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Evaluating the Correlation Between Petrophysical and Geomechanical Properties of Samples from the Defa Field

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تقييم العلاقة بين الخواص البتروفيزيائية والجيوميكانيكية لعينات من حقل الدفة

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Abstract

The two characteristics of rock are its mechanical and physical attributes. Through non-destructive testing, the physical characteristics of rocks are determined. Density, specific gravity, water content, saturation level, porosity, and pore number are the physical characteristics of rocks. On the other hand, destructive testing is used to determine mechanical properties. Compressive and tensile strength tests are examples of mechanical qualities that are acquired through laboratory testing.

In many geological issues, porosity and density are essential and significant physical characteristics of rocks that influence other physical characteristics. Consequently, measurements of the density and porosity of rock samples are crucial research topics in the fields of geoscience and geoengineering. There are numerous methods for measuring density and porosity that are currently in use. Because different measurement techniques are based on different concepts and test procedures, it is required to compare the measurement results from these approaches in order to ensure the quality of the data and to assess its quality. As study materials, we gathered eight different kinds of rock samples from Waha Oil Company's Defa Field. We also prepared a number of metal specimens for experimental comparison.

The eight rocks had porosities that ranged widely, from roughly 0.3% to 50%. We measured the volumes of regularly shaped specimens and calculated their bulk densities and porosities using three different techniques: a helium-displacement pycnometer, a buoyancy test, and a calliper. As a result, the three techniques yielded almost same bulk densities and porosities for all the specimens.

Furthermore, we used mercury intrusion porosimetry to quantify the rock samples' density and porosity and ascertain their pore size distribution. Porosity values obtained by the porosimetry method were underestimated in the case of high-porosity (soft) rock samples and overestimated for the very low-porosity rock samples. Ability to determine pore size distribution, however, is a very important advantage of the porosimetry method.

Keywords:

Helium-Displacement Pycnometer, Caliper Method, Buoyancy Method, Rock, Density, Porosity, and Mercury Intrusion Posimetry

الملخص

الصخور لها خاصيتان هما الخواص الفيزيائية والميكانيكية. يتم الحصول على الخواص الفيزيائية للصخور من الاختبارات غير المدمرة. الخصائص الفيزيائية للصخور هي الكثافة والجاذبية النوعية والمحتوى المائي ودرجة التشبع والمسامية وعدد المسام. بينما يتم الحصول على الخواص الميكانيكية من الاختبارات التدميرية. تشمل الخواص الميكانيكية التي يتم الحصول عليها من الاختبارات المعملية اختبارات قوة الانضغاط وقوة الشد.

تُعد المسامية والكثافة من الخواص الفيزيائية الأساسية والمهمة للصخور في مختلف المشاكل الجيولوجية، وتؤثر على الخواص الفيزيائية الأخرى. ولذلك، فإن قياسات الكثافة والمسامية لعينات الصخور هي عناصر استقصائية مهمة في كل من مجالات العلوم الجيولوجية والهندسة الجيولوجية. تتوفر العديد من تقنيات قياس الكثافة والمسامية ويتم تطبيقها حاليًا. ولضمان جودة البيانات وإجراء تقييم جودتها، من الضروري مقارنة نتائج القياس بتقنيات قياس مختلفة نظرًا لأن التقنيات تعتمد على مبادئ وإجراءات اختبار مختلفة. في هذه الدراسة، قمنا بجمع ثمانية أنواع من عينات الصخور (حقل ديفا – شركة الواحة للنفط) كمواد للدراسة، كما قمنا بإعداد عدة عينات معدنية للمقارنة التجريبية.

غطت مسامية الصخور الثمانية نطاقاً واسعاً جداً يتراوح بين 0.3% إلى 50% تقريباً. لقد استخدمنا ثلاث طرق (الفرجار والطفو ومقياس مسامية الإزاحة الهيليوم) لقياس أحجام العينات المنتظمة الشكل وتحديد كثافتها ومساميتها. ونتيجة لذلك، أسفرت التقنيات الثلاث عن نفس الكثافات السائبة والمسامية تقريبًا لجميع العينات.

بالإضافة إلى ذلك، طبقنا أيضًا قياس المسامية بالتسريب الزئبقي لقياس الكثافة والمسامية وكذلك لتحديد توزيع حجم المسام في العينات الصخرية. تم تقدير قيم المسامية التي تم الحصول عليها بطريقة قياس المسامية بأقل من قيمتها الحقيقية في حالة عينات الصخور عالية المسامية (اللينة) والمبالغة في تقديرها في عينات الصخور منخفضة المسامية. ومع ذلك، تعد القدرة على تحديد توزيع حجم المسام ميزة مهمة جدًا لطريقة قياس المسامية.

الكلمات المفتاحية

الصخور، الكثافة، المسامية، طريقة الفرجار، طريقة الطفو على سطح الماء، مقياس الهيليوم – الإزاحة – مقياس الإزاحة – مقياس الإزاحة – مقياس التداخل

Introduction

In many geological issues, density and porosity are essential physical characteristics of rocks that influence other physical characteristics including Young's modulus, permeability, resistivity, strength, and elastic wave velocity [1]. Thus, the most common and significant research items in the domains of geoscience and geoengineering are density and porosity assessments employing rock samples from geological outcrops and drilling core samples recovered from depths. There are numerous methods for measuring bulk density and porosity that are currently being used in the fields [2]. Since different measurement techniques are based on distinct principles and test procedures, it is required to compare and examine the measurement findings by the various techniques in order to ensure the quality of the data.

Eight different types of rock samples were collected for this experimental study in order to compare the measurement results. These samples included gabbro, granite, four sandstones, welded tuff, mudstone, and several metals. The density and porosity of the rock samples were then measured using various techniques. The eight rocks had porosities that ranged widely, from roughly 0.3% to 50%. The volume of normally shaped specimens was measured, and the bulk densities and porosities of the rock samples were ascertained using three different techniques (caliper, buoyancy, and helium-displacement pycnometer, also known as gas pycnometer) [2] [3]. Furthermore, we used mercury intrusion porosimetry to assess the porosities and ascertain the pore size distributions [4]. [5]. To provide relevant geological context for the study's core samples, particularly the four sandstones, it is important to note their origin. These sandstone samples were obtained from the **Dafa Oil Field** , a key **onshore field** located in the **Sirte Basin** of **central Libya**. This prolific field is known for its significant hydrocarbon reserves and is operated by the Waha Oil Company. The Dafa field is considered one of Libya's historical

producing assets, with commercial production having been established around **1968**.

Rock Samples and Test Methods

Eight different kinds of rock samples covering a very wide range of porosity were gathered as test materials for the planned studies of various procedures. The samples' rock types are Waha Oil Company's Defa Field. Every rock sample is fresh and rather uniform; that is, they are not worn and appear to be devoid of visible cracks. Table 1 listed the types of rocks and the quantity of specimens utilized in each experiment. We prepared five metal specimens (two aluminum, two brass, and one stainless) for the volume measurements in addition to the rock samples because they are of higher quality and do not have pores.

Table 1. Rock types and number of test specimens for the various experiments

Sample Type	Specimen number for individual method			
	Caliper method	Buoyancy method	Pycnometer	Porosimetry
AD	6	6	3	3
AC	6	6	3	3
ZE	3	3	3	3
DS	3	3	3	3
HR	3	3	3	3
MO	3	3	3	3
KL	3	3	3	3
BT	3	3	3	3
Metals	5	5	5	–

For the measurements, we created rock specimens for eight different types of rocks in the shape of a normal cylinder. All of the cylinder specimens have the same diameter (around 25 mm), but their lengths vary by 20 to 35 mm, depending on the size of the initial rock sample.

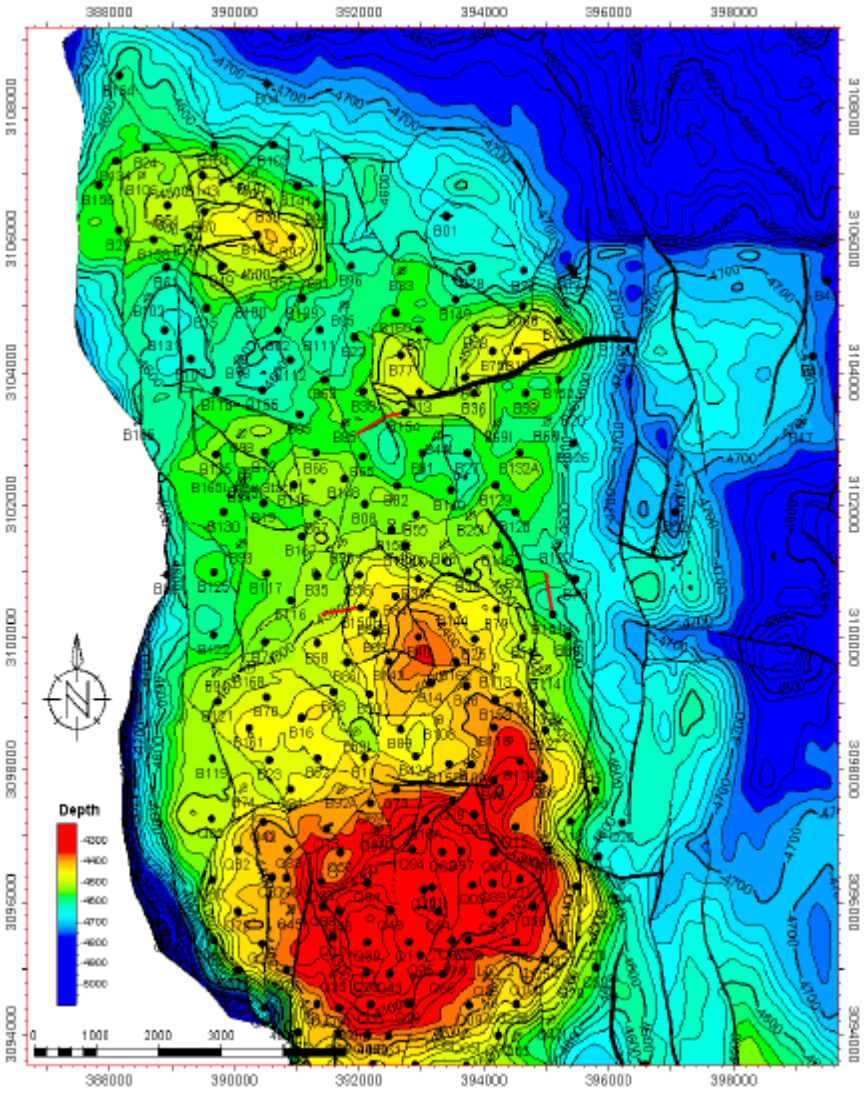

Figure. 1 Depth map for Defa field

Procedures and Methods for Measurement

The most straightforward technique for figuring out the bulk density of rock samples is to determine their mass and volume, as indicated by Equation (1):

$$\rho = M / V \quad (1)$$

where ρ is bulk density ($g/cm3$), M is mass (g), and V is the bulk volume including both solid's and pore's volume ($cm3$). If mass M was measured using dry rock specimen, ρ is the bulk dry density.

On the other hand, bulk wet density is determined by the mass of the rock specimen at water saturated state. In this study, we deal with the bulk dry density. Porosity (n in %) is defined as the ratio of accumulated (total) pore volume (VP in $cm3$) included in a rock specimen to the bulk volume VB of the specimen as follow:

$$n = V_P / V_B \times 100 \quad (2)$$

These equations make it evident that bulk volume and pore volume measurements, as opposed to mass (or weight) measurements, which are rather simple and accurate to obtain using an electrical balance, determine the density and porosity of rock specimens. Thus, the main concern is to analyze the findings of volume measurements using various techniques.

For bulk volume measurements, three methods *i.e.* caliper (resolution of the caliper used: 0.05 mm) [2], buoyancy based on Archimedes' principle [6], and helium-displacement Penta-Pycnometer which is according to Boyle's Law [7], were employed in this study.

To achieve water saturation, the rock samples were first immersed in a vacuumed desiccator for almost three days. The three methods were then used independently to estimate their bulk volumes, and an electrical balance with a resolution of 0.001 g was used to quantify their weights in the wet condition. Following these measurements, the samples were dried for over twenty-four hours at 110°C in an oven. The same electrical balance was used

to measure the specimens' dry weights after they had cooled to room temperature in a desiccator. A pycnometer was used to measure the dry volumes, or the volumes of the solid component solely. Pore volume VP (cm3) is calculated using the following formula:

$$Vp = (M_{wet} - M_{dry}) / \rho_{water} \quad (3)$$

where ρwater (g/cm3) is the water density at room temperature, Mwet (g) is the specimen's mass at water saturation, and Mdry (g) is its mass at dryness. Here, we employ the same rock specimens for each measurement method since we think this is crucial for experimental comparative studies of various measurement techniques. The specimens were downsized (cut) to suit the sample container of the mercury intrusion porosimetry device following the caliper, buoyancy, and pycnometer measurements.

Then, the pore volumes and pore size distributions in dry specimens were determined by the porosimetry method [4].

Measurements of Bulk Volume Using Various Techniques

Table 2 contained the all-bulk volume data for the eight different types of rock and metal specimens that were measured separately using the caliper, buoyancy, and pycnometer methods. Both wet and dry conditions of the rock specimens were used for pycnometer readings. The bulk volume (which includes both solid and pore volumes) can be computed by adding the measured solid volume to the pore water volume, which is derived from the difference between the weights of the wet and dry specimens, as the measured volume at the dry state only corresponds to the volume of the solid section.

Table 2. a comparison of bulk volumes determined using various techniques.

Sample Type	Specimen ID	Bulk volume (cm3)				Pore volume (cm3)	Solid volume (Pycnometer, dry) (cm3)
		Caliper method	Buoyancy method	Pycnometer (wet)	Solid volume + Pore volume		
AD	AD1	13.41	13.35	13.45	13.46	0.02	13.33
	AD2	13.08	16.99	16.97	17.03	0.02	13.11
	AD3	13.74	16.63	16.54	16.62	0.01	13.40
	AD4	11.25	11.27			0.02	
	AD5	9.63	9.62			0.02	
	AD6	8.90	8.90			0.02	
AC	AC1	15.59	15.52	15.96	16.55	0.14	18.41
	AC2	15.21	15.14	15.50	16.20	0.17	18.03
	AC3	14.77	14.69	15.02	15.72	0.15	17.57
	AC4	10.05	10.03			0.07	
	AC5	9.58	9.50			0.06	
	AC6	8.93	8.93			0.06	
ZE	ZE1	17.83	17.73	17.08	17.26	1.49	15.77
	ZE2	17.66	17.51	16.86	17.00	1.70	15.30
	ZE3	15.85	15.74	15.02	15.18	1.18	14.00
DS	DS1	17.67	17.52	16.80	17.32	1.85	15.48
	DS2	17.63	17.51	16.76	17.30	1.86	15.44
	DS3	17.48	17.36	16.63	17.15	1.87	15.28
HR	HR1	17.17	17.09	16.04	16.78	2.27	14.51
	HR2	16.31	16.24	15.06	15.99	2.16	13.83
	HR3	14.97	14.87	14.11	14.59	2.08	12.51

MO	MO1	16.25	16.01	15.43	15.93	3.09	12.84
	MO2	15.80	15.53	14.79	15.39	3.09	12.30
	MO3	14.78	14.57	13.83	14.41	2.91	11.50
KL	KL1	15.46	15.47	14.86	15.48	4.87	10.60
	KL2	15.17	15.17	14.44	15.13	4.81	10.32
	KL3	14.09	14.11	13.37	14.18	4.60	9.58
BT	BT1	9.06	9.09	8.19	9.06	4.46	4.60
	BT2	8.27	8.79	7.80	8.79	4.32	4.48
	BT3	8.79	8.30	7.45	8.27	4.06	4.22
Metals	Aluminum 1	14.63	14.50	14.59	-	-	-
	Aluminum 2	25.34	25.23	25.43			
	Brass 1	14.37	14.29	14.35			
	Brass 2	25.06	24.98	25.22			
	Stainless	14.98	14.98	14.96			

Cross plots of the bulk volumes determined by buoyancy and the other techniques are shown in Figure 2, which indicates that the bulk volume values are roughly placed in the 1:1 line. In particular, the pycnometer's wet state readings (blue circles) appear to be marginally lower than those obtained using the buoyancy method.

We developed a parameter called "error" E (%) as follows in order to quantitatively compare the bulk volumes that were acquired using various methods:

$$E = 100 \times (V_B - V_{B-B}) / V_{B-B} \quad (4)$$

where VB−B is the bulk volume by the buoyancy technique, and VB is the bulk volume derived by the individual approach. The % value of this parameter

makes it easier to see how much the buoyancy and individual readings differ (Figure 3).

In general, there was less than 1% variation in the bulk quantities of metal specimens (aluminum, brass, and stainless) produced using the three different procedures. When measuring "convex" portions of rock specimens, a caliper may indicate slightly bigger results than the buoyancy method if the specimen surface is not smooth. When comparing the two pycnometer measurements, the dry one agrees better with the caliper and buoyancy methods. However, based on this result, it may be concluded that the dry specimen appears to provide a superior pycnometer measurement than the wet one. It's also important to see a trend that indicates the wet pycnometer data's error level rises as the water content does.

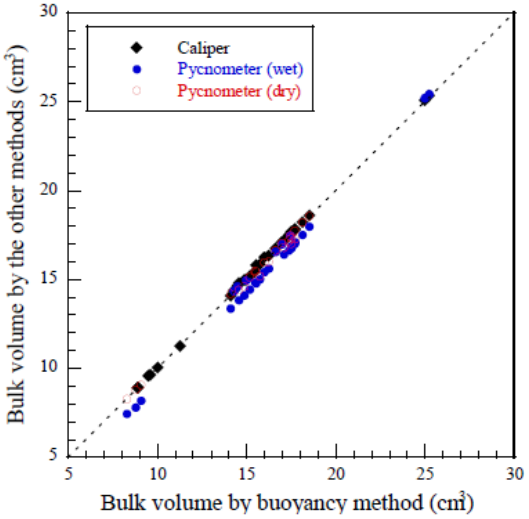

Figure 2. A comparison of buoyancy-measured bulk volumes with alternative techniques

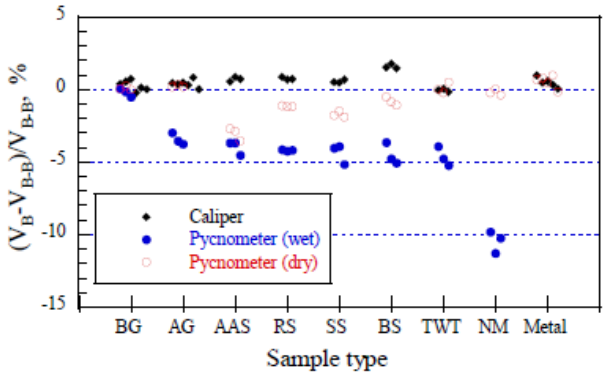

Figure 3. A quantitative comparison among the bulk volumes obtained by different methods

Measurements of Bulk Density and Porosity Using Various Techniques

Using various techniques, we calculated the bulk dry densities of all the metal and rock specimens as well as the porosities of the rock specimens (Table 3). The porosities were determined using Equation (2) and the mass (weight) difference between the wet and dry states, while the densities were determined using the bulk volumes (Table 2) and specimen masses (weights) at dry state as determined by the electrical balancing in accordance with Equation (1). Mercury intrusion porosimetry also yields the porosity by measuring mercury volume injected into the rock specimens at high pressures; and bulk dry density using bulk volumes measured by the apparatus based on mercury displacement principle.

Table 3. A comparison of porosities and bulk dry densities determined using different methods

Sample Type	Specimen ID	Bulk volume (cm3)			Porosity (%)		
		Caliper method	Buoyancy method	Pycnometer (wet)	Buoyancy method	Pycnometer (dry)	Porosimetry
AD	AD1	2.942	2.954	2.952	0.20	0.20	0.35
	AD2	2.942	2.958	2.952	0.18	0.18	0.35
	AD3	2.921	2.941	2.942	0.19	0.19	0.35

	AD4	2.952	2.945		0.21		0.35
	AD5	2.942	2.945		0.24		
	AD6	2.940	2.945		0.24		
	Average	2.940	2.948	2.949	0.21	0.19	0.35
AC	AC1	2.635	2.647	2.633	0.76	0.75	0.66
	AC2	2.636	2.647	2.633	0.95	0.95	0.66
	AC3	2.635	2.648	2.633	0.85	0.85	
	AC4	2.639	2.646	2.633	0.70		
	AC5	2.625	2.647		0.63		
	AC6	2.641	2.642		0.63		
	Average	2.642	2.643	2.633	0.75	0.85	0.66
ZE	ZE1	2.406	2.419	2.485	8.39	8.62	10.87
	ZE2	2.360	2.380	2.451	9.72	10.01	10.66
	ZE3	2.405	2.422	2.510	7.48	7.76	10.51
	Average	2.390	2.407	2.482	8.53	8.80	10.69
DS	DS1	2.325	2.345	2.372	10.55	10.67	10.54
	DS2	2.327	2.343	2.371	10.60	10.72	10.50
	DS3	2.323	2.340	2.368	10.77	10.90	
	Average	2.325	2.342	2.370	10.64	10.76	10.52
HR	HR1	2.275	2.328	2.291	13.28	13.52	14.15
	HR2	2.273	2.319	2.285	13.30	13.50	13.78
	HR3	2.268	2.327		13.98	14.25	
	Average	2.272	2.325	2.288	13.52	13.76	13.96
MO	MO1	2.107	2.151	2.138	19.29	19.39	19.41
	MO2	2.084	2.141	2.125	19.92	20.10	20.62
	MO3	2.086	2.140		19.96	20.17	
	Average	2.093	2.144	2.131	19.72	19.89	20.02
KL	KL1	1.713	1.710	1.727	31.50	31.49	27.71
	KL2	1.713	1.717	1.747	31.71	31.79	28.59
	KL3	1,707	1.695		32.59	32.42	
	Average	1.711	1.707	1.737	31.22	31.90	28.15
BT	BT1	1.373	1.392	1.454	49.14	49.26	43.56

	BT2	1.372	1.387	1.409	49.09	49.09	44.39
	BT3	1.381	1.401		48.83	49.03	
	Average	1.376	1.94	1.452	49.02	49.13	43.98
Metals	Aluminum 1	2.655	2.680	2.663			
	Aluminum 2	2.790	2.802	2.781	-	-	-
	Brass 1	8.441	8.488	8.453			
	Brass 2	8.459	8.485	8.405			
	Stainless	7.867	7.870	7.882			

Overall, there was a high degree of consistency among the bulk dry densities as obtained by the four methods (Table 3). Both the buoyancy method and the pycnometer (dry) method yielded nearly identical porosity readings for every rock. However, for AD with extremely low porosity, the porosities by porosimetry were bigger than those of the other two methods; for BT with very large porosity, the porosities were smaller (Table 3). The measurement precision of the injected mercury quantities, which are roughly 0.03 cc, may be the reason for the discrepancy for AD.

However, it is possible that the high pressure used for the mercury injection deforms the soft rock specimen and reduces its pore volume, which is the cause of the lower porosity result for BT. The bulk dry density and porosity of the eight rocks have a very good overall connection, as seen in Figure 4, with the bulk dry density rising as the porosity falls.

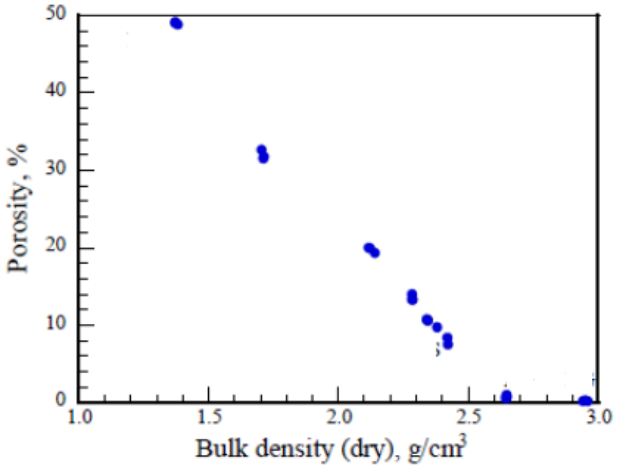

Figure 4. Porosity and bulk dry density as determined by the buoyancy method are related.

CONCLUSIONS

There are numerous methods for measuring the bulk density and porosity of rocks that are used in the geoscience and geoengineering domains. We conducted an experimental comparison research in which various measuring techniques (caliper, buoyancy, helium-displacement pycnometer, and mercury intrusion porosimetry) were used for the same rock specimens in order to guarantee the data quality and analyze its quality.
As test materials, we gathered samples of eight different kinds of rock. The eight rocks had porosities that ranged widely, from roughly 0.3% to 50%.

Thus, it can be concluded that the rock samples that were gathered are suitable for this kind of comparative study of various measuring methods. Consequently, the bulk dry density and porosity results from the caliper, buoyancy, and pycnometer approaches were nearly identical. In particular, it appears that the dry specimens are superior to the wet ones for the helium-displacement pycnometer measurement. However, the porosimetry showed some errors for the very low-porosity rock samples, most likely because of the inaccuracy of the mercury intrusion volume measurement, and underestimated porosity values in the case of very high-porosity rock (i.e., soft rock), most likely because the specimen deformed under intrusion pressure. One significant benefit of the porosimetry approach is its capacity to ascertain the distribution of pore sizes.

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