Mine Water and The Environment, Vol.11, No. 2, June 1992, pp 11-26
(Formerly International Journal of Mine Water)

RELATIVE PERMEABILITY MEASUREMENTS FOR TWO PHASE FLOW IN UNCONSOLIDATED SANDS

by
S. Abaci and J. S. Edwards, Department of Mining Engineering,
Nottingham University. University Park, Nottingham NG7 2RD
and
B. N. Whittaker, Department of Mining & Mineral Engineering,
Leeds University. Leeds

ABSTRACT

This paper presents the results of laboratory measurements of relative permeability for two phase flow in partially saturated samples of unconsolidated sands. Relative permeabilities for tap water and air, de-aired water and nitrogen were measured using a steady - state technique. Three different sand samples (fine sand, heterogeneous sand and coarse sand) were tested.

1. INTRODUCTION

Much research has been carried out in order to solve problems dealing with the movement or migration of fluids through porous, permeable media. Many researchers have studied the nature of fluid flow and its relationship to their own problems.

Fluid flow through porous, permeable material is a complex transport process. The flow of incompressible single phase fluids through permeable media is governed by Darcy's law which is valid for laminar flow of fluids. A measure of the capacity of a permeable material to transmit fluids is given by a transport coefficient - the permeability of the medium. In Darcy's equation for single phase flow this transport coefficient is called the specific permeability. However, if the permeable medium contains more than one fluid, an effective permeability to each fluid phase must be defined, where the effective permeability of a permeable medium is a measure of the ability of the material to conduct one fluid phase of a multiphase fluid system. In the case of a multiphase fluid system existing in the medium, the ability of each fluid to flow is reduced by the presence of the other fluids in the system. The effective permeability for all fluid phases is less than the specific permeability for single phase flow.

Another important property governing multiphase flow through porous media is the 'relative permeability' which is defined as the ratio of the effective permeability of the porous medium to the specific (absolute) permeability of the material. The relative permeability is a function of the system of the two or more fluids and the porous material and is used to describe quantitatively the simultaneous flow of multifluid phases through a porous medium. The relative permeability is dependent upon the fluid saturation levels, because part of the pore space in the porous medium is occupied by one fluid of the multiphase fluid system, so that flow of another fluid is impeded and reduced.

A number of measurement techniques for the determination of relative permeability of porous media have been developed and are described in the literature. Generally, two kinds of laboratory measurement techniques are used to determine relative permeability:

a) Steady state methods; a fixed ratio of two phases is driven simultaneously at constant rate and pressure through the medium until saturation and differential pressure along the sample become constant,

b) Unsteady - state methods; the quickest laboratory methods in which a gas phase only is injected into the sample, and saturation equilibrium is not attained. This technique involves displacing in - situ fluids by injection of the gas phase.

The steady state method has been used to determine the relative permeability of unconsolidated materials to gas and water in this research. Different grain sizes of sands were chosen as a porous medium and the relative permeability determined. Air and nitrogen were used as gas phases, water and de-aired water for liquid phases.

2. HISTORICAL BACKGROUND

In 1856, Henry Darcy investigated the flow of water through horizontal filter beds by conducting a series of experiments, and determined that the rate of flow of water through a sand column could be described by the following equation :

$$Q = K\ A \frac{dh}{dL} \qquad (1)$$

where Q is the rate of flow of water, K is the coefficient of permeability, A is the cross - sectional area of the sand column and (dh / dL) is the hydraulic gradient. Darcy's law is valid for the test sample when 100 % saturated with water.

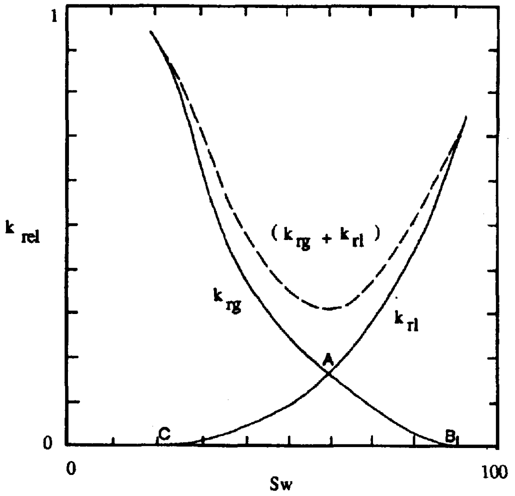

Figure 1. A Typical Example of Relative Permeability Curves [14]

Theoretical aspects and measurement techniques relating to the relative permeability of sedimentary rocks were investigated in the early 1900's [1, 2, 3, 4, 5]. These first investigations were in connection the petroleum industry and were concerned with reservoir rocks and their permeability properties because the relative permeability of the reservoir rock to the each of the fluids flowing through porous rock is important in the prediction of reservoir behaviour. In the 1930's Muskat and Botset [2, 3, 4] investigated the characteristics of the flow of gases through unconsolidated and consolidated porous materials for petroleum reservoir characterisation. Later, Wyckoff and Leverett [5, 6] described the flow of gas - liquid mixtures through unconsolidated sands and determined that the relative permeability curves generally have an " S " shape (Fig.1). Richardson, Hafford and other investigators [7, 8, 9, 10, 11] undertook further experimental studies and developed some laboratory measurement techniques for the flow of two fluids through reservoir rocks.

In recent years there has been considerable interest in permeability testing of materials found in the vicinity of waste disposal sites and the results of research relating to the relative permeability measurement for the study of the migration of typical contaminants have been published [12].

3. THEORETICAL DEFINITION OF RELATIVE PERMEABILITY

Darcy's law modified for single phase flow of incompressible fluids other than water can be expressed as :

$$v = \frac{q}{A} = \frac{k}{\mu}\left(\frac{dh}{dL}\right) \qquad (2)$$

where v is the velocity of fluid flow, μ is the viscosity of the fluid, and q is the volumetric flow rate. Muskat et al (1937), on the assumption that Darcy's law is valid for each flowing fluid when the fluids are a gas and a liquid, showed that the volumetric flow rate q can be written as :

$$q_g = \frac{k k_{rg} A \Delta P_g}{\mu_g L} \qquad (3)$$

$$q_l = \frac{k k_{rl} A \Delta P_l}{\mu_l L} \qquad (4)$$

where the subscript g refers to the gas phase, l to the liquid phase and ΔP denotes values of the pressure drop along the porous medium in the various fluid phases. The value kk_{rg} is the effective permeability of the medium to gas with liquid phase present in the medium, and kk_{rl} is the effective permeability of the medium to the liquid phase. According to these equations, each of the fluid phases is similar to a homogeneous system where the rate of flow is proportional to the differential pressure and effective permeabilities and inversely proportional to the viscosity of the fluid phases. The terms k_{rg} and k_{rl} are called the relative permeability and are given by

$$k_{rg} = \frac{k_g}{k} \qquad (5)$$

$$k_{rl} = \frac{k_l}{k} \qquad (6)$$

Effective and corresponding relative permeabilities are functions of the system of fluids present in the porous medium and the properties of porous media itself, e.g. porosity. Porosity and viscosity are variables that can easily be measured directly or be estimated indirectly. Effective and relative permeability define the flow characteristics of the porous medium when saturated with an immiscible fluid phase. Thus, the relative permeability of a porous medium depends on the saturation, so that measurements of relative permeability require accurate saturation determination [13]. The saturation of the one fluid is given by

$$S = \frac{V_f}{V_p} \qquad (7)$$

where S is the saturation, V_f is the volume of fluid and V_p is the total pore volume. Saturation is a term used to describe the relative volumes of fluids in a porous medium; the total saturation value for two fluids is equal to 1 when saturation is changing with time. Saturation and permeability are both effected by the porosity of materials.

4. EXPERIMENTAL TECHNIQUE

Steady - state methods for determining relative permeabilities have the widest application, resulting from the simplicity of the mathematical analysis, based on Darcy's law, and the fact that saturation can be measured directly. The steady - state methods give reliable relative permeability data for two or three fluids which are injected simultaneously at constant rates and pressure. Because of these reasons, a steady - state technique was utilized in this research. A standardized procedure consists of determining the following ;

1. The rate of flow of liquid;
2. The rate of flow of gas;

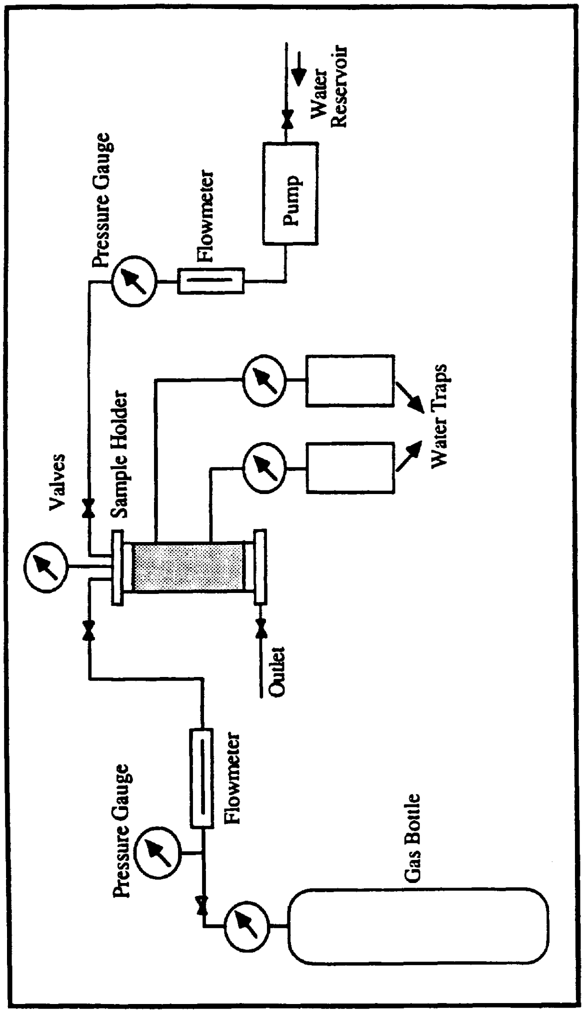

Figure 2. Schematic Diagram of Experimental Apparatus

3. The pressure gradient;
4. Liquid saturation of the sample.

The rate of flow of fluids (liquid and gas) was determined using flowmeters and the differential pressure along the porous test material was measured by pressure gauges connected across the sample holder. Saturation levels of materials can be measured by several methods. In this project, saturation was calculated by weighing the test sample before the test and after the system had reached steady condition. Saturation values are independent of fluid densities [14].

5. EXPERIMENTAL PROCEDURE

The procedure for the measurement of relative permeability consisted of injection, at a steady rate, of a mixture of gas and liquid into a vertical column of unconsolidated sand. Effective permeability and liquid (water) saturation were determined after steady conditions had been reached.

The schematic diagram of the test apparatus is shown in figure 2. The sample holder, which is known as a permeameter cell, was first filled with air - free water. Subsequently, the cell was filled with a known weight of the selected grain size of sand, which was saturated with water, through a funnel filled with water. Each part of the sand volume was carefully tamped by a rod. The water, which was deaerated, was passed downward through the sand column to dissolve any trapped air in the sand pack. The porosity of the sand column was determined from the known volume of the cell, the weight of the test sample and its specific gravity. The laboratory procedure commenced by applying one fluid phase (water) to the sample and adjusting the flow rate of this phase through the sample until a determined pressure was obtained. The determination and adjustment of the flow rates of each of the fluids was made by flowmeters, regulators and pressure gauges connected to the permeameter cell. Injection of a second phase, which was gas, started at a low rate and flow of the first phase was reduced slightly. This procedure maintained the differential pressure across the system at a constant level. After the system reached an equilibrium condition, the two flow rates and pressure differential were recorded and the percentage saturation of each fluid phase within the sample was determined by weighing. The differential pressure along the sample was measured by pressure gauges connected across the cell.

After the first readings, the rate of flow of the first phase was decreased slightly and the flow rate of gas was increased simultaneously to maintain the pressure differential across the sample at its previous value. When the system reached a constant level, flow rates and pressure differential were recorded.

The relative permeability tests were conducted on various grain sizes of sands ranging from silt size to coarse size. Different grain sizes of sand, which were chosen as a porous medium, were mixed at a definite percentage by weight. The experiments were conducted on three different mesh sands; 100-200 mesh sand, (porosity 40 percent), heterogeneous sands, (porosity 33 percent) and 7 - 20 mesh sand, (porosity 35 percent).

6. RESULTS AND DISCUSSION

Relative permeability measurements for unconsolidated sands were made at various rates of flow, degrees of saturation and pressures. Air and tap water were first utilized as multiphase fluids,and secondly, nitrogen and de - aired water were used for the same test sample. In each experiment the flow was continued at a constant rate until the pressure differential along the sand column became constant, at which time a series of reading were taken and the relative permeability value to each phase calculated. Results of the two experimental series were plotted in graphs. These graphs are shown in figures 3 - 8. Experimental results have been plotted using percent saturation of the sand versus relative permeability values. It is seen that the curves for gas and liquid phases have different shapes.The shape of the water relative permeability curve indicates that the relative permeability to water is sharply decreasing when there is a small reduction in water saturation. This rapid decline is due to occupation of the larger pores or flow paths by the gas phase. The gas phase in a porous system flows through the larger pores, and the presence of the gas in the medium interferes considerably with the flow of fluid. These curves also indicate that the relative permeability of the gas phase approaches unity whereas that for the liquid phase it is restricted. The value of the gas phase relative permeability is also greater than the liquid phase relative permeability at the same saturation. These, again, mean that the liquid phase occupies the smaller pores and has little influence on the flow of the gas phase.

Pore structure and pore - size distribution affect the relative permeability of the permeable media.The graphs show that the endpoint of the liquid phase curves

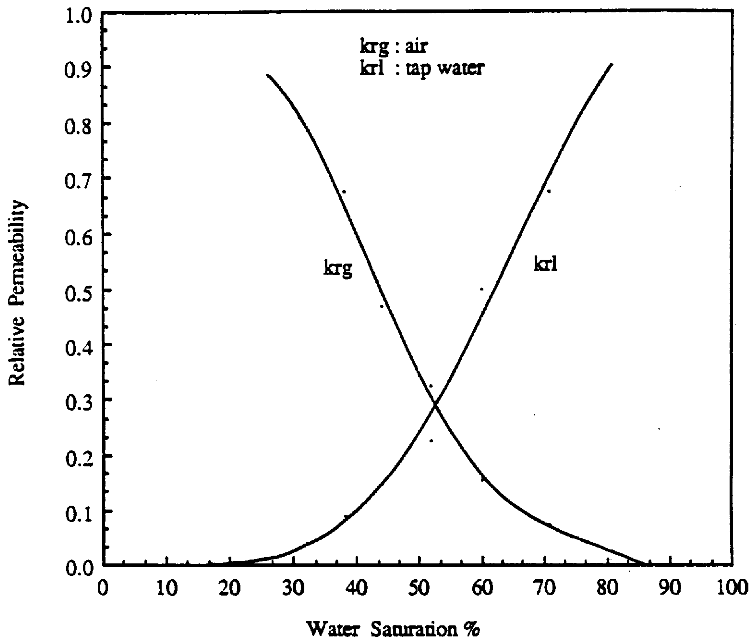

Figure 3. Relative Permeability - Saturation Relation for 100 - 200 Mesh Sand Using Air and Tap Water (Porosity 40 %)

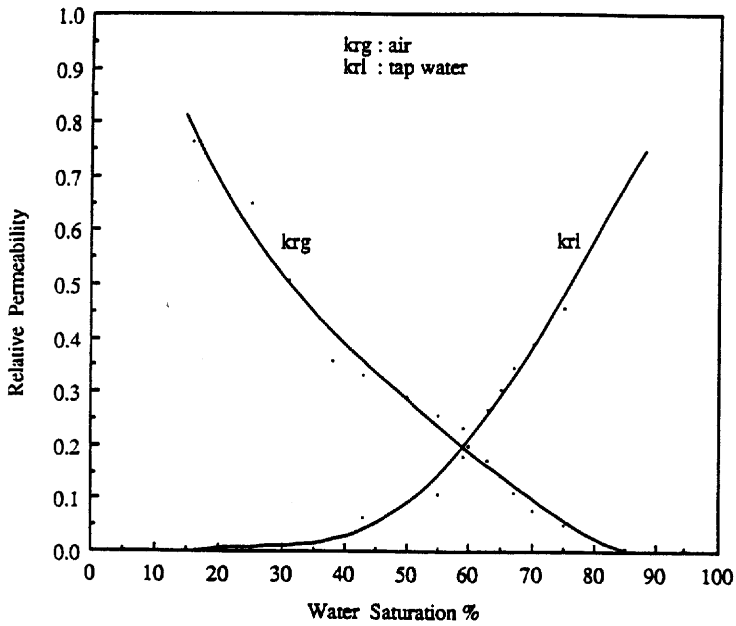

Figure 4. Relative Permeability - Saturation Relation for Heterogeneous Sand Using Air and Tap Water (Porosity 33 %)

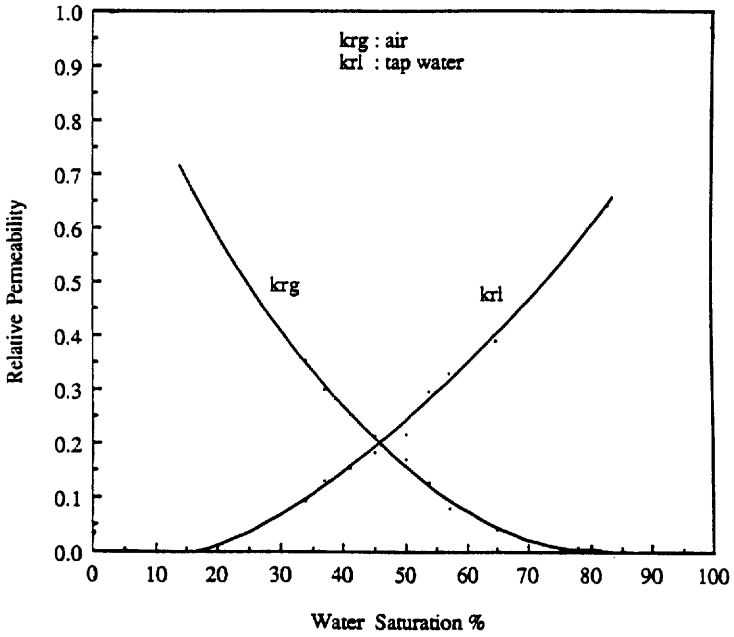

Figure 5. Relative Permeability - Saturation Relation for 7 - 20 Mesh Sand Using Air and Tap Water (Porosity 35 %)

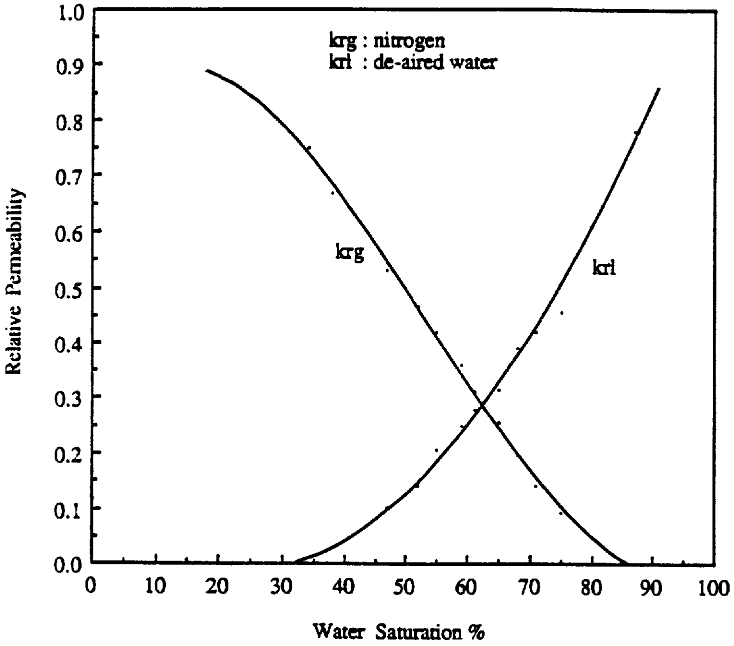

Figure 6. Relative Permeability - Saturation Relation for 100 - 200 Mesh Sand Using Nitrogen and De-aired Water (porosity 40 %)

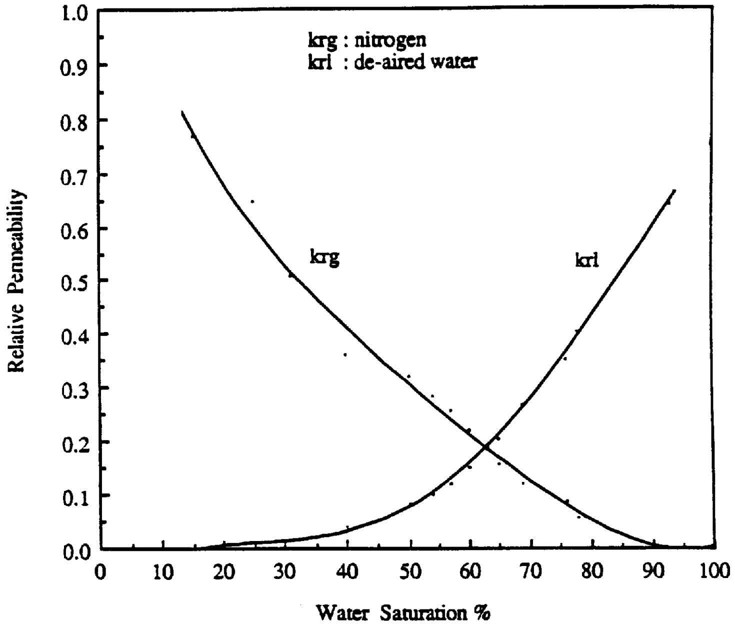

Figure 7. Relative Permeability - Saturation Relation for Heterogeneous Sand Using Nitrogen and De-aired Water (Porosity 33 %)

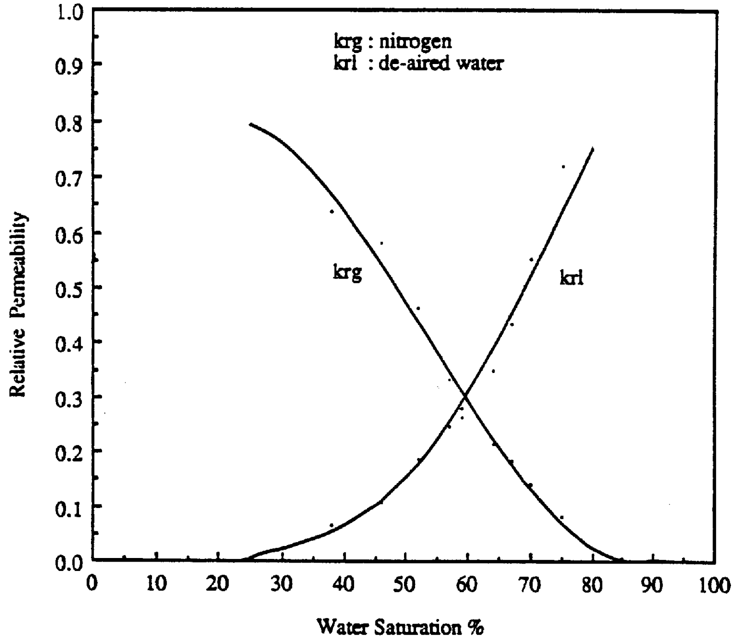

Figure 8. Relative Permeability - Saturation Relation for 7 - 20 Mesh Sand Using Nitrogen and De-aired Water (Porosity 35 %)

decrease, corresponding to an increment in saturation of the gas phase, as the proportion of the large pores increases.

7. CONCLUSION

The two phase flow of gases and liquids is becoming an increasingly important area of study in the context of the movement of contaminants in near - surface unconsolidated sediments. Computer - modelling techniques are being developed for the study of such problems but the behaviour of fluids in permeable media is strongly dependent on the values of permeability assigned.

In this research, the two - phase flow of a variety of combinations of liquids and gases is being investigated in order to provide data for modelling studies. An experimental technique has been developed for the measurement of relative permeability under steady - state dynamic conditions. In this paper the results of initial investigations are presented.

8. REFERENCES

1. **Chalmers, J., Taliaferro, D.B., Rawlins, E.L and Okla, B., 1932.** Flow of Air and Gas Through Porous Media. Trans. Am. Inst. Min. Met. Eng. (Petroleum Develop. and Techn.). Vol.98 : 375 - 400.

2. **Muskat, M., 1937.** The Flow of Homogeneous Fluids Through Porous Media. McGraw - Hill. New York.

3. **Botset, H.,G.,** 1940. Flow of Gas - Liquid Mixtures Through Consolidated Sand. Trans., AIME, 136,91.

4. **Muskat, M.,** 1949. Physical Principles of Oil Production, McGraw - Hill Book Co. Inc., New York.

5. **Wyckoff, R.D.,and Botset, H.G., 1936.** The Flow of Gas - Liquid Mixtures Through Unconsolidated Sands. Physics, Vol. 7 : 325 - 345.

6. **Leverett, M.C., 1939.** Flow of Oil - Water Mixtures Through Unconsolidated Sands. Trans. of AIME. Vol. 132 :149 - 171.

7. **Osoba, J.S., Richardson, J.G., Kerver,J.K., Hafford, J.A. and Blair, P.M.,1951.** Laboratory Measurements of Relative Permeability. Trans. of the AIME. Petroleum Branch. Vol.192 : 47 - 46.

8. **Geffen, T.M., Qwens, W.W., Parrish, D.R. and Morse, R.A., 1951.** Experimental Investigation of Factors Affecting Laboratory Relative Permeability Measurements. Trans. of AIME. Petroleum Branch. Vol. 192: 99 - 110.

9. **Caudle, B.H., Slobod, R.L. and Brownscombe, E.R., 1951.** Further Developments in the Laboratory Determination of Relative Permeability. Trans. of AIME. Petroleum Branch . Vol. 192: 145 - 150.

10. **Corey, A.T., 1957.** Measurement of Water and Air Permeability in Unsaturated Soil. Soil Science Society of America, Proceedings. Vol. 21 : 7 - 11.

11. **Corey, A. T., 1954.** The Interrelation Between Gas and Oil Relative Permeabilities, Producers Monthly, Vol. 19 (1) : 38 - 41.

12. **Faust, C. R., 1985.** Transport of Immiscible Fluids Within and Below the Unsaturated Zone: A numerical Model. Water Resources Research, 21 (4): 587 - 596.

13. **Honarpour, M. and Mahmood, S. M., 1988.**Relative Permeability Measure-ments: An Overview, Soc.of Pet. Eng.(SPE), Journal of Petroleum Technology, Today Series, 963 - 966.

14. **Honarpour, M., Koederitz, L. and Harvey, A.H.,** 1986. Relative Permeability of Petroleum Reservoirs, CRC Press, Inc. Boca Raton, Florida.