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HYDROGEOLOGICAL PROPERTIES OF THE MATRIX IN UPPER JURASSIC LIMESTONES (OLKUSZ AND KRAKÓW AREA, POLAND)

Jacek MOTYKA, Kajetan D'OBYRN & Adam POSTAWA *

AGH University of Krakow, Faculty of Geology, Geophysics and Environmental Protection, Mickiewicza 30, 30-059 Kraków, Poland;
e-mails: motyka@agh.edu.pl, dobyrn@agh.edu.pl, postawa@agh.edu.pl
** Corresponding author*

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Abstract: Quantitative description of the rock pore space properties provides important data for considerations, related to the quantitative description of mass transport or estimation of the aquifer's resources. Carbonate rocks are characterized by a particularly complex groundwater flow system. The hydraulic network in these rocks consists of three types of voids: pore space (matrix), fractures and caverns. The authors present the results of research on selected hydrogeological parameters of the Jurassic rock samples, taken from drill cores in the Olkusz region and Kraków (southern Poland). The values of porosity, hydraulic conductivity, specific yield and relative drainability were determined; 159 samples from the Olkusz region and 90 samples from the Kraków region were tested. The porosity of the tested samples varied from 0.64% to 21.9% for the Olkusz region and 0.62%–9.6% for Kraków. Hydraulic conductivity ranged from 2.52×10^{-12} m/s to 1.53×10^{-9} m/s for the Olkusz region and from 5.40×10^{-12} m/s to 9.06×10^{-7} m/s for Kraków and the specific yield from 0 to 0.0123 for the Olkusz region and from 0.00051 to 0.00737 for Kraków. There were no statistically significant relationships between the values of individual parameters for samples, tested perpendicular and parallel to the direction of drilling the test borehole in the case of samples from the Olkusz area. In the case of samples from Kraków, there was a weak, but statistically significant correlation between specific yield vs porosity, and the correlation between specific yield vs hydraulic conductivity

Key words: S Poland, carbonate rocks, Jurassic limestones, hydraulic properties, matrix porosity.

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INTRODUCTION

Carbonate rocks have a very complex system of groundwater flow. In its most complex form, the hydraulic network in such rocks consists of three void types: pore spaces, fractures and cavities (Motyka, 1998; Zuber and Motyka, 1998). Pore space (matrix), as defined by Choquette and Pray (1970), represents all the voids in the finer portion of rock, with a volume of several dozen cubic centimetres. The above definition of a pore space (matrix) includes all voids present in a small, analysed section of a rock, irrespective of their origin or geometry. Such pores can be syngenetic and epigenetic and may include interparticle and intraparticle types, microfissures, initial karst or stylolites.

In carbonate rocks that include karst voids, two components of groundwater flow are distinguished: diffuse flow (White, 1969; Atkinson, 1977) and free flow (White, 1969) or conduit flow (Atkinson, 1977). For solving many of the practical problems related to carbonate aquifers, the numerical values (hydrogeological parameters) of pore space properties, such as the coefficient of porosity (porosity), hydraulic conductivity or specific yield should be known. Studies on the porosity and permeability of a rock matrix are routinely performed by petroleum geologists, because these are the parameters necessary for estimating the resources of oil and gas deposits. In the field of hydrogeology, detailed knowledge of the hydrogeological properties of rock matrix is often underestimated, although the results of research on these properties - interconnected porosity, hydraulic conductivity and specific yield – can help in developing conceptual models, in interpreting pumping and tracer tests, in analysing the mass transport and in calculating water resources (Zuber and Motyka, 1994, 1998; Motyka, 1998).

The main objective of this paper is to characterize the matrix of the Upper Jurassic limestones from a hydrodynamic point of view. Limestone samples were collected at two locations in SW Poland: the area of Olkusz (the Silesia-Kraków Homocline) and in Kraków (the Carpathian Foredeep). Hydrogeological properties of the Jurassic limestone matrix in the Kraków-Częstochowa Upland were studied in the past, but outside of the Olkusz region (Różkowski *et al.,* 2001, 2005; Różkowski, 2006). The porosity of rocks of this age in the Olkusz area was analysed by Juśko *et al.* (2015*,* 2018), and from the 'Zakrzówek' Quarry in Kraków by Motyka and Postawa (2000, 2004).

GEOLOGICAL SETTINGS

Olkusz area

The Olkusz area is geologically a part of the Silesia-Kraków monocline, a regional tectonic structure of SE–NW orientation, situated in South-West Poland. It consists of Mesozoic formations of Triassic, Jurassic and Cretaceous age, located discordantly on the Palaeozoic fold/fault structures. The oldest sediments in the Olkusz region, encountered during the drilling of boreholes, are Devonian carbonate rocks. Variegated clastic sediments represent the Lower Devonian (Alexandrowicz, 1970), while the Middle and Upper Devonian are represented mainly by carbonate rocks (Ekiert, 1971; Narkiewicz, 1978). Carboniferous sediments have a lithologically dual structure. Carbonate rocks occur in the western part of the Olkusz area, mainly in the form of limestone with dolomite interlayers. In its central and western parts, they have the form of claystones and sandstones. Variscan tectonic movements in the Permian period resulted in the creation of a narrow, but relatively deep mid-mountain trench of NW–SE orientation in the Olkusz area (Buła, 2000). This trench is filled with typical molassic sediments, consisting predominantly of the conglomerates of older Palaeozoic rocks, mainly limestones and Devonian and Carboniferous dolomites, as well as quartzite, porphyry and melaphyre. The maximum thickness of the Permian sediments is approximately 300 m. Triassic rocks also rest discordantly on various Palaeozoic sediments and are represented by the variegated sandstone (Rhaetian), shell-bearing limestone (Muschelkalk) and Keuper. Variegated sandstone sediments include marlstones and dolomites with a thickness of 30–35 m. Shell-bearing limestone consists of carbonate rocks, mainly limestones and dolomites, including also metasomatic metalliferous dolomites, which contain deposits of zinc and lead ore. The sequence of shell-bearing limestone is approximately 110 m thick. Upper Triassic (Keuper) packages have developed in the continental facies, with interlayers composed of shallow-marine facies. They mostly consist of variegated silts, clays and claystones that contain thin interlayers of carbonate rocks and sandstones. The sequence of Upper Triassic rocks is approximately 200 m thick. Jurassic sediments are present in the northern and western parts of the Olkusz region (Fig. 1A). They are represented by Middle and Upper Jurassic rocks. Middle Jurassic rocks include mainly marlstones, but also lesser amounts of clay-conglomerate rocks. The Middle Jurassic succession is rather thin with a thickness of 10–30 m. The Upper Jurassic sediments mainly include slab limestone, massive and chalky limestones, with a marlstone layer in the bottom part. The thickness of the Upper Jurassic sediments reaches approximately 200 m.

The older Mezozoic and Palaeozoic substratums are covered with Quaternary sediments. They consist mainly of glaciofluvial sands with interlayers, consisting of gravels, debris, silts, loams and clays. In the top parts formed by older rocks, they have the form of an eluvial clay layer with a thickness of 1–2 m. The layer of glacio-fluvial sediments is usually 20–30 m thick, while in buried valleys it reaches 70 m.

Kraków area

Kraków is located in a geologically complex area. This complexity is mainly caused by its tectonic structure that derives from the Caledonian orogeny, but regional and local tectonic structures found today were formed during the Alpine orogeny. This area is the location of the convergence of three regional tectonic provinces: the Silesia-Kraków Homocline, the Miechów Basin and the Carpathian Foredeep. The presence of zones of tension and compression of different orientations during the Alpine mountain-building movements has resulted in the creation of many horsts of relatively small sizes that cut through younger Neogene formations, mainly of Miocene origin. The largest of these is the Sowiniec Horst, which is located in the western part of Kraków. The horsts consist of Jurassic and, subordinately, Cretaceous sediments (Fig. 1B).

Jurassic, Cretaceous, Tertiary and Quaternary sediments can be found on the terrain surface within the Kraków area (Rutkowski, 1989; Buła, 2000; Gradziński, 2009). The Jurassic aquifer system is related to the presence of fractured and partially karstic slab and massive limestones of the Upper Jurassic period. The Cretaceous system is related to the presence of fractured marlstones and Senonian gaizes, organogenic and sandy limestones, as well as Cenomanian and Turonian conglomerates (Rutkowski, 1989; Kleczkowski *et al.,* 1994). Cretaceous formations can be found locally at ground level in the overburden of Jurassic limestones in horst structures (Fig. 1B). The thickness of Cretaceous formations ranges from several metres in the western Kraków area, to 40–50 m in the northeastern part of the city.

Tertiary formations, mainly Miocene, consist mainly of silts and marl silts, in some locations with gypsum and tuffite interlayers as well as with marl and fresh-water limestones, which can be found locally in shallow layers. Pliocene gravels with flints and conglomerates can be found at the northwestern margin of Kraków (Rutkowski, 1989). In some places, sinkholes were formed in the roof of the Jurassic limestone layer and filled with fragmented limestone, supplemented with silt and sand. The sediments in these sinkholes have been assessed as dating back to the Paleogene Period (Gradziński, 1962; Bogacz, 1974), or more precisely to between the Oligocene and Lower Miocene (Felisiak, 1992).

Quaternary formations consist of sand and gravel with interlayers made of mud, clay and silt, locally of peat found in deposits, occurring in the Vistula River basin. The youngest Quaternary sediments are of anthropogenic origin, mainly all kinds of embankments that are typical of centuries-old

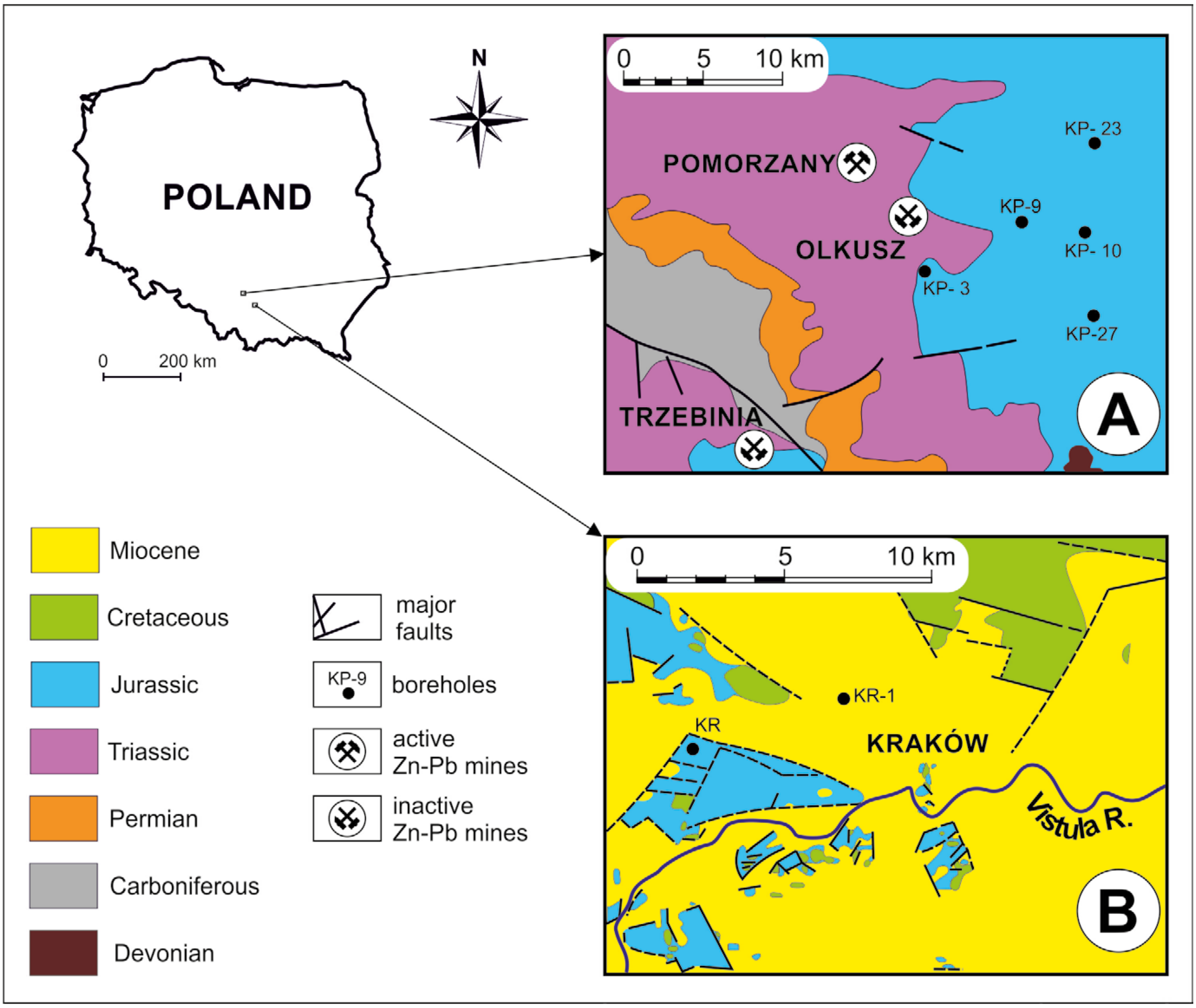

Fig. 1. Geological maps of study areas. **A.** Olkusz area (after Juśko *et al.,* 2018). **B**. Kraków area (after Gradziński, 2009).

urban settlements. There are also piles of gangue in the vicinity of Kraków's numerous limestone quarries, as well as disposal sites of post-production waste in the vicinity of various industrial plants. Natural Quaternary sediments have a thickness of 30 m in the Vistula River basin, while anthropogenic deposits have a thickness of ten to twenty metres in the city centre (Fig. 1B).

MATERIALS AND METHODS

Samples of Jurassic limestone were collected from 5 boreholes in the Olkusz area and from two boreholes drilled in Kraków (Fig. 1). From the drill holes in the Olkusz area, 164 core fragments (with a diameter of 100 mm) were collected, and from them cylindrical samples with a diameter of 43 mm and a length of 40–50 mm were extracted. Samples were taken in a direction perpendicular to the layers from all core samples, and additionally parallel to the layers in some core samples (Fig. 2). In Kraków, core samples were extracted from 2 boreholes and were then used to drill 90 samples, extracted mainly in a perpendicular direction, as well as partially also in a direction parallel to the layers.

Open (interconnected) porosity was measured, using a vacuum chamber, i.e., all the air from the sample was extracted and the space filled with water to weight the sample repeatedly. Thus, the volume of the interconnected pores was measured. Before the samples were put in the vacuum chamber, they were dried in a stove at 105–110 °C for a period of 24 hours.

The following formula was used to calculate the value of the open porosity coefficient p_o (Borczak *et al.,* 1990; Motyka *et al.,* 1998):

$$p_o = (G_n - G_s)/(G_n - G_{nw}) \quad (1)$$

where: G_n is the weight of the sample saturated with water, G_s is the weight of the sample dried at 105–110°C, and G_{nw} is the weight of the sample, saturated with water weighted in water, applying the Archimedes principle.

The method, used for calculating the specific yield (S), is based on the centrifugation of the samples (Prill *et al.*, 1965). Because in natural conditions water drains slowly by gravity, a centrifuge was used to accelerate the process.

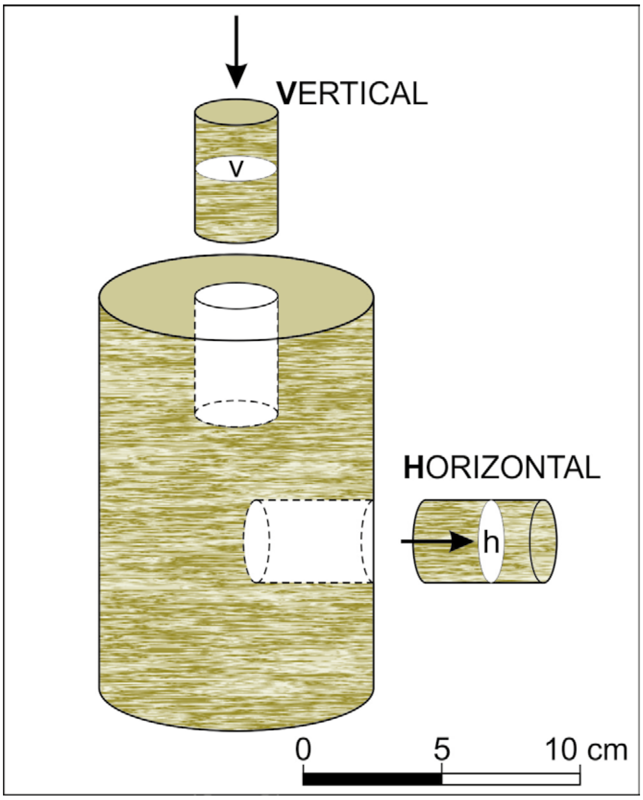

Fig. 2. Extraction of samples from a drill core.

The suction pressure, affecting the sample due to centrifugal power, liberates part of the water content of the sample (the gravitational water), calculated with the following formula:

(2) $$H = \frac{\left(\frac{2\pi n}{60}\right)^2 rh}{g}$$

where: H is the suction pressure of water from the matrix, expressed as metres of the water column, n is the number of revolutions per minute, r is the centrifugation radius (the distance in metres from the centrifuge axis to the centre of gravity of the sample), h is the length of the sample in metres and g is the gravitational acceleration (9.81 m/s^2).

Natural conditions were simulated, using a suction pressure equivalent to a 10 m-high water column. Establishing all the variables (H = 98 kPa and length of each sample), the number of revolutions required for each sample was calculated. The amount of water obtained by centrifugation allows calculation of the specific yield (S):

(3) $$S = \frac{V_w}{V_r}$$

where: V_w is the water volume liberated by suction water, equivalent to a 10-m-high column (cm^3) and V_r is the rock volume (cm^3). The extraction pressure of the water, simulated by centrifugation for small samples, is equivalent to the maximum natural extraction pressure for water, exerted by gravity in a stratum of thickness h.

The centrifugal acceleration (a) is expressed as:

$$a = \omega \cdot r^2 \quad (4)$$

where: ω is the angular velocity. From equation (2), it is possible to write:

$$\frac{H}{h} = \frac{a}{g} \quad (5)$$

where:

$$\alpha = \left(\frac{2\pi n}{60}\right) r \quad (6)$$

from which n (rpm) can be calculated for each sample. According to Prill (Prill *et al.,* 1965), the relationship between the percolation time of gravitational water in nature (T_n) and the centrifugation time (t) can be expressed as:

$$\left(\frac{T_n}{t}\right) = \left(\frac{a}{g}\right)^2 \quad (7)$$

All the samples were centrifuged for 30 min (t), which, depending on the length of the sample, would be equivalent to a percolation time under natural conditions (T_n) of between 660 and 940 days (from 2 to 2.5 years).

The relative drainability (S_o) is defined as:

$$S_o = \frac{S}{p_o} \quad (8)$$

where: S is the specific yield and po the interconnected porosity. Both coefficient's values depend on the pore diameter of the matrix as well as on the nature of the porosity (fissures, small capillary pores, stylolites, etc.). Under unconfined conditions specific yield represents the ratio of the volume of water that a saturated rock will yield by gravity to its total volume. In confined aquifers, the storage coefficient is represented by the elastic storativity that shows its ability to store water by deforming elastically in response to changes in pore pressure. It accounts for the volume of water released, when the aquifer's skeleton expands or compacts elastically.

The hydraulic conductivity was measured using the method proposed by Duliński (1965). The samples were dried at 105–110°C and then placed in an air permeameter. The expression, used to calculate Darcy's permeability coefficient (K_g), is:

$$K_g = \frac{2Q_o\, p_o\, L\eta}{F(p_1^2 - p_2^2)} \quad (9)$$

where: Qo is the gas flow (cm^3/s), po is the atmospheric pressure (atm), L is the sample length (cm), η is the viscosity coefficient of the gas, F is the area of the section of the sample (cm^2), p1 is the gas pressure before passing through the sample (atm) and p_2 is the pressure after passing through the sample (atm). The coefficients obtained were then recalculated for water at 10 °C (K_{10}), according to the equation:

$$K_{10} = K_g \frac{\gamma}{\eta} \quad (10)$$

where: γ is the specific weight of the water, so this can be expressed as:

$$K_{10} = 7.66 \times 10^{-6} \cdot K_g \quad (11)$$

Nevertheless, the hydraulic conductivity values obtained this way do not coincide with those, obtained by natural means using water. Therefore, the Klinkenberg correction factor (K_a) should be applied. This coefficient depends on many factors and is specific to each type of rock. According to Klinkenberg, K_g and the values, recalculated for water at the temperature of 10 ºC (K_{10}), are in fact lower, especially in samples with a low hydraulic conductivity (Klinkenberg, 1941). This phenomenon is typical for samples with small pore sizes, close to the mean free path of the gas. The mean free path of a gas is a function of the molecular size and the kinetic energy of the gas. It is defined as the average distance a gas molecule travels between two consecutive collisions with other gas molecules.

RESULTS

Porosity

The values of open porosity of the Jurassic limestone matrix in the Olkusz area are between 0.0064 and 0.219 with an average value of 0.099 (Tab. 1). Noteworthy is the large difference between the maximum and minimum values, reaching almost 0.21 (Fig. 3).

The comparison of the value of open porosity of samples, extracted in directions perpendicular and parallel to the layers, reveals the dispersion of values in relation to the $p_{ov} = p_{oh}$ line (Fig. 4), nevertheless the difference between the mean values of porosity, measured in the different directions, is small (Tab. 1). The statistical correlation between these values $p_{ov} = f(p_{oh})$ is high, which is demonstrated by the value of the coefficient of determination of $R^2 = 0.73$.

The value of open porosity of the matrix of analysed Jurassic limestone in Kraków is between 0.0062 and 0.096; 89 out of 90 analysed samples exhibited a porosity of less than 0.04 (Fig. 4), with the mean value equal to 0.0167 (Tab. 2). The values of porosity of samples, extracted in directions perpendicular and parallel to the layers, demonstrated significant dispersion in relation to the $p_{ov} = p_{oh}$ line (Fig. 4). A slightly higher value of porosity was demonstrated by samples, extracted perpendicular to the layer structure (Tab. 2), nevertheless the statistical correlation $p_{ov} = f(p_{oh})$, for which the coefficient of determination is $R^2 = 0.23$, is rather weak.

Hydraulic conductivity

The range of the values of hydraulic conductivity of the pore space of Jurassic limestones in the Olkusz area ranges four orders of magnitude, i.e., from 2.52×10^{-12} to 1.53×10^{-9} m/s. The mean geometrical value of the hydraulic conductivity for the entire population of analysed samples equals 3.02×10^{-10} m/s. The distribution of hydraulic conductivity values is lognormal (Fig. 5). With a similar range of extreme values, the geometric mean of the hydraulic conductivity for samples, drilled in the direction perpendicular to the layer structure (vertical), reaches 6.35×10^{-11} m/s and is slightly lower than the mean value for samples, drilled in the direction parallel to the layer structure, which is equal to 3.02×10^{-10} m/s (Tab. 1). There is visible significant

Table 1

Range and mean values of hydrogeological properties of the Jurassic limestone matrix – Olkusz area.

	Porosity	Specific yield	Relative drain-ability	Hydraulic conductivity
	[-]			[m/s]
All samples N = 159				
min	0.00644	0.00	0.00	2.52×10^{-12}
max	0.219	0.0123	0.199	1.53×10^{-9}
mean [1)]	0.0994	0.00066	0.00589	3.02×10^{-10}
sd	0.0481	0.00176	0.0199	4.15×10^{-10}
Vertical N = 94				
min	0.0103	0.00	0.00	2.50×10^{-12}
max	0.197	0.0115	0.199	7.72×10^{-9}
mean [1)]	0.096	0.00062	0.00557	6.35×10^{-11}
sd	0.0453	0.00167	0.0219	1.04×10^{-9}
Horizontal N = 65				
min	0.00644	0.00	0.00	2.52×10^{-12}
max	0.219	0.0123	0.135	1.53×10^{-9}
mean [1)]	0.102	0.00071	0.00634	3.02×10^{-10}
sd	0.0475	0.00176	0.0199	4.14×10^{-10}

[1)] for hydraulic conductivity geometric mean

Table 2

Range and mean values of hydrogeological properties of the Jurassic limestone matrix – Kraków area.

	Porosity	Specific yield	Relative drain-ability	Hydraulic conductivity
	[-]			[m/s]
All samples N = 90				
min	0.00624	0.00	0.00	5.40×10^{-12}
max	0.0964	0.00737	0.150	9.06×10^{-7}
mean [1)]	0.0167	0.00021	0.00538	1.78×10^{-10}
sd	0.0112	0.00094	0.0233	1.22×10^{-7}
Vertical N = 55				
min	0.00624	0.00	0.00	5.40×10^{-12}
max	0.0964	0.00354	0.150	9.06×10^{-7}
mean [1)]	0.0183	0.00018	0.00664	5.35×10^{-11}
sd	0.0137	0.00067	0.0272	1.22×10^{-7}
Horizontal N = 35				
min	0.00692	0.00	0.00	2.33×10^{-11}
max	0.0223	0.00737	0.0861	2.75×10^{-9}
mean [1)]	0.0141	0.00025	0.00341	8.96×10^{-11}
sd	0.00420	0.00127	0.0154	5.01×10^{-10}

[1)] for hydraulic conductivity geometric mean

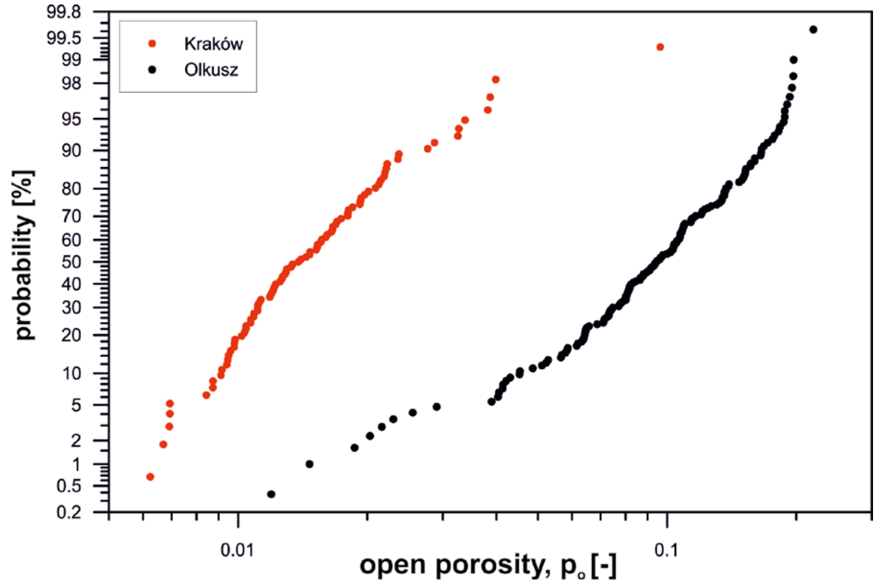

Fig. 3. Cumulative frequency of open porosity (p_o) values.

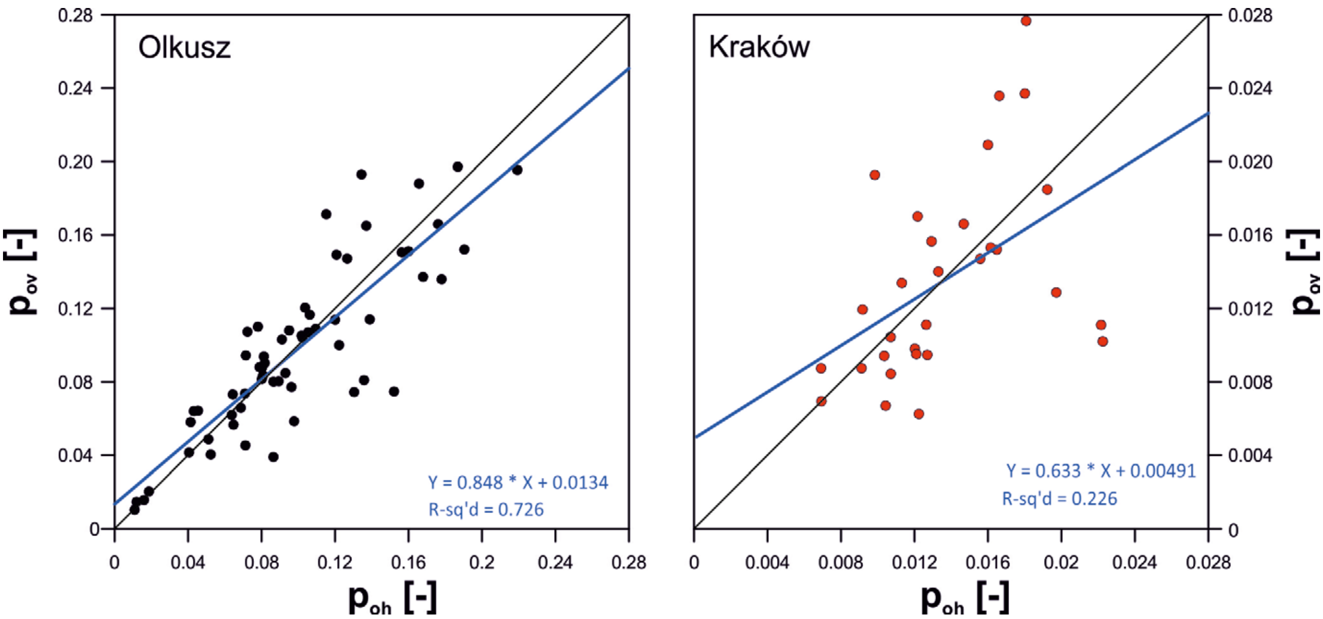

Fig. 4. Scatter graphs of the correlation between p_{ov} and p_{oh}

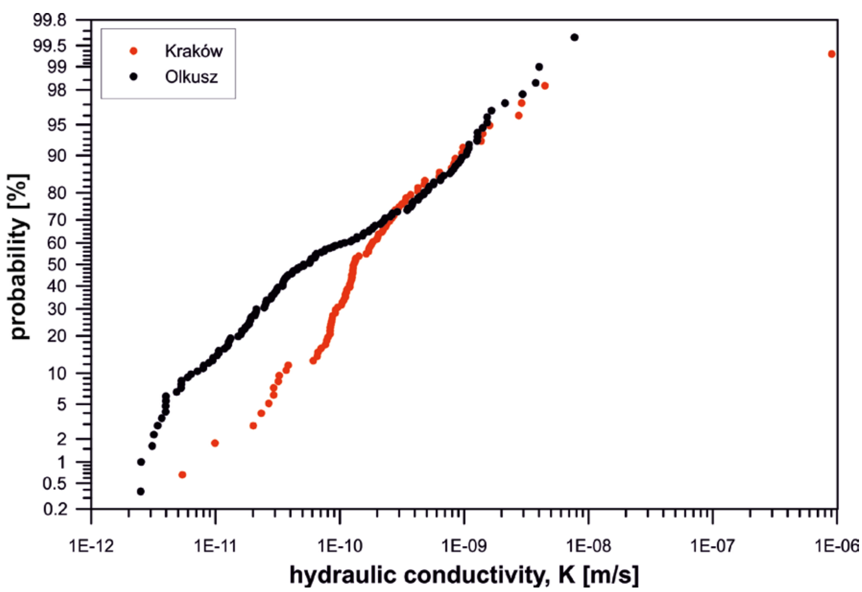

Fig. 5. Cumulative frequency of hydraulic conductivity (K) values.

dispersion of hydraulic conductivity values in relation to the $k_v = k_h$ line (Fig.6), nevertheless the $K_v = f(K_h)$ correlation is statistically significant. The value of the coefficient of determination for this correlation is $R^2 = 0.597$.

The hydraulic conductivity values of the pore space of Jurassic limestones in Kraków ranges between 5.40×10^{-12} and 9.06×10^{-7} m/s, while the geometric mean amounts to 1.78×10^{-10} m/s (Tab. 2). Except for one sample, all other samples (89) had a hydraulic conductivity of $n \cdot 10^{-9}$ m/s. The distribution of hydraulic conductivity values is log-normal (Fig. 5). With a similar range of extreme values, the geometric mean of the hydraulic conductivity for samples, drilled in the direction perpendicular to the layer structure, amounts to 6.35×10^{-11} m/s, while for samples, drilled in the direction parallel to the layer structure, it equals 8.96×10^{-11} m/s (Tab. 2), wherein the differences between these values are not statistically significant. Noteworthy is the very significant dispersion of hydraulic conductivity values in relation to the $K_v = K_h$ line (Fig. 6) and the absence of the $K_v = f(K_h)$ correlation, which is demonstrated by the value of the coefficient of determination of $R^2 = 0.0095$.

Specific yield and relative drainability

Jurassic limestones from the Olkusz area have demonstrated poor draining properties. Out of 159 analysed samples, only 45 released water under the influence of gravity, which represents 28.3% of the total population (Fig. 5). Out of 94 samples, extracted in the direction perpendicular to the layer structure, 25 of them, i.e., 26.6%, released water, while out of 65 samples, extracted in the direction parallel to the layers, only 20 (30.8%) released water. The specific yield value for the entire set of tested samples is between 0 and 0.0123, while its mean value amounts to 0.00066 (Tab. 1). The mean pore space drainability coefficient value for the set of samples, extracted in the direction perpendicular to the layer structure, is 0.00062, while for samples, extracted in the direction parallel to the layers, this value is 0.00071 (Tab. 1). The differences between the two sets are statistically insignificant.

The value of relative drainability (S_o), which represents the quotient of the values of drainability coefficient and open porosity, is between 0 and 0.199 for the entire population, while its mean value is 0.00589. For samples, extracted in the direction perpendicular to the layer structure, the range of these values is between 0 and 0.199 and their mean value is 0.00557, while in the case of samples, extracted in the direction parallel to the layers, the range of S_o values is between 0 and 0.199, with the mean value at 0.00634 (Tab. 1).

Jurassic limestones from Kraków showed negligible gravitational drainability. Only 7 out of 90 analysed samples released water, which represented 7.8% of the entire population (Fig. 5). The specific yield of these samples was between 0.00051 and 0.00737. Considering the test results of all samples, the average value of the, the mean value of the specific yield of the matrix of Jurassic limestones from Kraków is 0.00021 (Tab. 2). Only 5 out of 55 (9.1%) samples, extracted in the direction perpendicular to the layer structure, had a specific yield of the matrix higher than zero, while only 2 out of 35 (5.7%) samples, extracted in the direction parallel to the layer structure, demonstrated the ability to drain water under the influence of gravity. Nevertheless, the mean value of specific yield for the set of samples, extracted in the direction perpendicular to the layer structure (vertical), is 0.00018, while for those, extracted in the direction parallel to the layers (horizontal), it is 0.00025 (Tab. 2). This is a small difference, if the small size of both sets is considered. The relative drainability values for the entire sample population were between 0 and 0.15, while their mean value is 0.00538 (Tab. 2). In the case of samples, extracted in the direction perpendicular to the layer structure, the values were between 0 and 0.15 with a mean value of 0.00664, while for those, extracted in the direction parallel to the layers, the values were between 0 and 0.0861, with a mean value of 0.00341 (Tab. 2).

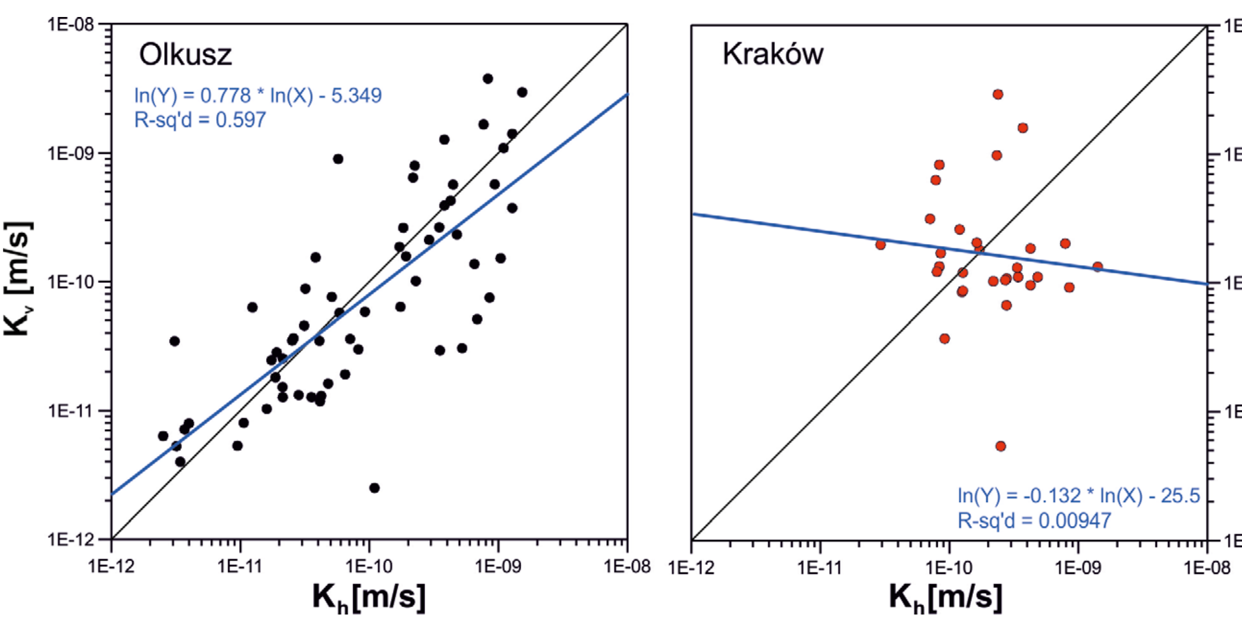

Fig. 6. Diagram of the K_v vs K_h correlation.

Correlation between hydrogeological parameters

Correlations between the hydrogeological parameters of the matrix permit a quality assessment of the heterogeneity of the hydraulic network of the set of pores that comprise the matrix. Porosity is a primary physical characteristic of rocks, but it is the geometry of the matrix that determines the values of basic hydrogeological parameters, such as hydraulic conductivity (K) and specific yield (S). The complex parameter of relative drainability (S_o) is also related to the geometry of the pore space. A thorough analysis of the statistical correlations discussed allows assessment on a wider scale of the volume of the groundwater reservoir that was sampled for laboratory testing (mesoscale).

The values of the hydraulic conductivity of the Jurassic limestone matrix tend to increase together with their porosity (Fig. 7). This is, however, a weak statistical correlation, which is demonstrated by the determination coefficient value of $R^2 = 0.169$. In the case of the Jurassic limestones from Kraków, the permeability of the matrix does not effectively depend on its porosity (Fig. 7), which is reflected in the value of the determination coefficient for the statistical correlation $K = f(p_0)$ of $R^2 = 0.000865$.

The value of the specific yield of the Jurassic limestone matrix, both in the case of the limestones from the Olkusz and from the Kraków area, did not demonstrate a statistical correlation with the value of porosity (Fig. 8). In the case of the limestones from the Olkusz area, the coefficient of determination for the $S = f(p_0)$ correlation was $R^2 = 0.0055$, while in the case of the limestones from Kraków, where only 7 samples had a drainability coefficient of S>0, the coefficient of determination was $R^2 = 0.0542$.

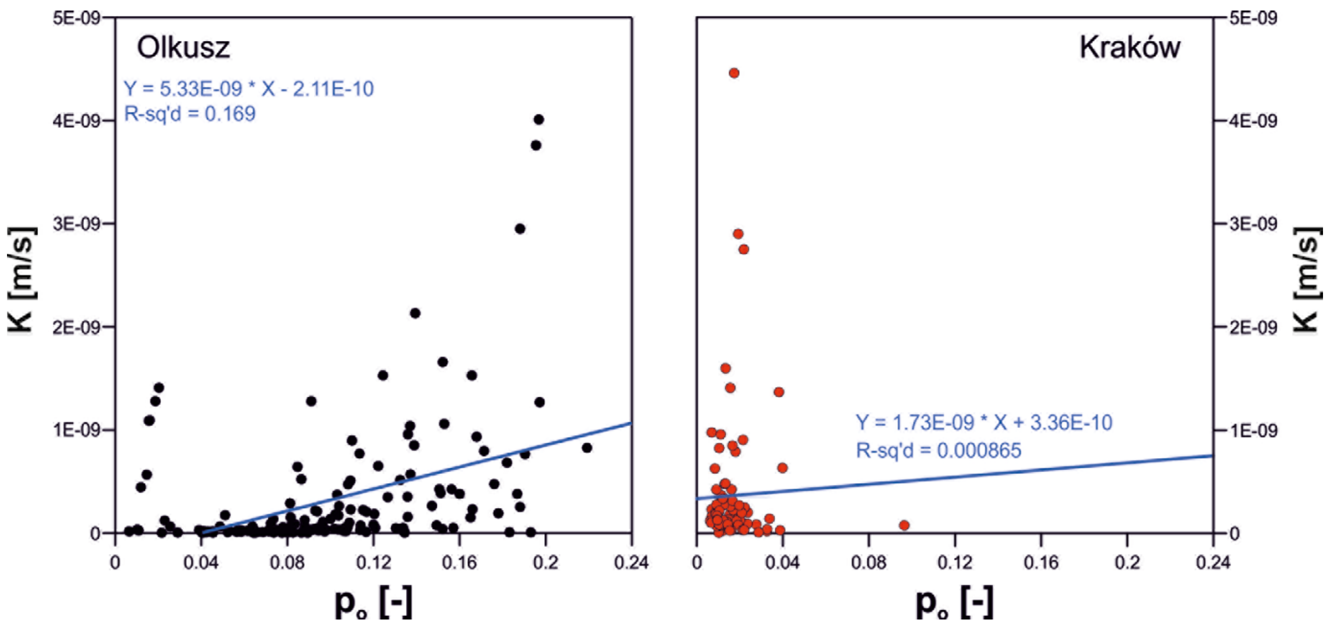

Fig. 7. Hydraulic conductivity (K) vs open porosity (p_o).

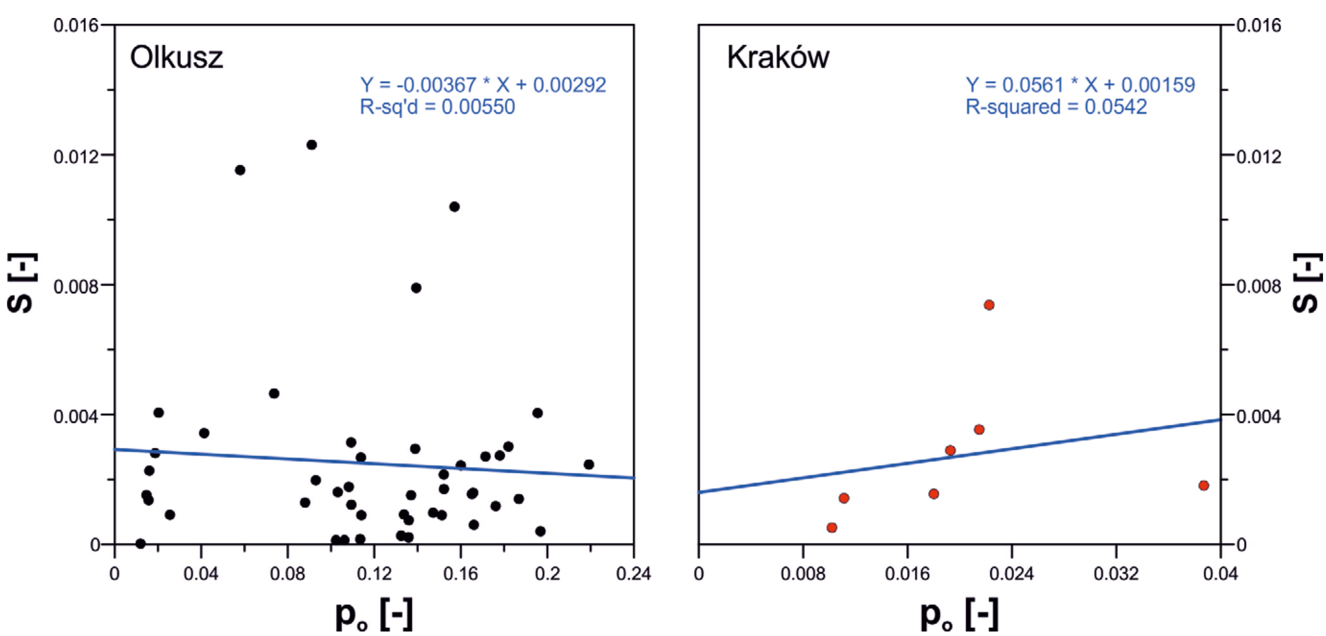

Fig. 8. Specific yield (S) vs open porosity (p_o).

The values of the relative drainability of the Jurassic limestones from the Olkusz area and from Kraków have a clear tendency to decrease, as their porosity increases (Fig. 9). In the case of the limestones from the Olkusz area, this correlation is statistically insignificant, which is reflected in the low determination coefficient of $R^2 = 0.0472$. In the case of the limestones from Kraków, where the data set consists of 7 samples, the coefficient of determination for the $S_o = f(p_o)$ correlation is $R^2 = 0.334$, but this value is greatly affected by the test results for samples of the highest porosity in this data set that have a marginal relative drainability (Fig. 9).

The specific yield of the matrix does not depend on its permeability to water, both for the Jurassic limestones from the Olkusz area and those from Kraków (Fig. 10). In the case of the limestones from the Olkusz area, the coefficient of determination for the S = f(K) correlation is $R^2 = 0.00967$, while in the case of the limestones from Kraków it is $R^2 = 0.00012$.

The case is different with the correlation of the relative drainability (S_o) of the matrix with its hydraulic conductivity (K). In the case of the limestones from the Olkusz area, this correlation is statistically insignificant, which is reflected in the value of the coefficient of determination for the $S_o = f(K)$ correlation of $R^2 = 0.00126$. In the case of the Jurassic limestones from Kraków, this correlation demonstrates a statistically significant progressive tendency (Fig. 11). The value of the coefficient of determination for this correlation is $R^2 = 0.652$.

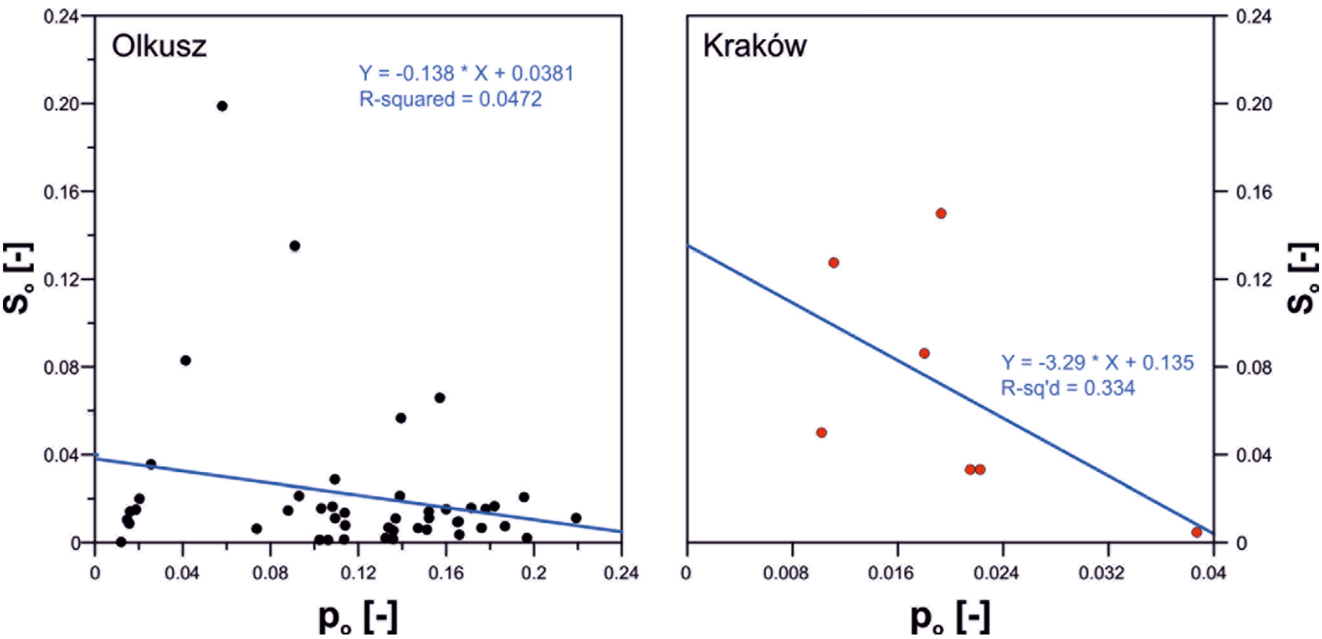

Fig. 9. Relative drainability (S_o) vs open porosity (p_o).

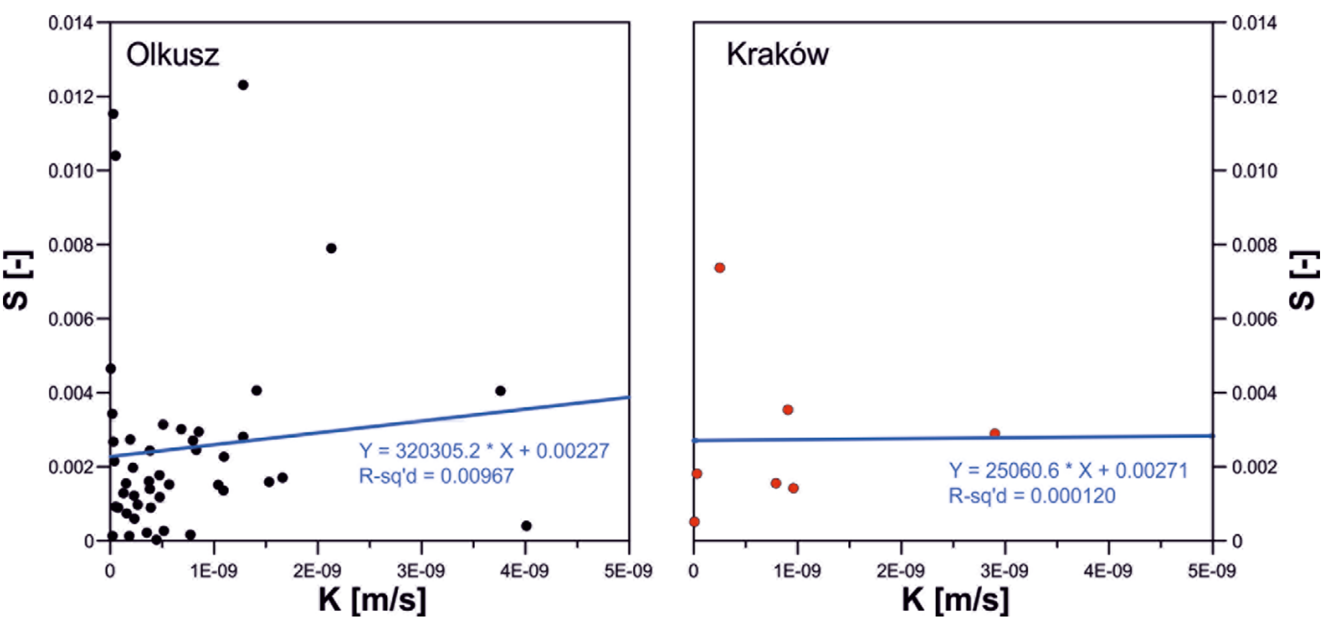

Fig. 10. Specific yield (S) vs hydraulic conductivity (K).

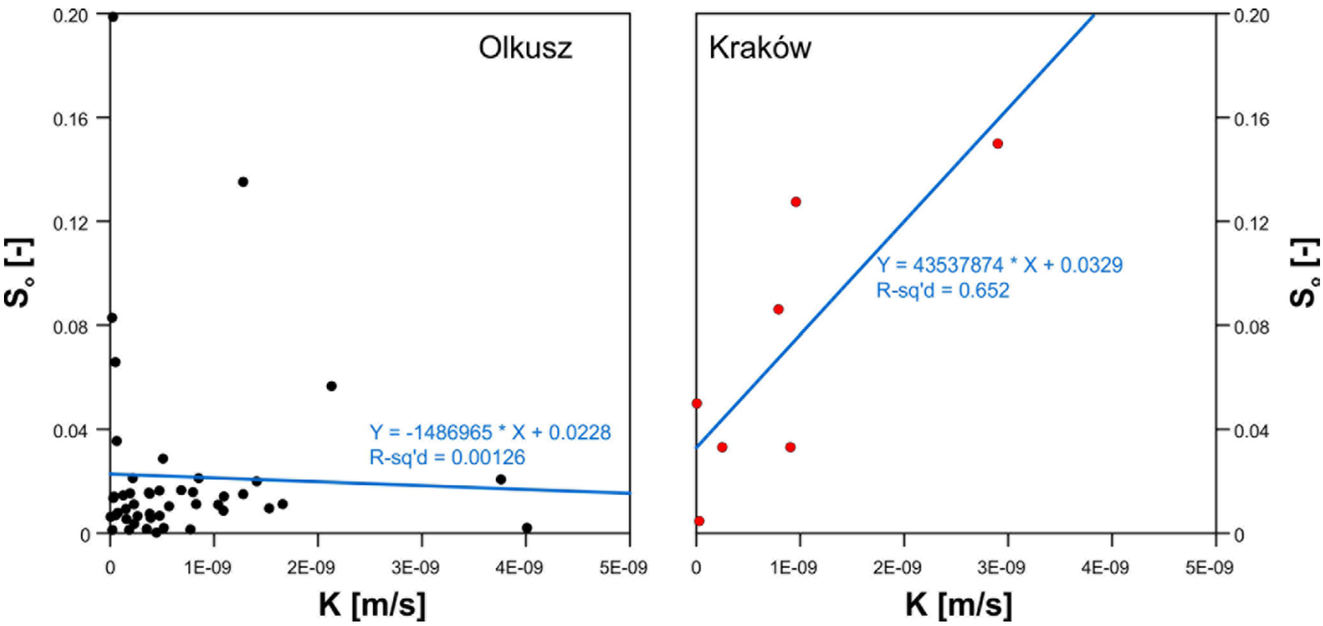

Fig. 11. Relative drainability (S_o) vs hydraulic conductivity (K).

DISCUSSION

The pore space in Jurassic rocks is the result of a combination of many different, complex processes over their long geological history. Choquette and Pray (1970) identified three main phases of this history: pre-depositional, depositional and post-depositional. The pre-depositional phase relates to the porosity of the sedimentary grain and in the case of carbonate rocks it refers to granular rocks (e.g., detrital or oolithic), or to the deposition of organic remains that are partially made of carbonates. The depositional phase refers to the period of the formation of sediment and its early diagenetic transformation. According to Choquette and Pray (1970), this phase also includes pore space, formed during the period of the development of biomorphic rock-building organisms. The post-depositional phase begins only after the settlement of the primary sediment. In comparison to the previous phases, this phase is characterised by the endurance and variability of pore-space-forming processes, which include diagenesis-related processes of compaction, dissolution, cementation, crystallisation, as well as tectonic processes.

The most important is the process of compaction, which reduces the initial porosity of carbonate silt from the level of 0.4–0.7, to 0.05–0.15 (Choquette and Pray, 1970). The processes of cementation and crystallisation, together with the process of lithification, are also responsible for the reduction of the initial porosity. A specific example involves chalk, composed of very fine grains (mainly coccoliths) of dimensions that normally do not exceed 0.001 mm (Chilingar *et al.*, 1967; Rzonca, 2014). Despite the lithification-related processes, chalk is a rock of high porosity, in the range of 0.4–0.5 (Borczak *et al.,* 1990). Fissures and macropores (e.g., initial karst) are an important element of the carbonate rock matrix that affects its hydrogeological parameters.

Porosity is a primary hydrogeological feature of a matrix, but its water transporting and draining properties are affected, apart from the volume of individual pores by the geometry of the pore space, especially by the dimensions of the pores. Choquette and Pray (1970) compared the porosity of sandstones and carbonate rocks. They pointed out that fractures in the sandstone matrix do not have a significant effect on its hydrogeological parameters, while the presence of such fractures in carbonate rocks greatly affects these parameters. Analogically, it may be stated that the effect of fractures on the hydrogeological properties of the matrix of granular carbonate rocks is insignificant, while in the case of fine rocks, derived from carbonate silt, this effect is decisive.

Jurassic limestones from the Olkusz area and from Kraków represent pelite, mudstone and chalky limestones. The content of the chalk fraction in the set of limestones from the Olkusz area is higher than that in the set of limestones from Kraków, therefore the porosity of the population of Olkusz limestones is significantly higher than the porosity of the Kraków limestones (Fig. 3; Tabs 1, 2). This principle also applies to limestones from other areas of the Kraków-Częstochowa upland (Różkowski *et al.,* 2001). The mean values of hydraulic conductivity and specific yield, which depend on the size of the pores, are very similar for both analysed areas (Tabs 1, 2). This kind of correlation is clearly visible, especially in the case of different kinds of Jurassic limestones from the northeastern border of the Świętokrzyskie (Holy Cross) Mountains (Rzonca, 2014).

The comparison of the values of microhydraulic properties of the matrix of the analysed limestone samples, extracted in the direction perpendicular and parallel to the layer structure, is informative about the heterogeneity of these properties, and in the case of hydraulic conductivity about the level of its anisotropy, as well. Rock samples extracted in different directions from a larger core sample, nevertheless, represent different samples and a higher dispersion of the measurement results around the $p_{ov} = p_{oh}$ line translates into higher heterogeneity of the analysed hydrogeological parameter (p_o) of the matrix. Limestone samples, from the

Olkusz area present significantly higher values of determination coefficient between pv and ph porosity, ($R^2 = 0.726$) and $K_v = K_h$ hydraulic conductivity ($R^2 = 0.597$) than those from the Kraków area ($R^2 = 0.226$ and $R^2 = 0.00947$ respectively). This proves that the matrix of limestones from the Olkusz area is much more homogeneous, in terms of porosity and permeability, than that of limestones from the Kraków area. The reason for this is the much higher content of chalky limestone in the population of samples from the Olkusz area than in the population of limestones from the Kraków area, and the higher density of microfractures and stylolites in limestones from the Kraków area, the presence of which greatly affects the hydraulic conductivity of the matrix. The anisotropy of permeability can be observed in both populations of analysed limestones. The ratio between mean hydraulic conductivity values for samples, extracted in the direction perpendicular to the layer structure (K_v), and the values for samples, extracted parallel to the layer structure (K_h), is 0.71 for limestones from the Olkusz area and 0.81 for limestones from Kraków. This means that flow within the matrix in these limestones in the direction parallel to the microbedding is more favourable than in the direction perpendicular to the microbedding.

Statistical correlations between the values of individual hydrogeological parameters also indicate the heterogeneity of the matrix. In the case of granular rocks, the hydrogeological properties of which depend on intergranular porosity and as a result they are characterised by a high degree of homogeneity of the matrix geometry, the values of these parameters correlate well with one another. One example of this is the Carboniferous sandstones from the area of the Lublin Coal Basin, in southeast Poland (Motyka and Witczak, 1974). The geometry of the matrix in carbonate rocks is more complex, because apart from intergranular pores of usually small sizes, it contains such microirregularities as stylolites, microfractures or microcavities. As a result, the values of porosity, hydraulic conductivity and specific efficiency are very poorly correlated (Borczak *et al.,* 1990*,* 1994; Motyka *et al.,* 1998; Pulido-Bosch *et al.,* 2004; Rzonca, 2014). This rule does not apply to Triassic carbonate rocks from the Olkusz area, the population of which demonstrates a high content of granular dolomite (Wilk *et al.,* 1985).

CONCLUSIONS

The carbonate rock matrix generally consists of pores of variable genesis and geometry - interparticles, microbedding, microfissures, stylolites, microcaverns, and breccias - and demonstrates great heterogeneity of hydrogeological properties. The results of tests of Upper Jurassic limestone samples from the Olkusz and Kraków areas have confirmed this pattern.

The values for the interconnected porosity of the analysed limestones from the Olkusz area were between 0.00644 and 0.219, with a mean value of 0.0994, while those for limestones from Kraków were between 0.00624 and 0.0964, with a mean value of 0.0167.

The specific yield values for samples from the Olkusz area were between 0.00 and 0.0123, with a mean value of 0.00066, while for samples from Kraków, these values were between 0.00051 and 0.00737, with a mean value of 0.00021.

The comparison of the results of measurement of hydrogeological parameters of limestone samples, extracted from the same core sample in directions perpendicular and parallel to the layer structure, revealed a high level of heterogeneity of the matrix in both limestone populations analysed. This points to the anisotropy of this hydrogeological property, meaning a greater ability to transport fluids along the microbedding than in the direction perpendicular to it.

The analysis of the hydrogeological properties of a compact rock matrix is not only of cognitive, but also of practical significance. The results of such tests can support the estimation of the groundwater resources of an aquifer, the output of wells and its stability, as well as the inflows into mines, or the analysis of the mass transport in groundwater. This may mean limited infiltration recharge but facilitates horizontal flow and drainage through wells and mine workings.

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