Effect of Sandstone Anisotropy on its Heat and Moisture Transport Properties

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Each type of natural stone has its own geological history, formation conditions, different chemical and mineralogical composition, which influence its possible anisotropy. Knowledge in the natural stones anisotropy represents crucial information for the process of stone quarrying, its correct usage and arrangement in building applications. Because of anisotropy, many natural stones exhibit different heat and moisture transport properties in various directions. The main goal of this study is to analyze several anisotropy indices and their effect on heat transport and capillary absorption. For basic characterization of studied materials, determination of their bulk density, matrix density and total open porosity is done. Chemical composition of particular sandstones is analyzed by X-Ray Fluorescence. Anisotropy is examined by the non-destructive measurement of velocity of ultrasonic wave propagation. On the basis of ultrasound testing data, the relative anisotropy, total anisotropy and anisotropy coefficient are calculated. Then, the measurement of thermal conductivity and thermal diffusivity in various directions of samples orientation is carried out. The obtained results reveal significant differences between the parameters characterizing the heat transport in various directions, whereas these values are in accordance with the indices of anisotropy. Capillary water transport is described by water absorption coefficient measured using a sorption experiment, which is performed for distilled water and 1 M NaCl water solution. The measured data confirm the effect of anisotropy which is qualitatively the same as for the heat transport parameters. Summarizing the obtained results, it can be concluded that the anisotropy of sandstone should always be considered in planning the restoration works on the architectural heritage, in order to ensure compatibility between the original and replacement material.

Keywords: anisotropy, sandstone, ultrasound velocity, water transport, heat transport.

1. INTRODUCTION

Natural stone is one of the most frequently used building materials all over the world. Mainly the historical constructions were built by several different types of stone [1]. In presence, when concrete plays the most important role in building materials base, studying the natural stones properties aims at the conservation of historical structures.

Natural stone is a very broad term covering a wide spectrum of mineral composition, texture, structure, colours, chemical and mechanical properties. Description of these properties allows a suitable usage of natural stones, taking into account their strength and potential durability problems.

Many authors [2 – 5] in previous works referred about the relation between the pore size distribution and its effects on chemical, physical and biological degradation of stone. Porosity of stones affects damage phenomena like salt crystallization, frost attack and biodegradation processes. Total porosity consists of open pores that are accessible for water and closed pores [6]. The open porosity is more important for describing hygric behavior of natural stones [7]. Other study shows the relationship between porosity of natural stones and compressive strength [4]. Many types of natural stone (sandstone, spongillite) exhibit different transport parameters in various directions [8]. Investigation of anisotropy effect on compressive strength showed that the strength varies with the orientation tremendously [9]. It was found out that using ultrasonic device there is possible to define anisotropy of natural stones which affects their water permeability and shows different water transport trends related to penetration directions [10]. Material anisotropy indices were proposed by many authors [11 – 13]. Anisotropy indices and their influence on capillary absorption [14] revealed a strong effect of anisotropy on various types of rocks (granite, slate and marble).

Understanding the material behavior is crucial for prolonging its service life and proper usage in restoration of historical buildings which are built mainly from stones. For reduction of deterioration of historical buildings, complex characterization of materials properties (hygric, mechanical, thermal) represents first step to a successful accomplishment of this uneasy task.

2. EXPERIMENTAL

2.1. Studied materials

In this study, five types of sandstone (see Table 1) traditionally used in historical buildings on the Czech territory were examined. Particular types of sandstone are labeled for simplification as A1 – A5. All of the quarries used for samples extraction are still functional and supply the market of building stones. Photos (8x zoom) of examined materials obtained by optical microscopy (Jenoptic ProgRes CT3 equipped with Tubus Navitar lens) are shown in Fig. 1 a, b, c. Blocks of researched materials were taken from particular quarries and several cubic

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specimens were cut from them. For the measurement of the index of anisotropy and thermal conductivity, cubic specimens having side of 100 ± 5 mm were used.

Table 1. Overview of studied sandstones

Symbol	Sandstone type (according to the quarry location, in Czech)
A1	Libnavský
A2	Mšenský
A3	Těšínský
A4	Úpický
A5	Zámělský

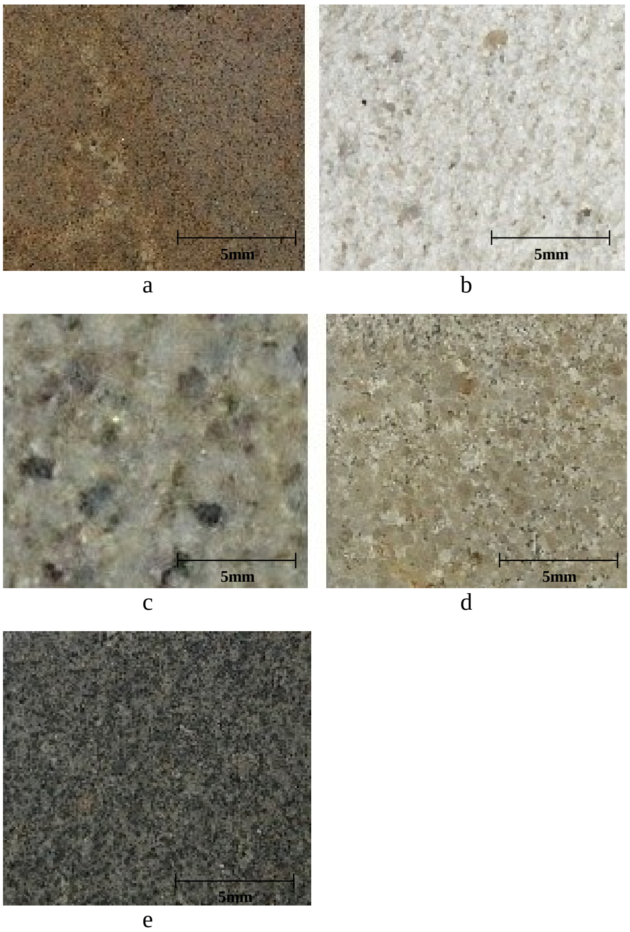

Fig. 1. Microscope photos of studied materials: a – Libnavský sandstone; b – Mšenský sandstone; c – Těšínský sandstone; d – Úpický sandstone; e – Zámělský sandstone

Determination of water transport parameters was done on cubic samples of side 50 ± 5 mm. The sample sizes were measured using a Mitutoyo digital caliper. Sides of all samples were marked to abide the way of sample orientation in the quarries. The samples were dried out in an oven at 80 °C to a constant mass. The dry state was achieved when the difference in mass after two consecutive measurements was lower than 1 %.

For the characterization of studied sandstones, basic material properties were determined. Bulk density was calculated on the basis of knowledge of dry mass and sample dimension. Helium pycnometer Pycnomatic ATC (Thermo Scientific) was used for the measurement of matrix density. Total open porosity ψ (%) was calculated using the matrix density and bulk density values [15]:

$$\psi = \left(1 - \frac{\rho_b}{\rho_{mat}}\right) \cdot 100, \qquad (1)$$

where ρ_b (kg/m^3) is the bulk density and ρ_{mat} (kg/m^3) the matrix density.

Chemical composition of studied sandstones was measured by XRF analysis (X-Ray Fluorescence spectrometer ARL 9400 XP, Thermo Scientific).

2.2. Experimental methods

2.2.1. Ultrasound velocity

Ultrasonic testing is often performed on steel and other metals, though it can be used for concrete or other building materials. The velocity of propagation of ultrasound waves was measured by device DIO562 (Starmans) equipped with 50 kHz transmitters. The cubic samples having the side of 100 mm were used. The applied method is based on measuring the time of the ultrasonic pulse passing through the measured material. During the measurement, the ultrasonic pulse-waves with frequency of 50 kHz are launched. The transmitter sends the ultrasound through one surface, the separate response transducer detects the time of the signal travelling through the specimen and the diagnostic device displays the time [16].

2.2.2. Sorptivity test

The sorptivity test is based on one dimensional free water uptake [17]. Sorptivity S (m/s$^{1/2}$) is defined as

$$I = S \cdot t^{1/2}, \qquad (2)$$

where I (m) is the cumulative absorption of water and t (s) the time of absorption.

Eq. (2) is based on a simplification of the general expression for the cumulative mass of water in terms of the square-root-of-time rule that is commonly employed in the diffusion theory,

$$i = A \cdot t^{1/2}, \qquad (3)$$

where i (kg/m^2) is the cumulative mass of water and A (kg/m^{2}s$^{1/2}$) the water absorption coefficient that is related to the sorptivity by the equation

$$A = S \cdot \rho_w, \qquad (4)$$

where ρ_w (kg/m^3) is the density of water.

2.2.3. Thermal conductivity

Thermal conductivity was measured by the device ISOMET 2114 (Applied Precision) working on dynamic measurement principle which reduces the time of thermal conductivity measurements to 10-20 minutes. This type of measurement is based on the analysis of the temperature response of the analysed material to heat flow impulses. The measuring range of applied apparatus is from 0.015 W/mK to 6 W/mK.

3. RESULTS AND DISCUSSION

Table 2 shows mean values of basic physical properties calculated from 5 measurements. All sandstones have similar values of matrix density, whereas materials denoted A3 and A4 exhibit significantly lower open porosity than the others. The XRF analysis revealed a difference in composition of particular studied sandstones. In Table 3, there is distinct the dominant content of SiO_2 in all types of sandstones.

Table 2. Basic materials properties of studied sandstones

Sandstone type	Open porosity, %	Bulk density, kg/m^3	Matrix density,kg/m^3
A1	17.9	2 191	2 668
A2	30.6	1 845	2 656
A3	5.8	2 490	2 642
A4	8.0	2 438	2 652
A5	22.6	2 076	2 683

Table 3. Chemical composition of studies sandstones

Sandstone	A1	A2	A3	A4	A5
Compound	mass %				
SiO_2	89.52	98.4	75.72	87.88	92.92
Al_2O_3	3.63	0.946	10.12	11.27	2.721
Fe_2O_3	4.61	0.301	3.17	0.243	2.42
CaO	0.12	0.0176	5.17	0.0333	0.173
MgO	0.31	–	0.965	0.069	0.533
K_2O	1.32	0.183	2.66	0.254	1.08
P_2O_5	0.11	–	0.097	0.041	0.008
TiO_2	0.14	0.064	0.348	0.142	0.072
Na_2O	0.05	0.0178	1.52	–	–

For determination of anisotropy, all types of sandstone were tested using an ultrasound device and the velocity of ultrasonic waves in dependence on direction of measurement was calculated. The obtained results of ultrasonic measurements are given in Table 4.

Table 4. Velocity of ultrasonic waves

Material	Direction	Velocity, m/s
A1	Δ	3320.1
	x	2816.9
	o	3175.6
A2	Δ	2216.3
	x	1365.9
	o	2010.5
A3	Δ	3971.4
	x	3001.2
	o	3775.1
A4	Δ	3825.6
	x	3221.7
	o	3781.3
A5	Δ	3115.3
	x	2480.2
	o	2901.1

Here, Δ, o and x are marked directions of ultrasound wave propagation. The given values represent mean values calculated from five measurements. Every sample exhibited similar velocities in two directions and in the third one (denoted as x) the velocity was significantly lower. This reflected the fact that sandstone is a sedimentary rock; the lowest velocity indicated the direction of sedimentation.

The anisotropy indices were determined according to equations (5) – (9), using the maximum (v_{max}), minimum (v_{min}), and intermediate (v_{mean}) velocity.

$$A_v = \left(\frac{v_{\max} - v_{\min}}{v_{\min}} \right) \cdot 100 ; \tag{5}$$

$$ARS = \left(\frac{v_{\max} - v_{\min}}{v_{\max}} \right) \cdot 100 ; \tag{6}$$

$$AD = \frac{v_{\min}}{v_{\max}} ; \tag{7}$$

$$dM\,\% = \left[1 - \left(\frac{2v_{\min}}{v_{mean} - v_{\max}} \right) \right] \cdot 100 ; \tag{8}$$

$$dm\% = \left[\frac{2 \cdot (v_{\max} - v_{mean})}{v_{mean} - v_{\max}} \right] \cdot 100 . \tag{9}$$

The particular formulas used for indices calculation were originally introduced in [11 – 13]. Av is the anisotropy coefficient defined as the ratio of the difference between the maximum and minimum wave velocity and minimum wave velocity. ARS is the relative anisotropy coefficient defined using Eq. 7. AD is the anisotropy coefficient defined as the ratio of the minimal and maximal wave velocity values measured in the three main axes of the cubic samples. dM % is the total anisotropy taking into consideration three spatial axes. dm % is defined as relative anisotropy excluding the axis with the smallest wave velocity. Table 5 shows that the biggest anisotropy was observed for material A2 (Mšenský sandstone), where all indices indicated the highest level of anisotropy.

Table 5. Anisotropy indices

Material	*Av*	*ARS*	*AD*	*dM%*	*dm%*
A1	17.9	15.2	0.8	12.7	5.8
A2	62.3	38.4	0.6	33.0	17.3
A3	32.3	24.4	0.8	21.2	8.6
A4	18.7	15.8	0.8	11.3	10.7
A5	25.6	20.4	0.8	15.4	12.5

The results of the sorptivity test are presented for water transport in Fig. 2 and for the transport of 1M water solution of NaCl in Fig. 3.

The directions perpendicular to sedimentary layers are denoted as "x" and parallel with sedimentary layers as "o". Looking at the measured values, one can see a significant decrease of water absorption coefficient for water transport in the direction of sedimentation. Here, a higher decrease was observed for sandstones with higher indexes of anisotropy. In case of 1M NaCl water solution, the rate of moisture transport was slower compared to the penetration of pure distilled water and can be assigned to the higher viscosity of NaCl solution. Looking at anisotropy indices, the highest differences in moisture transport in respect to direction of sedimentation were obtained for material A2 that exhibits also the highest values of anisotropy parameters. Thus, the accessed data is in good agreement, and support the validity of Eq.5 – Eq.9. Thermal conductivity data measured in different directions of heat transport (marked as Δ, o and x) is given in Table 6.

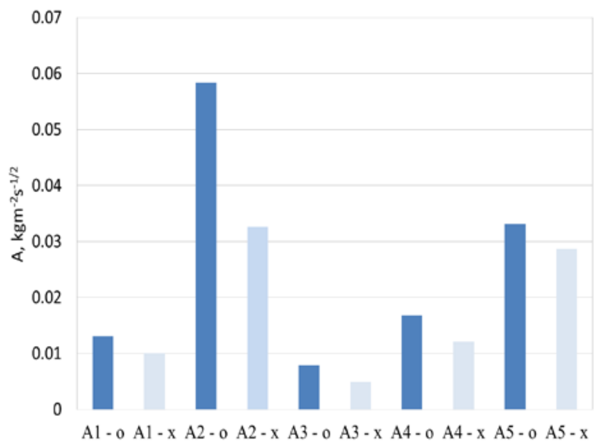

Fig. 2. Water absorption coefficient in dependence on direction of measurement

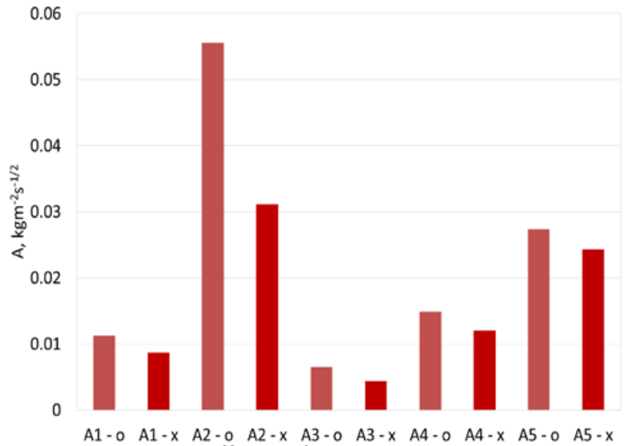

Fig. 3. Absorption coefficient for 1M NaCl in dependence on direction of measurement

Obtained results show a moderate influence of anisotropy on heat transport. However, it is also possible to define the measurement through the sedimentary layers and in the direction parallel to the sedimentary layers.

Table 6. Thermal conductivity in dependence on direction of measurement

Material	Direction	Thermal conductivity, W/mK
A1	Δ	2.73
	x	2.63
	o	2.71
A2	Δ	1.63
	x	1.42
	o	1.61
A3	Δ	2.82
	x	2.23
	o	2.77
A4	Δ	3.75
	x	3.16
	o	3.71
A5	Δ	2.06
	x	1.95
	o	2.10

4. CONCLUSIONS

In the presented work, anisotropy of five types of sandstone quarried in the Czech Republic was studied, with a focus on the influence of the indices of anisotropy on water absorption and heat transport.

The capillary water uptake test showed a high correlation between the values of several anisotropy indices and water absorption coefficient, whereas water absorption was greater in the direction parallel with the sedimentary layers and lower perpendicular to the sedimentary layers.

Similar material performance was observed also in the case of heat transport. The biggest changes in investigated transport properties were revealed in the materials with a high level of anisotropy. On the other hand, the smallest disproportion between the material parameters, as for the dependence on the direction of measurement, was obtained for sandstones with lower open porosity.

Identification of anisotropy of building stones was confirmed as a significant factor of material characterisation affecting their material parameters, which are important for the description of their behaviour in a structure. It was found that the mean ultrasound propagation velocity (v_{mean}) is not enough to determine the quality of the natural stone; the minimum propagation velocity (v_{min}) is more representative, as it has a more direct effect on stone decay.

Looking at measured data of water absorption coefficient it is quite clear that construction material anisotropy determines the material resistance to the agents inducing decay. The way these materials are positioned in building structure may contribute to decay by facilitating water ingress. Capillary water uptake is also influenced by the direction in which the stone is laid: absorption is greater in more anisotropic, more porous varieties and in the direction parallel to the plane of anisotropy, where water is absorbed more quickly. Therefore, the higher quality of building structures can be attained by choosing stone varieties with low anisotropy indices.

Ultrasonic method for anisotropy parameters assessment is in a comparison with mechanical compression tests non-destructive. It allows repeated testing of researched materials, what is highly beneficial especially for materials with high inhomogeneity and multi-layered structure.

The obtained data proved that the restoration of architectural heritage cannot be performed without a detailed knowledge of used materials, especially in the case of sedimentary rocks. A proper knowledge and usage of building stones can provide significant cost savings in the reconstruction works, as well as a longer lifetime of materials due to delaying decay and increasing the overall service life of buildings.

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