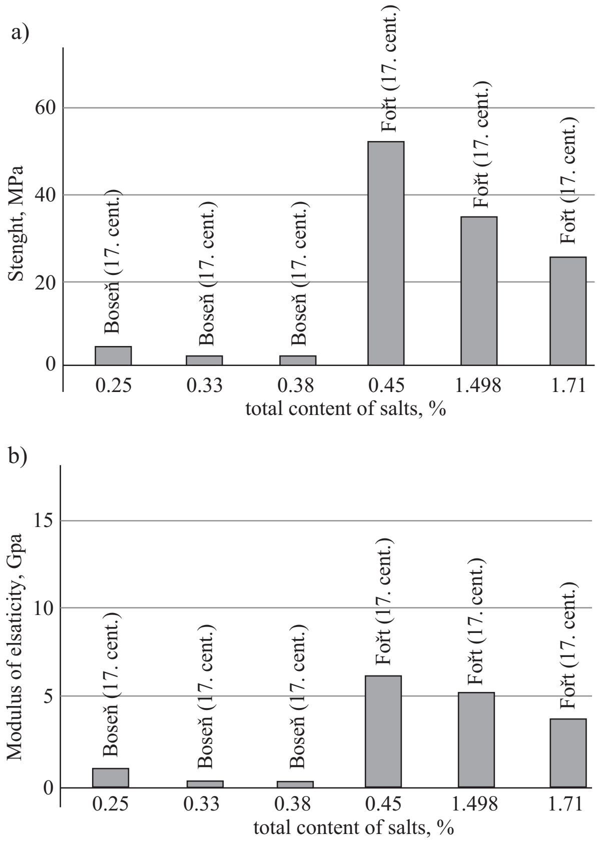

Fig. 7. Relationship of compressive strength and modulus of elasticity of bricks, sandstone and arenaceous marl on total salt contents in the porous system (according to Wasserbauer)

perspective, in the reduction of the binder component content, particularly in building materials of sedimentary rock, but also immediately affect the values of the strength f_b and the modulus of elasticity in compression E (Fig. 7).

3. The effect of moisture content changes along the cross section of an extruded unit on compressive stress redistribution

In terms of the requirement for mechanical resistance and stability, an issue of relevance is the assessment of the structural qualification of particularly load-bearing masonry structures with increased moisture contents caused e.g. by extraordinary effects (floods, leaking pipes etc.), or insufficient protection from groundwater and rainwater.

A change in the moisture content along the cross section of an extruded masonry unit (pillar, wall) is accompanied by a change in the modulus of elasticity E and the strength f_{uc} along the unit's cross section. A change in the rigidity $E_i U_i$ along the cross section of an extruded unit results in the redistribution of internal forces – in the "pouring" of normal forces into the parts of the cross section with a higher modulus of elasticity from the parts where the modulus of elasticity has fallen. At the same time, shear forces arise between the parts of the unit's cross section with different values of the modulus of elasticity E (rigidity E^*U) and thus with a tendency towards a different primary deformation ensuring the unit's integrity and preventing its separation. The exceeding of the shear strength of masonry may lead to the appearance of vertical cracks. The disturbance of the equilibrium state of an extruded unit (the equilibrium of internal and external forces) due to a change in the distribution of the rigidity along the unit's cross section E^*U, or a drop in the strength f_{uc} due to the effect of moisture in cases where the load-bearing structure possesses sufficient reserves in load-bearing capacity is limited to a mere redistribution of internal forces. In the cases where sufficient reserves in the load-bearing capacity no longer exist in the masonry structure due to e.g. degradation processes, the disturbance of the equilibrium state due to changes in the moisture content w and the induced redistribution of compressive stresses may cause an integrity failure or the exceeding of the ultimate bearing capacity of a masonry unit.

Numerical analyses of masonry pillars 600 mm in thickness made of bricks, sandstone and arenaceous marl exposed to continuous loading on the upper edge proved that due to a non-uniform distribution of moisture along the cross section of extruded masonry pillars ($w \in (0\%; 20\%)$), contrary to the constant moisture content pattern (w = const.), the equilibrium state is disturbed and the normal compressive stresses are redistributed along the cross section of the masonry pillar (Fig. 8).

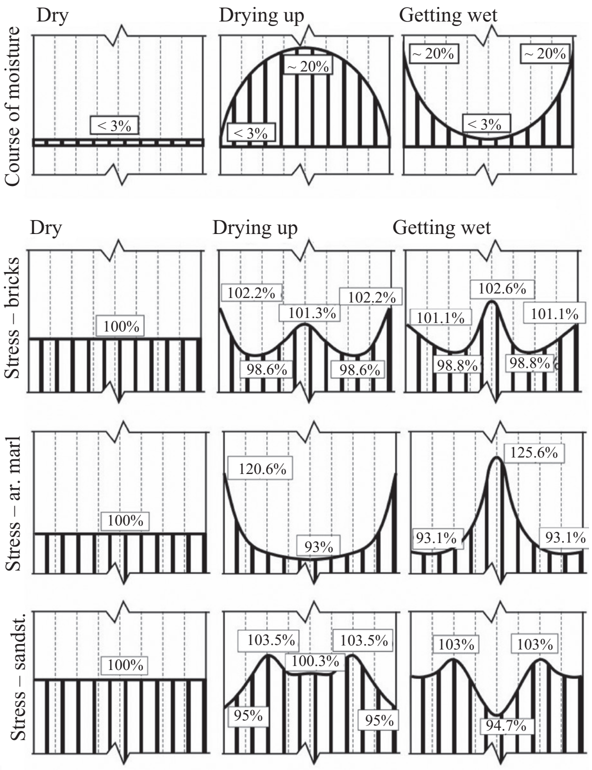

Fig. 8. Idealized moisture profiles of a wetting and drying masonry unit, The pattern of normal stress in compression corresponding to an idealized moisture content pattern along the cross section – stone masonry (arenaceous marl, brick masonry, sandstone)

4. The effect of moisture on the load-bearing capacity and deformation characteristics of masonry

Experimental research of the effect of moisture on the load-bearing capacity and rigidity of masonry pillars has manifested a prominent drop in the load-bearing capacity of extruded masonry pillars with their growing moisture content up to a value of 60% at a moisture content of 15.81% by weight, as compared to their 100% load-bearing capacity at a 3.5% moisture content by weight (Fig. 9).

A relative drop in the experimentally determined load-bearing capacity of masonry in compression in relation to the masonry moisture content is in a good accord with the relative drop determined using the regulations for reconstruction design currently in force as well as the results of experimental research of the effect of moisture on the strength R and the modulus of elasticity E of P15 and P30 bricks (Witzany *et al.* 2003; Čejka 2002), in the moisture content interval $w_{hm} \in (3.5\%; 15\%)$ (Fig. 10).

The comparison of vertical and horizontal deformations of extruded masonry pillars with different moisture contents of masonry ($w_{hm} \in (1.36\%; 15.81\%)$) clearly shows a progressive growth in the deformations (strain) of masonry pillars with high moisture contents by weight (Figs. 11, 12). Fig. 13 manifests the effect of increased masonry moisture contents on a drop in the masonry rigidity (growth in deformations, additional pushing) by up to 80 to 90% with a simultaneous drop in the masonry strength by up to 40% (Fig. 9) at a masonry moisture content of 15.81% by weight as compared to the masonry moisture content of 3.56% by weight (Witzany *et al.* 2009).

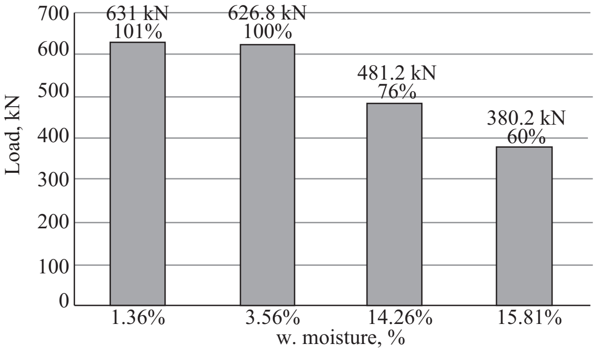

Fig. 9. Comparison of ultimate bearing capacity of masonry pillars in relation to moisture content (Witzany *et al.* 2003) of P15, P30 bricks

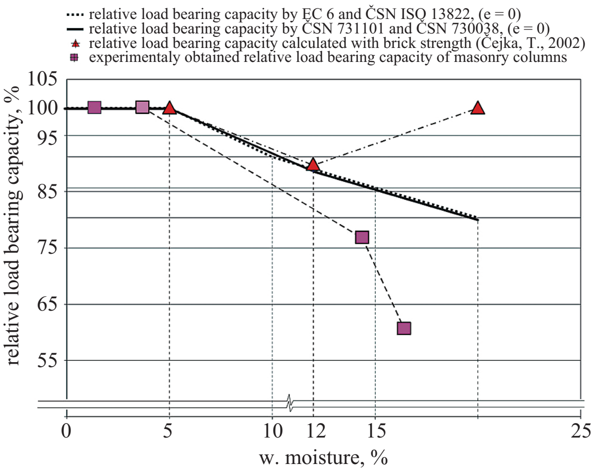

Fig. 10. Comparison of load-bearing capacity of masonry in compression determined experimentally (Witzany *et al.* 2003), using regulations for reconstruction design currently in force and using experimentally determined relationships R x w for P15 bricks (Čejka 2002)

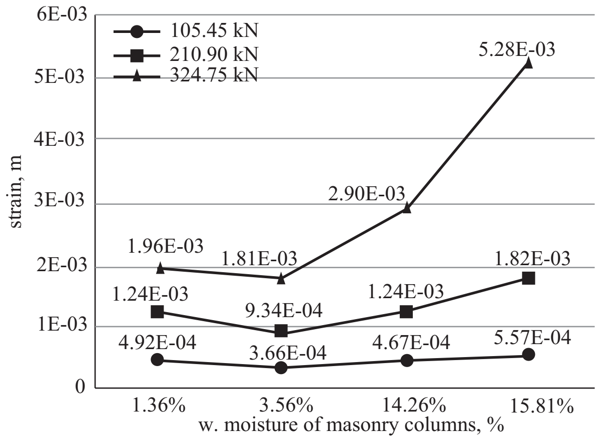

Fig. 11. Comparison of experimentally determined vertical deformations of extruded masonry pillars for selected levels of loading with compressive force and masonry moisture content

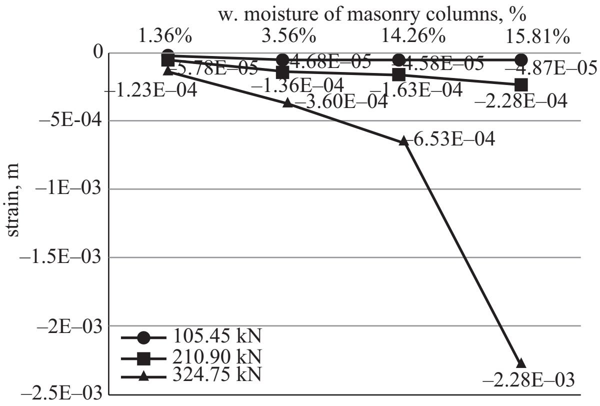

Fig. 12. Comparison of experimentally determined horizontal deformations of extruded masonry pillars for selected levels of loading with compressive force and masonry moisture content

5. Summary

Research into residual characteristics of selected types of masonry units used in historical structures has manifested a need for further theoretic and experimental research of the effects of moisture, porosity and chemism on their physical and mechanical characteristics. Among serious findings there is, in particular, a drop in the strength and modulus of elasticity of masonry units of sedimentary rock – mainly sandstone and arenaceous marl, i.e. masonry units applied in a large scope in historical structures built in the early Middle Ages due to their availability and good workability (e.g. St. George's Basilica, St. Vitus's Cathedral, Charles Bridge). Without the necessary knowledge in this area, adequate reliability and durability of structural interventions implemented within repair or reconstruction projects of mainly listed monuments where masonry structures had been exposed to long-term effects of moisture cannot be guaranteed.

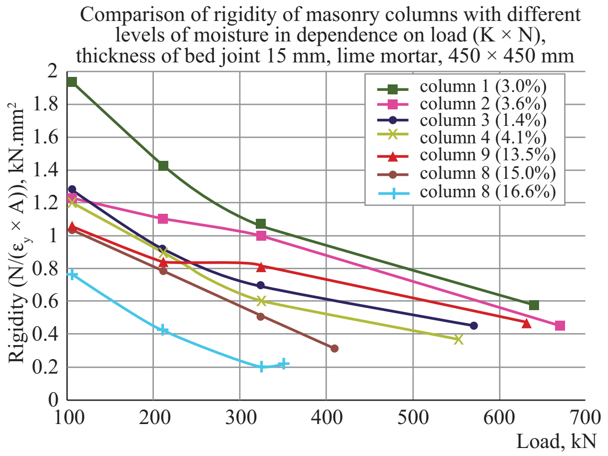

Fig. 13. Comparison of rigidity of masonry pillars for various moisture content values in relation to loading

In connection with the reconstruction of historical structures, the models of homogenized masonry are presently applied in numerous cases. Numerical analysis based, on the one hand, on mathematical models and, on the other hand, on insufficiently accurate material and physical models, may lead to erroneous conclusions, but it may also be the cause of a faulty reconstruction concept and a subsequent appearance of structural failures and defects. Insufficiently cogent boundary conditions and input parameters describing the physical and mechanical characteristics of masonry and its individual components cannot be overrated by the application of "the most sophisticated" numerical model.

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DRĖGMĖS ĮTAKA SVARBIAUSIOMS MECHANINĖMS MŪRO CHARAKTERISTIKOMS

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Santrauka. Straipsnyje pateikti eksperimentiniai ir laboratoriniai tyrimai nustatant tokias fizines ir mechanines istorinių pastatų mūro charakteristikas (GAČR 2008; Witzany, Čejka, Zigler 2008), kaip faktinis (liekamasis) mūro gniuždomasis stipris bei gniuždomojo tamprumo modulis, įvertinant drėgmės ir poringumo įtaką mūrui (plytoms, smiltainiui ir mergeliui). Dalis rezultatų publikuota Witzany, Čejka, Zigler (2008) straipsnyje. Jame aiškiai parodytas tolesnių tyrimų tikslingumas siekiant išplėtoti istorinių pastatų mūro svarbiausių charakteristikų nustatymo metodus, įvertinant drėgmės, cheminių medžagų (pvz., druskų kristalizacijos) ir poringumo įtaką.

Reikšminiai žodžiai: mūrinės konstrukcijos, drėgmė, poringumas, faktinis (liekamasis) gniuždomasis stipris, tamprumo modulis, plytos, smiltainis, mergelis.

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