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Variations in Permeability and Porosity of Synthetic Oil Reservoir Rock—Methods of Control

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ABSTRACT

Synthetic rock with predictable porosity and permeability has been prepared from mixtures of sand, cement and water. Three series of mixes were investigated primarily for the relation between porosity and permeability for certain grain sizes and proportions. Synthetic rock prepared of 65 per cent large grains, 27 per cent small grains and 8 per cent Portland cement, gave measurable results ranging in porosity from 22.5 to 40 per cent and in permeability from 0.1 darcies to 6 darcies. This variation in porosity and permeability was caused by varying the amount of blending water. Drainage-cycle relative permeability characteristics of the synthetic rock were similar to those of natural reservoir rock.

INTRODUCTION

The fundamental behavior characteristics of fluids flowing through porous media have been described in the literature. Practical application of these flow characteristics to field conditions is too complicated except where assumptions are overly simplified. The use of dimensionally scaled models to simulate oil reservoirs has been described in the literature.[1-3] These and other papers have presented the theoretical and experimental justification for model design. Others have presented elements of model construction and their operation. In most investigations the porous media have consisted of either unconsolidated sand, glass beads, broken glass or plastic-impregnated granular substances — materials in which the flow behavior is not identical to that in natural reservoir rock.

The relative permeability curves for unconsolidated sands differ from those for consolidated sandstone. The effect of saturation history on relative permeability measurements is discussed by Geffen, *et al.*[4] Wygal[5] has shown quite conclusively that a process of artificial cementation can be used to render unconsolidated packs into synthetic sandstones having properties similar to those of natural rock.

Many theoretical and experimental studies have been made in attempts to determine the structure and properties of unconsolidated sand, the most notable being by Naar and Wygal.[6] Others have theorized and experimented with the fundamental characteristics of reservoir rocks.

This study was conducted to determine if some general relationship could be established between the size of sand grains and the porosity and permeability in consolidated binary packs.

This paper presents the results obtained by changing some of the factors which affect the porosity and permeability of synthetically prepared sandstone. In addition, drainage relative permeability curves are presented.

EXPERIMENTAL PROCEDURE

Mixtures of Portland cement with water and aggregate generally are designed to have certain characteristics, but essentially all are planned to be impervious to water or other liquids. Synthetic sandstone simulating oil reservoir rock, however, must be designed to have a given permeability (sometimes several darcies), a porosity which is primarily the effective porosity but quantitatively similar to natural rock, and other characteristics comparable to reservoir rock, such as wettability, pore geometry, tortuosity, etc.

Unconsolidated ternary mixtures of spheres gave both a theoretically computed and an experimentally observed minimum porosity of about 25 per cent.[7] By using a particle-distribution system, one-size particle packs had reproducible porosities in the reproducible range of 35 to 37 per cent.[6]

For model reservoir studies of the prototype system, a synthetic rock having a porosity of 25 per cent or less and a permeability of 2 darcies was required. The rock had to be uniform and competent enough to handle.

Synthetic sandstone cores were prepared utilizing the technique developed by Wygal.[5] Some slight variations in the procedure were incorporated. The sand was sieved through U. S. Standard sieves. A 18-20 sand denotes that the sand passed the Number

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[1]References given at end of paper.

18 (1 mm) sieve but was retained on the Number 20 (0.84 mm) sieve. The materials were proportioned by weight, blended and then poured through a series of screen wire into a mold. Water of hydration was then added by imbibition, the sample was covered, and allowed to cure for a week.

MATERIALS USED

Portland cement, common river sand and water were used in forming the rock. Both normal tap water and de-ionized water were used, but no appreciable difference was noted in results. After hydration of the cement, de-ionized water was used in all tests requiring water saturation or flow.

PROPORTIONS

It has been both observed and computed[7] that for binary packs of glass spheres the percentage by weight of the larger spheres necessary to produce minimum porosity is 70 to 73 per cent. The mixtures in this study consisted of a ternary pack of large sand grains, small sand grains, and Portland cement. This gave a mixture of two binary packs; one of large and small sand grains and the other of small sand grains and Portland cement grains. The final proportions of large sand grains, small sand grains and cement were 65, 27 and 8 per cent by weight, respectively.

The size of the sand grains should be such that the smaller grains fit within the interstices between the larger grains. For such conditions, the diameter of the large grains should be approximately five to six times that of the smaller grains. The diameter used was the average opening of the passing and retaining sieves. The exact ratio of large-diameter sand grains to small-diameter sand grains was based on a curve of binary mixtures at maximum density prepared by Naar and Wygal.[6] Sand coarser than 2-mm diameter (No. 10 sieve) and finer than 200 sieve was not used.

BLENDING

Whether the mix is blended by hand, by small laboratory blenders or by large commercial machines, the main purpose is to induce random distribution. Fisher presented the theory and practical application of solid-solid blending.[8] Throughout most of the experimentation described in this report, blending was standardized by adding the blending water to the fine sand, mixing thoroughly, adding cement, again mixing thoroughly and then blending the resultant mix with the large sand grains.

POURING

The size of the particles governs the optimum height of fall. Where three sizes of particles are involved, the height of fall is adjusted by trial and error, but is controlled chiefly by the size of the large sand grains. A height of fall of 36 in. was used in these experiments. A thorough investigation of pouring rate was not undertaken, but for the grain sizes and other conditions incident to this study, a pouring rate of 2 to 5 gm/sq cm/min proved satisfactory.

ADDITION OF WATER OF HYDRATION

If water is added to the sand-cement blend and mixed into a plastic mass, the resulting rock matrix might have a porosity range from a trace to 45 per cent. The resulting rock is non-uniformly vugular, with extreme variations in permeability. Water of hydration was not added in this manner, but rather by imbibition. The addition of water by imbibition allows the blend to remain in its original stable or semi-stable position. Water maintained at a head of 1 cm enters at the base of the perforated mold. The imbibition rate varied naturally but was allowed to proceed until the top of the mixture was wetted before the sample was removed from contact with the water.

No attempt was made to investigate the effect, if any, an increase or change in the imbibition rate might have on permeability or other characteristics of the samples prepared.

CURING AND TESTING

The cement samples were allowed to hydrate for one week before being removed from the mold, oven dried, trimmed and tested.

Test procedures were standard: porosity was determined by a combination of weighing, volume measuring, water saturation and use of specific gravity. Permeability to air was measured at a differential pressure of approximately 1½ in. of water.

RESULTS

Three series of mixes were investigated. All mixes had the same proportions of large grain, small grain and cement, and each individual series had the same size sand and cement grains. The relationships between sieve size, series and proportions are shown by Table 1. Each sample was visually examined and then tested by routine methods.

VARIATIONS IN POROSITY AND PERMEABILITY

When the packing technique is maintained constant, the initial moisture content controls the porosity of a sample to a great extent and within definite limits. As the blending-water content decreases, the porosity decreases. And, as the amount of blending water is increased, the porosity approaches a maximum. For any given series the only variable was the amount of blending water.

Eight samples were prepared in Series 3 with the water limited to 1 cc (0.167 per cent by weight).

TABLE 1

Series	Sieve Sizes 1	2	3
Large sand grains (65% of dry mix by weight)	10–12	16–18	18–20
Small sand grains (27% of dry mix by weight)	40–45	70–80	80–100
Cement (8% of dry mix)	170–270	270–325	170–270

TABLE 2

Blending Water		Porosity (Per Cent)		
cc	Per Cent by Weight	Min	Max	Avg
1	0.17	23.7	26.2	25.1
2	0.34	25.6	28.8	27.1
3	0.50	28.7	29.8	29.4
4	0.67	30.2	33.0	31.7

These samples had virtually the same porosity, equal to 25.1 ± 1.4 per cent. A comparison of initial moisture with porosity is shown in Table 2 for a portion of the Number 3 series.

When the amount of blending water was increased above 0.67 per cent, the rate of change in porosity was smaller; 1.65 per cent by weight of blending water produced an average porosity of 40 per cent. There were not enough data at the higher rates of blending water to justify definite conclusions. All other factors being constant, the porosity and permeability can be approximately predetermined by the amount of blending water. Other parameters such as height of fall and pouring rate can affect porosity and permeability.

Fig. 1 shows the relationship of permeability to porosity for several grain-size combinations and amount of blending water. For any given sand-size combination, a small change in porosity caused a large but variable change in permeability. A Series 3 binary pack had approximate values of porosity from 24.5 to 40.5 per cent and permeability values ranging from 0.115 to 5.6 darcies. As the size of the sand grains was increased, the permeability at any value of porosity was materially increased. A Series 1 binary pack of 24 per cent porosity had a permeability greater than 1.6 darcies. This series was not investigated for porosity values higher than 32 per cent.

UNIFORMITY AND REPRODUCIBILITY

Uniformity of the sample is influenced by the initial moisture content, the rate of feed into the particle distributor and the angle of feed. The drier the mix the greater the segregation of the different size particles with a resultant layer effect. Too

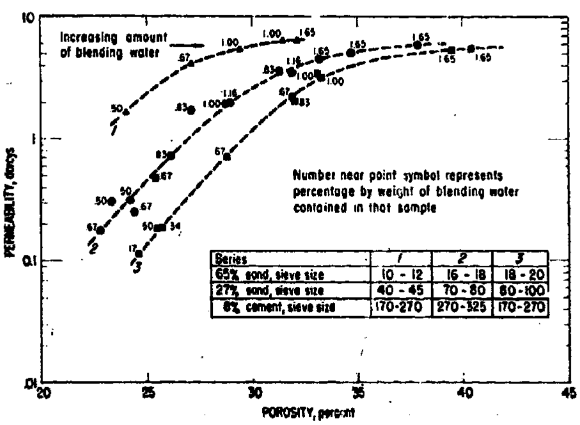

FIG. 1 — RELATIONSHIP OF PERMEABILITY TO POROSITY FOR SEVERAL GRAIN-SIZE COMBINATIONS AND BLENDING WATER CONTENT.

much moisture causes difficulty in pouring, and the mix tends to bridge on the screens. If the rate of pouring is too fast, segregation results; but if the rate is too slow, the packing effect is minimized, resulting in an increase in porosity. If the mix does not strike the distributor vertically and does not fall straight, the resulting sample is not uniform, the fine grains tend to accumulate on one side and the coarse grains to the other side of the container.

The most uniform samples were prepared when the blending water was limited to an amount equal to 0.5 per cent by weight of the total mix. At these conditions the sand was dry enough to be very fluid but too moist to segregate. It was also apparent that the human element was an important factor in both uniformity and reproducibility. Good control of several factors is necessary in obtaining uniform and reproducible results. These factors and their effect are as follows:

1. Grain size—Permeability increases with grain size for a given porosity. To obtain a low-porosity mix, it is necessary to combine two sizes at a grain-diameter ratio of about 6:1.

2. Proportion of different sizes—In using a binary sand mix, an optimum ratio of large grains to small grains of about 3:1 by weight yields minimum porosity.

3. Amount of blending water — Initial moisture for maximum uniformity should be about 0.5 per cent by weight. More water increases both porosity and permeability. Decreasing the amount of water causes segregation of the different size grains and non-uniformity.

4. Amount of cement—Both porosity and permeability decrease with increasing amount of Portland cement. Decreasing the cement content decreases the firmness of the synthetic rock.

5. Rate of pouring through particle distributor — A rate of 2 to 5 gm/sq cm/min proved successful. An optimum rate yields lowest porosity. Higher rates cause separation of particle size and non-uniformity. Lower rates minimizes the packing effect, thus increasing the porosity.

6. Height of fall during packing — There is an optimum height of fall for each grain size and mixture to yield minimum porosity. This height can best be established by trial and error.

RELATIVE PERMEABILITY CHARACTERISTICS

The relative permeability curves shown in Fig. 2 illustrate the similarity of synthetic sandstone to natural rock. Physical characteristics of the cores are shown in Table 3.

Both cores were encased in epoxy plastic, the ends trimmed and grooved for O-rings, and the entire assembly placed between pressure plates. Measurements of the relative permeability to gas (k_{rg}) on both cores were by the stationary-phase method (liquid stationary). The curves for the synthetic rock are displaced to the right of those for Berea sandstone. This displacement is due to the greater irreducible water saturation of the synthetic rock, 43.5 per cent, compared with 26.5

TABLE 3

	Diameter (cm)	Length (cm)	Porosity (per cent)	Permeability (md)
Berea	5.15	10.5	21.8	350
Synthetic	4.94	11.4	24.7	570

per cent irreducible water saturation for the Berea sandstone.

Imbibition curves were not determined either for the synthetic cores or for the Berea cores. Consequently, hysteresis effects are not presented. A comparison of flow properties is made using the drainage curves. A review of the many gas relative-permeability curves for drainage indicates definite trends. If a fairly uniform but slightly anisotropic consolidated sandstone cut parallel to the bedding is assumed as normal, then the following trends are evident at 50 per cent gas saturation: (1) a stratified core cut perpendicular to the bedding has a k_{rg} lower than normal; (2) a poorly consolidated core has a k_{rg} lower than normal; (3) an unconsolidated sand has a k_{rg} much lower than normal; (4) glass spheres give a k_{rg} lower than unconsolidated sand; (5) a capillary tube gives the lowest k_{rg} value.

Pore-size distribution, oil and water wettability and type of cementation, if applicable, can cause variations in the k_{rg} range for each of the above categories.

A glance at Fig. 2 shows that at a gas saturation of 50 per cent the k_{rg} for the synthetic core corresponds almost identically in value to that of Botset's[9] consolidated sand; is higher than for Wygal's[5] consolidated sand; is higher than for the Berea sandstone; and is much higher than for the unconsolidated sand of Muskat, *et al.*[10] Wygal's curve for glass spheres shows a very low value of k_{rg} at 50 per cent gas saturation.[5]

CONCLUSIONS

A general relationship can be seen between the porosity and permeability and the several factors attendant to the preparation of synthetic reservoir rock. Careful control of these factors is necessary in the preparation of synthetic rock having predictable porosity and permeability.

For the drainage cycle, the synthetic sandstone shows flow characteristics similar to consolidated sand. The position of the drainage-cycle curve implies that the flow properties for the synthetic core during imbibition would be similar to consolidated sand.

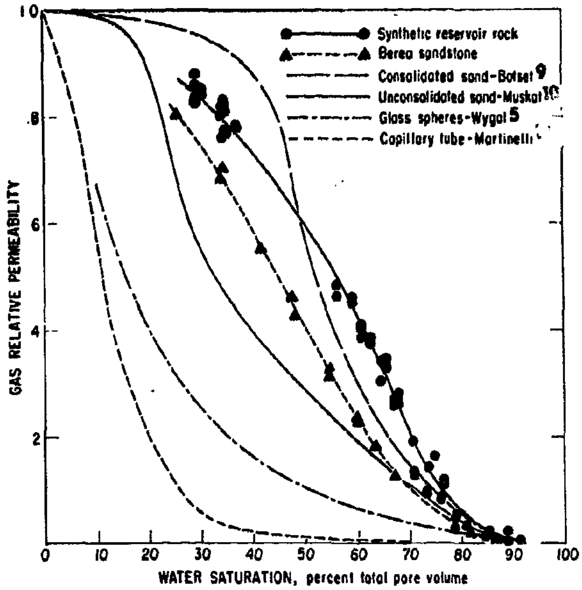

FIG. 2 — GAS RELATIVE PERMEABILITY CURVES, DRAINAGE.

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