

A Practical Technique for Quantifying Drainage Porosity

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Abstract

Obtaining accurate drainage or effective porosity values has historically been difficult and time consuming, both in the field and laboratory. With the increasing use of free product mobility models, obtaining these parameters is a fundamental part of subsurface investigation. Existing laboratory methods are of limited accuracy or long duration. Modification of a centrifugal technique for measuring drainage porosity results in a practical method for quantifying effective porosity of both coarse and fine-grained sediments. Modifications include use of undisturbed core material, use of site field waters and/or NAPL's, and application of appropriate drainage forces. Results obtained correlate well with published laboratory and field data. This paper describes overall procedure including the laboratory technique for measuring drainage or effective porosity.

Introduction

Effective (drainage) porosity is often a critical parameter in the development of free product mobility and subsurface conceptual models. Obtaining accurate drainage or effective porosity values has historically been difficult and time consuming both in the field and laboratory.

Effective Porosity, n_e , is the porosity available for fluid flow (Peyton et al (1986), Fetter (1988). Peyton et al (1986) also suggests that at least for sediments, effective porosity is the same as interconnected or total porosity. This neglects the phenomena of dead-end pores or water that is immovable due to the effects of surface tension, adsorption, or wettability factors. Effective porosity is better defined as the part of the pore volume where the water can circulate. In naturally occurring porous materials such as sediments or subsurface soils, capillary, gravitational, and molecular forces govern water flow and effective porosity can be approximated by the specific yield or drainage porosity. Drainage porosity is defined as the ratio of the volume of water drained by gravity from a saturated soil or rock sample to the total volume of the sample.

For development of conceptual models describing hydrocarbon impacted sites effective porosity is better described in terms of pore fluid displacement rather than the percentage of the volume of fluid occupied pore spaces. The pore volume occupied by circulating pore fluid is smaller than total pore space and therefore the effective porosity is always smaller than the total porosity.

$$\text{Drainage Porosity or } n_e = \frac{V_{mob}}{V_t} = \frac{V_{mob}}{V_t + V_{mob} + V_{imm}}$$

Where:

V_{mob} = volume of pores available for fluid flow or circulation

V_t = volume of the solid phase (soil)

V_{imm} = volume of pores containing immobile water and dead-end pores unavailable for fluid flow

A soil parameter closely related to effective porosity is field capacity or specific retention (also called irreducible volumetric water content or residual water content). Specific Retention is defined as the ratio of the volume of water a soil or rock can retain against gravity drainage to the total volume of the sample (Meinzer, 1923). These relationships can be expressed as:

$$n_t = \frac{V_{mob} + V_{imm}}{V_t} \quad \text{and} \quad \theta_r = \frac{V_{imm}}{V_t}$$

Where:

n_t = total porosity

θ_r = field capacity

Effective porosity is related to the total porosity and the field capacity by the following equation:

$$n_e = n_t - \theta_r$$

The centrifuge moisture equivalent as determined by ASTM method D 425 approximates the water holding capacity (field capacity or specific retention) and when combined with bulk density can be used to calculate an approximate specific retention and specific yield (American Society for Testing and Materials, 1996). As shown from the above equation, effective or drainage porosity is determined by measuring total porosity and specific retention. Additional modifications are made to method ASTM D 425 to provide an even closer approximation of effective porosity. This paper describes a practical overall procedure including the laboratory technique for measuring drainage or effective porosity.

Method

There are several techniques used to determine drainage or effective porosity including field methods, laboratory methods, and estimations from other types of data. Every technique has drawbacks. The easy tests or methods are qualitative and the quantitative tests are expensive and time consuming.

The field methods are often preferred over laboratory methods because they may be more representative of macro scale or average properties in the subsurface. Some of the more popular or common field methods are the use of tracer studies and field pumping combined with well logging and/or sampling. There are other methods in use although they are not as popular such as tensiometer installation or electrical resistivity. What most of these methods share in common is that they are often tedious, time consuming, and expensive.

While field methods are often preferred over the laboratory because they may be more representative of bulk or average properties, the laboratory more than makes up for this by providing detailed study and controlled conditions. The tests available to measure effective porosity in the laboratory include bromide breakthrough method, soil column drainage studies, and nuclear magnetic resonance (NMR). Bromide breakthrough and soil column studies are lithology dependent, of limited accuracy, and long duration; they may take up to several months to complete if a low permeability material is encountered. NMR is a fairly rapid technique but is moderately expensive and is limited to soils not containing iron particles.

The ideal method for determining drainage or effective porosity should be a laboratory test that is rapid, accurate, and inexpensive. *ASTM D 425 - 01 Standard Test Method for Centrifuge Moisture Equivalent of Soils* (American Society for Testing and Materials, 1996) is used to provide a starting point for the methodology and is chosen because it is relatively simple, has widespread usage, and the method designated 1000 X Force of Gravity when applied for one hour is a conservative value for driving a sample to residual moisture or saturation. Method ASTM D 425 is a centrifugal method and modifications made to the technique result in a practical method for quantifying effective porosity of both coarse and fine-grained sediments.

Modifications to Method ASTM D 425

Although method ASTM D 425 provides a convenient starting point for quantifying drainage (effective) porosity, the method was originally designed for disturbed specimens of coarse-grained soils having low plasticity (American Society for Testing and Materials, 1996). The use of disturbed core samples or specimens limits the ability of the method to provide the most representative values of drainage porosity because the porosity is altered by disturbance. These restrictions mean that the method can inherently provide at best only a fair representation of drainage porosity. Conceptual models used today to evaluate product recovery, NAPL mobility, and fate and transport require data that provides the most accurate and representative characteristics of the parameters being measured. To this end the major advancement in the method is the use of undisturbed core or soil specimens for analysis. This requires a laboratory experienced with the handling of unconsolidated soils and sediments. Other modifications may consist of adjusting the centrifugal displacement force to site-specific requirements or increasing centrifuge run times to account for fine-grained sediments. In order to provide accurate and representative values of drainage (effective) porosity, the following modifications are made to method ASTM D 425:

- 1.2 The test method uses undisturbed specimens of rock or soil.
- 4.1 Residual saturation determination is conducted on a native-state (undisturbed) sample by centrifuging for one hour at a force equal to 1000 times that of gravity at a controlled temperature of $20 \pm 1^\circ\text{C}$. Fluids produced are monitored for mobility evaluation and material balance calculations.
- 5.2 When water and NAPL are present in a sample, the centrifuge moisture equivalent approximates conservative residual saturations for water and NAPL. If NAPL is present, it may be removed and the test conducted on a fully water saturated sample.
- 6.1-6.4 Beckman type PIR 16.5 rotor and standard rock (soil) core buckets (centrifuge cups) are used for centrifuging undisturbed samples. A 200 or 325 mesh stainless steel screen may be substituted for filter paper.
- 6.6-6.10 The samples are tested in undisturbed condition. Dean-Stark extraction method (API RP40) is used to determine residual saturations as a check on material balance calculations.
- 7.1-7.2 The samples are tested in undisturbed condition. A 1-1/2" dia. x 2" long sample is used. If only small diameter core is available for analyses, the use of one-inch diameter samples may be substituted.
- 8.1 The native-state (undisturbed) samples are vacuum and or hydrostatic pressurized overnight to 100% saturation. Following saturation the sample is placed in the centrifuge cup for centrifuging.
- 8.4 Immediately after centrifuging, the volume or mass of fluids produced is recorded and the sample is weighed and placed in the Dean-Stark extraction vessel. Following Dean-Stark extraction, dry bulk density and total porosity are determined.
- 9.1 The test may be performed on only one sample due to core or material availability constraints.
- 10.1.2 Post-centrifuging residual saturations and pre-centrifuging initial saturations may be reported as pore fluid saturations, percent pore volume.

Laboratory Experimental – Determine Drainage Porosity

Approximating effective porosity through the measurement of drainage porosity has the advantage of being rapid and inexpensive. Determination of specific retention from the laboratory measurement steps can often be completed in a few days. The actual laboratory drainage portion of the test is usually only one hour or less in duration. The technical procedure consists of five basic steps:

1. Obtain undisturbed core samples.
2. Obtain (cut and package) undisturbed sub-samples from the core.
3. Saturate samples with water.
4. Use centrifuge technique to desaturate sample.
5. Determine sample properties.

Obtain undisturbed core

The process begins with core samples taken in the field. Core study and analyses requires proper handling of the core with the goal of providing representative undisturbed material. As material from the shallow subsurface is most often unconsolidated material, proper handling is not only difficult, but also critical. Fortunately, there are advanced techniques for the handling of soft, unconsolidated sediments and selection of the proper core handling facility and geotechnical laboratory should be based on this factor. It is not within the scope of this paper to provide core handling and preservation methods as these may be found by contacting drilling professionals, core analysis laboratories or in other publications. After coring, the cores are removed from the sampler, labeled, organized for the site geologist and preserved. The core is then transported to the laboratory for processing, sample selection and analysis.

Obtain (cut and package) undisturbed sub-samples from the core

Soft-sediment sampling techniques are used to obtain samples from the core. If soft-sediment sampling techniques are not applicable to the specific material being analyzed, then cryogenic methods (freezing the core with liquid nitrogen or dry ice and cutting with diamond segmented core bits) may be necessary to obtain representative undisturbed samples. Following cutting and/or sub-sampling from the core, a package consisting of a flexible Teflon jacket with stainless steel end screens is applied to each sample.

Saturate samples with site water (or NAPL)

The samples are vacuum saturated with 0.45um filtered site or field water. To ensure complete saturation of fine-grained sediments, the samples may hydrostatically pressurized for a period of 16 hours. For evaluating specific retention of hydrocarbons, the samples may be saturated with site-specific NAPL.

Use centrifuge technique to desaturate sample

The centrifuge technique consists in rotating a core at a velocity equal to 1000 times the force of gravity for one hour. In the drainage process, the fluid(s) (water and/or NAPL) is forced out of the core by rotation. Fluid production or saturation in the core is measured at the completion of the run. A Beckman© Rock/Core Ultracentrifuge is the preferred method for centrifugal desaturating core samples and was used for this study. The Beckman ultracentrifuge is specially equipped with a viewing port in the chamber door and a strobe light assembly beneath the rotor chamber. A strobe control unit is used to “stop” a bucket directly under the view port so rotor buckets can be visually observed during centrifugation for accurate measurements of liquid volume displaced from the saturated samples. Centrifugal force may be increased or decreased depending upon site-specific requirements and model goals.

Determine sample properties

Immediately after centrifuging, the samples are removed from the centrifuge cups, weighed, and extracted with toluene (Dean-Stark method). Following Dean-Stark extraction, the samples are dried to stable weight and sample properties (total porosity, dry bulk density) determined by Archimedes or Boyles Law method. Drainage (effective porosity) is calculated from material balance and pore fluid measurements.

Comparison of Results

Several studies of effective porosity are available in published literature. This paper uses the widely accepted source of McWorter and Sunada (1977) for total and effective porosity values (Table 1) and data from Johnson (1967) for Specific Yield values (Table 2) for comparison. Laboratory values determined in this study are from 60 samples and results are listed in Table 3. Review of the published values for effective porosity demonstrates a wide range of values for each lithology type measured. The values obtained from this study show a narrower range for each lithology type measured. Arithmetic means from the laboratory measurements of this study are also lower than the arithmetic means for the published values for each lithology type measured.

Conclusions

Modifications developed for an accepted analytical method have resulted in a practical method that is rapid and simple. Results obtained using this technique correlate well with published laboratory and field data. However the narrower range in values and lower arithmetic means obtained from this study for each specific lithology demonstrates that a critical parameter such as drainage (effective) porosity should be measured at each site-specific location.

References

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Table 1

Representative Porosity Values

Material	Total Porosity, n_t		Effective Porosity, n_e	
	Range	Arithmetic Mean	Range	Arithmetic Mean
Sedimentary material				
Sandstone (fine)	N/A	N/A	0.02 - 0.40	0.21
Sandstone (medium)	0.14 - 0.49	0.34	0.12 - 0.41	0.27
Siltstone	0.21 - 0.41	0.35	0.01 - 0.33	0.12
Sand (fine)	0.25 - 0.53	0.43	0.01 - 0.46	0.33
Sand (medium)	-	-	0.16 - 0.46	0.32
Sand (coarse)	0.31 - 0.46	0.39	0.18 - 0.43	0.30
Gravel (fine)	0.25 - 0.38	0.34	0.13 - 0.40	0.28
Gravel (medium)	-	-	0.17 - 0.44	0.24
Gravel (coarse)	0.24 - 0.36	0.28	0.13 - 0.25	0.21
Silt	0.34 - 0.51	0.45	0.01 - 0.39	0.20
Clay	0.34 - 0.57	0.42	0.01 - 0.18	0.06
Limestone	0.07 - 0.56	0.30	~0 - 0.36	0.14
Wind-laid material				
Loess	N/A	N/A	0.14 - 0.22	0.18
Eolian sand	N/A	N/A	0.32 - 0.47	0.38
Tuff	N/A	N/A	0.02 - 0.47	0.21
Igneous rock				
Weathered granite	0.34 - 0.57	0.45	N/A	N/A
Weathered gabbro	0.42 - 0.45	0.43	N/A	N/A
Basalt	0.03 - 0.35	0.17	N/A	N/A
Metamorphic rock				
Schist	0.04 - 0.49	0.38	0.22 - 0.33	0.26

Source: McWorter and Sunada (1977)

N/A = Data Not Available

Table 2

Specific Yields in Percent

Material	Specific Yield		
	Maximum	Minimum	Average
Clay	5	0	2
Sandy clay	12	3	7
Silt	19	3	18
Fine sand	28	10	21
Medium sand	32	15	26
Coarse sand	35	20	27
Gravelly sand	35	20	25
Fine gravel	35	21	25
Medium gravel	26	13	23
Coarse gravel	26	12	22

Source: Johnson (1967)

Table 3

Laboratory Determined Values of Drainage Porosity

Material	Drainage Porosity	
	Range	Mean
Silt	4.3 – 29.1	13.9
Fine sand	1.1 – 40.2	18.7
Medium sand	6.7 – 38.5	25.6
Coarse sand	12.1 – 28.2	18.0
Gravelly sand	8.9 – 19.7	14.0

60 samples analyzed