Mechanical, hygric and thermal properties of building stones

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Abstract

Basic physical properties, pore distribution, mechanical, hygric, and thermal properties of several types of building stones which were used in historical buildings on the Czech territory in medieval times, namely several types of sandstone and argillite, are investigated. Bulk density, matrix density and open porosity are measured using the water vacuum saturation method, pore distribution by mercury porosimetry, compressive and bending strength by a hydraulic testing device. Apparent moisture diffusivity is determined by utilizing the results of water sorptivity measurements, the dependence of moisture diffusivity on moisture content is obtained by measuring moisture profiles using a capacitance technique and subsequent solution of the inverse problem of moisture diffusion. Water vapor diffusion permeability is measured by the cup method, sorption isotherms are determined by the desiccator method. Thermal conductivity and specific heat capacity are measured by an impulse technique in the moisture range from the dry state to full water saturation.
Keywords: sandstone, argillite, mechanical properties, hygric properties, thermal properties.

1 Introduction

Understanding the hygrothermal behavior of historical buildings exposed to various environments represents a first step in avoiding damage or the undue heat loss from constructions. It also creates a basis for constitutive models for

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porous materials whose time-dependent properties, such as shrinkage, creep, strength, etc., are strongly affected by the moisture and temperature fields. Their prediction is a very important task when preserving historical bridges and buildings, and insulating existing buildings or their parts.

The damage assessment of historical masonry due to the negative effects of moisture and temperature can be done most effectively by means of mathematical and computational modeling. In this way, the time development of moisture and temperature fields can be obtained which is a crucial for a proper assessment of possible future damage; the moisture and temperature values can be assigned to the mechanical properties, thus to the risk of consequent damage.

In the modeling of coupled moisture, heat and momentum transport in historical masonry, there are two types of input parameters which have to be known in advance. The first are initial and boundary conditions. Initial conditions can be determined using on site and subsequent laboratory analysis of moisture and temperature fields in the historical masonry walls. Boundary conditions are of two types. The first of them are meteorological data for temperatures, relative humidities, rainfall and solar radiation, possibly also concentration of acid-forming gases in the atmosphere. This type of data can be obtained from meteorologists in the form of so-called TRY (Test Reference Year) data which present certain average values over a sufficiently long time period. The second type of boundary conditions involves moisture content (possibly also salt concentration) in the underground soil close to the studied building. These data can be obtained again by on site analysis.

The second type of input parameters is represented by hygric, thermal, and mechanical properties which appear in the complex hygro-thermo-mechanical models. These parameters can be determined by laboratory methods. Samples for the determination of material parameters can be obtained most easily from the walls of the analyzed historical building. If this is not possible, masonry stone samples can be taken from the original quarries which are usually known for a particular building. In the case of brick masonry, similar bricks can be found.

In this paper, basic physical properties, pore distribution, mechanical, hygric and thermal properties of several types of building stones which are used in reconstructions of historical buildings on the Czech territory, namely several types of sandstone and argillite, are investigated. The main aim of the presented work is to obtain sufficiently wide set of input data for the computational damage assessment of historical masonry.

2 Materials

Three types of sandstone coming from different quarries in the Czech Republic are analyzed together with one type of argillite. Many historical buildings in Czech Republic were built using several kinds of sandstone. Siliceous raw-grained sandstone was usually used for historical architectural constructions (walls, portals, window frames) for its strength. Ornamental parts of the architecture (gothic flowers, romantic shells) and sculptures (from the Romanesque period up to now) were made of fine-grained calcite-argillaceous sandstone. The studied sandstones originate from the quarries Mšené-lázně (it will be denoted as PM in what follows), Božanov (PB), and Hořice (PH). They are formed by suboval quartz clasts, tourmaline, epidote, muscovite and zircone. Also argillite was very popular material in historical architecture. It was used for sacral as well as for secular buildings, flagstone pavements, roof slabs, and facing. The studied argillite (it will be denoted as O) is coming from quarry Džbán. Its main constituents are illite, calcite, minerals on the basis of SiO_2 having granularity 0.3–0.15 mm, feldspar, and mica. Rigid materials form 40–60% of its volume.

3 Experimental methods

3.1 Basic physical properties

The bulk density ρ_b [kgm^{-3}], open porosity Ψ [%] and matrix density ρ_{mat} [kgm^{-3}] were determined by the water vacuum saturation method [1]. Each the specimens having a size of 40 x 40 x 20 mm was dried in a drier to remove majority of the physically bound water. After that the samples were placed into the desiccator with deaired water. During three hours air was evacuated with vacuum pump from the desiccator. The samples were then kept under water not less than 24 hours.

Characterization of pore structure was performed by mercury intrusion porosimetry. The experiments were carried out using the instruments PASCAL 140 and 440 (Thermo Scientific). The range of applied pressure corresponded to the pore diameters of 3 nm to 1000 μm. The specimens with a volume of about 1 cm^3 were used in the tests.

3.2 Mechanical properties

The measurement of bending strength was done on 40 x 40 x 160 mm prisms. The experiment was performed as a common three-point bending test using a VEB WPM Leipzig device. The distance of the supporting cylinders was 100 mm. The bending strength was calculated according to the standard evaluation procedure. Compressive strength was determined on the halves of the specimens left over after the bending test. It was calculated as the ratio of the ultimate force and the load area.

3.3 Water transport properties

The liquid water transport was characterized by two different methods. In the first one, the water absorption coefficient A [kg m^{-2} s$^{-1/2}$] and apparent moisture diffusivity κ [m^2 s^{-1}] were determined by a free water intake experiment [2]. The specimen was water- and vapor-proof insulated on four lateral sides and the face side was immersed 1 mm under the water level. Constant water level in the tank was achieved by a Mariotte bottle with two capillary tubes. The balances allowed continuous recording the increase of specimen´s mass. The water absorption coefficient of each specimen was calculated from the linear part of the dependence of the increase of tested sample's mass on the square root of time. Then, the apparent moisture diffusivity was calculated using the saturated moisture content and water absorption coefficient [3]. The measurement was done on the samples with the dimensions of 40 x 40 x 20 mm.

In the second method, the moisture dependent moisture diffusivity was determined using an inverse analysis of measured moisture profiles. The experiment was realized in the form of horizontal suction of liquid water into dry materials. The sample size for moisture profiles measurement was 20 x 40 x 300 mm and the samples were on all lateral sides insulated by epoxy resin to ensure 1-D moisture transport. The moisture content measurements were done by capacitance technique using capacitance device [4] having low-voltage supply that drives an oscillator of 400 kHz working frequency. It has a constant output voltage feeding a circuit where the measuring capacitor (with the analyzed moist sample as dielectric) is connected in series with a resistance. The obtained moisture profiles were then analyzed using solution of the inverse problem of moisture diffusion. For this purpose, the Boltzmann-Matano method [5] was used.

3.4 Water vapor transport properties

The dry cup and wet cup methods were employed in the measurements of water vapor transport parameters [1]. The water vapor diffusion permeability δ [s], water vapor diffusion coefficient D [m^2s^{-1}] and water vapor diffusion resistance factor μ [-] were determined. The circular samples had diameter of 95 mm and thickness of 20 mm.

3.5 Sorption isotherms

Water adsorption and desorption isotherms were determined using the desiccators method [1]. The measurement was done on the samples with the dimensions of 40 x 40 x 10 mm.

3.6 Thermal properties

Thermal conductivity λ [W m^{-1} K^{-1}] and specific heat capacity c [J kg^{-1} K^{-1}], were measured using the commercial device ISOMET 2104 (Applied Precision, Ltd.). The measurement is based on analysis of the temperature response of the analyzed material to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater having a direct thermal contact with the surface of the sample. The measurement was done on the samples with the dimensions of 70 x 70 x 70 mm.

4 Experimental results and discussion

4.1 Basic physical properties

Basic physical properties of the analyzed stones are presented in Table 1. The lowest bulk density and highest open porosity had argillite, the highest bulk density and lowest open porosity showed sandstone Božanov. The other two sandstones were in between these two extremes, Mšené sandstone being closer to argillite and Hořice sandstone closer to Božanov sandstone. The matrix densities of all three sandstones were similar, the Mšené sandstone with the highest ρ_{mat} differed only by about 2–3% from the others. This reflected their similar composition. Argillite, on the other hand, had the matrix density about 12–15% lower than the sandstones.

Table 1: Basic physical properties of building stones.

Material	ρ	ρ_{mat}	ψ
	[kg m^{-3}]	[kg m^{-3}]	[%]
PM	1807	2627	31.0
PB	2154	2566	16.1
PH	2004	2556	21.6
O	1353	2235	39.4

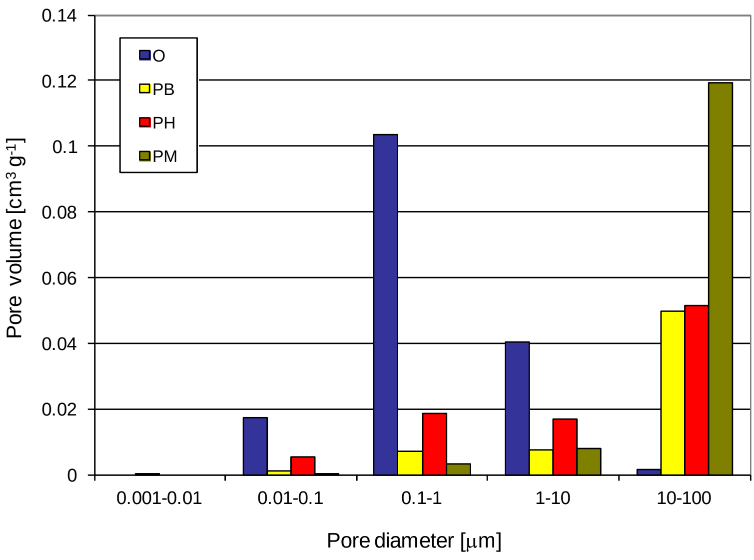

Figure 1: Pore size distribution of building stones.

The pore distribution of sandstones and argillite was very different (Figure 1). While the sandstones had a majority of pores in the range of 10–100 µm, argillite exhibited the major peak between 0.1 µm and 1 µm.

4.2 Mechanical properties

Table 2 shows that the highest compressive and bending strength had Božanov sandstone which corresponded with its lowest open porosity (Table 1). The lowest compressive strength exhibited argillite with the highest total porosity but the lowest bending strength had Mšené sandstone with the highest amount of big pores with the radii between 10 μm and 100 μm. Thus, while for the compressive strength the main factor was the total porosity, for the bending strength crack formation in the system of big pores was most important.

Table 2: Mechanical properties of building stones.

Material	Compressive strength [MPa]	Bending strength [MPa]
PM	21.7	2.2
PB	53.1	5.8
PH	27.0	5.5
O	15.9	4.4

4.3 Water transport properties

Apparent moisture diffusivity and water absorption coefficient are presented in Table 3. The fastest liquid water transport exhibited Mšené sandstone. The other building stoned transported water in a much slower way; their apparent moisture diffusivity exhibited values about three orders of magnitude lower. This was in basic accordance with the open porosity (Table 1) and pore distribution (Figure 1) data.

Table 3: Water transport properties of building stones.

Material	A $[kg\ m^{-2}s^{-1/2}]$	κ $[m^2\ s^{-1}]$
PM	0.8841	1.24E-05
PB	0.0254	2.50E-08
PH	0.0433	4.14E-08
O	0.0959	5.29E-08

The moisture diffusivity as a function of moisture content is shown in Figure 2. While the highest moisture diffusivity in the whole range of moisture content had Mšené sandstone, the lowest values achieved argillite. This was in a good qualitative agreement with their pore distribution. The high amount of capillary pores in the range of 10 - 100 μm (Figure 1) was clearly responsible for the very fast water transport in Mšené sandstone. Argillite with the majority of

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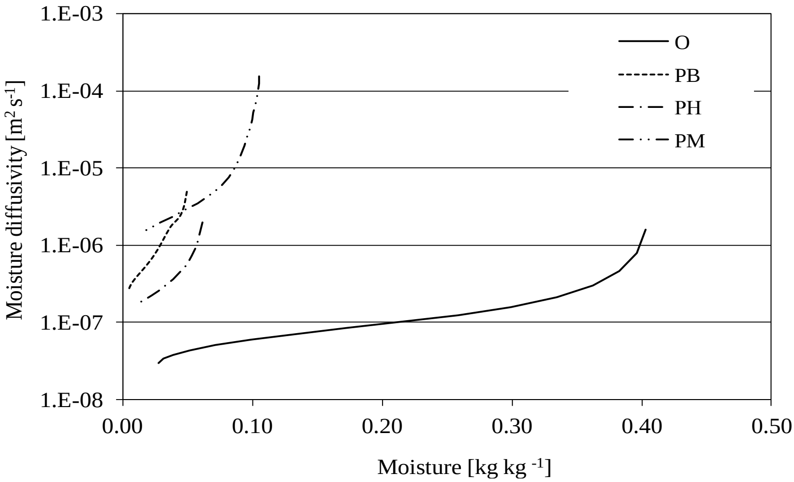

Figure 2: Moisture diffusivity of building stones as a function of moisture content.

pores in the 0.1–1 μm range, on the other hand, did not have good prerequisites for such a fast liquid water transport although its total porosity was higher than of Mšené sandstone. The other two sandstones exhibited liquid moisture transport capabilities closer to Mšené sandstone than to argillite. In this case, the relatively high amount of big pores in the 10–100 μm range was clearly the decisive factor.

A comparison of liquid water transport properties in Table 3 and Figure 2 shows that the apparent moisture diffusivity was (except for Mšené sandstone in the range of highest moisture content) lower than the moisture diffusivity determined as a function of moisture content. The main reason was the very different character of both methods. While the free water intake experiment can be considered only a tool for getting estimated moisture diffusivity values which should serve just for orientation purposes [2], the method based on the inverse analysis of moisture profiles is more rigorous; thus the latter is supposed to give higher-accuracy results [6]. Another factor that could influence the obtained results was that in the free water intake experiment the water transport was realized in vertical direction, while the moisture profiles were measured in an experiment with horizontal water transport. Thus, the effect of gravity could lead to slowing down water transport in the pores with the highest radii. This may partially explain the relatively high differences between the results obtained by both methods for Hořice sandstone and Božanov sandstone, in particular.

4.4 Water vapor transport properties

The water vapor diffusion resistance factor of all analyzed building stones (Table 4) was very low which can partially explain their successful use in historical buildings having traditionally no horizontal waterproof insulation, contrary to the contemporary structures. The moisture content in the walls of

Table 4: Water vapor transport properties of building stones.

Material	5/50%			97/50%		
	δ	D	μ	δ	D	μ
	[s]	[m^2s^{-1}]	[-]	[s]	[m^2s^{-1}]	[-]
PM	2.41E-11	3.32E-06	6.98	3.11E-11	4.28E-06	5.49
PB	1.27E-11	1.74E-06	13.38	3.08E-11	4.23E-06	7.18
PH	1.55E-11	2.13E-06	11.59	3.07E-11	4.22E-06	5.77
O	2.96E-11	4.06E-06	5.66	8.92E-11	1.23E-05	1.91

historical buildings could thus be moderated by the easy water vapor removal during the warm periods of the year. The values of the water vapor transport parameters were in a qualitative agreement with the total porosity (Table 1). Contrary to the liquid water transport, the total pore volume is a more important factor for water vapor transport than the pore size distribution [6].

The measured data revealed that the values of water vapor diffusion coefficient corresponding to the lower values of relative humidity (5/50%) were always lower than those for higher relative humidity values (97/50%). This is related to the partial transport of capillary condensed water in the wet-cup arrangement [6].

4.5 Sorption isotherms

Figure 3 shows the measured adsorption (lower curves) and desorption (upper curves) isotherms. The highest overall water vapor adsorption capacity exhibited

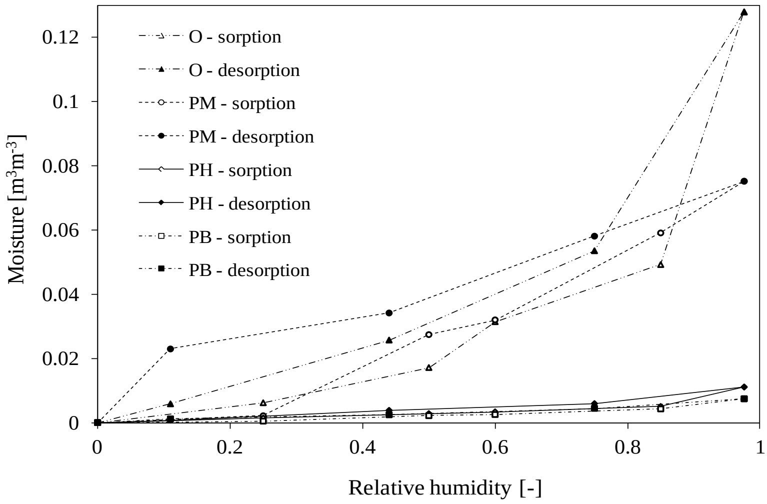

Figure 3: Sorption isotherms of building stones.

argillite. This was in accordance with its highest porosity (Table 1) and highest amount of small pores (Figure 1) having high specific surface. The lowest water vapor adsorption showed Božanov sandstone with the lowest porosity and very low amount of small pores. The other two sandstones were in between, Mšené sandstone being closer to argillite and Hořice sandstone closer to Božanov sandstone.

In the range of lower relative humidity up to 0.7, the highest capability of water vapor adsorption presented Mšené sandstone. This can be explained by a different adsorption mechanism in Mšené sandstone as compared to argillite. At very low relative humidity, the molecules of water are bound in one layer to the surface of pores by hydrogen bonds or van der Waals forces [6]. The significance of this phase of sorption was manifested by the relatively fast moisture increase in the initial region of the adsorption isotherm of Mšené sandstone which provided, apparently, a high amount of possible sites for bonding water vapor molecules. Once all surfaces of pores are covered by one layer of molecules, further layers begin to be formed, typically 2–3 at maximum [6]. This phase is characterized by the linear part of the isotherm; for Mšené sandstone the increase of adsorbed water vapor was here already less remarkable than for argillite. The final phase is the phase of capillary condensation, which can be expressed for a single capillary by the Kelvin equation [6]. Here, the amount of small pores up to 50 nm was clearly the decisive factor (Figure 1).

It should be noted that the differences in adsorption and desorption isotherms were for Mšené sandstone and argillite relatively high. This indicated a considerable amount of “bottleneck” pores.

4.6 Thermal properties

Figure 4 shows that the dependence of thermal conductivity of studied building stones on moisture content was very significant; up to 100% increase of thermal conductivity was observed for water saturated specimens as compared with the dry state.

The specific heat capacity increased considerably with increasing moisture content (Figure 5) which was related to the high specific heat capacity of water.

5 Conclusions

For the determination of hygrothermal performance of historical buildings, methods of computational modeling are often applied in building practice and research. In this way, the time development of moisture and temperature fields can be obtained. This information can be then used for the identification of weak areas of investigated structures and possible future damage. On the basis of hygrothermal analysis coupled with mechanical models, the risk analysis of buildings and inbuilt materials can be done as well. However, in practical application of computational modeling, one must take into account the accuracy of calculated data which is critically dependent on the availability of all input parameters.

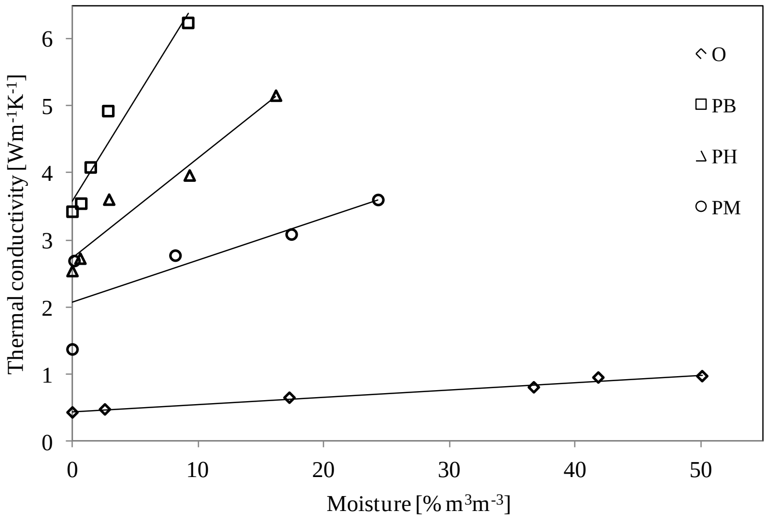

Figure 4: Thermal conductivity of building stones.

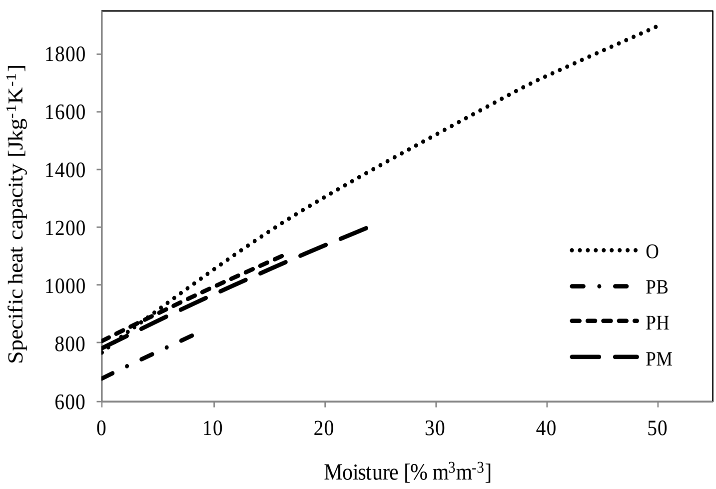

Figure 5: Specific heat capacity of building stones.

The experiments presented in this paper provided information on the basic physical properties, mechanical, hygric, and thermal properties of four building stones which were frequently used on the territory of the Czech Republic in medieval rimes. The obtained data revealed very significant differences in measured properties of the particular materials which underlined the necessity of such kind of experimental analysis before the materials' application.

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