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PERMEABILITY AND POROSITY OF ROCKS AND THEIR RELATIONSHIP BASED ON LABORATORY TESTING

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ABSTRACT

Physical mass properties of various types of rocks were ascertained, and their relationships are discussed in this article. Based on water permeability and mercury intrusion porosimetry methods, conductivity coefficient, porosity, and pore size distribution were determined. Furthermore, bulk and particle densities of rocks were determined. All laboratory tests were carried out according to Czech version of the Technical specification CEN ISO/TS 17892-11:2004. The above-mentioned specification has the status of the Czech standard (ČSN, CEN). Permeability and porosity are in close relation, and it could be assumed that its relationship is linear, i.e., with increasing porosity, permeability increases as well. This relationship is influenced by other rock properties, such as the amount of open and closed pores within the rock sample, size, and distribution of pores or mineral admixtures. From this point of view, it is necessary to study these physical properties of rocks as well, because this enables an overall analysis of rocks and its possible use for engineering constructions.

KEYWORDS: permeability, porosity, laboratory tests, rock samples

INTRODUCTION

Permeability and porosity are two of the primary properties that control the movement and storage of fluids in rocks. They represent an important characteristic of materials. On the basis of the known permeability and porosity, possible influences of water on an engineering construction are considered. Furthermore, knowledge of permeability and porosity is necessary at water leakages, at the structural foundation in order to evaluate affluent to a foundation pit, and in terms of the design of waterproofing of buildings. Permeability and porosity are also very important indicators for the utilization of various kinds of rocks (Christensen et al., 1996).

Mainly sandstones are used for various purposes in the building industry, for the renovation of historical monuments, stonework, and sculptures, etc. Limestone and arenaceous marl are used as facing material and for the restoration of historical buildings. For building foundations, and construction of underground structures, marlite is used. Permeability and porosity have an impact on rock weathering, which affects the field of engineering utilization.

Permeability is one of the rock properties that are necessary for considering the solving of hydrological and hydrogeological problems by methods of numerical and physical modelling (Huenges and Zimmermann, 1999; Sudo et al., 2005).

It follows that faultless determination of both the referred rock properties is very important. Discussion of the laboratory methods used for measuring of permeability and porosity and its relationship is carried out in this paper.

PERMEABILITY, POROSITY AND PORE SIZE DISTRIBUTION

Permeability is the ability of porous material to allow the passage of a fluid. To determine permeability of rocks, various methods can be applied, which differ in the medium used. In the case when the fluid that passes through the porous material is water, permeability can be expressed by the coefficient of conductivity k [$\mathrm{m.s^{-1}}$], which means a discharge velocity of water flow in a rock under the action of a unit hydraulic gradient, usually expressed in meters per second

$$k = \frac{Q \cdot l}{A \cdot h \cdot t} \qquad [\mathrm{m.s^{-1}}] \qquad (1)$$

where

Q is the volume of water leaking through the specimen during time t
l is the height of the tested specimen
A is the cross-section of the specimen
h is the difference in the water pressure levels
t is the period of measurement.

Porosity of porous medium describes the fraction of void space in the rock, where the voids may contain air or water. The porosity is defined as the ratio of the volume of voids expressed as a percentage of the total (bulk) volume of a rock, including the solid and void components. Porosity is calculated from the derived formula:

$$n = \left(1 - \frac{\rho_d}{\rho}\right)100 \quad [\%], \tag{2}$$

where ρ_d is bulk density of the dry specimen and ρ is particle density.

Bulk density can be determined from a regular specimen by stereometric method. Our tests were carried out on samples of cylindrical form, with parameters 50 mm in diameter and 50 mm in height. Particle density, an average mass per unit volume of the solid particles in a rock sample, is usually determined by applying the pycnometer method (Head, 1992).

Permeability and porosity depend on pores in the rock. There are two discerned typologies of pores in rocks: closed and open pores. Closed pores are completely isolated from the external surface, not allowing the access of external fluids in either the liquid or gaseous phase. Closed pores influence parameters such as density and mechanical and thermal properties. Open pores are connected to the external surface and are therefore accessible to fluids, depending on the pore characteristics/size and the nature of fluid. Open pores can be further divided into dead-end or interconnected pores. The percentage of interconnected pores within the rock is known as effective porosity. Effective porosity excludes isolated pores and pore volume occupied by water adsorbed on clay minerals or other grains. Total porosity, determined from formula No. 2, is the total void space in the rock, whether or not it contributes to fluid flow. Effective porosity is typically less than total porosity.

Character of porosity alters with the genesis of rocks and strongly determines its physical properties, e.g., permeability, adsorption properties, mechanical strength, or durability. On the basis of known character of porosity, predicting rock behaviour under different environmental conditions and its usage is considered.

One of the most important parameters is the pore size and pore size distribution. Pores are classified according to four groups depending on the access size: micropores, with size less than 2 nm diameter; mesopores, ranging between 2 and 50 nm diameter; macropores, which are in range from 50 nm to 7500 nm diameter and rough pores in size over 7500 nm.

APPARATUS AND METHOD OF PERMEABILITY MEASUREMENT

An apparatus of a high technological standard was used, enabling permeability measurements on fully saturated specimens of soil and rock under constant hydraulic incline (Brůha et al., 2001). The apparatus is composed of a panel with measuring and regulation elements, containing a horizontal burette [H] enabling exact measurements of the water volume flowing through the sample during saturation as well as during permeability measurement; vertical (overflow) burette [G], which enables exact measurements of the volume of water flowing through the sample during measurement of permeability; a differential micro-manometer [J] for level difference measurement; a piston hand pump [I] for pulling in/pulling away membrane on the measured specimen in the cell during handling, before and after measuring, and a needle valve which opens the water intake from pressurized vessels to the panel and regulation cocks. There is also a permeability cell of a membrane type placed on the apparatus. In the cell [D], it is possible to place cylindrical specimens of 50 mm in height, and a diameter up to 50 mm. Lower and upper bases of the cell have an outlet for pressure difference monitoring.

Sources of saturated pressure and differential pressure are two interconnected pressurized cylindrical vessels with heavy pistons [B, C]. Pistons are exchangeable and their mass graded to allow setting the required pressure by combining the pistons. Hydrostatic cell pressure is created by a separated pressure tank [E], located several meters above the level of the other parts of the apparatus. Location of this tank guarantees that the cell (confining) pressure in the cell is always higher than the pressure at the bottom base of the cell. Hydrostatic cell pressure is constant; it is not measured, and presses only the membrane to the cylindrical surface of a specimen. This prevents water passing around the specimen during testing. The apparatus has three sensors for water temperature monitoring. Measured values are recorded by a central programmable measuring device. Communication with the central measuring device and subsequent processing are performed by the Windows operating system (Straková et al., 2002).

Laboratory tests were accomplished on rock specimens of cylindrical shape drilled from compact rock materials with the following proportions: height of tested sample 50 mm, basis diameter of tested sample 50 mm. The test consisted of two basic phases after placing the specimen in a cell: (i) saturation of specimen, (ii) running permeability test. The saturation of the specimen and also the permeability measurement are carried out under the saturate pressure of 150 kPa for all tested specimens. During the permeability measurement, the quantity of water going through the specimen is measured. The course of the test is observed on the computer monitor. The test of permeability is finished when time dependence of flowing water quantity is constant.

In the case of permeable rock specimens (coefficient of conductivity varies from 10^{-8} to 10^{-6}), experiments last from 30 to 60 minutes. For some rock specimens, which represent very few permeable rocks (coefficient of conductivity varies from 10^{-11} to 10^{-9}), the permeability measurement experiment lasted up to several days.

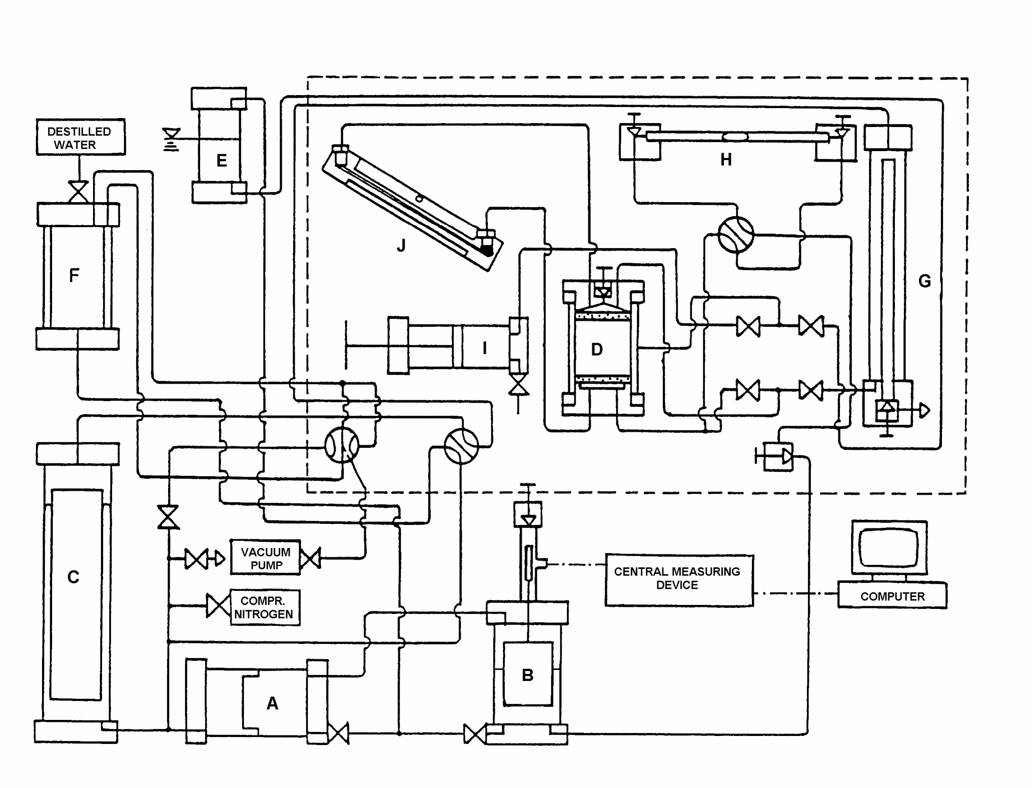

Fig. 1 Scheme of apparatus for permeability measurement.

MERCURY POROSIMETRY

Method of the high pressure porosimetry is based on phenomenon of the mercury capillary depression, where the wettability angle is > 90° and mercury leaks into pores by the effect of pressure. Mercury volume infiltrated into a porose system is generally interpreted as total pore volume in measured specimen. Relationship between actual pressure p and cylinder pore radius r is expressed by Washburn equation:

$$p = -\frac{2\sigma \cos \varphi}{r} \qquad (3)$$

where p [Pa] is an actual pressure, r [nm] half-length distance of two opposite walls of a pore expressed by an effective radius, σ surface tension of mercury [$480 \cdot 10^{-3}$ N·m^{-1}] and φ contact angle [141.3 °].

The laboratory tests of mercury intrusion porosimetry are carried out on Pascal 140 and 240 fy Thermo Electron-Porotec porosimetres. Porosimeter 140 is used as filling device and for low pressure measurements up to pressure of 100 kPa. Porosimeter 240 works in pressure range of 0.1 – 200 MPa. By using above mentioned pressure interval, pores with diameter ranging from 3.7 mm to 58 µm can be determined.

Pore shape is mainly unknown, but it could be approximated by the model. Four basic pore models exist: i) cylindrical pores, circular in cross section, ii) ink-bottle pores having a narrow neck and wide body, iii) slit-shaped pores with parallel plates, and iiii) conical pores.

TESTED SAMPLES AND THEIR MEASURED PROPERTIES

In total, 23 various rock samples were tested, and values of the conductivity coefficient, particle and bulk densities, and porosity are listed in Table 1. The values of the presented rock properties were predominantly determined as an arithmetic average of two to five rock specimen tests. For each specimen, the permeability and particle and bulk densities were measured, and porosity calculated. All laboratory tests were carried out according to Czech version of the Technical specification CEN ISO/TS 17892-11:2004. The above-mentioned specification has the status of the Czech standard (ČSN, CEN).

DISCUSSION

Permeability and porosity are in a close relationship that depends on the amount of void space in the tested material. It is widely accepted that permeability is determined by microstructure, which is, in this context, defined in terms of pore and crack structures. So it could be supposed that with increasing porosity, the permeability should increase as well. But there are some other facts to note when speaking about this relationship. Therefore,

Table 1 Selected physical properties of rocks.

Types of Rock	**Location**	**Permeability**		**Bulk density**	**Particle density**	**Porosity**
		Coefficient of conductivity k_{10} [m/s]	**Designation according to CEN ISO/TS 17892-11:2004**	ρ_d [g/cm^3]	ρ [g/cm^3]	n [%]
Sandstones	Podhradí	7.33 E-06	C	2.20	2.61	15.45
	Lány	6.01 E-06	C	1.95	2.59	24.94
	Kamenné Žehrovice	3.34 E-06	C	1.96	2.56	23.44
	Hamr	2.82 E-06	C	2.01	2.63	23.05
	Hořice	2.30 E-06	C	2.11	2.65	20.38
	Záměl	1.72 E-06	C	2.18	2.63	16.98
	Kocbeře	9.25 E-07	C	2.25	2.62	14.22
	Prácheň	5.78 E-07	C	1.97	2.62	24.85
	Zámostí	5.69 E-07	C	2.16	2.63	17.76
	Opočno	1.51 E-07	C	2.08	2.63	20.94
	Úpice	1.16 E-07	C	2.32	2.64	11.95
	Jitrava	7.07 E-08	B	2.17	2.62	16.99
	Zdislava	4.55 E-09	B	2.25	2.64	14.62
Arenaceous marl	Velké Žernoseky	3.00 E-07	C	1.63	2.39	31.74
	Přední Kopanina	1.50 E-09	B	1.86	2.46	24.54
Gneiss	Františkov	1.63 E-09	B	2.69	2.72	1.21
Marlite	Vraňany	2.871 E-09	B	2.19	2.70	19.03
	Litoměřice	8.64 E-10	A	2.22	2.63	15.45
Limestone	Úvaly	5.34 E-09	B	2.33	2.65	12.09
	Litoměřice	2.82 E-10	A	2.41	2.52	4.44
	Koněprusy	5.67 E-11	A	2.67	2.73	2.00
Granite	Potůčky	3.15 E-10	A	2.59	2.66	2.70
Basalt	Boží Dar	5.15 E-11	A	3.17	3.27	3.06

Rock classification according to the Czech version of the Technical specification CEN ISO/TS 17892-11:2004:
A - almost impermeable rocks, B - impermeable rocks, C - a few permeable rocks

permeability of porous material is influenced not only by porosity, but also by shape and arrangement of pores, or by the amount of clayey component.

Firstly, it is necessary to distinguish between total and effective porosity. We are not able to make assumptions on water permeability of tested material from values of total porosity, due to the fact that it is the total void space in the rock. A rock may be highly porous, but if the voids are not interconnected, fluids within the closed (isolated) pores cannot leak.

Secondly, pore size distribution is important. To clarify the relationship between permeability and porosity, pore size and pore size distribution were determined for selected rock samples. Pore dimensions cover a very wide range. Within our research, two samples of sandstones (Úpice, Prácheň), which have approximately the same order values of permeability, but very different porosities, were tested by mercury porosimetry for pore size distribution. Results are shown in Figures 2 and 3.

As we can see from Figures 2 and 3, sandstone from locality Úpice has a more uniform distribution in range of pore size. The rough pores of this sample do not exceed 30% in total. In the case of sandstone sample from Prácheň locality, the distribution of pore size is different. The rough pores of this sample reach approximately 65% in total. The prevailing part of pores belongs to the rough pores, which can create main transport ways for liquid.

Average pore diameter is usually used as a representative parameter of the pore size distribution. In case of sandstone Úpice, average pore size diameter is 2.2 μm; for sandstone Prácheň, average pore size diameter is 3.2 μm (Table 2).

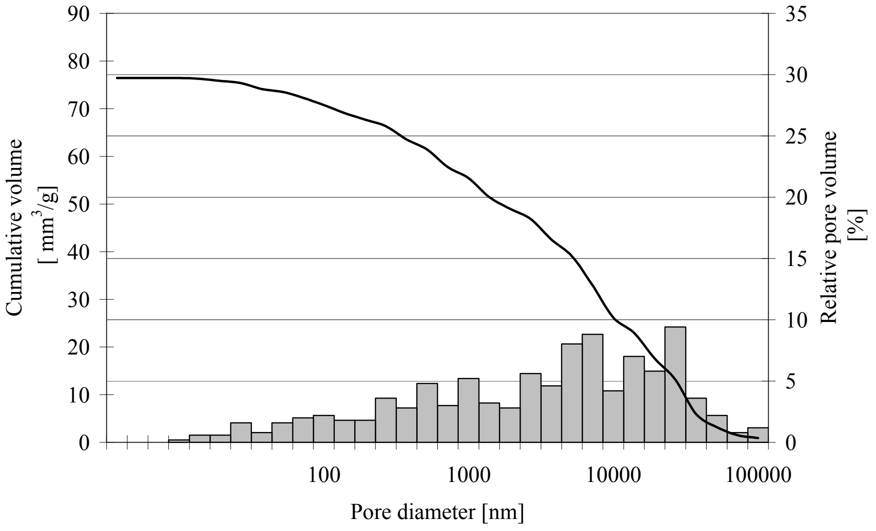

Fig. 2 Pore size distribution of sandstone sample Úpice.

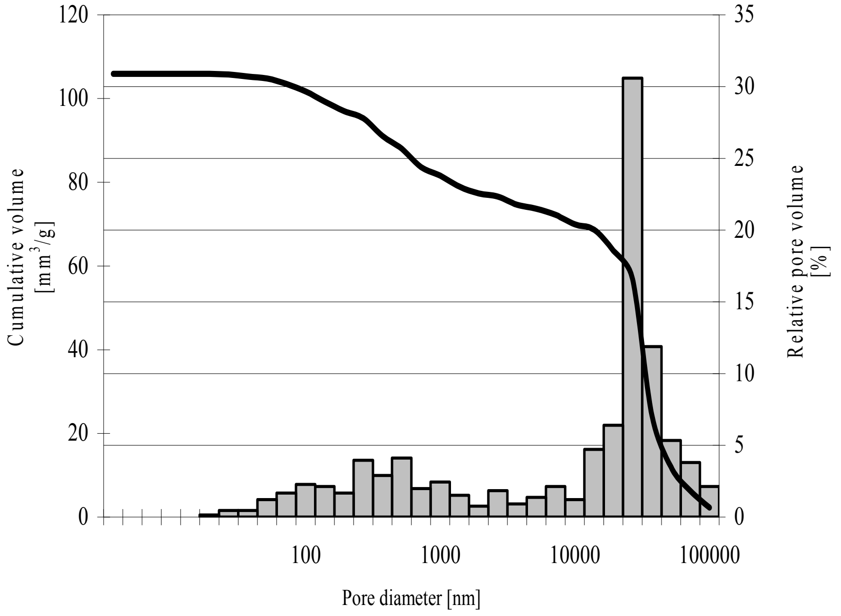

Fig. 3 Pore size distribution of sandstone from Prácheň lokality.

It is well known that mineral admixtures affect permeability. The basis for this effect can be understood in terms of the formation of a large amount of porosity in the mesopore range. This assertion requires further experimental verification. Mesopores are of a size range for which electrostatic interactions between the pore walls and the liquid would extend over a significant fraction of the cross-sectional area. A consequence of this may be that transport processes through pores having diameters in this range are hindered by electrostatic effects (Roy et al., 1993). Our research can confirm this. A sample of sandstone from Úpice locality, where the amount of mesopores is 5.40%, is less permeable than a sample of sandstone from Prácheň locality, with 2.29% of mesopores.

Finally, there are some other characteristics of samples we observed, such as the relationship between bulk density and porosity. We have obtained the generally known fact from sandstone rock samples. The relationship between bulk density [g/cm^3] and porosity [%] of all 13 tested samples can be seen in Figure 4. We can clearly identify that with decreasing bulk density, the porosity of the sample

Table 2 Selected physical properties of sandstones.

Types of Rock	Locality	Coefficient of conductivity k_{10} [m/s]	Bulk density ρd [g/cm^3]	Partical density ρ [g/cm^3]	Porosity n [%]	Average pore size diameter [μm]
Sandstone	Prácheň	5.78 E-07	1.97	2.62	24.85	3.2
	Úpice	1.16 E-07	2.32	2.64	11.95	2.2

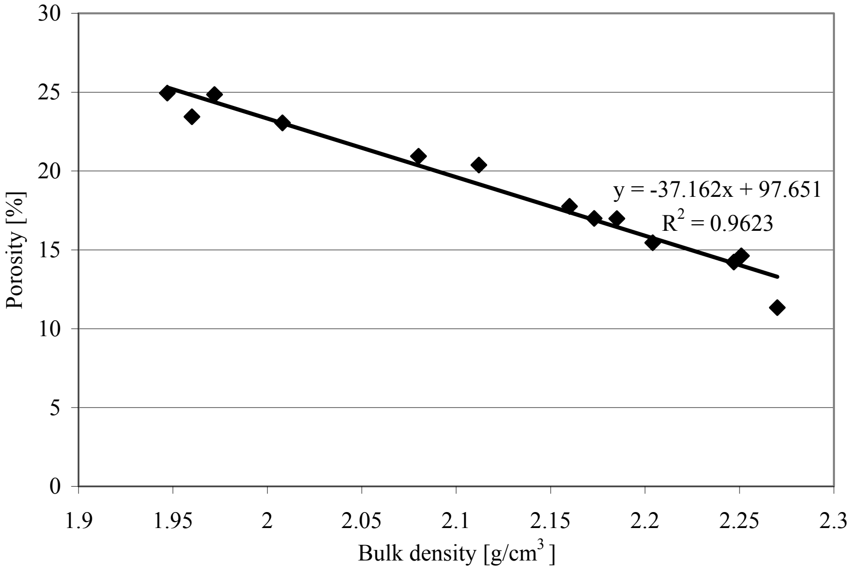

Fig. 4 Relationship between bulk density and porosity of sandstones.

increases. It is due to the small differences in particle densities, which are not depend on porosity, but only on modal composition. The modal compositions of sandstone samples are assumed to be approximately the same. The relationship between bulk density and porosity of all tested samples is shown in Figure 5.

Arenaceous marls have high porosity. Similarly, marlites usually have higher porosity, too. The conductivity coefficient of the above-mentioned rocks depends on the amount of clayey components. Despite the fact that clays have very high porosities, the permeability is very low (about $10^{-10} – 10^{-11}$). It is due to the structured nature of clay minerals. Clays can trap a large volume of water per volume of bulk material, which is caused by swelling, but they do not release water very quickly and cause a decrease of the conductivity coefficient.

Tested samples of limestones, gneiss, granite and basalt are fine-grained rocks, so they have low porosity, and this fact causes a low conductivity coefficient as well. A limestone sample from Úvaly, compared to other two tested samples, has high porosity, which is caused by micro fissures, which increase permeability of rock.

CONCLUSION

Permeability of rocks is determined by microstructure, which is, in this context, defined in terms of pore and crack structures. The conductivity coefficient of porous material is influenced not only by porosity, but also by the shape and arrangement of pores, or by the amount of clayey component. Only effective porosity can influence permeability, because only open pores are interconnected and allow leaking water through. Another important factor is pore size distribution, or amount of clayey component. By evaluating relationship of porosity and permeability, it is also necessary to take into account rock bulk and particle density.

Laboratory tests of the basic physical properties of different types of rocks were carried out and their relationships were discussed. The above-mentioned physical properties of rocks, such as water permeability, porosity, pore size distributions and

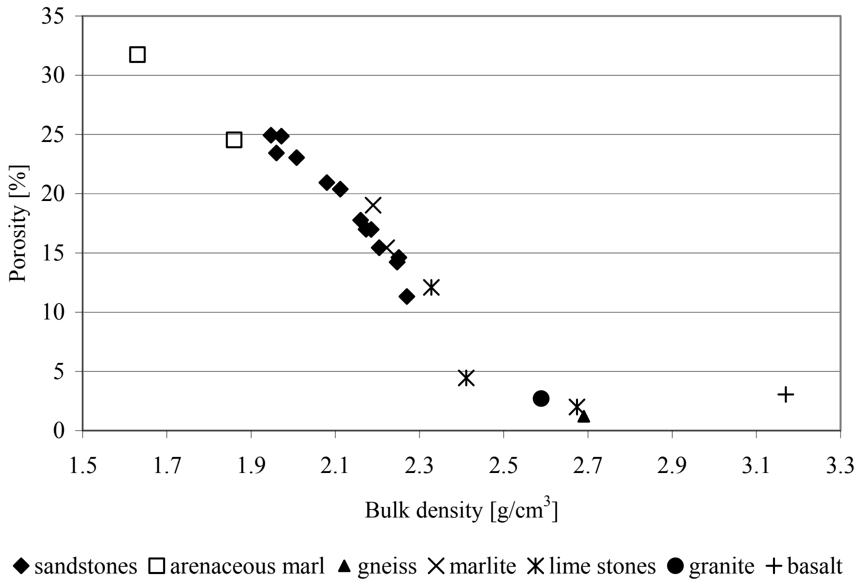

Fig. 5 Relationship between bulk density and porosity of all tested symplex.

other similar adsorption properties, mechanical strength, or durability are very important characteristics. On the basis of these physical characteristics, prediction of rocks' behaviour under different environmental conditions and its usage is considered.

There is another important characteristic influencing porosity and permeability, namely grain size. Rocks with grains of approximately one size have higher porosity than similarly-sized poorly sorted materials, where smaller particles fill the gaps between larger particles. This fact significantly reduces porosity and can influence permeability as well. Influence between permeability of rocks and grain size distribution is another object for studying.

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