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Comparison of porosity and permeability of sandstones from MIP and laboratory tests

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Abstract

The microstructure of pores, defined primarily by their size distribution, shape and mutual connectivity, has a fundamental influence on physical-mechanical and deformation properties of rocks. It also significantly influences fluid transport and storage capacity and co-determines rock resistance to weathering. Precise characterization of pore microstructure and permeability is therefore essential for evaluation of hyrocarbon reservoirs, assessment of the suitability of the rock environment for CO_2 storage and as a geological barrier in deep geological repositories of high-level radioactive waste, or for the protection of stone monuments. In this study, porosity and hydraulic properties of four Czech sandstones (Godula, Mšené, Hořice and Kocbeře) of different microstructure, composition and physical-mechanical properties were investigated using high-pressure mercury intrusion porosimetry (MIP) and direct laboratory measurements of gas permeability and hydraulic conductivity. The most porous sandstones are Mšené (ca 30 %) and Hořice (ca 25 %), followed by the moderately porous Kocbeře sandstone (ca 15 %), while the least porous is the Godula sandstone (ca 5 %). Hydraulic conductivities derived from MIP are in the order of 10^{-9} m·s^{-1} for all sandstones, whereas laboratory tests yield markedly different values: $10^{-5}$to 10^{-7} m·s^{-1} for highly porous sandstones, 10^{-6} to 10^{-8} m·s^{-1} for moderately porous sandstone, and as low as 10^{-12} m·s^{-1} for the least porous sandstone. Similar discrepancies were also found when comparing coefficients of permeability derived from MIP and obtained from laboratory tests. These results highlight differences between porosimetry-based and laboratory-derived hydraulic parameters, reflecting the influence of pore microstructure, pore-throat geometry, tortuosity and connectivity on fluid transport in sandstones, but the different size of the test specimens used in these two methods also plays an undeniable role. The findings confirm that for a reliable evaluation of transport properties of porous rocks, it is necessary to combine MIP results with laboratory tests on larger volumes.

Keywords

Sandstone, Pore microstructure, Fluid permeability, Mercury porosimetry, Permeability measurements.

1 Introduction

Clastic sedimentary rocks, particularly sandstones, are widely utilized both as natural building materials and as reservoirs in hydrogeology and petroleum engineering. In the near future, sandstone formations will also play a crucial role as host rocks for storing greenhouse gases, especially CO_2. Mechanical and deformation behavior of rocks in general, as well as their durability and ability to transport fluids are strongly influenced by pore microstructure and the connectivity of the pore space (Rasiņa et al. 2022; Řimnáčová et al. 2020; Sufian and Russell 2013). Cracks and the pore network therefore determine the overall porosity, permeability and hydraulic conductivity of the rock (Lokajíček et al. 2026; Řimnáčová et al. 2024). Understanding these parameters is essential not only for predicting the long-term stability of sandstones in architectural applications, but also for evaluating their role in groundwater flow and hydrocarbon migration. Many different experimental approaches can be employed to characterize pore systems, such as optical microscopy, scanning electron microscopy, high-pressure mercury intrusion porosimetry (MIP), gas adsorption, X-ray computed micro-tomography, small-angle neutron scattering, nuclear magnetic resonance or laboratory measurements of permeability and hydraulic conductivity (Freire-Lista et al. 2015; Jun and Liang 2024; Košek et al. 2024; Wang et al. 2022; Zeng et al. 2021; Zhao et al. 2024). Among them, MIP, which provides detailed information on pore size distribution and laboratory permeability tests, which directly measure fluid transport properties, are currently among the most widely applied. Comparison of these methods offers valuable insights into how pore geometry translates into effective hydraulic behavior and highlights the importance of integrating multiple techniques when assessing the complex fluid permeability of porous rocks.The aim of this study was to compare commonly used methods for the determination and assessment of porosity and permeability of porous rocks. For this purpose, four types of sandstones with distinct properties were selected, each expected to exhibit different pore space parameters and fluid permeabilities depending on their specific microstructural characteristics.

2 Rock material used for the experiment

The following four types of Czech sandstones, differing in microstructure, composition and physical-mechanical properties were selected for this study: (i) fine- to medium grained glauconitic sandstone from the Řeka quarry, often referred to in literature as Godula sandstone (Vavro et al. 2016), (ii) fine- to medium-grained quartz sandstone from the Kocbeře quarry (Kytýř et al. 2024; Vavrik et al. 2021; Vavro et al. 2026), (iii) fine-grained quartz sandstone from the Podhorní Újezd quarry, commonly referred to as Hořice sandstone (Vavro et al. 2019), and (iv) fine-grained, quartz-rich Mšené sandstone (Koudelka et al. 2020; Kytýř et al. 2024). All of these sandstones are well-known building and sculpture stone materials that have been used in the territory of the present-day Czech Republic for many centuries. In particular, Hořice sandstone has been used in a number of well-known historical monuments, such as St. Vitus Cathedral, Charles Bridge and the National Theatre in Prague.

Physical and mechanical properties of studied rocks are presented in Table 1.

Table 1. Range of values of selected physical-mechanical parameters of rocks used for experiment (according to previous own measurements and data published in above mentioned literature).

Rock property	Godula sandstone	Kocbeře sandstone	Hořice sandstone	Mšené sandstone
Bulk density [kg·m^{-3}]	2440 – 2610	2140 – 2270	1760 – 1960	1850 – 1930
Total porosity [%]	5.4 – 9.4	12.0 – 17.2	27.9 – 28.4	26.3 – 29.7
Open porosity [%]	4.0 – 5.8	9.2 – 17.1	23.8 – 26.3	24.0 – 28.2
Water absorption capacity [%]	0.7 – 3.0	2.2 – 6.1	7.3 – 11.6	10.8 – 13.3
Ultrasonic wave velocity [km·s^{-1}]	3.12 – 4.29	2.74 – 3.48	2.39 – 2.55	2.13 – 2.36
Uniaxial compressive strength [MPa]	103 – 156	56 – 87	26 – 33	21 – 33
Splitting tensile strength [MPa]	4.0 – 10.0	2.6 – 6.1	1.2 – 1.6	1.1 – 1.4

strength properties were tested on dried test specimens, water absorption capacity was determined after 48 hours of soaking

3 Methods, test samples and equipment used in the experiment

Mineral composition and internal texture of sandstones were studied using optical polarization microscopy (OPM) and X-ray powder diffraction (XRPD). OPM for basic petrographic analysis was undertaken in transmitted light on cover-slipped thin sections using a NIKON Eclipse LVDIA-N polarizing microscope (Nikon, Japan), coupled with the NISElements image processing and analysis

software (Laboratory Imaging, Czech Republic). Analysis of mineralogical composition of the sandstone matrix was carried out using XRPD with a Rigaku SmartLab diffractometer (Rigaku Corporation, Japan) with a D/teX Ultra 250 detector. The powder samples were gently ground using agate mortar before analysis and pressed using microscope glass in a rotational sample holder and measured in a reflection mode (Bragg-Brentano geometry). The measured data were evaluated using PDXL 2 software 2.4.2.0 (Rigaku Corporation, Japan) and compared with database PDF-2 (International Centre for Diffraction Data, USA).

The pore space of sandstones and their hydraulic properties were investigated using MIP and direct laboratory measurements of gas permeability and hydraulic conductivity. For MIP measurements, a small piece of rock measuring approximately 0.5 x 0.5 x 0.5 cm and weighing about 1 g was chipped off from the rock using a sharp hammer. This piece was dried in a drying oven at 105 °C before measurement and then weighed. The measurement was performed twice for each rock, with a piece of approximately the same size used for each partial measurement. The MIP measurements of pores in the size range 7 nm – 112 μm were performed using Pascal 140 EVO and Pascal 440 EVO (Thermo Fisher Scientific, USA)mercury porosimeters equipped with SOLID software.The permeability evaluation from MIP data is based on the studies of Scheidegger (1974) and Carniglia (1986).

Hydraulic conductivity measurements were performed in a permeameter from the Infratest Prüftechnik GmbH (Germany) in a triaxial pressure chamber using deaerated pressurized water under the constant hydraulic gradient. For this measurement, cylindrical test specimens with a diameter and length of 48 mm, i.e. with the length-to-diameter(L/D) ratio of 1:1, were prepared. The confining pressure was set at 0.55 MPa during the testing. The calculated hydraulic conductivity coefficient (HCC) at the ambient temperature was subsequently recalculated to the comparative value for HCC k_{10} at 10 °C.Gas permeability of sandstones was measured using a KTK 100 triaxial cell (UNIPRESS, Poland) modified for gas passage. A computer-controlled mechanical press ZWICK 1494 (Zwick/Roell, Germany) served as the source of axial stress, and nitrogen was used as the measuring gas. For the test, cylindrical specimens with 48 mm in diameter and ca 96 mm in length, i.e., with an L/D ratio of 2:1, were used. They were covered with a rubber membrane, then clamped in jaws of the press machine and the confining pressure was set to 3 MPa. Throughout the experiment, the nitrogen pressure was regulated using the control valve and kept at 0.1 MPa. Within the laboratory measurements of gas permeability and hydraulic conductivity, the open (effective) porosity of sandstones was also determined, by calculating it from the measured values of bulk density and water absorption capacity until the sample weight stabilized. Bulk density was calculated from the mass of the specimen and the bulk volume. Water absorption capacity was determined from the weights of dry and water-saturated test specimens. The soaking time until the weight stabilized was approximately 4 to 6 weeks depending on the type of sandstone.

4 Experimental results

Basic petrographic parameters of studied sandstones are presented in Table 2 and in Fig. 1.

Table 2. Mineralogical composition and grain size of studied sandstones obtained using OPM and XRPD.

Sandstone	***Md*of quartz grains [mm]**	**$M_{max}$of quartz grains[mm]**	**Main clastic components**	**Rock matrix and cement**
Godula	0.18 – 0.39	1.35 – 1.55	quartz + quartzite > orthoclase > plagioclase > muscovite > biotite± other rock fragments	ca 10 – 20% of rock volume; clay matrix (illite>illite-smectite mixed-layers>kaolinite) with siliceous and carbonate rock cement and glauconite grains
Kocbeře	0.19 – 0.33	0.95 – 1.45	quartz + quartzite > orthoclase >> muscovite	ca 10 – 15 % of rock volume; clay and siliceous matrix with local limonite, locally intense secondary silicification
Hořice	0.19 – 0.25	0.40 – 1.15	quartz + quartzite > orthoclase + plagioclase >> muscovite	ca 15 – 20 % of rock volume; clay matrix (kaolinite >>illite + smectite) with finely dispersed limonite
Mšené	0.12 – 0.18	0.46 – 0.95	quartz + quartzite >>> orthoclase > plagioclase > muscovite	ca 3 – 5 % of rock volume; clay matrix (kaolinite>>illite) with finely dispersed limonite

Md– average grain size, M_{max}– maximum grain size

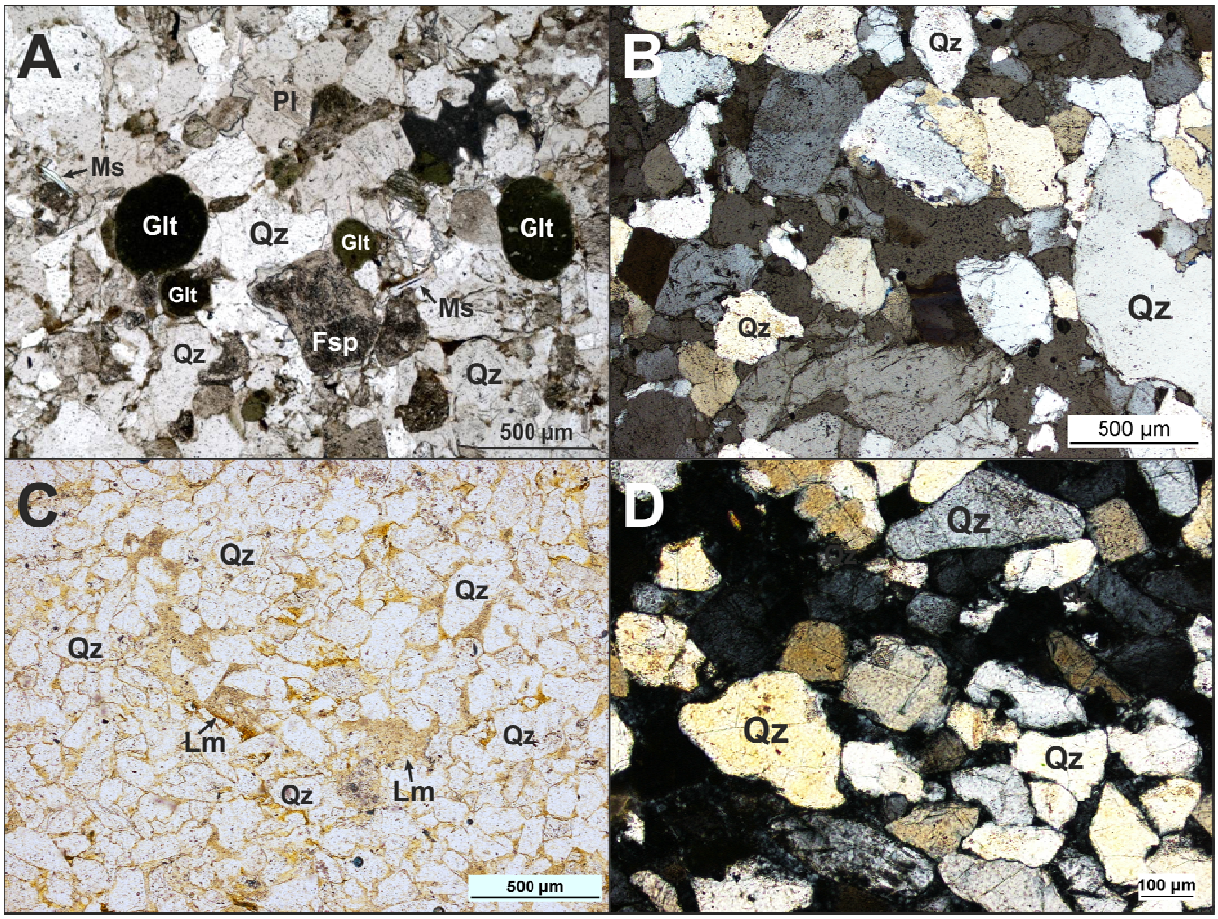


Fig. 1 Micrographs of studied sandstones: Godula (A), Kocbeře (B), Hořice (C) and Mšené (D). Rock-forming mineral abbreviations (in alphabetical order):Fsp – potassium feldspar (orthoclase), Glt – glauconite, Lm – limonite, Ms – muscovite, Pl – plagioclase, Qz– quartz.

From Table 2 and Fig. 1 it is evident that at least the Kocbeře, Hořice and Mšené sandstones are highly similar in the mineralogical composition of clastic framework grains and their size. However, they differ in the rock microstructure, in particular in the type of contacts between quartz grains and therefore the degree of rock compaction, and in the degree of secondary silicification (for details see e.g. Kytýř et al. 2024). These differences consequently affect not only their physical-mechanical properties (Table 1), but also their fluid permeability.

The basic textural parameters, pore size distribution and permeability coefficient (K) and HCC (k) of sandstones derived from MIP measurements are summarized in Fig. 2 and Table 3.

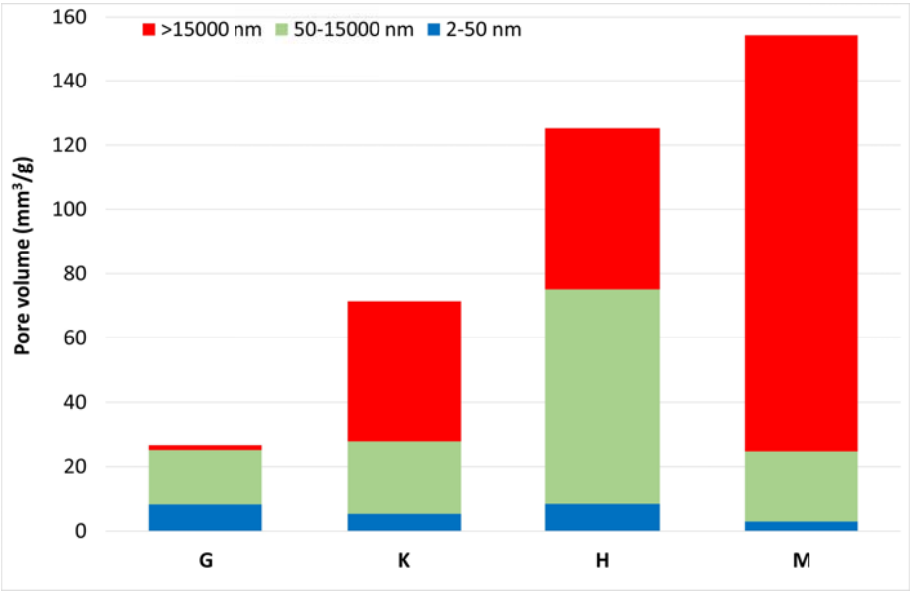


Fig. 2 The volume of pores in selected size classes for individual sandstones (G – Godula, M – Mšené, H – Hořice, K – Kocbeře, 2 – 50 nm = mesopores, 50 – 15000 nm = macropores, > 15000 nm = coarse pores).

Table 3. Average values of textural parameters, open porosity and permeability parameters of tested sandstones based on MIP.

Sandstone	V	S	r	φ	K_{MIP}	k_{MIP10}
	$mm^3 \cdot g^{-1}$	$m^2 \cdot g^{-1}$	nm	%	m^2	$m \cdot s^{-1}$
Godula	26.5	1.7	30.9	6.6	1.6×10^{-16}	1.2×10^{-9}
Kocbeře	71.2	1.6	90.3	15.8	3.8×10^{-16}	2.9×10^{-9}
Hořice	126.8	2.2	116.3	25.3	6.1×10^{-16}	4.6×10^{-9}
Mšené	157.4	1.1	282.2	29.5	7.1×10^{-16}	5.3×10^{-9}

V – total pore volume, S – total pore surface, r – average pore radius, φ – open porosity, K_{MIP} – coefficient of permeability obtained from MIP, k_{MIP10} – coefficient of hydraulic conductivity calculated from MIP for 10 °C

The values of open porosity, coefficient of permeability and HCC, determined based on laboratory tests on cylindrical test specimens, are presented in Table 4.

Table 4. Average values of open porosity and permeability parameters of tested sandstones based on laboratory tests.

Sandstone	BD	WAC	OP	K_{N2}	k_{H2O10}
	$kg \cdot m^{-3}$	%	%	m^2	$m \cdot s^{-1}$
Godula	2530	2.2	5.5	$7.6\times 10^{-18} – 1.5\times 10^{-17}$	$1.4 – 8.0\times 10^{-12}$
Kocbeře	2210	7.0	15.6	$4.9\times 10^{-14} – 6.8\times 10^{-12}$	$3.5\times 10^{-8} – 6.4\times 10^{-6}$
Hořice	1930	12.9	25.0	$8.8\times 10^{-15} – 1.2\times 10^{-14}$	$1.9\times 10^{-7} – 1.1\times 10^{-6}$
Mšené	1850	15.5	28.4	$1.2 – 1.3\times 10^{-14}$	$9.4\times 10^{-6} – 1.3\times 10^{-5}$

BD – bulk density, WAC – water absorption capacityto constant mass,OP – open porosity, K_{N2} – coefficient of permeability obtained from gas permeability measurements, k_{H2O10} – laboratory measured coefficient of hydraulic conductivity for 10 °C

5 Conclusions

The four selected rocks represent a broad spectrum of microstructural, mineralogical, and physical-mechanical characteristics typical of Czech sandstones. Their different degrees of compaction and secondary cementation, reflected in contrasting porosity and other material properties, provide a suitable basis for evaluating how pore space architecture affects fluid transport properties.

The data above clearly illustrate the extent of these differences. The different inner rock texture features lead to variability in bulk density (ca 1800 to 2600 $kg \cdot m^{-3}$), and a wide range of total porosity from ca 5% in the Godula sandstone to nearly 30 % in the Mšené sandstone. These variations are also reflected in mechanical properties, where, for example, uniaxial compressive strength decreases from ca 100 – 150 MPa (Godula sandstone) to only ca 20 – 30 MPa (Hořice and Mšené sandstones).

Fluid transport properties differ by several orders of magnitude. Gas permeability coefficients range from 10^{-17} m² to 10^{-12} m², while HCC spans from 10^{-12} $m \cdot s^{-1}$ to 10^{-5} $m \cdot s^{-1}$. These contrasts highlight how the described differences in pore content and geometry, grain contacts, and secondary silicification lead into major differences in effective fluid movement.

However, significant differences were observed between the hydraulic parameters obtained inthe laboratory and those derived from MIP. HCC derived from MIP are in the order of 10^{-9} $m \cdot s^{-1}$ for all sandstones, whereas laboratory tests provided different values, ranging from $10^{-5}$to 10^{-7} $m \cdot s^{-1}$ for highly porous sandstones to 10^{-12} $m \cdot s^{-1}$ for the least porous sandstone. Similar discrepancies were described by Vavro et al. (2026) when comparing HCC derived from X-ray CT scanning and from direct laboratory tests. Differences were also found in the case of permeability coefficients, where laboratory determined values range from 10^{-17} to 10^{-18} m^2 for Godula sandstone to mainly 10^{-14} m^2 for other sandstones, while the permeability calculated from MIP is in the order of 10^{-16} m^2 for all rocks.

These discrepancies reflect the importance of pore network microstructure such as pore-throat geometry, tortuosity and connectivity in controlling fluid transport. The different specimen sizes in both analyses also play an important role. It is therefore evident that a multi-scale approach combining MIP with testing on larger volumes is required for reliable evaluation of transport properties of porous rocks.

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