THE EFFECT OF DEGRADATION PROCESSES ON THE SERVICEABILITY OF BUILDING MATERIALS OF HISTORIC BUILDINGS

Witzany Jiří[1], Čejka Tomáš[1], Kroftová Klára[2], Markéta Šmidtová[1]

[1] *CTU in Prague, Faculty of Civil Engineering, Department of Building Structures, Prague, Thákurova 7, Czech Republic; witzany@fsv.cvut.cz, cejka@fsv.cvut.cz, smidtmar@fsv.cvut.cz*

[2] *CTU in Prague, Faculty of Civil Engineering, Department of Architecture, Prague, Thákurova 7, Czech Republic; klara.kroftova@fsv.cvut.cz*

ABSTRACT

The article presents an analysis of degradation processes and partial results of an experimental research into materials and structures exposed to the effects of external environments with an emphasis on the effects of moisture and chemical degradation processes on major mechanical properties of sandstone.

KEYWORDS

degradation process, moisture, sandstone, mechanical properties

INTRODUCTION

An inseparable part of the restoration of historic and heritage buildings is the assessment of residual service life of materials and structures. The starting point for the determination of the presumed service life and durability of building materials and structures, or residual service life of materials and structures of historic buildings is study of degradation processes and effects and conditions which cause them. Based on the study of degradation processes and their causes, reliable preventive measures can be designed. The growing aggressiveness of the external environment highlights the importance of degradation processes, preceding the appearance of failures of buildings and the loss of their serviceability.

Degradation, according to ČSN EN 1990 and ČSN ISO 13822 standards, is a process affecting serviceability, including reliability, over time due to

- naturally existing chemical, physical and biological effects
- repetitive loading which can cause fatigue
- common or adverse environmental effects
- wear caused by the type of utilisation
- incorrect operation or maintenance.

EFFECTS AND IMPACTS CAUSING DEGRADATION PROCESSES

Environmental effects and impacts which cause degradation processes can be superposed only with difficulty as these phenomena change the major properties of materials and structures over time. Study of the relationship of monitored material parameters to a certain time-variable external effect requires the observance of the stability of all the other characteristics of the respective external environment. This allows obtaining a theoretical image of the influence of this effect on the behaviour of a material or structure, but not a real image when the other effects co-act simultaneously and mutually interact with each other. This fact must be kept in mind when applying various laboratory measurements and tests which usually require rather complicated interpretation and they frequently have only limited usage.

The assessment of the time duration of a degradation phenomenon requires the determination of its start and finish. A greater part of degradation processes running in nature reach a state of equilibrium after some time, i.e. a state when the degradation process has stopped running – the "sources" of on-going processes have been exhausted, external conditions have changed, etc. – without reaching the complete degradation of the respective member, material or building as a whole, while the other degradation processes keep running until the complete degradation (destruction) of the "work" [1].

In processes (phenomena) resulting in permanent degradation, the state of equilibrium can be established. In phenomena causing transient degradation, on the contrary, the state of equilibrium can only be established with difficulty as the magnitude of degradation due to exposure to the atmosphere with permanently on-going changes in the intensity of climatic factors is constantly changing.

The establishment of the state of equilibrium for phenomena with transient degradation requires the assessment of the state of equilibrium as the state when the magnitude of degradation fluctuates around a roughly constant value. This state is called the state of dynamic equilibrium.

Due to the effect of climatic factors, structures and materials are exposed to degradation which, in terms of the recovery ability, can be either of permanent (irreversible), temporary (transient) or reversible nature [2].

The degradation of structures or materials considered as permanent degradation is such degradation which does not fade away even if the magnitude of the decisive external factor which induced it has fallen below the critical value and the external critical factor has stopped inducing further degradation.

Irreversible changes in the properties of building materials are almost exclusively connected with long-term phenomena depending on the length of their duration, and in their consequence e.g. after a change of external parameters back to the starting, initial state, the building material does not regain the original, initial properties, or the parameter values describing these properties after some time.

The degradation considered as transient degradation is such degradation that will fade away as soon as the magnitude of the decisive external factor has fallen below the critical value. It will fade away either spontaneously or due to the action of another external factor or by the co-action of several other external factors, without the addition of any energy or without the effect of any other intervention. These are relaxation degradation phenomena in which induced degradation fades away as soon as the external factor stops inducing the degradation, i.e. with a change in the weather or climate (external) conditions.

The degradation of structures and materials considered reversible degradation is such degradation which can fade away as soon as the magnitude of the decisive external factor has fallen below the critical value, but only due to some energy which will be added to the exposed material or structure (not due to the effect of the energy of some other external or several other external factors), or if some intervention has been performed on the exposed structure or material.

Reversible changes in the properties of building materials are almost exclusively connected with short-term processes (warming, cooling, wetting, drying) and the dependence of property changes of e.g. a building material on the monitored parameter runs following a hysteresis loop of closed shape.

Naturally exposed structures or materials may simultaneously exhibit degradation of different types in terms of its regeneration ability due to the effect of several or even one external factor. The most common case in the simultaneous appearance of permanent and transient degradation.

By its nature, each degradation phenomenon is a complex set of series of partial phenomena and processes which in their total make up the substance of the degradation process. For example, degradation caused by water vapour sorption is a phenomenon whose substances in different climate conditions or in different materials are various partial phenomena with different relevance such as diffusion, adsorption, capillary condensation, chemisorption, molecular flow, capillary elevation, swelling, etc. Therefore, the explanation of various degradation processes, their mechanisms and velocity is very difficult and often requires a long-term monitoring.

Practical experience gained from existing buildings shows that, together with reliable diagnostic methods used for building surveys, the characteristics of materials and structures must be investigated as changing variables, time- and environment-dependent. The knowledge of time-dependent behaviour of materials is the issue of reliability and durability of buildings.

MECHANISMS OF DEGRADATION PROCESSES

The mechanisms of **degradation processes**, their intensity and the velocity of their time pattern are related to the material structure, particularly the pore system, surface areas, etc. [2]. These parameters affect, in a decisive way, mainly transport processes in materials, primarily the moisture content (in the liquid as well as gaseous phase), which is the principal carrier of various aggressive substances transported into the internal structure of building materials and structures, which, as a rule, change their chemical, physical and mechanical characteristics due to their action. In this perspective, it is obvious that the **properties of building materials** should be understood as **time-variable parameters** dependent on the environment. At the same time, the structural non-homogeneity of the vast majority of building materials characterised by a **multi-phase structure and discontinuous changes in properties** at the interphase of individual phases must be respected.

The research to-date manifests that the study of **structural parameters** in particular can be the starting point for finding accurate models of the behaviour and properties of building materials, or functions describing the development and dependence of these properties on changes in external conditions. The main agents of the external environment include, above all, **temperature and moisture effects**, **radiation, chemical and biological effects**.

Part of the design and restoration of buildings in terms of reliability and durability is the analysis of the **mutual interaction of the external and internal environment** with the "structure (building) and its parts", **mutual interaction of individual parts of the "building", materials** and layers at the interface of their mutual contact and the design of preventive measures against undesirable consequences of this interaction. Insufficient and inaccurate analysis of the consequences of mutual interaction of parts of a building, together with the underestimation of the significance of cyclic non-force temperature and moisture effects, are a frequent cause of mechanical damage and degradation of building materials before and after the restoration of the building.

The non-homogeneity of the majority of building materials, dispersion of their physical and mechanical, chemical and mineralogical properties, non-constant temperature and moisture pattern over the member's cross section, different dilatometric characteristics of individual layers in multi-layer members, non-sliding mounting of a member in the structure and mutual interaction of members bound within a certain (e.g. load-bearing) system are the causes of internal stresses. The upper or the lower temperature or moisture limit defining, in a simplified way, the range of both effects which do not have a substantial influence on the mechanical or other physical properties varies for different groups of building materials.

Temperature and moisture have a decisive influence on major characteristics of building materials, e.g. concrete, in the phase of their formation and in relation to the physical and chemical reactions and processes running in this phase.

CHEMICAL DEGRADATION PROCESSES

An extensive group of degradation processes are chemical degradation processes accompanied by elevated moisture contents of building materials and structures, mainly historic buildings with ineffective or non-functional damp-proofing systems. Chemical corrosion of building materials is a process or a series of processes during which the action of aggressive environments produces a chemical reaction leading to the decrease in major physical and mechanical properties of materials below values necessary for their serviceability.

Chemical degradation processes are characterised by a change in the pore system due to chemical reactions of dissolved salts with building material components, mainly binders. Chemical degradation processes are caused, above all, by the reaction of chemically less stable components of building materials with solutions of weak acids, etc. Chemical degradation processes, the formation of salts, etc. affect **dilatometric** and some other significant properties (porosity, hygroscopicity, water absorption, modulus of elasticity, strength, electrical conductivity, electric potential, etc.). An inseparable part and condition of chemical degradation processes is moisture which, in most cases, is the "carrier" of stable solutions of acids, freely dissociated gases, the condition for the growth and production of metabolisms of microorganisms, etc.

In a general case, in terms of transport phenomena, the interaction pattern between solid mater and a liquid can be, in a simplified way, divided into the following phases:

a) transport of effective components to the phase interface,
b) reaction at the phase interface,
c) transport of products from the phase interface.

In the case of building materials, it is also necessary to take into consideration the fact that a porous material is involved. For phases a) and b), the mass transport through the pore system must be also considered. Furthermore, the dissimilarity of the acting medium and hence the dissimilarity of on-going chemical reactions must be taken into account.

DEGRADATION PROCESSES – SEDIMENTARY ROCKS

The most commonly used sedimentary rocks – stone types – for masonry structures – strip foundations, walls, pillars and vaults – are arenaceous marl, sandstone and limestone. Experimental research [3, 4] has manifested the severe effect of moisture, the mineralogical composition and porosity (number, distribution and type of pores) on the intensity of chemical degradation processes and their effect on the mechanical properties of rocks.

Since the beginning of the 15th century, **sandstone** has belonged to the main building materials. The milestone in using arenaceous marl is the period of the end of the 14th and the start of the 15th century, when arenaceous marl was gradually replaced with sandstone. The obvious reason was higher resistance of sandstone to weathering. The collective term – building sandstone – includes several rock types of sedimentary origin, non-identical chemical composition, age and physical characteristics (water absorption, porosity, frost resistance). They are mostly quartz, fine-grained, medium to coarse-grained sandstones of all categories with grading from 0.5 to 2 mm (arkoses with increased contents of clays and kaolinite binder are also present). The highest-quality sandstones in our territory are sandstones quarried in the Božanov locality (compressive strength of 63 MPa, water absorption of 9.2%, 15.5% porosity), which are used for the reconstruction of prominent historic buildings. The specific cause of serious failures of sandstone is the swelling of clay minerals (kaolite, montmorillonite) where the percentage of clays in some types of sandstone is 10 to 25%, in arkoses of up to 75 % [5, 6].

The major physical characteristic which significantly determines the successive time pattern of degradation processes is the porosity of building materials, which changes over time and affects their water absorption.

Building materials and thus whole structures possess some infiltration capacity. Clastic sediments – sandstones have very favourable conditions for infiltration. **Sandstones** differ by their grain size (coarse-grained, fine-grained), the size and distribution of pores (from macropores of 10^{-7} to micropores of 10^{-9}) and **are non-homogenous by their microstructure.**

Tab 1. Comparison of water absorption of sandstones from original localities and building blocks from Charles Bridge

	Water absorption w_t [%]	Water absorption w_t [%]
Stone type	Quarried raw material	Building stone in structure
Quartz kaolinite sandstone	6.1	9.5
Iron sandstone	6.0	11.1

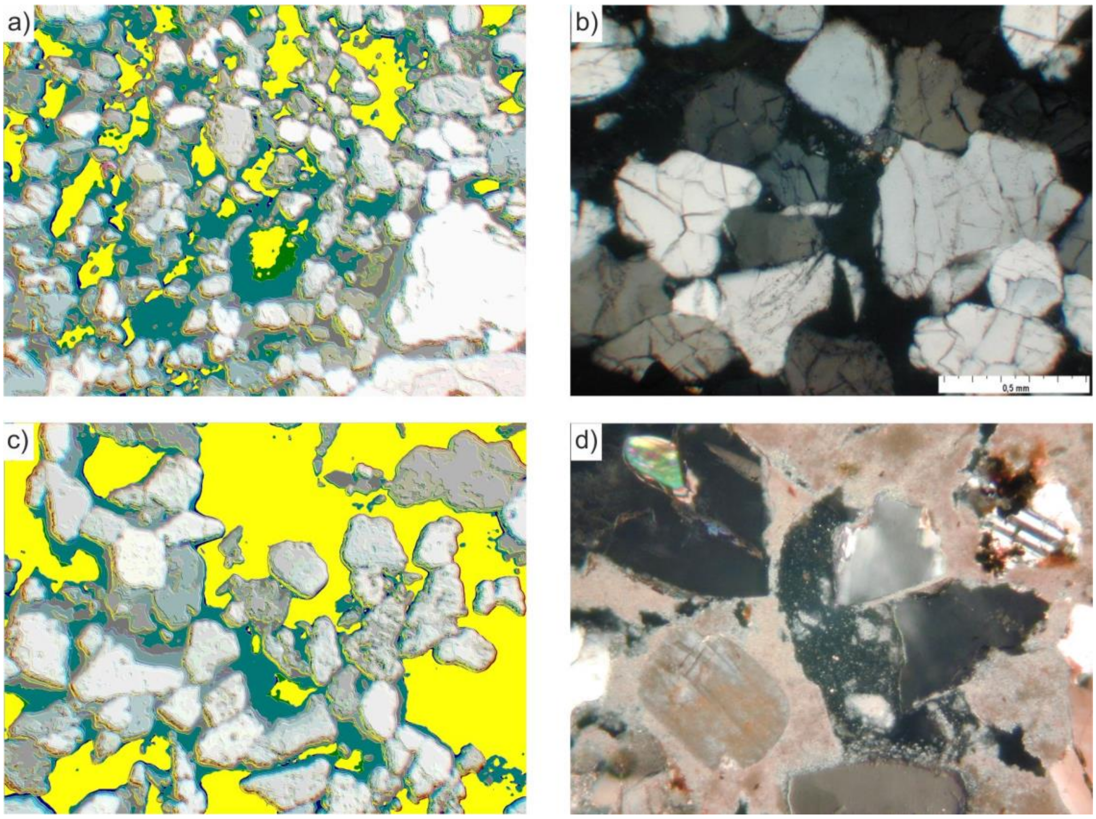


Fig. 1 - a) Pore system of quartz-kaolinite sandstone – initial raw materials, b) Structure and mineral composition of quartz-kaolinite sandstone – initial raw materials. Polarized light microscopy, XPL. Photo by Gregerová, c) Pore system of quartz-kaolinite sandstone – building stone of Charles Bridge, d) Structure and mineral composition of quartz-kaolinite sandstone – building stone of Charles Bridge with carbonate-sulphate binder. Polarized light microscopy, XPL. Photo by Gregerová

The microstructure of sandstone blocks is weakened by the effect of polarization pressures (2-50MPa, Winkler 1975). The original **face masonry blocks** used in the structure of Charles Bridge (14th century), for example, presently **differ by their carbonate-sulphate binder from primary sandstone sources** s.l. It has been manifested that sulphates are found to a depth

---

of ca 1-2mm and below them calcite can be identified in the binder to a depth of max. 5cm (see Figure 2). The results of long-term experimental research [7, 8] of degradation processes on sandstone blocks of Charles Bridge prove a serious effect of these processes – of physical, chemical and mineralogical nature accompanied usually by the effect of elevated moisture.

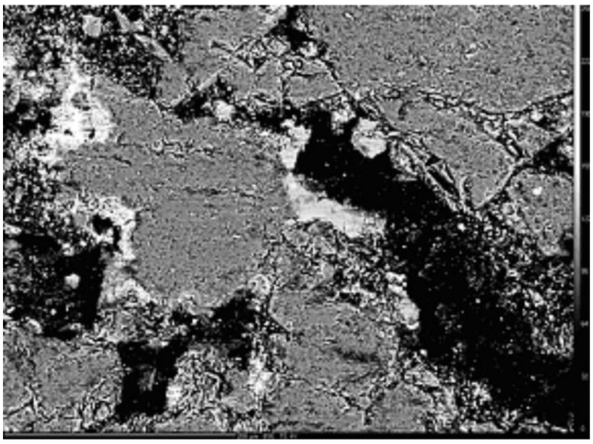


Fig. 2 - Overall distribution of Ca manifesting its presence in carbonate-sulphate binder. Electron microscopy - Cameca SX 100, photo by R. Čopjaková

The action of degradation processes e.g. on the building stone of Charles Bridge in the final phase results in the disintegration of the structure of sandstones s.l. and mechanical disintegration of rocks (building blocks). The exfoliation is most intensively manifested on the face of sandstone blocks s.l. (see Figures 3 and 4).

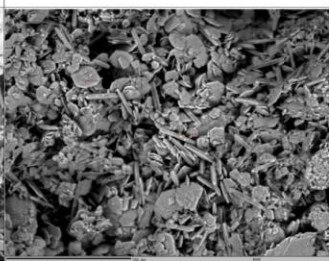
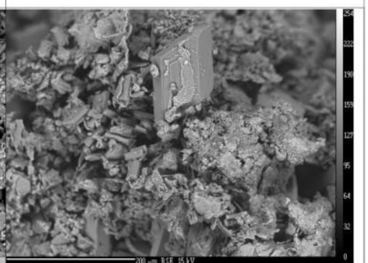
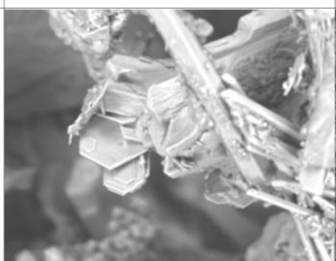
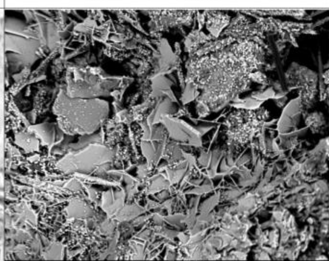
Arch and place	*Summer 2003*	*Winter 2004*	*Summer 2004*
III-5 C	 Crystals tron $Na_3(HCO_3)(CO_3)\cdot 2(H_2O)$. Cameca, fig. R. Čopjaková.	 *The gypsum crystals and chloritu Na-chlorite with a fine coating of clay minerals Cameca, fig. R. Čopjaková.*	 *Gypsum crystals covered with clay minerals. Cameca, fig. R. Čopjaková.*
IV -3-D	 *Detail jarosite (sulfate K and Fe).Cameca, fig. R. Čopjaková .*	 *Crystals alunogenu. Cameca, fig. R. Čopjaková.*	 *Corrosion of gypsum. Cameca, fig.R. Čopjaková.*

Fig. 3 - Gradual change in the mineralogical composition of efflorescence in the annual cycle in selected sampling places of Arch III and IV of Charles Bridge

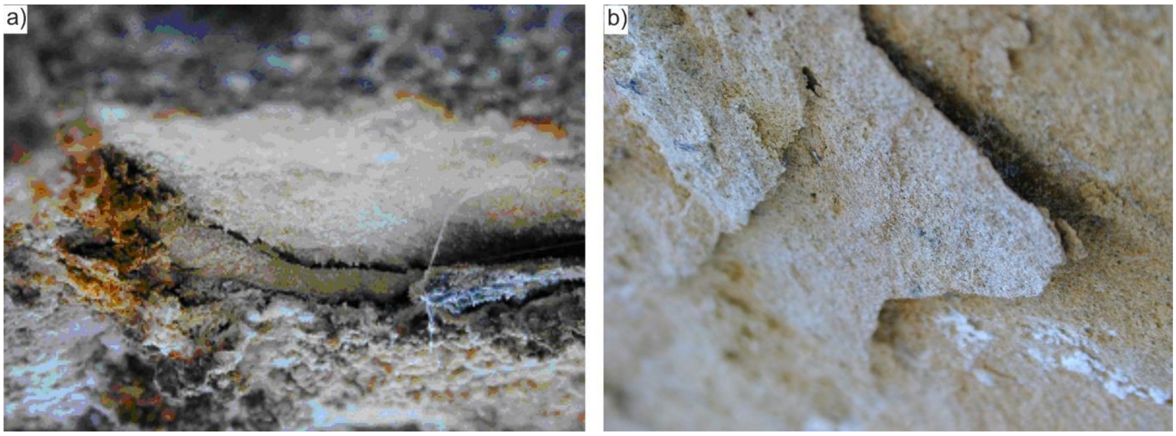


Fig. 4 - a) Example of plate exfoliation of sandstone (cm), b) Example of exfoliation of sandstone laminas (mm). Photo by P. Pospíšil

Degradation processes disintegrating the structure of sandstones in surface layers also result in changes in the physical and mechanical properties of the whole rock mass volume of freestone masonry (Table. 2).

The results of laboratory analyses also confirm the severe effect of moisture changes on the strength of freestone masonry.

Tab. 2 - Compressive strength of sandstone in saturated state and dry state tested on test pieces 50 mm in diameter and the softening coefficient (according to Cikrle)

Test piece	Locality	Initial raw material		Building stone of Charles Bridge				Softening coefficient KZ_c
		Compressive strength $R_{c,n}$ saturated [MPa]	Compressive strength R_c dry [MPa]	Compressive strength $R_{c,n}$ Saturated [MPa]		Compressive strength R_c dry [MPa]		
				individual	mean	individual	Mean	
B 1	Božanov	51.7	57.0		33.9	47.4	44.1	0.77
B 3	Božanov			33.9		40.8		
Z 1	K. Žehrovice	55.4	70.2	41.6	45.6	58.0	58.5	0.78
Z 3	K. Žehrovice			51.9		61.2		
Z 5	K. Žehrovice			43.2		56.4		

Note: The falling values of the softening coefficient document the decrease in the compressive strength (quality) of building stone exposed to elevated moisture contents.

Experimental research (MSM6840770001, GAČR 103/02/0990/A, DF12P01OVV037) conducted at the authors' workplace has manifested a significant effect of moisture on the physical and mechanical properties of porous materials.

Figures 5 to 8 present partial results of experimental research which document the effect of moisture on the compressive strength and modulus of elasticity of fine-grained and coarse-grained sandstone.

Fine-grained sandstone

The correlation of the ultimate compressive strength f_{ubexp} with the percentage of moisture content by weight w_{hm} (Figure 5) showed a nearly identical pattern in all specimens of fine-grained sandstone characterised by a gradual decrease in the ultimate compressive strength in compression f_{ubexp} with the growing moisture content by weight w_{hm}, where in some specimens of fine-grained sandstone this decrease was more prominent in the interval of 0-50% saturation.

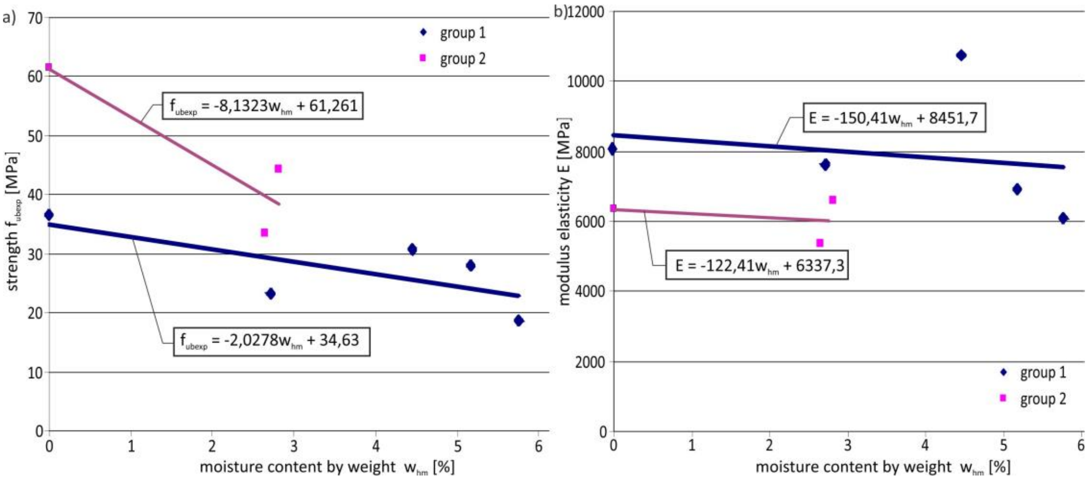


Fig. 5 - Correlation of the ultimate compressive strength f_{ubexp} (a) and the static modulus of elasticity in compression E (b) with the moisture content by weight w_{hm} of groups of fine-grained sandstone specimens [10]

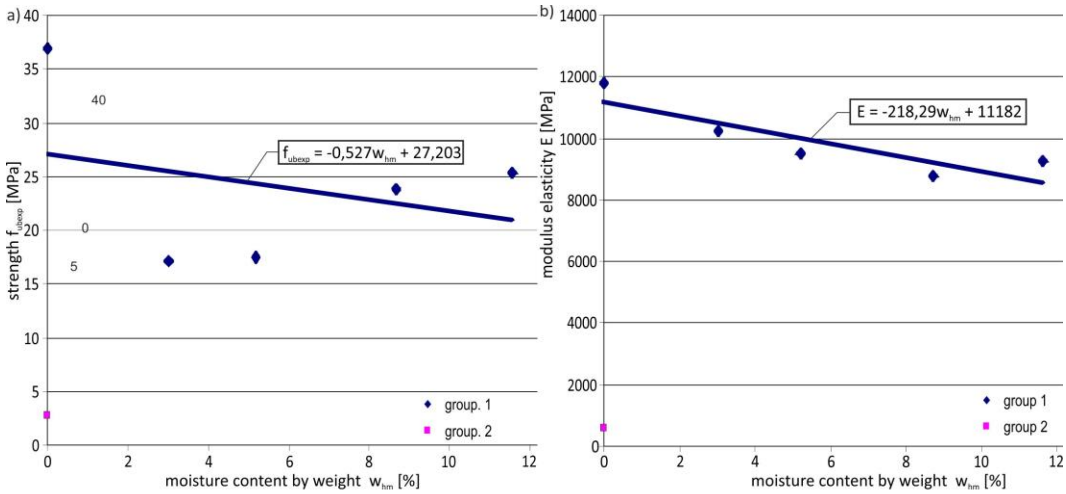


Fig. 6 - Correlation of the ultimate compressive strength f_{ubexp} (a) and the static modulus of elasticity in compression E (b) with the moisture content by weight w_{hm} of groups of coarse-grained sandstone [10]

The correlations of the static modulus of elasticity in compression *E* with the saturation of pores are, with some exceptions, characterised by a relatively low dependence of the values of the static modulus of elasticity in compression *E* on the saturation of pores (Figure 5). In the interval of

0 - 100% saturation, in specimens with the values of the static modulus of elasticity *E* higher than $2*10^3$ MPa, this change does not exceed ca 20 - 30% of the static modulus of elasticity in compression *E* of a dry specimen.

Coarse-grained sandstone

The correlation of the ultimate strength f_{ubexp} with the percentage of the moisture content by weight w_{hm} of a coarse-grained sandstone specimen (Figure 6) is characterised by an initial decrease in the ultimate strength in compression f_{ubexp} with the growing moisture content by weight and a subsequent increase in the ultimate compressive strength f_{ubexp}, where at full saturation of pores the ultimate strengths in compression f_{ubexp} of coarse-grained sandstone reach lower values compared to the ultimate strength in compression f_{ubexp} of dry specimens. The lowest values of the ultimate compressive strength f_{ubexp} of coarse-grained sandstone were identified at saturation $w_{hm} \in (5 - 8)$ %. This decrease accounted for ca 50% compared to the ultimate strength of dry specimens.

The dependence of the static modulus of elasticity in compression *E* of coarse-grained sandstone on the saturation of pores (Figure 6) is characterised by a relatively small decrease in the static modulus of elasticity in compression *E* at greater saturation of pores. At 100% pore saturation (w_{hm} = 11.8%), there was a decrease in the value of the static modulus of elasticity in compression *E* of coarse-grained sandstone by ca 20% compared to the value of the static modulus of elasticity in compression *E* of a dry specimen of coarse-grained sandstone.

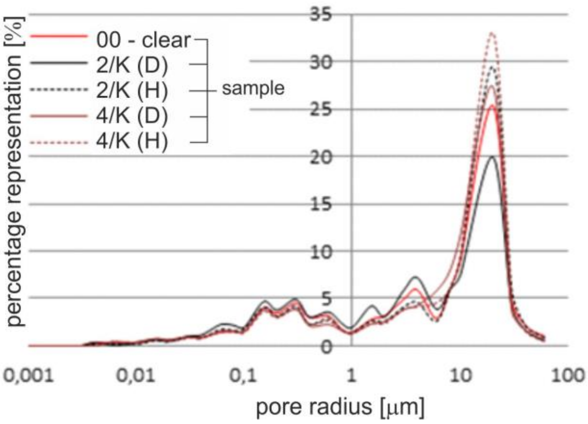


Fig. 7 - Change in the pore distribution of sandstone specimens from Ostroměř loaded by the H2O solution – specimen 00 – original pure sandstone, specimen 2 – after 14 loading cycles using water, specimen 4 - after 41 loading cycles using water [11]

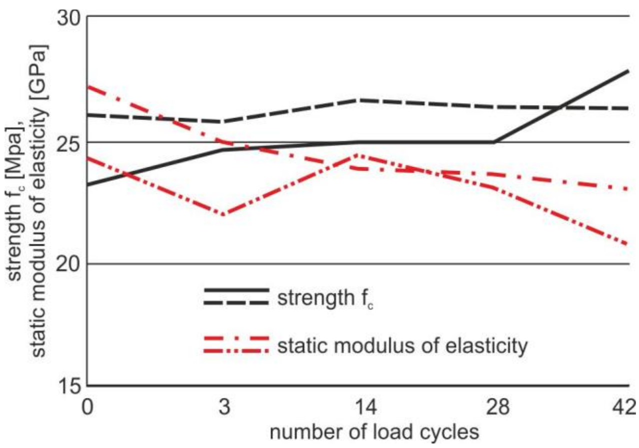


Fig. 8 - Correlation of the uniaxial compressive strength Rc [MPa], the static modulus of elasticity Eb [GPa] of sandstone from Ostroměř locality with the number of loading cycles using 0.5% and 3% NaCl solutions and distilled water [11]

Figure 7 presents the experimentally identified dependence of the pore distribution in sandstone on the number of loading cycles using water (DP SN). Figure 8 shows the dependence of the uniaxial compressive strength Rc [MPa], the static modulus of elasticity Eb [GPa] of sandstone on the number of loading cycles using distilled water.

CONCLUSION

Experimental research has manifested that the determination of the degree and extent of degradation processes of historical building materials, mainly sedimentary rocks, is the basis for not only the identification of their residual service life, but also for the design of rehabilitation – conservation and restoration – methods used during the restoration of historic and heritage buildings.

ACKNOWLEDGEMENTS

The article was written with support from the NAKI DG16P02M055 project "Research and development of materials, processes and techniques for restoration, preservation and strengthening of historic masonry structures, surfaces and systems for preventive care of heritage buildings exposed to anthropogenic and natural risks" of the Ministry of Culture of the Czech Republic.

REFERENCES

[1] Witzany, J., Stařecký, I., Michalko, O., Toman, J.: Degradation Processes of Building Materials and Structures. A report for MIT CR. FCE CTU, 1992. (in Czech)

[2] Witzany, J.; Čejka, T.; Wasserbauer, R.; Zigler, R. 2010 FDR – Failures, Degradation, Reconstructions, 1st edition. in Czech, *CTU Publishing House*, Praha. ISBN 978-80-01-04488-9 (in Czech).

[3] Witzany, J.; Čejka, T.; Zigler, R. Load-bearing capacity determination of historic masonry structures In: Advanced Materials Research. 2014. ISBN 978-3-03835-083-5.

[4] Witzany, J.; Čejka, T.; Zigler, R. The effect of moisture on significant mechanical characteristics of masonry In: Structural Stability and Ductility. 24.09.2009 - 25.09.2009. Vilnius, LT.

[5] Witzany, J. et al..: Chemical and Biochemical Degradation of Charles Bridge, Analysis of the Resistance and Safety of the Stone Bridge Structure in Floods, Investigation of Foundation Masonry and Bridge Pier Foundations, Stavební obzor, 12, 2003, No. 6, p. 161–180, ISSN 1210-4027.

[6] Witzany, J. - Wasserbauer, R. - Gregerová, M. - Pospíšil, P. - et al.: Comprehensive Assessment of a Theoretical and Experimental Investigation of Charles Bridge 1994 to 2004, Part 2. In Stavební obzor. 2005, vol. 14, No. 4, pp. 65-82. ISSN 1210-4027. (in Czech)

[7] Grant GAČR 103/06/1801 "Reliability Analysis of the Properties of Building Materials ad Structures with a Focus on their Time-related Changes and Time-variable Effects", in Czech, 2006- 2008, senior researcher prof. Ing. Jiří Witzany, DrSc.

[8] Research Plan MSM 6840770001 "Reliability, optimization and durability of building materials and structures", senior researcher prof. Ing. Jiří Witzany, DrSc., 2005-2011

[9] Research Project NAKI DF12P01OVV037 project "Progressive non-invasive methods of the stabilisation, conservation and strengthening of historic structures and their parts with composite materials based on nanofibres", 2012 – 2015, senior researcher prof. Ing. Jiří Witzany, DrSc.

[10] Čejka, T.: Experimental In-situ Research of Moisture Effect on Mechanical Properties of Historic Masonry Structures, Habilitation thesis, FCE CTU, Praha 2009.

[11] Neubergova, S.: Analysis of selected degradation factors´ influence on physical and mechanical properties of natural stone; Doctoral dissertation, FCE CTU, Praha 2015.