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PHYSICAL AND MECHANICAL CHARACTERISTICS OF BUILDING MATERIALS OF HISTORIC BUILDINGS

Jiří Witzany[1], Radek Zigler[1], Tomáš Čejka[1], Pavel Pospíšil[2] , Milan Holický[3], Jan Kubát[1], Aneta Maroušková[1] and Klára Kroftová[4]

1. *CTU in Prague, Faculty of Civil Engineering, Deparment of Building Structures, Prague, Thákurova 7, Czech Republic; wizany@fsv.cvut.cz, zigler@fsv.cvut.cz, cejka@fsv.cvut.cz, jan.kubat.2@fsv.cvut.cz, aneta.marouskova@fsv.cvut.cz*
2. *VŠB Ostrava, Faculty of Civil Engineering, Department of Geotechnics and Underground Engineering, L. Podéště 1875/17, Ostrava – Poruba, Czech Republic; pavel.pospisil@vsb.cz*
3. *CTU in Prague, Klokner Institute, Prague, Šolínova 7, Czech Republic; milan.holicky@klok.cvut.cz*
4. *CTU in Prague, Faculty of Civil Engineering, Deparment of Architecture, Prague, Thákurova 7, Czech Republic; klara.kroftova@seznam.cz*

ABSTRACT

The article presents partial results of laboratory research into physical and mechanical characteristics of materials most commonly used as walling units in masonry structures of historic and heritage buildings. Core boreholes and specimens for the laboratory research of selected characteristics were sampled from accessible places of historic buildings, which had not been restored or reconstructed.

The results of the research brought new knowledge about the unreliability (variance) of the properties of historical, mainly natural building materials, and, at the same time, pointed out the need for further research and extension of knowledge necessary for the assessment of residual physical and mechanical characteristics of historic masonry structures.

KEYWORDS

physical and mechanical characteristics, unreliability, masonry components, heterogeneous nature, variable factors

INTRODUCTION

Individual masonry components – walling units and binder – manifest a considerable variability of initial physical and mechanical characteristics. The manufacturing, extraction and processing methods of individual masonry components – walling units and binder – and the walling technology are processes with a relatively high degree of variability. Their contribution to the heterogeneous nature of masonry in terms of its mineralogical, chemical, physical, mechanical and other significant characteristics is crucial.

In the case of natural building blocks, the above variable factors are further assisted by other effects, e.g. the effect of the locality, extraction method and processing of natural stone, in the case of bricks, in turn, the effect of the brick clay quality, manufacturing technology, mainly the firing time and technology, ceramic body composition and porosity, in the case of binder, the effect of individual components, their ratio and processing method. Subsequently, due to the effect of degradation processes, changes in these major characteristics of masonry and its components occur over time, the structure is impaired, there are changes in porosity, mineralogical composition, chemical changes, etc. The intensity of degradation processes depends on the aggressiveness of the external environment to which the masonry is exposed, the effects of moisture and ongoing transport processes which trigger off chemical, biochemical and physical changes in the masonry.

There are many historical methods of mutual bonding of building blocks, so-called masonry bonds, a large number of assembly and composition types of load-bearing masonry members. The size, shape and structure of bricks, the working method, shape and dimensions of building blocks of natural stone, various stiffening methods of e.g. historic masonry also play their role here, plus other facts significantly affecting the load-bearing capacity and failure mechanisms of masonry, mechanical and physical characteristics of brick, stone and mixed masonry which must be considered while assessing residual load-bearing capacity of masonry.

Despite relatively extensive research into masonry structures, the issue of a reliable identification of the load-bearing capacity (loadability) of existing, mainly historic masonry structures still has not been solved in a satisfactory way [1]. The identification of the load-bearing capacity of existing historic masonry structures is an extremely difficult task because of the variability and vagueness of the parameters [2, 3] describing the physical and mechanical characteristics of masonry – walling units and mortar. Moreover, there is a great variability in the quality and characteristics of masonry structures used e.g. within the masonry structure of a building, one storey, within a masonry member (e.g. wall, pillar) along its height and length [4].

The decreasing reliability in the identification of mechanical characteristics of historical materials requires a corresponding scope and number of diagnosed elements and parts of historic masonry (e.g. number of core boreholes) and, during the interpretation of the results of this research, the adequate setting of the ratio between e.g. experimentally identified and design strength.

DEGRADATION EFFECTS ON PHYSICAL AND MECHANICAL CHARACTERISTICS OF BUILDING MATERIALS OF HISTORIC BUILDINGS

All building materials used for the masonry of historic buildings have a porous structure, most frequently a system of open pores, which allows the transport of moisture through the pore system. These transport processes are related to the pore system, specific surfaces, moisture content in the masonry, etc. and are essential in terms of the mechanism of degradation processes, their intensity and kinetics. Moisture in the liquid and gaseous phase is the principal carrier of various aggressive substances transported into the interior structure of building materials.

An inseparable part of degradation processes caused by moisture are chemical degradation processes. Chemical corrosion of building materials is an action or a series of actions during which as a consequence of the effects of the aggressive environment the major physical and mechanical characteristics of materials fall below values necessary for their serviceability.

The basis of these actions are chemical reactions, reactions between the solid and liquid or gaseous phase. During the reactions, apart from the chemical reaction itself, transfer phenomena interact at the phase interface supplying reacting substances and removing reaction products. So that the reaction can run, permanent mass transfer – transport – of the reacting liquid phase and its effective substances must be provided.

Salt crystallization in pores or hydration pressures produce pressures inside the building material structure which gradually impair this structure and cause so-called physical degradation processes. The volume expansion of some salts which pass into hydrates (increased water content) causes crystallization hydration pressures reaching values in the order of tens of MPa, which exceed common real tensile strengths of building materials. The growth of crystals is limited by small pore spaces and the crystals develop considerable expansive pressures which grow with temperature. Water evaporation leads to the dehydration of crystals and to their disintegration. With a new increase in moisture, hydroscopic salts reabsorb water and recrystallize. This repetitive process (crystallization and recrystallization), together with the washout of binder components, leads to a gradual disintegration of the structure.

A significant physical property which substantially conditions the successive course of degradation processes is the porosity of building materials, which changes over time and affects their water absorption.

Building materials and, hence, entire structures, have some infiltration capacity. Building stone (clastic sediments – sandstones) offers very favourable conditions for infiltration. Different materials differ by their grain size, pore size and distribution and are inhomogeneous in their microstructure.

As a consequence of and in direct proportion to the intensity and kinetics of degradation processes, the parameters describing the characteristics of masonry components – walling units and binder – must be assessed as time variable values.

BUILDING MATERIALS USED IN HISTORIC AND HERITAGE MASONRY BUILDINGS

Masonry structures of historic and heritage buildings, such as strip footings, walls, pillars and vaults, are most frequently made up of walling units of sandy marlstone, sandstone and limestone, granite, trachyte and fired bricks. Experimental research [5, 6] pointed out the severe effect of the moisture content, mineralogical composition and porosity (number, distribution and type of pores) on the intensity of chemical degradation processes and their effect on the mechanical characteristics of walling units.

In the Middle Ages, apart from local resources, relatively easily accessible and workable **sandy marlstone** belonged to the most common walling materials. It was the main material used for the construction of religious as well as civic buildings in the Romanesque to the early Gothic period. Judging by the quality of sandy marlstone, the durability of sandy marlstone masonry exposed to the present-day environment with its growing aggressiveness may be, in some cases, assessed for less than 50 years (depending on the intensity of degradation processes).

Note: Sandy marlstones are marlites to spongilites (or spongolites), mostly with slight sand contents, composed of various forms of SiO2 (opal, chalcedony, cristobalite or micro-grained quartz), consolidated clay (aqueous aluminium silicates) and variable amounts of calcite (mostly as a binder), substances of biological origin (opal needles of sea sponges, etc., hence spolgilite) [2, 7]. The mechanical strength of sandy marlstone grows with higher contents of SiO2, and, on the contrary, falls with higher porosity and higher contents of CaCO3. Decalcified sandy marlstone (calcium carbonate is washed out) is highly porous, it has extremely low specific mass and low strength and is used for the production of lightweight building materials.

From the start of the 15th century, **sandstone** belonged to the main building materials. The turning point in using sandy marlstone is the end of the 14th century and the start of the 15th century, when sandy marlstone was gradually replaced with sandstone. The evident reason was higher resistance of sandstone to weathering. The collective term – building sandstone – covers a series of rock types of sedimentary origin, variable chemical composition, age and physical characteristics (water absorption, strength, porosity, frost resistance).

Note: Sandstones form a large group of clastic consolidated sediments, most often with quartz grains, but also with calcite, 0.063-2 mm in size. They are classified as fine-grained (grains in an interval of 0.063-0.5 mm), medium-grained (grains of 0.5-1.0 mm) and coarse-grained (grains larger than 1.0 mm). The space between the grains can be void space or can be filled with a binder – fine-grained sedimentary rock component of a *different structure, which makes the rock cohesive [7, 8]. The properties of sandstone (porosity, mechanical characteristics, colour, chemical resistance) are significantly affected by the binder quality and amounts. A considerably lower water absorption and porosity are the precondition for high strength and resistance to weathering and are typical of sandstones with a porous or filler binder. Sandstones mostly tend to be more resistant to the effects of degradation agents (water, acid exhalations from the air) than e.g. sandy marlstone.*

Limestones belonged to rock types, less frequently used in the construction of historic buildings, they were used in historic buildings on a relatively small scale and, as a rule, in the locality where they were quarried; in Bohemia, a major area with limestone quarries are the surroundings of the town of Beroun.

Note: Limestones are non-clastic, compact to fine-grained sedimentary rocks (marbles have visible grains) formed by calcite CaCO3 (rhombohedral calcite and its orthorhombic modification – aragonite, in two-component rocks they must be represented by at least 50%) with a smaller proportion of admixtures (admixtures of clastic particles do not exceed 10%), which colour them. Aragonite is more soluble, therefore, it tends to be easily leached and, for this reason, it cannot be found in geologically older limestones. Limestones are connected via continuous interfaces mainly with clay sediments (marl, marlite), sandy sediments (sandy limestones and lime sandstones) and very often with dolomite. In relation to the proportion of carbonate contents, some types of sandstone can be classified as sandy limestones or lime sandstones.

Walling units were also prepared from granites, e.g. from granite, **trachyte** and others. Like in the case of limestone, their use in the construction of historic buildings was linked to a respective locality of their quarrying.

Note: Trachyte is an extrusive magmatic rock, light whitish to grey in colour, of very fine-grained, porous structure. By its mineralogical composition, it is mostly formed by feldspar (potassium feldspars prevail over plagioclases), foide (representative of feldspars) - nepheline, sodalite and leucite, smaller amounts of quartz or smaller amounts of tridymite. In the Czech Republic, it is found sporadically, e.g. near the settlement of Úterý close to Mariánské lázně.

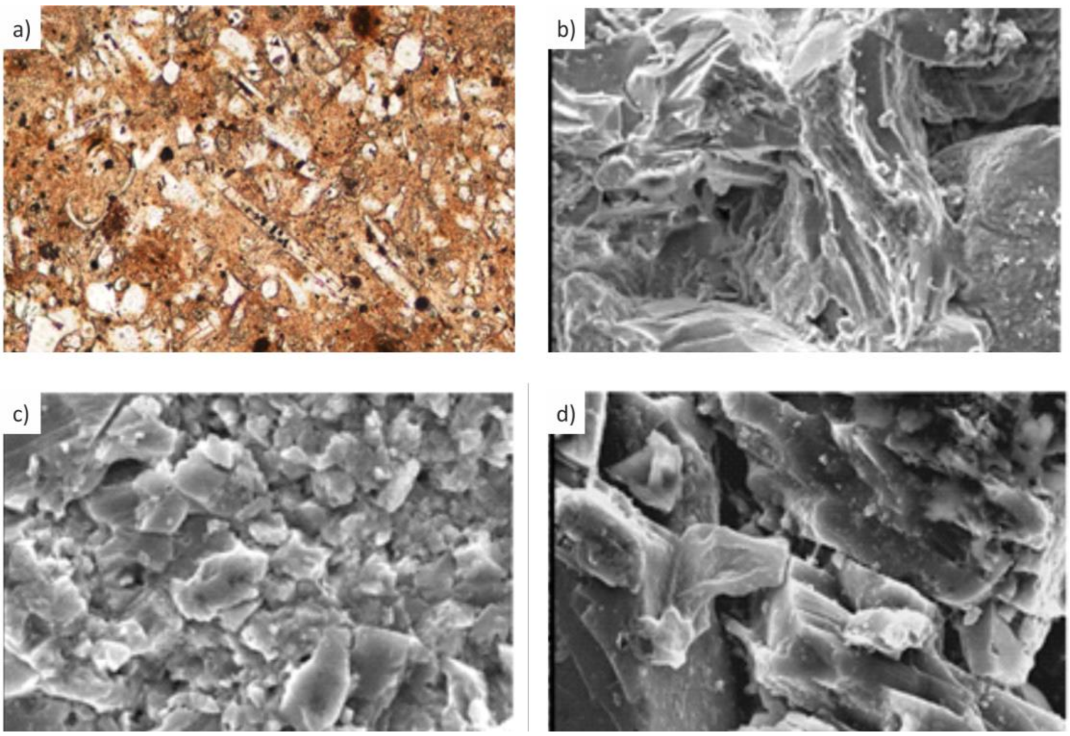

Fig. 1 - Microscopic images of walling materials, a) Sandy marlstone (photo by P. Pospíšil), b) Sandstone [9], c) Limestone [9], d) Trachyte [9]

Starting from the Middle Ages, **burnt bricks** have been used for the construction of masonry buildings. They were used for brickwork or mixed masonry structures, together with walling units of natural materials, or they formed their reinforcing parts, e.g. outside corners of stonework and mixed masonry walls, linings, etc. Depending on the firing temperature and brick mix composition, bricks with different strengths, porous systems, etc. were manufactured.

Note: The basic raw material for burnt bricks are loams based on clay minerals (mainly illite, montmorillonite and kaolinite). Non-clay components (mainly quartz, to a lesser extent calcite, mica, chlorite, etc.) are added to them. The dehydration of clay minerals takes place at temperatures of 500 - 600°C, while at 950°C amorphous SiO2 parts split off and dehydrated aluminosilicates change into a spinel-type compound. This, in turn, starts to pass into mullite $3Al_2O_3 \cdot 2SiO_2$ at temperatures above 1100°C. At temperatures higher than 1200°C, the split-off amorphous SiO_2 changes into cristobalite. The manufacturing technology and brick mix composition are essential for the physical and mechanical characteristics of burnt bricks, e.g. a higher firing temperature also increases the amount of melt (glass phase) thus increasing the strength of the resulting product. [7, 8].

EXPERIMENTAL RESEARCH INTO SELECTED MECHANICAL CHARACTERISTICS OF HISTORICAL MATERIALS

The specimens sampled from selected historic buildings differing in age were exposed to laboratory research focused on the identification of mechanical characteristics (tensile and compressive strength, dynamic modulus of elasticity, modulus of elasticity in compression) and selected physical characteristics (overall porosity, pore distribution) and chemism.

Note: Uniaxial compressive strength was identified using procedures under ČSN EN 1926:2007. The test pieces used for the tensile strength test had the same dimensions as those used for the uniaxial compressive strength test, whose bases were fitted with anchoring steel elements glued with two-component epoxy adhesive. The dynamic modulus of elasticity of the test pieces was identified on all test pieces before the compressive or tensile tests using the TICO device. Water absorption up to a constant mass was tested by the immersion of the whole specimen in water. Mercury porosimetry performed on chips of sedimentary rocks 10-20 g in weight served to identify overall porosity and pore distribution in a range of 1 to $60 \cdot 10^3$ nm. Moisture profiles and basic chemism were detected on powder specimens (samples were performed in three different height levels – 0.25m, 0.75m and 1.3m above terrain level to assess the moisture distribution in masonry).

The experimental, predominantly laboratory research conducted within the Ministry of Culture research project NAKI II was primarily concentrated on research into sedimentary rocks – sandy marlstone, sandstone, lime sandstone – from granites on trachyte and from artificial building materials on burnt bricks. The dimensions of partial specimens for the identification of the required characteristics obtained from core boreholes were modified to comply with ČSN standards (ČSN EN 1926:2007, ČSN EN 1996-1-1+A1:2013). Tab. 1 presents the list of sampled specimens which were the subject of laboratory research.

Tab. 1 - List of test specimens

Sampled specimens	Labelling	Sampling site	Type of structure	Age (years)	Locality
Sandy marlstone	M1 - M3	quarry	quarry	0	Přední Kopanina
	M4 - M5	farmstead	barn	170	Tuchoměřice
	M6 - M9	Václav Havel Library	library	345	Praha
	M10 - M16	Ursuline Convent	convent	340	Praha
Sandstone	S1	quarry	quarry	0	Hořovice
	S2	quarry	quarry	0	Božanov
	S3 - S8	church	church	340	Fořt
	S9 - S14	former poorhouse	residential building	350	Kutná Hora
	S15	quarry	quarry	0	Hořice v Podkrkonoší
	S16 - S17	Jeřice Castle	barn	170	Jeřice
	S18 - S20	farmstead	barn	140	Chotíkov
	S21 - S23	farmstead	stable	350	Boseň
Lime sandstone	LS1 - LS6	former vicarage	vicarage	340	Hořovice
Trachyte	T1 - T6	farmstead	stable	270	Teplá, Ovčí Dvůr
	T7 - T10	farmstead	stable	270	Teplá, Hájčí Dvůr
	T11 - T14	Premonstrate Monastery	fence	370	Teplá
Bricks	B1 - B4	from manufacture	from manufacture	0	Praha
	B5 - B7	carpenter’s workshop	carpenter’s workshop	120	Kutná Hora
	B8 - B11	printing house	printing house	120	Humpolec
	B12 - B13	church	church	340	Fořt
	B14 - B17	former poorhouse	residential building	350	Kutná Hora
	B18 - B20	Václav Havel Library	library	345	Praha

STATISTICAL ANALYSIS OF LABORATORY OBTAINED VALUES

The section below presents the results of statistical analysis subdivided according to materials. Due to the limited scope of data, together with the mean measured values, coefficients of variation, skewness of a distribution, etc., other theoretical assumptions supported by previous findings and experience are used [10, 11].

Tab. 2 - Results of laboratory research – sandy marlstone

Labelling	f_b (Mpa)	f_t (Mpa)	E (Mpa)	E_{dyn} (Mpa)	Water absorption (%)	Porosity (%)
M01	76.15	-	11755	-	10.24	26.15
M02	49.63	-	6388	-	10.04	32.08
M03	72.69	-	21200	-	10.16	26.15
M04	29.57	1.47	4514	3700	10.27	-
M05	29.12	1.39	5184	10644	9.74	-
M06	39.4	3.52	6556	12241	4.86	-
M07	45.81	3.48	5749	2149	8.31	-
M08	35.29	1.97	6515	14053	-	-
M09	46.91	1.53	5023	25950	-	-
M10	29.35	2.97	3980	7144	16.09	27.42
M11	19.92	1.45	3300	5518	20.85	30.2
M12	66.81	4.14	5035	6765	4.22	22.33
M13	43.62	0.34	4930	6668	12.76	-
M14	39.27	3.36	4995	10751	16.39	-
M15	38.41	3	4324	12236	11.86	-
M16	34.43	4.49	4180	10609	12.6	-

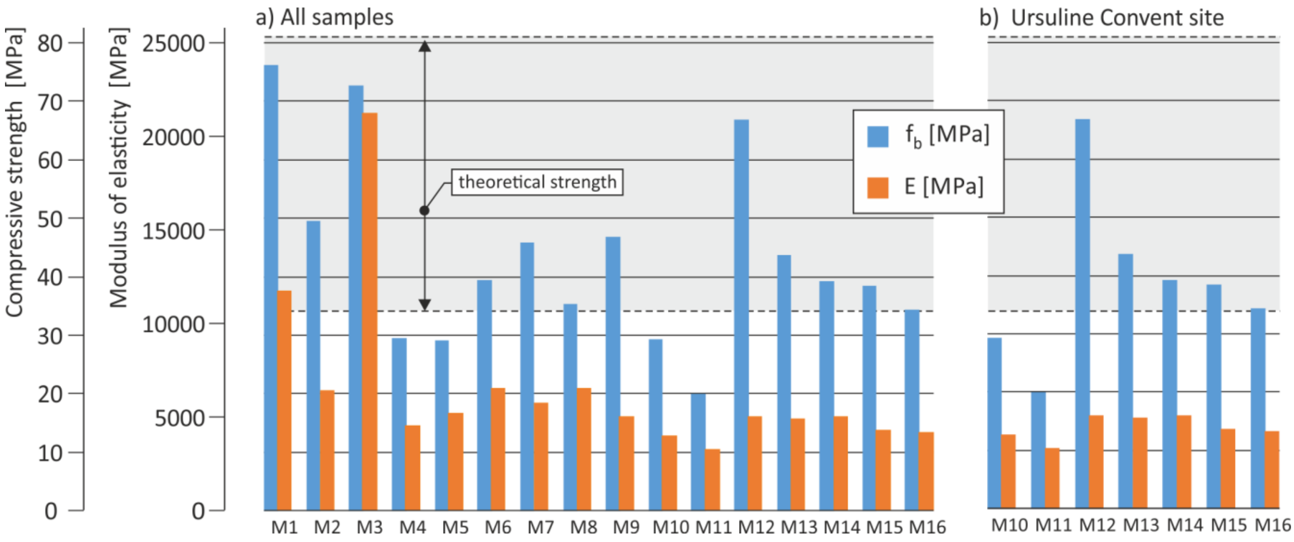

Fig. 2 - Results of laboratory research – sandy marlstone

Tab. 3 - Statistical analysis – sandy marlstone (entire data set)

	arithmetic mean	median	lower quartile	upper quartile	standard deviation	coeff.of variation	coeff. of kurtosis	coeff.of skewness
f_b (MPa)	43.5	39.3	33.2	47.6	15.6	35.8%	0.151	0.81
E (MPa)	6476.75	5029	4466.5	6419.8	4225.8	62.25%	9.471	2.688

Tab. 4 - Statistical analysis – sandy marlstone (selected locality – Ursuline Convent)

	arithmetic mean	median	lower quartile	upper quartile	standard deviation	coeff.of variation	coeff. of kurtosis	coeff.of skewness
f_b (MPa)	38.8	38.4	31.9	41.4	13.5	34.7%	2.37	0.83
E (MPa)	4392.0	4324.0	4080.0	4962.5	595.01	14%	-0.37	-0.5

The entire data set of compressive strengths f_b shows a significant dispersion of measured values (coefficient of variation of 0.36) corresponding to a slightly peaked probability density distribution (positive kurtosis of 0.151) and a markedly positive skewness (0.81). It is a slightly peaked distribution with a positive skew.

The strengths from a selected locality (Ursuline Convent) are of a similar nature, but the probability density distribution has a higher degree of peakedness (positive kurtosis of 2.37).

The entire data set of the modulus of elasticity E shows a very significant dispersion of measured values (coefficient of variation of 0.63) with a very sharp peaked probability density distribution (positive kurtosis of 9.471) and a markedly positive skewness (2.69). It is a sharp peaked and positively skewed distribution.

The modulus of elasticity values from a selected site (Ursuline Convent) show a markedly lower dispersion of measured values (coefficient of variation of 0.14) corresponding to a flat probability density distribution (negative kurtosis of 0.37) with a negative skewness (-0.5).

The normal and three-parametric lognormal distribution for the entire data set of sandy marlstone strengths (derived from the mean value of 43.5 MPa, standard deviation of 15.6 and skewness of 0.81), including the minimum (19.92) and the maximum (76.15) measured values, is presented in Figure 3.

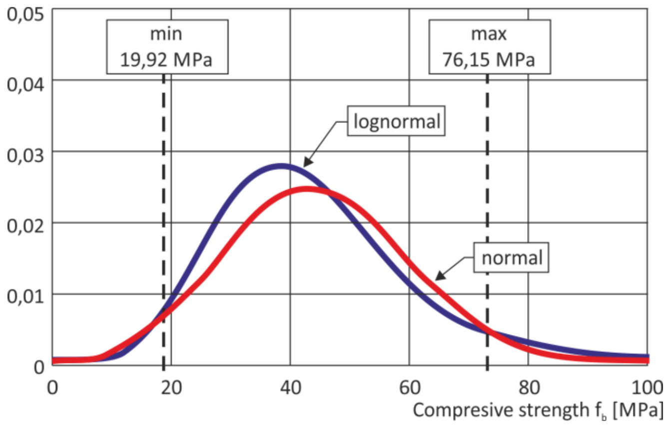

Fig. 3 - Normal and three-parametric lognormal distribution for the entire data set of sandy marlstone strengths showing minimum and maximum measured values

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Tab. 5 - Results of laboratory research – sandstone

labelling	f_b	f_t	E.	E_{dyn}	water absorption	porosity
	(Mpa)	(Mpa)	(Mpa)	(Mpa)	(%)	(%)
S01	30.9	-	4100	-	5.24	22.13
S02	43.91	-	19500	-	5.64	19.06
S03	52.16	-	3900	-	3.44	13.63
S04	29.16	-	3800	-	5.6	15.12
S05	71.07	-	8900	-	-	14.72
S06	41.1	-	4900	-	4.28	14.3
S07	33.49	-	5369	-	-	13.63
S08	50.39	-	6272	-	-	14.72
S09	39.7	-	2879	15156	1.06	-
S10	39	1.35	3009	24270	-	-
S11	48.29	-	3103	-	-	-
S12	47.39	-	5777	-	-	-
S13	45.03	-	5334	-	-	-
S14	47.39	-	5524	-	-	-
S15	36.8	-	11800	-	-	16.26
S16	44.79	1.48	6355	8174	-	5.53
S17	48.63	1.65	7111	16000	-	5.36
S18	55.1	1.04	3097	8010	8.67	-
S19	60.48	0.58	3942	5401	13.54	-
S20	31.16	1.48	3120	3953	3.73	8.25
S21	1.83	-	400	-	-	23.89
S22	1.93	-	300	-	-	26.01
S23	4.31	-	1100	-	-	23.89

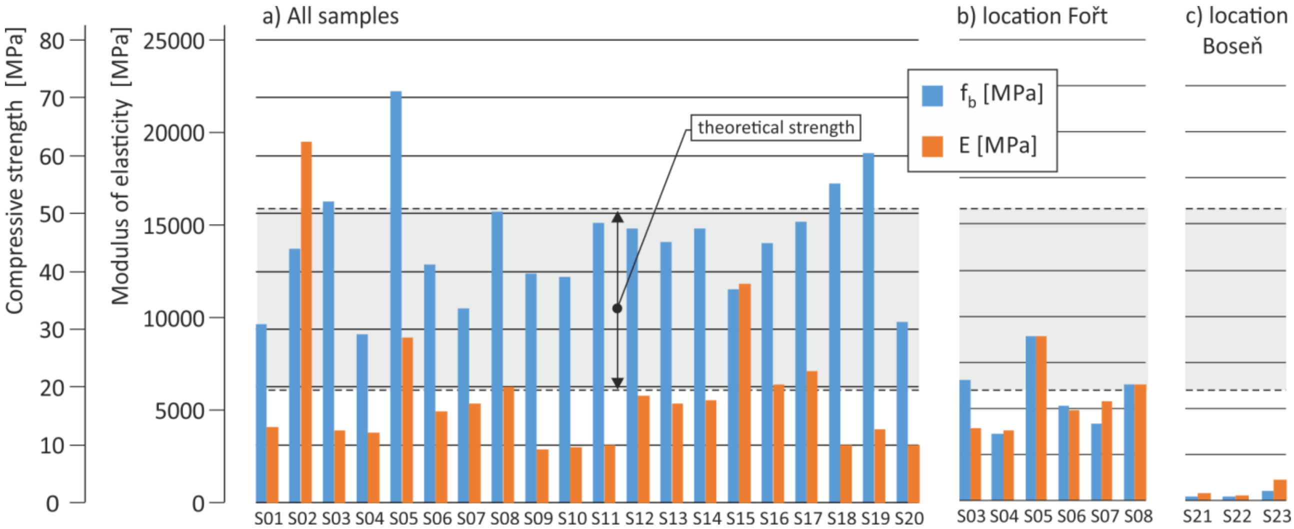

Fig. 4 - Results of laboratory research – sandstone

Tab. 6 - Statistical analysis – sandstone (entire data set)

	arithmetic mean	median	lower quartile	upper quartile	standard deviation	coeff.of variation	coeff. of kurtosis	coeff.of skewness
f_b (MPa)	44.8	44.91	38.45	49.07	10.14	22.64%	0.813	0.595
E (MPa)	5889.6	5117.0	3630.0	6292.8	3799.5	64.51%	7.727	2.379

Tab. 7 Statistical analysis – sandstone (selected locality - Fořt)

	arithmetic mean	median	lower quartile	upper quartile	standard deviation	coeff.of variation	coeff. of kurtosis	coeff.of skewness
f_b (MPa)	46.23	45.75	35.39	51.72	13.84	29.94%	0.296	0.530
E (MPa)	5523.5	5134.5	4150.0	6046.3	1731.08	31.34%	1.665	0.940

The entire data set of compressive strengths f_b shows a significant dispersion of measured values (coefficient of variation of 0.23) with a peaked probability density distribution (positive kurtosis of 0.813) and a positive skew (0.595). It is a slightly peaked and positively skewed distribution.

The strengths from a selected site (Fořt) are of a similar nature with a positive skew (positive skewness of 0.53), but their probability density distribution is flatter (positive kurtosis of 0.296).

The entire data set of the modulus of elasticity E shows a significant dispersion of measured values (coefficient of variation of 0.65) with a markedly sharp peaked probability density distribution (positive kurtosis of 7.727) and a significantly positive skewness (2.38). It is a sharp peaked and positively skewed distribution.

The modulus of elasticity values from a selected site (Fořt) have a lower dispersion of measured values (coefficient of variation of 0.31), their probability density distribution is less sharp peaked (positive kurtosis of 1.67) with a positive skew (0.94).

The normal and three-parametric lognormal distribution for the entire data set of sandstone strengths (derived from the mean of 44.8 MPa, standard deviation of 10.1 and skewness of 0.59), including the minimum (29.16) and the maximum (71.07) measured values, is presented in Figure 5.

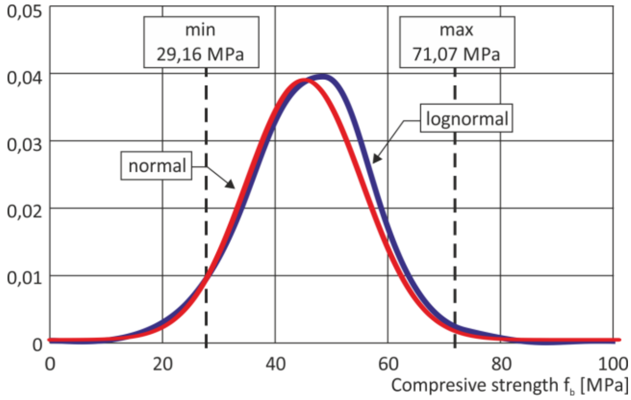

Fig. 5 - Normal and three-parametric lognormal distribution for the entire data set of sandstone strengths showing minimum and maximum measured values

Tab. 8 - Results of laboratory research – lime sandstone

labelling	f_b (Mpa)	f_t (Mpa)	E. (Mpa)	E_{dyn} (Mpa)	water absorption (%)	porosity (%)
LS01	173.35	2.52	6320	15476	1.31	-
LS02	155.27	6.23	5971	18540	0.69	-
LS03	103.53	3.77	6210	9080	1.99	7.53
LS04	98.59	2.75	6153	12991	2.25	7.75
LS05	105.6	3.99	60478	12278	3.0	7.24
LS06	81.62	2.39	4754	17075	3.14	9.98

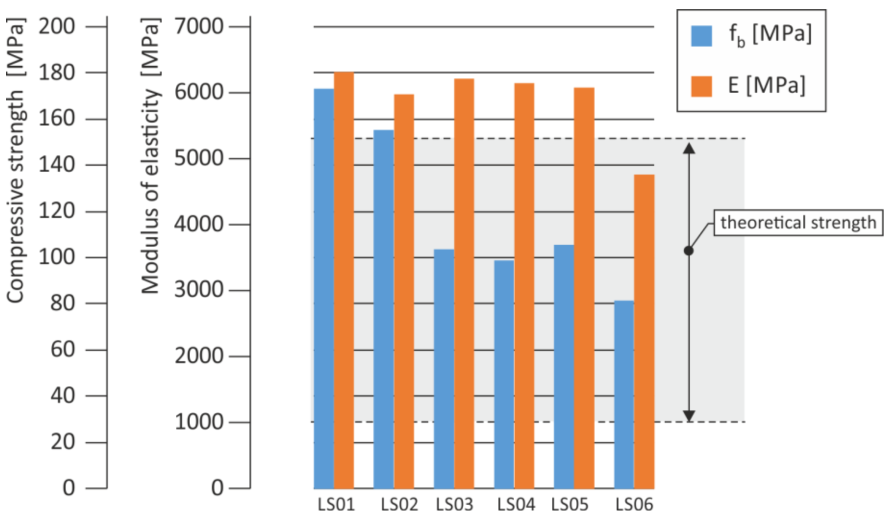

Fig. 6 - Results of laboratory research – lime sandstone

Tab. 9 - Statistical analysis – lime sandstone (entire data set)

	arithmetic mean	median	lower quartile	upper quartile	standard deviation	coeff.of variation	coeff. of kurtosis	coeff.of skewness
f_b (MPa)	119.66	104.56	99.83	142.86	32.91	27.51%	-1.148	-0.731
E (MPa)	5916.0	6115.5	6005.3	6195.8	530.18	8.96%	5.210	-1.633

The entire data set of compressive strengths f_b shows a dispersion of measured values (coefficient of variation of 0.28) corresponding to a flat probability density distribution (negative kurtosis of -1.15) and a negative skew (-0.731). It is a flat and negatively skewed distribution.

The entire data set of the modulus of elasticity E shows a lower dispersion of measured values (coefficient of variation of 0.09) corresponding to a sharp peaked probability density distribution (positive kurtosis of 5.21) and a markedly negative skewness (-1.63). It is a sharp peaked and negatively skewed distribution.

The normal and three-parametric lognormal distribution for the entire data set of lime sandstone strengths (derived from the mean of 119.66 MPa, standard deviation of 32.91 and skewness of -0.731), including the minimum (81.62) and the maximum (173.35) measured values, is presented in Figure 7.

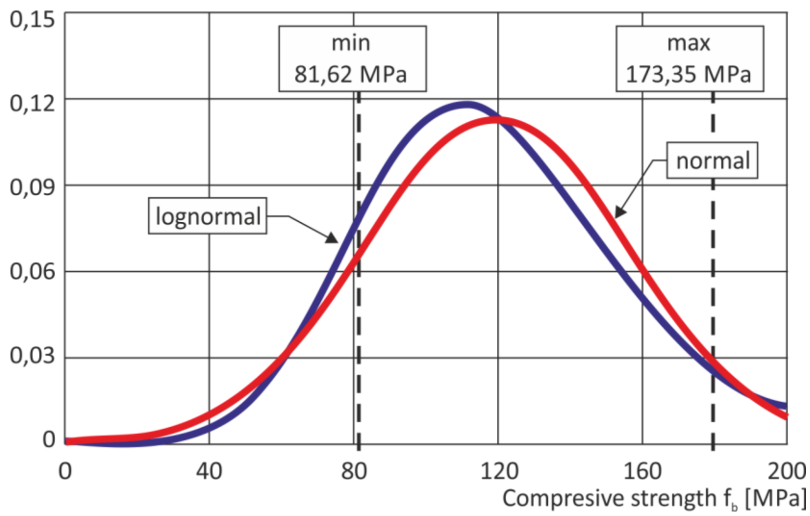

Fig. 7 - Normal and three-parametric lognormal distribution for the entire data set of lime sandstone strengths showing minimum and maximum measured values

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Tab. 10 - Results of laboratory research – trachyte

labelling	f_b (Mpa)	f_t (Mpa)	E. (Mpa)	E_{dyn} (Mpa)	water absorption (%)	porosity (%)
T01	55.07	1.2	10700	9984	3.45	-
T02	53.31	1.37	12900	12100	-	-
T03	76.16	-	8666	-	-	-
T04	85.39	-	9366	-	-	-
T05	82.63	3.31	8486	14096	-	-
T06	71.11	4.76	8754	17226	-	-
T07	55.61	1.02	8331	5094	3.49	-
T08	54.91	0.78	9007	7497	-	-
T09	42.03	-	8726	-	-	-
T10	51.92	-	8919	-	-	-
T11	75.74	3.85	6530	8676	1.19	10.28
T12	77.12	3.86	5543	6569	2.81	10.5
T13	58.635	1.38	4015	8488	2.05	10.93
T14	67.48	1.78	3619	6317	2.17	12.18

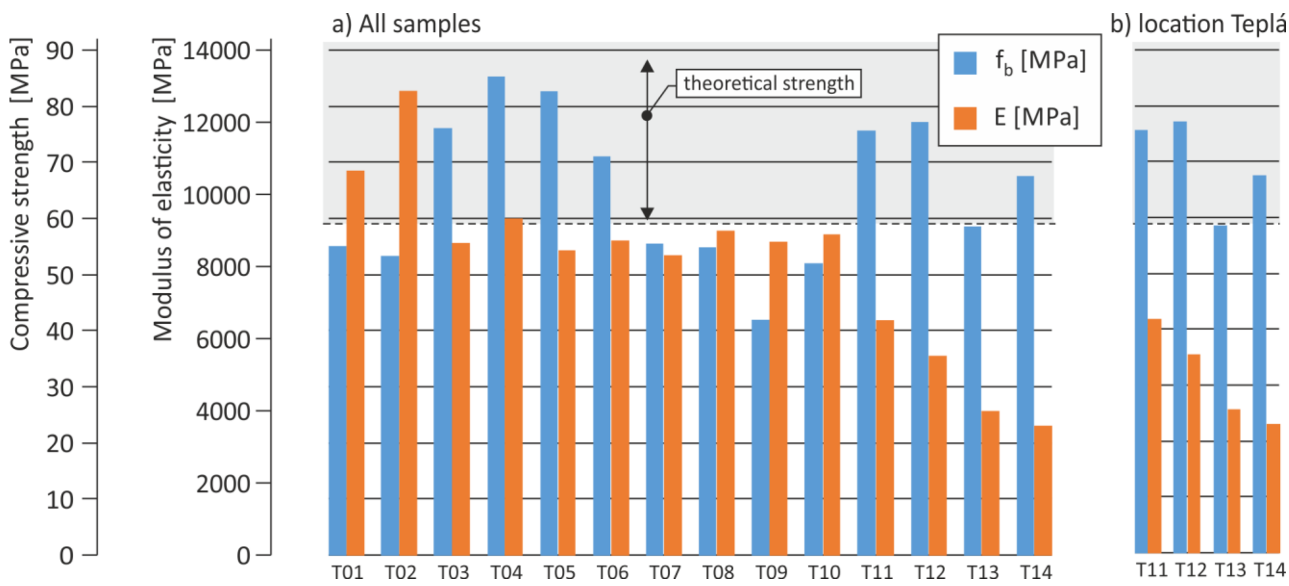

Fig. 8 - Results of laboratory research – trachyte

Tab. 11 - Statistical analysis – trachyte (entire data set)

	arithmetic mean	median	lower quartile	upper quartile	standard deviation	coeff.of variation	coeff. of kurtosis	coeff.of skewness
f_b (MPa)	64.79	63.06	54.95	76.06	12.87	19.87%	-1.240	0.033
E (MPa)	8111.6	8696.0	6980.3	8985.0	2390.6	29.47%	0.403	-0.257

Tab. 12 - Statistical analysis – trachyte (selected locality - Teplá)

	arithmetic mean	median	lower quartile	upper quartile	standard deviation	coeff.of variation	coeff. of kurtosis	coeff.of skewness
f_b (MPa)	69.74	71.61	65.27	76.09	7.40	10.61%	-1.286	-0.473
E (MPa)	4926.8	4779.0	3916.0	5789.8	1171.7	23.78%	-3.178	0.211

The entire data set of compressive strengths f_b shows a significant dispersion of measured values (coefficient of variation of 0.20) corresponding to a flat probability density distribution (negative kurtosis of -1.24) and a nearly negligible skewness (0.03). It is a flat and nearly symmetrical distribution.

The strengths from a selected locality (Teplá) are of a similar nature, but the value of the probability density distribution coefficient of variation is by one half lower (0.11) and the distribution is negatively skewed (skewness of -0.47).

The entire data set of the modulus of elasticity E shows a significant dispersion of measured values (coefficient of variation of 0.29) with a slightly peaked probability density distribution (positive kurtosis of 0.403) and a negative skewness (-0.257). It is a slightly peaked and negatively skewed distribution.

The modulus of elasticity values from a selected site (Teplá) show a similar dispersion of measured values (coefficient of variation of 0.24), but their probability density distribution is markedly flat (negative kurtosis of 3.18) with a positive skewness (0.21).

The normal and three-parametric lognormal distribution for the entire data set of trachyte strengths (derived from the mean of 64.79 MPa, standard deviation of 12.87 and skewness of 0.03), including the minimum (42.03) and maximum (85.39) measured values, is presented in Figure 9.

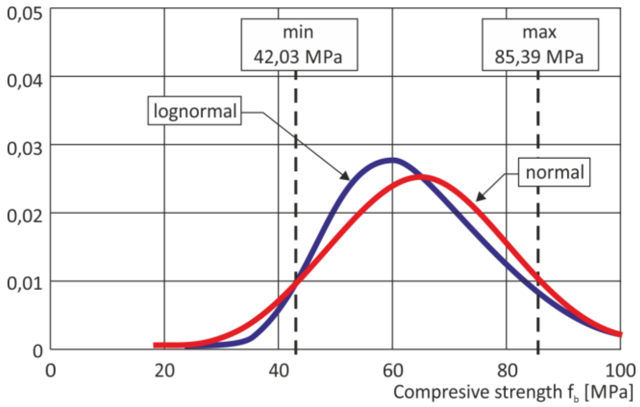

Fig. 9 - Normal and three-parametric lognormal distribution for the entire data set of trachyte strengths showing minimum and maximum measured values

Tab. 13 -Results of laboratory research – burnt bricks

labelling	f_b (Mpa)	f_t (Mpa)	E. (Mpa)	E_{dyn} (Mpa)	water absorption (%)	porosity (%)
B01	14.31	-	5600	-	20.88	31.92
B02	26.23	-	8500	-	18.49	34.36
B03	20.02	-	2600	-	11.9	38.41
B04	17.76	-	2400	-	16.4	37.4
B05	17.08	-	2300	-	18.3	37.5
B06	34.78	-	5300	-	22.5	31.27
B07	21.39	-	3200	-	19.2	31.78
B08	19.57	-	2400	-	-	26.15
B09	23.82	-	3100	-	-	18.44
B10	12.02	-	1400	-	-	24.93
B11	11.21	-	3072	-	-	18.44
B12	11.15	-	2200	-	-	31.8
B13	7.59	-	1400	-	-	34.32
B14	9.28	1.15	2710	3684	17.44	-
B15	16.17	1.45	4763	6652	16.27	-
B16	21.4	-	5090	2477	-	-
B17	32.54	-	6630	6104	-	-
B18	8.28	0.5	1522	1130	12.95	-
B19	6.82	0.8	1768	-	-	-
B20	8.08	2.13	2072	-	-	-

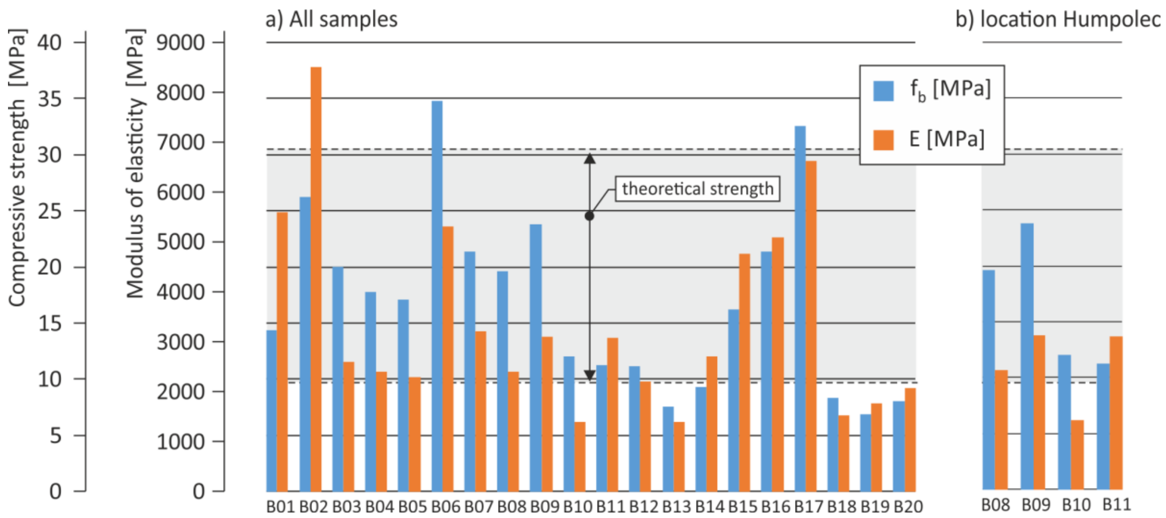

Fig. 10 - Results of laboratory research – burnt bricks

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Tab. 14 - Statistical analysis – burnt bricks (entire data set)

	arithmetic mean	median	lower quartile	upper quartile	standard deviation	coeff.of variation	coeff. of kurtosis	coeff.of skewness
f_b (MPa)	16.98	16.63	10.68	21.39	7.91	46.61%	-0.106	0.659
E (MPa)	3401.4	2655.0	2168.0	4844.8	1891.6	55.61%	1.010	1.150

Tab. 15 - Statistical analysis – burnt bricks (selected locality - Humpolec)

	arithmetic mean	median	lower quartile	upper quartile	standard deviation	coeff.of variation	coeff. of kurtosis	coeff.of skewness
f_b (MPa)	16.66	15.80	11.82	20.63	5.27	31.62%	-3.637	0.225
E (MPa)	2493.0	2736.0	2150.0	3079.0	690.47	27.70%	0.321	-0.675

The entire data set of compressive strengths f_b shows a significantly high dispersion of measured values (coefficient of variation of 0.47) corresponding to a flat probability density distribution (negative kurtosis of -0.11) and a significantly positive skewness (0.66). It is a slightly flat and positively skewed distribution.

The strengths from a selected site (Humpolec) are of a similar nature, but their probability density distribution is significantly flatter (negative kurtosis of -3.64).

The entire data set of the modulus of elasticity E shows a significant dispersion of measured values (coefficient of variation of 0.56) with a peaked probability density distribution (positive kurtosis of 1.01) and a positive skewness (1.15). It is a sharp peaked and positively skewed distribution.

The modulus of elasticity values from a selected site (Humpolec) show a lower dispersion of measured values (coefficient of variation of 0.28), their probability density distribution is less peaked (positive kurtosis of 0.32) with a negative skewness (-0.68).

The normal and three-parametric lognormal distribution for the entire data set of brick strengths (derived from the mean of 16.98 MPa, standard deviation of 7.91 and skewness of 0.66), including the minimum (6.82) and the maximum (34.78) measured values, is presented in Figure 11.

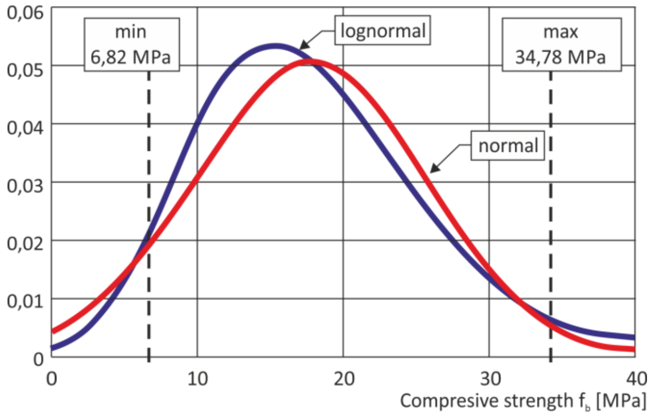

Fig. 11 - Normal and three-parametric lognormal distribution for the entire data set of brick strengths showing minimum and maximum measured values

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Overall assessment

The statistical analysis of major mechanical characteristics (compressive strength f_b, modulus of elasticity E) of selected materials (sandy marlstone, sandstone, lime sandstone, trachyte, burnt bricks) has manifested a significant to a very significant dispersion of measured values (coefficient of variation € (0.11; 0.47)) corresponding to a flat probability density distribution except for sandstone, whose measured values have a sharp peaked distribution.

The standard deviations € (5.3; 32.9) where the lowest standard deviation values were calculated for burnt bricks (7.9 for the entire data set, 5.3 for a selected locality – structure), and the highest standard deviation values were calculated for lime sandstone (32.9 for the entire data set) and for sandy marlstone (15.6 for the entire data set of values, 13.5 for a selected locality – structure).

CONCLUSION

The significant dispersion of measured values of major mechanical characteristics of natural stone and burnt bricks requires obtaining the values describing the major characteristics of walling units (strength, modulus of elasticity and others) from a sufficient number of sampling sites in order to identify the residual loading capacity of particularly stonework and mixed masonry. The values obtained on the basis of e.g. sampled core boreholes are valid mainly in the immediate vicinity of the sampling site and cannot be extrapolated for larger masonry parts. The residual load-bearing capacity of masonry, identified on the basis of an insufficient number of sampling sites or values obtained from respective regulations and literature can only be classified as approximate.

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