Progress Report No. 2

FLUID MECHANICS OF POROUS MEDIA

I. HYDRAULIC CHARACTERISTICS OF POROUS MEDIA

by

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In Progress Report No. 1, to the W-51 Committee, a theory showing how the variables capillary pressure and the air and water permeability are related to saturation was described in some detail. A description of the equipment and methods used to verify the theory was also presented.

During the past year verification of the theory has continued with good success. Some modifications of the air permeability-capillary pressure cell were necessary to obtain reliable data for a wide range of media. Figure 1 shows some experimental data and theoretical curves for three materials. Relative air permeability is plotted on the ordinate and relative capillary pressure on the abscissa. The three materials have different pore-size distributions as indicated by their η values. According to the theory, media having a narrow range of pore sizes would have a large value of η, which would increase without bound for media with a single pore size. Media having a wide range of pore size would have a small value of η approaching 2.0 as a lower limit. The agreement between theory and experimental data is excellent. Other data obtained through the past year provided information for a paper entitled "Critical Capillary Pressure for Minimum Aeration in Soils." The paper was presented before the Western Society of Soil Science Meeting in Corvallis, Oregon; August 30, 1962. The paper discussed the significance of the capillary pressure obtained from the air permeability-capillary pressure measurements when air first became continuous or measurable in the sample. When capillary pressure is converted to elevation above the water table for static conditions, it was shown that for one soil no aeration was possible for a distance of 80 cm above the water table. This critical capillary pressure is an important factor to consider in drainage design.

Critical capillary pressure, permeability and the slope of the capillary pressure-permeability curve are also important hydraulic characteristics of porous media needed for laboratory modeling of field problems. Problems involving flow of fluids in partially saturated soils often cannot be solved except by inferences derived from the performance of models. A necessary condition for similarity in performance of a model and its prototype is that the relationship between relative permeability and relative capillary pressure be the same for both. Relative permeability is the ratio of the permeability at any particular saturation to the permeability when the medium is completely saturated with a given fluid. Relative capillary pressure is the ratio of capillary pressure at any saturation to the critical capillary pressure at which air is continuous throughout the medium. At the present time the selection of a porous medium suitable for a particular model is partly by trial. This circumstance discourages the use of models in many studies for which they would be the most logical analytical tool. A thorough understanding of the way relative permeability is effected by other measurable properties of porous media might eliminate the necessity of selecting a porous medium by trial. If sufficient basic information were available it might be possible to synthesize a laboratory medium suitable for studying any particular problem involving unsaturated flow in soils. The criteria of similitude for flow in partially saturated media have been determined theoretically by Miller and Miller and by several other investigators. Among the several criteria mentioned by them, the most difficult to satisfy is the requirement that the relationship between relative permeability and relative capillary pressure be the same. The problem remaining, is to find media that meet this requirement for particular cases and that meet other requirements for similitude and for stability and flexibility as well. One obvious possibility is sands with various grain size distribution. The range of functional relationships between relative permeability and capillary pressure obtainable with sands, unfortunately, is not that which is most often encountered in soils, regardless of the grain-size distribution of the sand. Soils containing clay and organic matter although they may have a suitable relationship between relative permeability and relative capillary pressure will usually not meet the requirement for similitude with respect to the time scale and the height of capillary rise. The selection of suitable media for use in models, therefore, requires a thorough knowledge of the factors controlling the pore-size distribution in the porous media.

The air permeability-capillary pressure measurements described in this and the previous progress report provides a rapid and simple way in which to study factors affecting the pore-size distribution, critical capillary pressure, and the absolute permeability for use in model studies. The slope η of the relative permeability and relative capillary pressure curve obtainable with sands ranges in value from 8 to 16. Soils on the other hand, which are well aggregated have η values which range from 3 to 6. In some recent tests on a bentonite clay, information was obtained which showed how the structure of the media affects the pore-size distribution. A clay was oven dried and passed through a number 20 sieve. Liquid and air permeability measurements were made as a function of capillary pressure using a light hydrocarbon called soltrol. The results are shown in figure 2, in which η is noted to be 3.6. When the same oven dried clay sample was allowed to absorb a small amount of water before the sample was packed for permeability-capillary pressure measurements, the results were entirely different as also shown in figure 2. By blocking the small pores in the aggregates with water, the flow of oil is forced around the aggregates and thus the porous system acts like a sand as indicated by the η value. It therefore appears possible that by controlling the aggregation of porous materials and by using a non-polar wetting fluid so that the aggregation is not destroyed upon wetting, porous media models may be used in the laboratory to study field problems which involve flow above and below the water table.

Plans for the coming year will include a study of clay and non-polar fluids for use in model studies. The results of such a study can be applied to a model study previously initiated and reported in 1961 to the W-51 Committee entitled "Flow in a Sloping Aquifer as Affected by Hydraulic Properties of Porous Media." This study was curtailed because of insufficient information on the type of media needed to obtain the desired results.

The theoretical analysis of this study showed how the pore-size distribution, height of the capillary fringe, and permeability affected the flow in the aquifer. The problem of showing their effects experimentally by using sands has been very difficult. When the value of η becomes greater than a certain value depending upon the boundary conditions, additional changes in the flow system are not appreciable. The family of curves shown in figure 3 of the above mentioned report shows how the value of η affects the flow system for several different boundary conditions. Since it is not possible to obtain η values in the lower range with sands, regardless of the grain-size distribution, it is necessary to obtain another type of medium for use in the experimental model. It now seems possible by using an aggregated clay material having a predetermined value of η and a hydrocarbon as the wetting fluid, the theory may be verified by the use of this model.

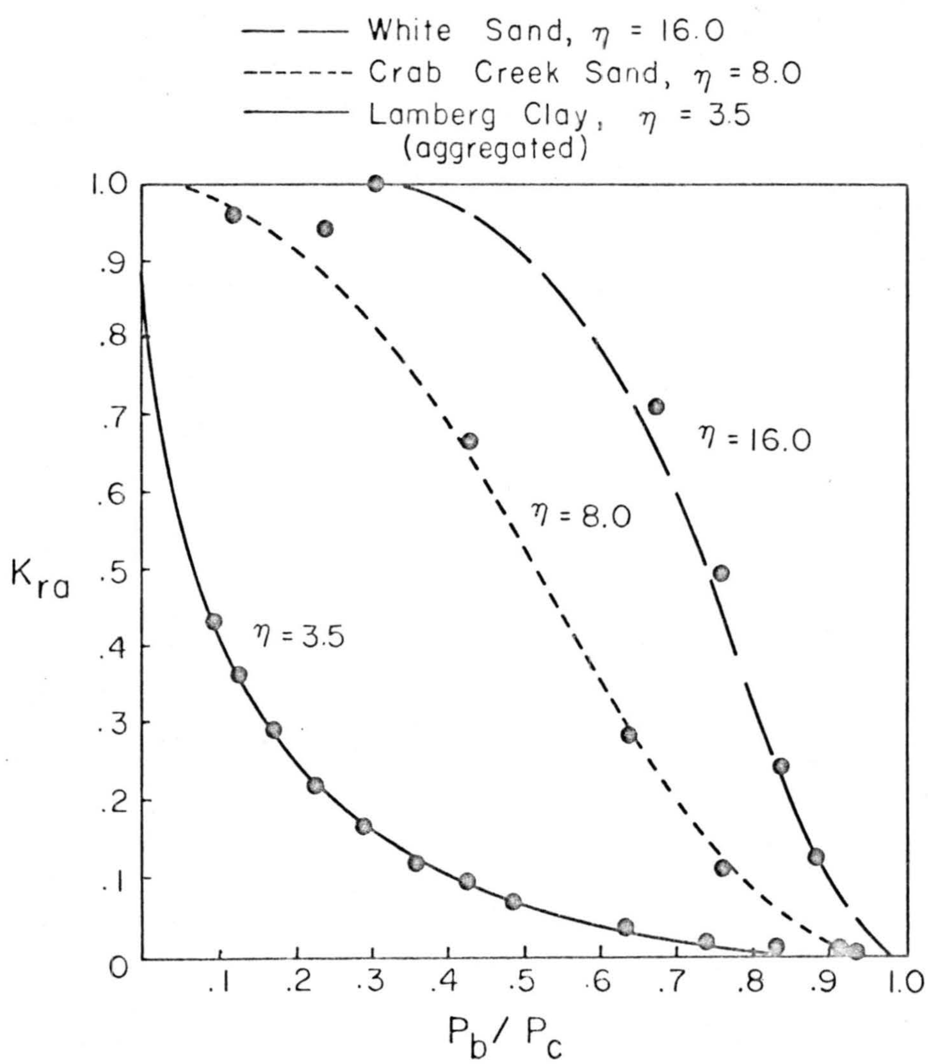

Fig. 1 - Relative air permeability as a function of relative capillary pressure for three porous materials.

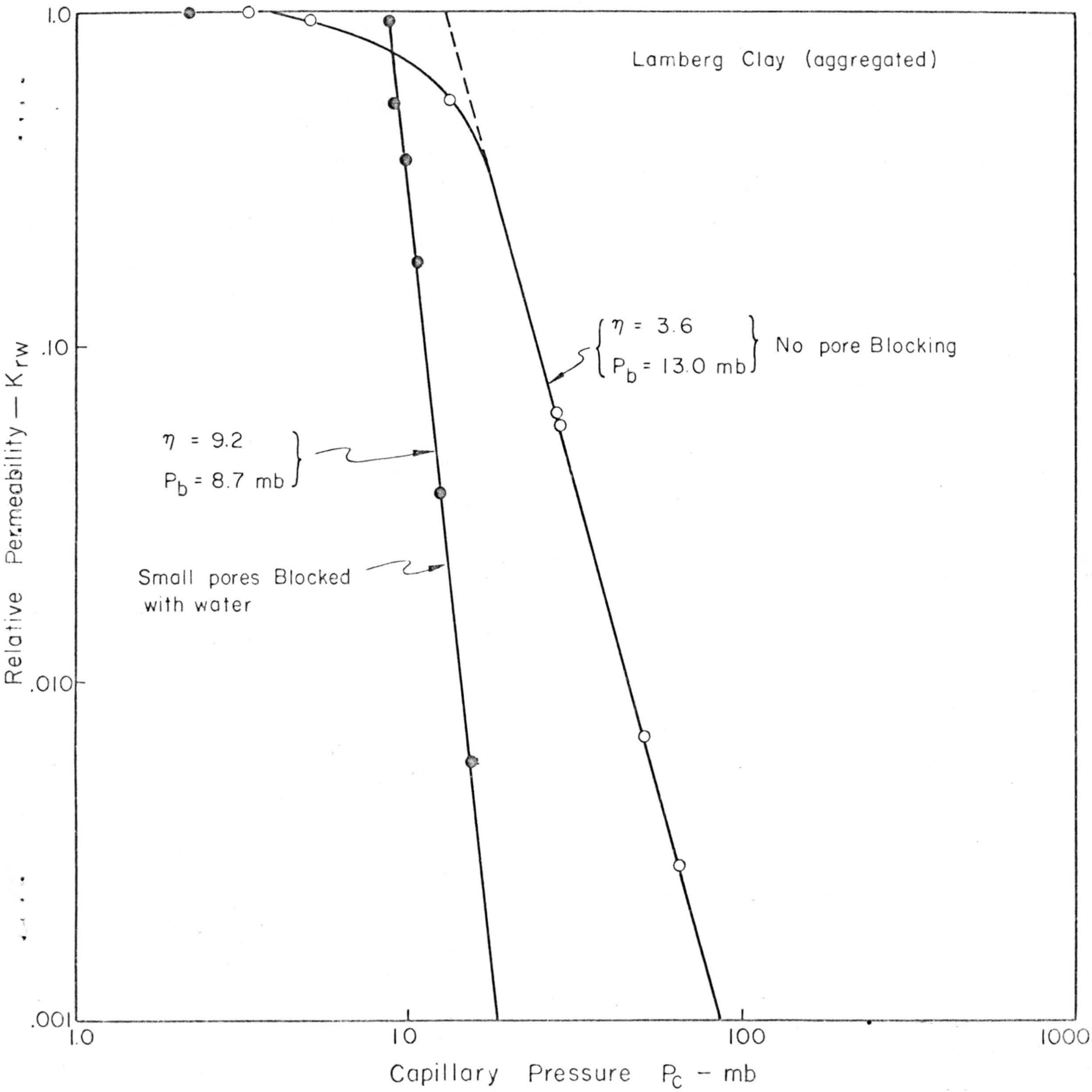

Fig. 2 - Relative liquid permeability as a function of capillary pressure for aggregated Lamberg clay.