TESTING MECHANICAL PROPERTIES OF NATURAL STONES USED AS A BUILDING MATERIAL

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The aim of the paper is further presentation of some destructive and non-destructive methods for investigation of mechanical properties of natural stone quarried and used as a building material in Bohemia in the past. Tested samples were made both from virgin material from existing quarries (e.g. sandstone from Hořice) and from material acquired from historical constructions (various sandstones from the Charles Bridge in Prague), which was built-in for a long time. The flexural strength, the compressive strength and Young modulus were obtained from basic destructive tests. Before performing these tests the identical samples were investigated non-destructively by ultrasound and so called peeling test so that the two ways of testing could be compared in the end.

Keywords : *mechanical properties, non-destructive testing, natural stone, historical buildings, ultrasound*

1. Introduction

Historical buildings are a part of the cultural heritage and have to be maintained as other structures to survive for next generations. Diagnosis of structures works not only with structure condition from the static point of view, but also with the condition of the used material. Material properties are influenced e.g. by loading of the structure or by the environment. Preliminary diagnosis operates with both destructive and non-destructive testing. Methods of non-destructive testing are mostly easy to handle and could be done in-situ; they do not leave any damage and give quick results. The results should be taken as a primary estimation. Destructive testing operates with samples cut from the structure. The results are exact, but the process is more time-consuming and leaves marks at the structure. Both ways of testing have their advantages and it is very useful to combine them.

2. Experimental work

2.1. Material specification

Various types of sedimentary rocks, which have been found in the Prague region in the middle ages, were tested. Virgin samples from existing quarries have been investigated so that new material could be compared with material already used in the structure; they were made from marlit stone, so called opuka stone, travertine and fine grained quartz sandstone from Hořice. Opuka stone is one of the most typical historical materials used in Prague in the middle ages and is composed of clay and calcareous elements with organic components (sponge and foraminifer shells). Horizontal layering is conditioned by lamination, which

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manifests itself as alteration of lighter and darker laminae, 1–2 mm thick. The average value of bulk density is 2080 kg m^{-3} and porosity of 'opuka' stone is 21.28 %.

In the past, travertine was generally used for monumental structures because it resists weathering very well. Nowadays it is one of the most popular natural stones used as a decorative element of facades. Travertine is composed from bifurcated clusters of micrite (calcite) and small quartz clasts have been identified inside the stone as accessories. Pores distribution resulting from mercury porosimetry shows that there is not one dominant characteristic pore diameter but it varies from 10 μm to 100 μm. The origin of pores is connected with the decomposition of organic material buried in the created sediment. The average value of bulk density is 2530 kg m^{-3} and the porosity of travertine is 21.28 %.

Sandstone from the Hořice quarry is often used for reconstructions of historical buildings in the Prague region. Quartz and kaolinite are the main mineralogical components of the stone; it also contains light fragments of clay in some places. There are flakes of mica as an accessory in the stone. Cement is composed of kaolinite. The average value of bulk density is 1810 kg m^{-3} and the porosity of Hořice sandstone is 25.84 %.

The other sandstone samples were made from stone blocks taken from the Charles Bridge. The light pinkish-grey hard porous arkose is coarse grained sandstone from Žehrovice. Clast's main component is quartz; the other participating elements are fine-grained quartzite, siltstones and feldspar. There are heavy metals and flakes of mica as accessories in the stone. The average value of bulk density is 2110 kg m^{-3} and porosity of arkose is 16.59 %.

Hard sandstone with ferruginous cement from the Petřín quarry is dark brown quartz stone with claystone fragments as accessories. Clasts are composed of quartz, 'iron quartz' and siltstones. Stratums were obvious at the samples. The oldest part of the cement, limonite-goethite, acts as a corrosion sealant covered by the other cements – kaolinite, apatite, quartz and potassium feldspar. The average value of bulk density is 2020 kg m^{-3} and porosity of sandstone is 24.84 %.

Middle grained crumble porous sandstone from the Nehvizdy quarry has horizontal layering conditioned by an alternation of middle grained lamins and fine grained lamins. The main component of both clasts and cement is quartz. Yellow coloured cement is also made of quartz, here in the form of discontinuous coat on the surface of grains. The average value of bulk density is 1940 kg m^{-3} and porosity of sandstone is 24.33 %.

2.2. Specimens and test conditions

The initial shape and size of test specimens in the form of beams was chosen according to the specifications for testing of mechanical characteristics. Therefore, the basic specimen dimensions were 50 mm × 50 mm × 300 mm as the European Standard EN 12372:2006 dealing with flexural strength requires [1]. The test specimens were manufactured within standard tolerance limits and dimensions were measured with accuracy of 0.1 mm (as required by EN 13373 [2]). Compression test specimens were grinded according to the standard tolerance (ČSN EN 1926 [3]) from remaining beam halves after bending tests. Dimensions of these cubes were 50 mm × 50 mm × 50 mm, also measured with accuracy of 0.1 mm.

All the specimens were tested in the ITAM laboratories with environment basically specified by temperature and relative humidity. Specimens themselves were conditioned for two physical states – dry conditions and fully water saturated conditions; described in the

Czech Standard ČSN EN 1936 [4]. Before testing the specimens were stored in a climatic chamber (for standard tests in 'dry conditions') at 70 °C ± 5 °C until the equilibrium state of moisture content was reached, which was measured by weighing in the intervals of 24±2 hours with accuracy of 0.1 g. At the equilibrium state the mass did not change more than 0.1 % of the mass of the test specimen. After drying and before testing specimens were kept in an environment with the temperature of 20 °C ± 5 °C and a very low humidity until the temperature was balanced, the test was then carried out within 24 hours. In [5] phenomena of moisture transport in building materials and comparative study of various physical methods of its determination has been evaluated.

Fully water saturated conditions were arranged by storing the specimens in a container with water until all the pores were filled with water. The water absorption was natural because no vacuum or negative pressure was used. Specimens were also weighed in the intervals of 24 ± 2 hours with accuracy of 0.1 g and at fully saturated state it was assumed, that the mass does not change more than 0.1 % of the mass of test specimen.

2.3. Test set up and measured quantities

Ultrasonic tests were carried out on basic specimens before bending, because following the orientation of sedimentation layers and controlling an assumed direction of ultrasonic transmission is easier on the beams than on the cubes. Non-destructive peeling test that focuses mainly on near surface cohesion characteristics was made on beams before bending, too.

The ultrasonic speed propagation was measured in longitudinal direction, i.e. ultrasound propagation goes along the beam. The device used for testing was UKS 12 produced by Geotron Elektronik. It composes of a generator of electric impulses, two transducers (a transmitting one and a receiving one) and microsecond timer. The timer has a screen where a received wave is shown so that the time of wave's passaging through the sample could be read. Frequency used for measurements was 20 kHz. Test conditions followed the Czech technical standard ČSN EN 14579: Natural stone test methods – Determination of sound speed propagation (a Czech version of the European Standard EN 14579:2004 [6]) and composition is shown on Fig. 1.

Ultrasound velocity c [$\times 10^3\,\mathrm{km\,s^{-1}}$] has been calculated according to (1)

$$c = \frac{L}{t} \tag{1}$$

where L [m] is the distance between transducers and t [μs] is the measured time.

Dynamic modulus of elasticity E_{dyn} [$\times 10^{-3}$ GPa] could be calculated from ultrasound speed propagation c and bulk density ϱ [$\mathrm{kg\,m^{-3}}$] of the material [7], see (2) below.

$$E_{\mathrm{dyn}} = c^2\,\varrho\ . \tag{2}$$

Peeling test is used for determination of material's surface strength. It can be used for surface degradation and/or for assessment of surface properties improvement by consolidation agent application [8]. During the test a set of adhesive strips (made of pressure-sensitive tape) is in sequence attached and then removed from the same surface area and the weight of the removed material is determined using laboratory scales. The process model expects

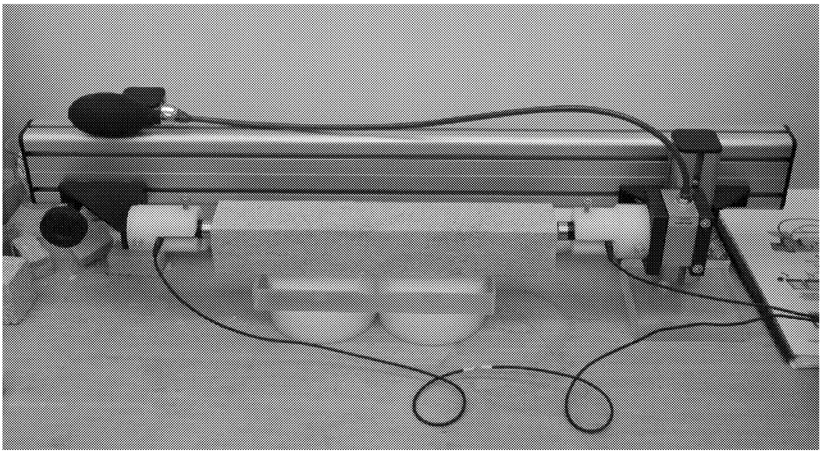


Fig.1: Tested beam sample with transmitting transducer (left) and receiving transducer (right)

some asymptotic value of the removed material to be reached by the end of the test (and denoted as A [g]). This value characterizes surface strength and should be related to the material's overall strength. The values of A should be indirectly proportional to material's strength.

Peeling was studied using double side opaque plastic tape 18 mm in width and 40 mm in length (Doppelband Stark 50 kg). The strips were stuck to the surface and smoothed with gentle finger pressure. Thereafter they were removed by pulling at an angle of 90°, and weighed on a balance with sensitivity of 0.0001 g, for better illustration see Fig. 2. The peeled off material was determined as the difference between the weight of the tape after removal from the surface and the weight of the clean tape before the application. One measurement set consisted of 10 strips.

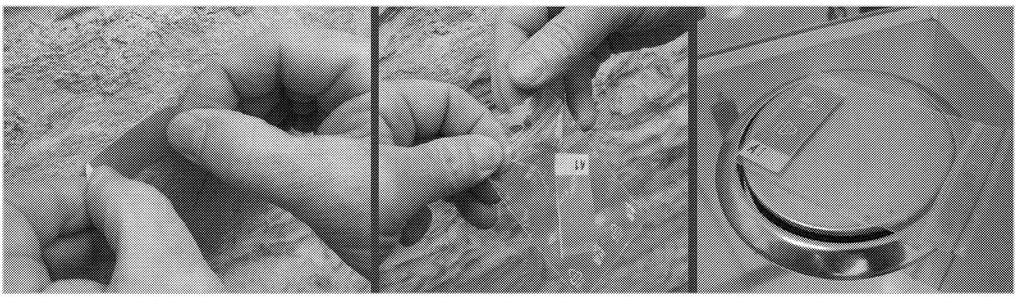


Fig.2: Basic steps of peeling test; a) strip being attached to the surface, b) saving removed material, c) weighing with laboratory scales

If the released material decreases with the increasing number of peelings, and the results approach a nonzero value, nonlinear regression of the measured data is used for each place where the measurements were made. The form (3) describing the sequence of weights of the removed material $m(n)$ has been suggested and the explanation of constants A, B and C is demonstrated on Fig. 3.

$$m(n) = A + B\,\mathrm{e}^{-C\,n} . \tag{3}$$

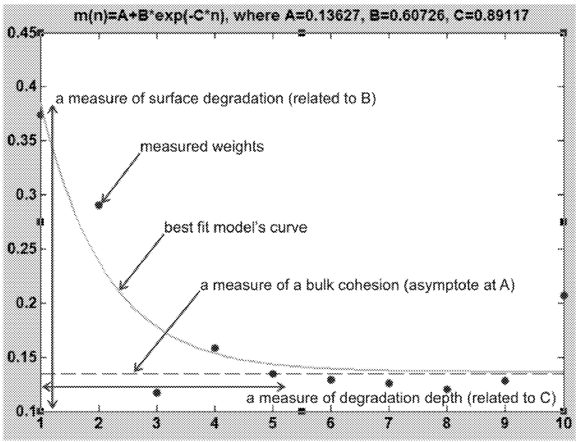


Fig.3: Typical evaluation diagram of peeling test

The flexural strength R_{tf} [MPa] is represented by the normal stress σ_{x} [MPa] in marginal parts of the cross section induced by the bending moment M_{y} [Nmm]. The inner force is caused by maximal force $F_{\max}$ [N] at the moment of damage. In final calculations used in ČSN EN 12372: Natural stone test methods – Determination of flexural strength under concentrated load (a Czech version of the European Standard EN 12372:2006), see equation (4) below, the moment of inertia I_{y} [mm^4] represents the dimensions of the specimen that were measured with accuracy of 0.1 mm. The z-variable [mm] with zero value in a centre of gravity represents a position of an extreme stress within the cross section. In the equation (4) l [mm] is the distance between supports, b [mm] is the width and h [mm] is the height of a cross section.

$$\sigma_{\mathrm{x}}(z) = \frac{M_{\mathrm{y}}}{I_{\mathrm{y}}}\, z \quad \rightarrow \quad R_{\mathrm{tf}} = \frac{\frac{1}{4}\, l\, F_{\max}}{\frac{1}{12}\, b\, h^3}\, \frac{h}{2} = \frac{3\, l\, F_{\max}}{2\, b\, h^2}\ . \tag{4}$$

Loading device used for testing was an electromechanical load frame 'WOLPERT' with the maximum force capacity of 100 kN, a load cell Lukas 10 kN and a deformation sensor HBM LVDT μm. Test arrangement is apparent in Fig. 4, the crosshead speed was 0.15 mm/min. All the tests kept to the conditions given by the Czech technical standard ČSN EN 12372: Natural stone test methods – Determination of flexural strength under concentrated load (a Czech version of the European Standard EN 12372:2006).

Young's modulus of elasticity E [MPa] has been calculated according to (5); ΔF [N] and Δu [mm] are read from line approximating the linear part of working diagram (area from $0.2\, F_{\max}$ to $0.5\, F_{\max}$).

$$E = \frac{\Delta F\, l^3}{48\, I_{\mathrm{y}}\, \Delta u}\ . \tag{5}$$

The compressive strength R_{c} [MPa] is represented by normal stress σ_{x} [MPa] caused by maximal force $F_{\max}$ [N] at the moment of damage operating on area A [mm^2] defined by base dimensions a [mm] and b [mm], see (6) below. Base dimensions were measured with accuracy of 0.1 mm. Calculation is used in ČSN EN 1926: Natural stone test methods –

Determination of uniaxial compressive strength (a Czech version of the European Standard EN 1926:2006).

$$N_x = \frac{\sigma_x}{A} \quad \rightarrow \quad R_c = \frac{F_{max}}{A} = \frac{F_{max}}{a\,b} \; . \tag{6}$$

Loading devices used for testing were a servohydraulic MTS 250 load frame (load cell MTS 250 kN) and an electromechanical load frame 'WOLPERT' of the maximum force capacity of 100 kN, (a load cell MTS 100 kN). Test arrangement is apparent in Fig. 4 and the crosshead speed was 0.45 mm/min. All the tests keep to the conditions given by the Czech technical standard ČSN EN 1926: Natural stone test methods – Determination of uniaxial compressive strength (a Czech version of the European Standard EN 1926:2006).

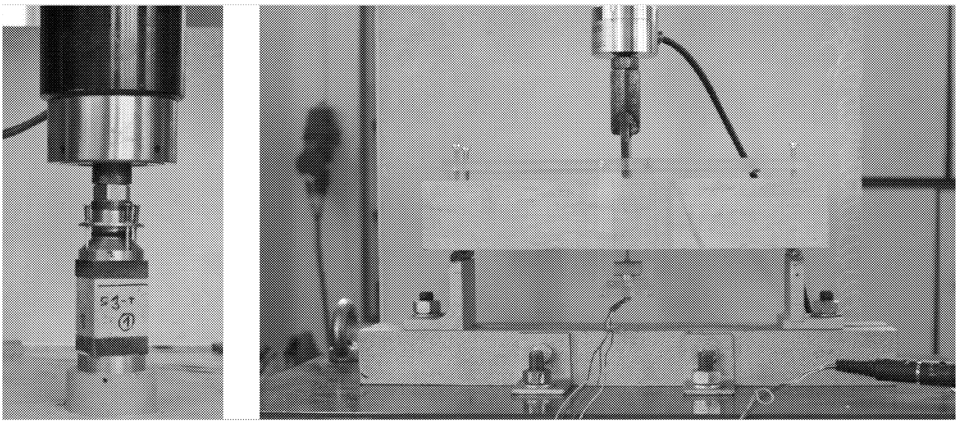


Fig.4: Loading arrangement for a) compressive strength, b) flexural strength

2.4. Results

Basic mechanical properties have been evaluated by both destructive and non-destructive methods for two conditions of the specimens. In Tab. 1 the results are summarized for dry samples, peeling test included, and in Tab. 2 are the results for fully saturated samples.

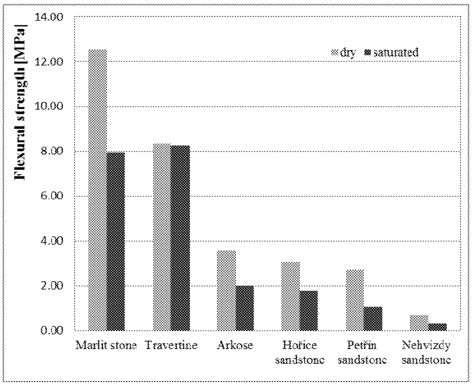
Stone dry samples	Flexural strength R_{ft} [MPa]	Compressive strength R_c (average value) [MPa]	Peeling test A ×1000 [g]	Ultrasound speed propagation (longitudinal direction) [km/s]
Marlit stone	12.55	52.50	2.04	3.70
Travertine	8.34	51.81	1.46	5.14
Arkose	3.58	26.70	3.10	2.64
Hořice sandstone	3.06	23.59	6.22	2.74
Petřín sandstone	2.72	19.37	1.73	2.93
Nehvizdy sandstone	0.68	7.93	63.07	1.83

Tab.1: Summary of the results for dry material

About five samples of each material for each condition have been tested. The average values were used to create final comparative diagrams. It has been observed that the dry samples were more resistant to mechanical loading than the saturated samples. Demonstration of the situation is in Fig. 5; both flexural and compressive strength was higher for the dry samples.

Stone saturated samples	Flexural strength R_{ft} [MPa]	Compressive strength R_c (average value) [MPa]	Ultrasound speed propagation (longitudinal direction) [km/s]
Marlit stone	7.97	47.11	3.21
Travertine	8.27	39.80	5.38
Arkose	2.02	19.45	1.90
Hořice sandstone	1.80	22.76	2.19
Petřín sandstone	1.06	12.96	2.62
Nehvizdy sandstone	0.33	12.54	1.42

Tab.2: Summary of the results for fully saturated material



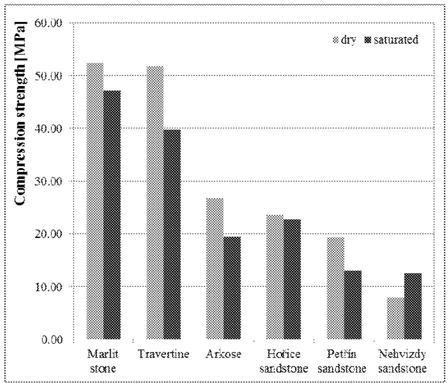
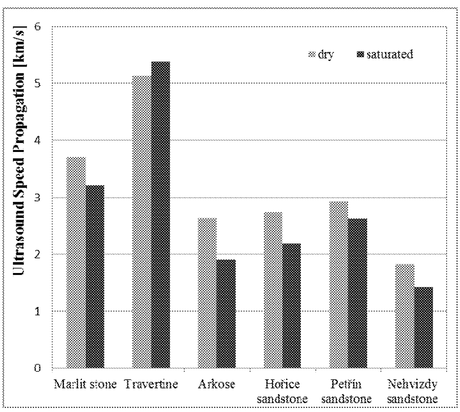


Fig.5: Comparison of dry and fully saturated material; a) flexural strength, b) compressive strength

Non-destructive testing of natural stones have been made by ultrasound and peeling test. Ultrasound speed propagation has been measured for both dry and saturated samples, so that comparison could be made. For all the materials with regularly distributed pores, not travertine, the ultrasound velocity was higher in dry samples than in saturated ones, see Fig. 6a below. Peeling test results confirmed that the materials with the lower compressive strength should have higher A-value, see Fig. 6b.



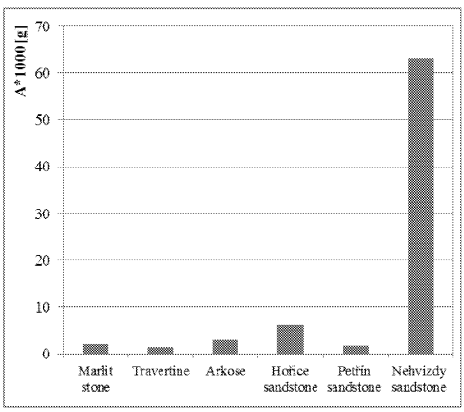


Fig.6: a) Comparison of ultrasound velocity in dry and fully saturated material; b) peeling test

To compare destructive and non-destructive testing of natural stones, modulus of elasticity has been calculated. Dynamic modulus of elasticity calculated from ultrasound velocity varies from static one evaluated from bending tests in general. The difference in this case is bigger, but it could have been caused by many heterogeneities in the samples. Similar values could be observed for materials that have small diameter of the most frequent pore. Peeling test results could corellate with compressive strength as is shown in Fig. 7b below.

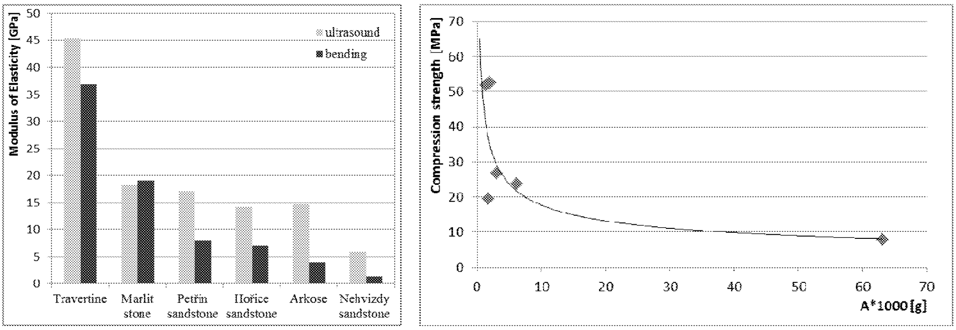


Fig. 7: a) Comparison of MoE obtained from bending tests and ultrasound tests, b) comparison of peeling tests and compression tests

3. Conclusions

Various types of sedimentary rocks used as a building material in the past have been investigated. Destructive and non-destructive testing was used for the evaluation of basic mechanical properties. Series of laboratory tests have also been used for observing how humid materials behave during the tests. This was simulated by two basic states of the stones; dry and fully saturated materials have been tested. Both destructive and non-destructive testing reacts to humidity of the material. With increasing humidity the flexural strength, compressive strength and even the ultrasound velocity decrease. Peeling test could be used for preliminary testing of materials; it provides an estimation of material resistance to mechanical loading based on surface strength. It is more relevant for new materials than for ones already used in structure, where degradation caused by environment has to be taken into account.

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