

## A role of water in the porosity evaluation of ground-rock media

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### Úloha vody pri vyhodnotení porozity hornín

In the paper the porosity was systemized in reference to multiphase multicomponent ground-rock media. The following geological-physical elements were accounted for: the geometry, the pore size in particular, the presence of strongly and weakly physically bounded water related to the structure of the electrical double layer, the rest saturation with water as a wetting phase, and a nonwetting phase represented by water immiscible fluids, in typical conditions e.g. air in the ground aeration zone, fluids and hydrocarbon gases.

**Key words:** porosity, water, ground-rock media

### Introduction

The subjects related to porous media are discussed by geosciences, e.g. engineering geology, hydrogeology, applied geophysics, pedology, ground science, geotechnics, mining, etc. A natural and obvious tendency to integrate narrow specializations forming broader areas has been recently observed, e.g. ground and rock mass physics/mechanics are forms of rock mass physics [8], or rock and ground physics/mechanics [2, 6]. Accordingly, the notion of ground-rock medium is assumed in various disciplines, e.g. engineering and environmental protection. It is understood as a fragment of rock mass in natural conditions of its deposition, regardless the depth. These are usually loose and comminuted or compact shallow media; rocks are compact media encountered at greater depths.

As observed by M. Rogoż [7], the terminology used for the porosity of ground-rock media still needs some specification. This especially applies to hydrogeology, where the main analyses concentrated on two-phase porous media – water-saturated ground and rocks.

### Physically bound water and capillary water in ground-rock media

Water may appear in ground-rock media in a number of forms [3,8], also as physically bounded water and capillary water.

**Physically bounded water** co-operates with the surface of a solid phase of the medium and has different properties than the free water. Nowadays most of the researchers divide physical water into: **strongly bounded water** and **weakly bounded water**, in view of the energy differences of waters in binding with mineral particles. Strongly bounded water corresponds to a certain extent adsorption water of the compact layer, or weakly bounded – to the diffusion layer in an *electrical double layer* (EDL). The maximal amount of strongly bounded water in ground corresponds to the maximal hygroscopicity, i.e. moisture absorbed by the ground in the form of steam particles on mineral grains, at the 100 % relative vapour pressure. This creates bases for assuming that strongly bounded water, hygroscopic water and adsorption water are synonymous.

*Properties of physically strongly bounded water* are similar to those of a solid phase, the structure of which differs from the structure of ice. It is frequently treated as another state of aggregation. It follows from analyses that the binding force reaches a value of 2500 MPa, and water density is equal to 1.2–2.4 g/cm<sup>3</sup>; on average ca. 1.7 g/cm<sup>3</sup>. Besides, strongly bounded water is strongly viscous, elastic and has a considerable strength to shearing.

*Physically weakly bounded water* is under the surface of mineral grains, outside the strongly bounded water. Weakly bounded water particles are held on the surface of the skeleton owing to the weak van der Waals forces and field forces of oriented water particles in the adsorption layer (diffusion EDL). The weakly bounded water layer is tens to hundreds times the water particle diameter thick (water particle diameter  $\approx$  0.138 nm). The weakly bounded water has an increased viscosity and can move slowly under the influence of considerable mechanical forces.

Beside gravity water, capillary water is usually classified as free water [8]. **Capillary water** fills small pores of 10<sup>-7</sup> to 10<sup>-4</sup> m size or sharp, narrow indentions of bigger pores. Owing to the capillary pressure, a result of molecular forces acting on the phase contact, a spontaneous movement of water may take

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place. When the amount of capillary water decreases in the course of drying out of a part of the medium, the water may be supplemented from other parts.

### Geometrical characteristics of pores

It is generally known that physical properties, especially reservoir-filtration properties of rocks and soils, are determined by a number of factors, e.g. the shape and size of pores, connections and their spatial distribution, the interrelations between pores of different size, and so the structure of the pore space.

If the surfaces of matrix have a significant influence on the hydrodynamics of fluid inside the pores, the pore body has capillary properties and the pores are called capillaries. It has been assumed in practice that the body is capillary-porous and the pores are capillaries when the capillary potential  $\mu_k$  is much higher than the gravity potential  $\mu_g$ . Otherwise, when the capillary potential is lower or equal to the gravity potential, the porous body is not capillary. It can also be assumed that the capillary potential expresses the capillary pressure  $p_k$ , and the gravity potential – the hydrostatic pressure  $p_h$  referred to the density of fluid  $\rho_c$  in pores, respectively [5]:

$$\mu_k = p_k / \rho_c \quad \text{and} \quad \mu_g = p_h / \rho_c \quad (1)$$

Accordingly, ground-rock pore media can be treated as capillary-porous bodies. Generally, for describing and modelling purposes, they should be treated as multiphase and multicomponent media.

It is quite evident for classical oil-gas reservoir rocks [3, 4, 10], however in the case of grounds it mainly refers to the zone of aeration, where apart from water wetting the solid phase, there are also other fluids that are not wetting the ground skeleton, in these gases (e.g. ground air) and/or fluids (e.g. oil products contaminations).

Additional classifications, basing on the type of fluid or gas movement possible in pores of a given size, have been introduced to the pore size characteristic.

According to the characteristic made in line with the International Union of Pure and Applied Chemistry standards for material engineering and chemistry, the following pores are distinguished depending on the boundary values of pore diameter [13]:

- macropores  $> 50$  nm,
- mezopores, also called transient pores,  $2 \div 50$  nm,
- micropores  $\leq 2$  nm.

The share of mezopores in the specific surface and volume of pores in porous media is generally small as compared to the share of macropores in the volume and micropores in the surface.

According to the pore classification with respect to the water movement abilities (most frequently applied in oil geology, rock mass physics and hydrogeology) the following pores can be defined [7, 12]:

- **overcapillary** (sometimes called ordinary) – above 0.5 mm,
- **capillary** – 0.5 mm to 0.2  $\mu\text{m}$ ,
- **subcapillary** – below 0.2  $\mu\text{m}$ .

In the overcapillary pores, water flows under gravity forces, in line with classical hydromechanics laws. In the capillary pores, water flows under capillary forces, possibly overcoming the force of gravity. On the contact of solid and liquid phase, i.e. on pore walls, surface molecular forces act on the fluid particles. The flow of fluid in the capillary pores is possible only when the gravity force or the pressure force considerably exceeds the surface forces. The subcapillary pores are under 0.2  $\mu\text{m}$ , therefore no flow of physically bounded water on the solid phase is possible. In the water-bearing ground-rock media with only subcapillary pores, the fluid particles (ions) can move only by means of diffusion.

Taking into account the **pore connectivity** among themselves and the environment, the following pore types can be distinguished:

- **open pores** – interconnected, forming the so-called open porosity,
- **closed pores** – isolated, without interconnections, forming the so-called closed porosity.

The open pores can be divided into the *open-end and the closed-end pores*; the latter occupying about 25  $\div$  60 % of total space [5].

The fluid and gas flow is possible only in the open pores. The volume of the open pores is frequently called the *effective* or *active* volume as only these pores participate in saturation or extraction processes. The closed-end pores participate only in unsteady processes. They constitute a source of mass (positive or negative) for processes taking place in the open-end pores.

### The role of electrical double layer in water-bearing ground-rock media

On the solid body-fluid phase contact, electrical charges may accumulate as a result of the transition of some ions from the solid surface to the solution, the exchange adsorption of ions from the solid surface with solution ions, the adsorption of potential-determining ions, the orientation of dipoles or the dissociation of solid surface groups. Owing to the existence of this excessive charge, a electric double layer is formed at the interface [3, 8].

The *Stern* theory accounts for the complex structure of the double layer, employing the *Helmholtz* notions of compact layer and *Gouy-Chapmann diffuse layer*.

The thickness of the electrical double layer  $l$  is a function of the valency of counterions  $z_j$ , the electrolyte concentration, the dielectric constant and the temperature.

In conditions of ambient temperature and molar concentration of electrolyte ( $c$ ) this dependence can be written as [9]:

$$l \sim \frac{1}{3 \cdot 10^7 z_j \sqrt{c}} \quad (2)$$

It follows from this equation that the thickness of the double layer decreases with the increase of valency and the ion concentration in the solution.

The Stern layer can be treated as immobile (or almost immobile) in the normal direction to the surface, as in the case of strong adsorption, influencing the ions stay in the layer for a relatively long time. Moreover, there is a problem of mobility in the direction parallel to the interface, i.e. the strength of the Stern layer to shearing. It seems probable that ions and the surrounding medium constitute a relatively stiff entity and that the Stern layer is immobile in the sense of strength to the shearing (tangent) forces. Being a property of the whole medium, it mainly refers to the solution and there is no reason why the interface of the immobile solution-slip surface should exactly coincide with the Stern layer. It can be also placed further in the solution at a distance increasing with the shearing forces (fig. 1).

From the point of view of the porous medium permeability, the location of the shearing surface separating hydrodynamically immobile (unrecoverable) the fluid from the free fluid (recoverable) is the most important issue.

### Types of porosity

In hydrogeology [12] and geotechnics [11], the ground/rock porosity is determined quantitatively by means of the porosity coefficient, frequently called the **porosity  $n$** .

**The porosity of medium  $n$**  is defined as a ratio of pore volume in a given sample of medium  $V_p$  to its total volume (skeleton and pores)  $V$ :

$$n = \frac{V_p}{V}. \quad (3)$$

Accounting for the interpore connectivity and fluid flow in the medium, the following types of porosity can be distinguished:

- **total** (total or full);
- **open** (open or saturation);
- **efficient** (active static or efficient static);
- **dynamic** (active dynamic or efficient dynamic or active).

**The total porosity  $n_c$**  characterizes the volume of all pores in the medium, both contacted (open) and not contacted (closed):

$$n_c = \frac{V_{p,c}}{V} = \frac{V - V_s}{V} = 1 - \frac{\rho_d}{\rho_s}, \quad (4)$$

where:  $V$  – volume of sample,  
 $V_{p,c}$  – total (summaric) volume of all pores in a sample,  
 $V_s$  – volume of skeleton in a sample,

$\rho_d$  and  $\rho_s$  – volume and specific density of skeleton, respectively.

**The open porosity  $n_o$**  describes the volume of interconnected pores which may be filled with the fluid when saturating a dry medium under a pressure or in vacuum:

$$n_o = \frac{V_{p,o}}{V}, \quad (5)$$

where:  $V_{p.o}$  – volume of interconnected (open) pores in the analysed medium.

For high-pore media, the total and open porosities differ slightly. For media containing a great number of subcapillary pores these differences can be significant.

The effective and dynamic porosity most frequently refer to three-phase media, i.e. media containing water and also a gaseous phase in the pore space (more generally, wetting and non-wetting phases), i.e. grounds in a non-saturated state (aeration zone) or media containing water (at least in rest quantities) and also other immiscible fluid, e.g. hydrocarbons.

**The Efficient porosity  $n_e$**  characterizes the active static volume of the medium available for non-wetting fluids (e.g., hydrocarbons), encompassing volume of interconnected (open) pores except for the space occupied by rest water – physically bounded water and capillary water (held by capillary forces and sometimes called “mobile”):

$$n_e = \frac{V_{p.o} - V_{w.r}}{V} = n_o \cdot (1 - K_{w.r}), \quad (6)$$

where:  $V_{w.r}$  – volume of rest water,  
 $K_{w.r} = V_{w.r} / V_{p.o}$  – coefficient of rest saturation of ground with water.

The index  $n_e$  determines the active static capacity of the medium which can be occupied by non-wetting fluids, e.g. air, hydrocarbons. However, only a part of the hydrocarbon fluid volume participates in the filtration when it is removed from the medium. At pressure gradients applied in practice, a defined part of the fluid remains in the pores (immobile hydrocarbons).

**The dynamic porosity  $n_d$**  indicates in what part of the volume of a three-phase medium at a given pressure gradient the non-wetting fluid (e.g., hydrocarbon) can flow. In oil laboratories it is determined on the basis of the rest water and petrol saturated sample of a porous medium. It is a difference of the efficient pores volume ( $V_{p.e} = V_{p.o} - V_{w.r}$ ) and the pores volume  $V_{nz.r}$ , where the petrol remained after being expelled from the sample with another fluid (usually air or nitrogen):

$$n_d = \frac{V_{p.o} - V_{w.r} - V_{nz.r}}{V} = \frac{V_{p.e} - V_{nz.r}}{V} = n_o \cdot (1 - K_{w.r} - K_{nz.r}) \quad (7)$$

where:  
 $V_{nz.r}$  – rest volume in the general case of non-wetting fluid, e.g. petrol, and in oil mining practice – immobile hydrocarbons,  
 $K_{nz.r} = V_{nz.r} / V_{p.o}$  – coefficient of rest saturation of the medium with a non-wetting fluid, e.g. hydrocarbon fluid.

The index  $n_d$  of a medium containing a hydrocarbon fluid has a considerable volume of open pores through which the hydrocarbons can flow. The parameter  $n_d$  depends not only on the properties of the medium but also on the gradient of pressure and time in which hydrocarbons are expelled with another fluid. At low gradients of pressure, most frequently  $n_d < n_e$ , whereas at long-term expelling and high gradients of pressure  $n_d \rightarrow n_e$ .

Generally, the relation between individual types of porosity, determined with the use of the same sample of the rock medium assumed the following form:

$$n_c \geq n_o \geq n_e \geq n_d. \quad (8)$$

### Closing remarks

A geologically-physically precised systematics of porosity, accounting the three-phase ground-rock media, is presented in the paper. A characteristic of the electrical double layer referred to the physically bounded water and the occurrence of capillary water in this type of media is taken into consideration.

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### References

1. Birdi, K., S.: Handbook of Surface and Colloid Chemistry. Boca Raton New York CRS Press 1997.
2. Derski, W., Izbicki, R., Kisiel, I. (red.), Mróz, Z.: Mechanika skał i gruntów. PWN, Warszawa 1982.
3. Dobrynin, V., M., Vendelštejn, B., J., Koževnikov: Petrofizyka. Izd. “Nedra”, Moskva 1991.
4. Gimatudinov, Š., K., Širkovski, A., I.: Fizika naftjanogo i gazovogo plasta. Izd. „Nedra”, Moskva 1982.
5. Kowalski, S., J.: Inżynieria materiałów porowatych. Wyd. Polit. Pozn., Poznań 2004.

6. Majcherczyk, T.: Zarys fizyki skał i gruntów budowlanych. *Bibl. Szk. Ekspł. Podz., Wyd. IGSMiE PAN, Kraków 2000.*
7. Rogoż, M.: Hydrogeologia kopalniana z podstawami hydrogeologii ogólnej. *Wyd. Główny Instytut Górnictwa, Katowice 2004.*
8. Ryncarz, T.: Zarys fizyki górotworu. *Śląskie. Wyd. Techn., Katowice 1993.*
9. Metody badań gruntów spoistych (red. nauk. B. Grabowska-Olszewska). *Wyd. Geologiczne, Warszawa 1980.*
10. Plewa, M., Plewa, S.: Petrofizyka. *Wyd. Geologiczne, Warszawa 1992.*
11. Polska Norma PN-98/B-02481: Geotechnika – Terminologia podstawowa, symbole literowe i jednostki miar.
12. Słownik hydrogeologiczny (red. nauk.: J. Dowgiałło, A., S. Kleczkowski, T., Macioszczyk, A., Rózkowski). *Wyd. PIG, Warszawa 2002.*
13. Twardowski, K.: Struktura przestrzeni porowej i potencjalna pojemność gazowa węgla kamiennych. *Rocznik AGH Wiertnictwo Nafta Gaz, t. 16, Kraków 1999.*