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EVALUATION OF PREDICTIVE METHODS OF HYDAULIC CONDUCTIVITY BASED ON POROUS MEDIA PROPERTIES

by

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ABSTRACT

In the first part of this thesis, five predictive methods of evaluating unsaturated hydraulic conductivity based on porous media properties available in published literature, were compared within each other and with the experimental data. The methods selected for this study were Childs and Collis-George, Marshall, Millington and Quirk, Brooks and Corey, and Kunze _et al_. The pore size distribution or capillary pressure saturation curves for fourteen samples of porous media with a wide range of pore size distribution were used as the data. The results showed the superiority of the Brooks and Corey method over the other methods for most of the samples. The Millington and Quirk method occupied the second place among the merit list of these methods.

The second part of this thesis consists of a stepwise regression analysis for predicting hydraulic conductivity from various physical properties of porous media. The physical properties used in the regression analysis are texture, bulk density, porosity, air-entry pressure, and pore size distribution index. The data used for this purpose were obtained in the laboratory during this study as well as from the published literature. The resulting regression equation has a squared correlation coefficient (R^2) value of 97.75% which is significant for predicting hydraulic conductivity (K) values that are close to the experimentally determined ones.

CHAPTER 1

INTRODUCTION

The transmission of fluids through porous media has wide spread relevance to petroleum engineering, geological and agricultural problems. The laws of flow and solutions of particular problems have received considerable attention. The one physical property which enters into a flow problem is permeability, and must be known if a complete solution of behavior of fluids in media is to be obtained. In principle, a measure of permeability is the rate of flow of fluid in a column of material between planes of measured separation and hydraulic potential. But the constant of porportionality known as 'Hydraulic Conductivity' (K) in Darcy's flow equation is a function of both viscous fluid and porous medium. Fluid variables are viscosity and density, and the porous medium is constituted of grains of material and pore spaces.

Unsaturated flow processes are in general complicated and difficult to describe quantatively, since they often entail changes in the state of porous medium and fluid content during flow. Such changes involve complex relations among the variable fluid content, pressure and conductivity, which may be effected by hysteresis. The formulation and solution of unsaturated flow problems require the use of indirect methods of analysis, based on approximation or numerical techniques.

In recent years, several investigators have explored the possibility of predicting the hydraulic conductivity of porous materials from pore size distribution data. Interest in such predictions is warranted inasmuch as the hyraulic conductivity - fluid content relationship K(θ) is relatively difficult to measure while the pore size distribution is characterized relatively easily by the standard measurement of fluid saturation vs. capillary pressure. Childs and Collis-George (1950), Marshall (1958), Millington and Quirk (1959, 1960, 1961), Brooks and Corey (1964), and Kunze, _et al_. (1968) developed equations for this purpose. These five proposed methodologies will be evaluated in this study. Nielson, _et al_. (1960), Jackson, _et al_. (1965), Green and Corey (1971), and Bruce (1972) have tested such equations against experimental data. Some of these tests have indicated the superiority of the Millington and Quirk method, but the widespread use of conductivity calculations has been discouraged somewhat by conflicting published results.

This study describes (a) the evaluation of different theoretical methods of determining hydraulic conductivity on available data on pore size distribution or capillary pressure - saturation curves from the published literature, and then it recommends the best method based on the results obtained; (b) the correlations of different physical properties of porous media such as texture, bulk density, porosity, bubbling pressure, and pore size distribution with hydraulic conductivity. The five different methods described above for predicting hyraulic conductivity will be compared with each other and with experimental data and the merits and demerits of each method will be discussed. An atempt will also be made to correlate easily measured physical properties of porous media with hyraulic conductivity through multiple regression analysis.

CHAPTER 2

HISTORICAL BACKGROUND

This chapter consists of two sections. In the first section the properties of porous media to be measured and used in this work are defined and discussed. The second section summarizes the results of selected studies made to evaluate hydraulic conductivity theoretically and to relate it with other characteristics of porous media.

2.1. Definitions and Discussion

2.1.a: Permeability

Permeability (k) is a measure of the ease with which fluid passes through a porous material under a potential gradient. Permeability or more properly, "intrinsic permeability", is a property of the porous medium alone and is independent of the density and viscosity of fluid. A common expression for permeability k can be derived from Darcy's Law for a constant density fluid:

$$V_s = - \frac{k\rho g}{\mu} \left(\frac{\delta h}{\delta S}\right) \qquad (2.1a)$$

Hence

$$k = -V_s \frac{\mu}{\rho g} \left(\frac{\delta h}{\delta S}\right)^{-1} \qquad (2.1b)$$

where s = distance in direction of flow and is always positive, (L)

V_s = volume flux across a unit area of porous medium in unit time along flow path s, (L/T)

ρ = density of fluid (M/L^3)

g = acceleration of gravity (L/T^3)

$\frac{\delta h}{\delta S}$ = hydraulic head gradient along S

μ = viscosity of fluid (M/LT)

k = permeability of medium (L^2)

Here the units of permeability are squared length, but the petroleum industry adopts as the unit of permeability the Darcy which is defined by the American Petroleum Institute (API) as follows:

A porous medium has a permeability of one darcy when a single phase fluid of one centipoise viscosity that completely fills the voids of the medium will flow through it under conditions of viscous flow at the rate of one cubic centimeter per second per square centimeter of cross-sectional area under a pressure or equivalent hydraulic head gradient of one atmosphere per centimeter

$$1 \text{ darcy} = 9.87 \times 10^{-9} \text{ cm}^2$$

2.1.b: Hydraulic Conductivity

The flow of a viscous liquid through a saturated medium in one dimensional system is commonly expressed by Darcy's Law:

$$V_s = -K \frac{dh}{dS} \tag{2.2a}$$

Hence

$$K = -V_s \left(\frac{dh}{dS}\right)^{-1} \tag{2.2b}$$

where K = hydraulic conductivity (L/T) and the other symbols are as defined previously.

The negative sign indicates that flow is in the direction opposite to the increase in head.

The permeability (k) is related to the hydraulic conductivity (K) by the relation

$$K = k \frac{\rho g}{\mu} \tag{2.3}$$

Because K depends on both porous medium and fluid properties, it measures the mobility of a given fluid in a given porous medium.

2.1.c: Porosity

Total porosity (ϕ) is the ratio of the total void space in the rock to the bulk volume of the rock. The effective porosity (ϕ) is the ratio of the interconnected void space in the rock to the bulk volume of the rock.

From the reservoir engineering point of view, effective porosity is the quantitative value desired, as this represents the space which is occupied by mobile fluid. Porosity is related to bulk density (ρ_b) and particle density (ρ_s) by the relationship

$$\phi = 1 - \frac{\rho_b}{\rho_s} \tag{2.4}$$

Porosity can be an important controlling influence on porosity include hydraulic conductivity. Factors effecting structure, shape of grain, grain size distribution, mixing, packing and cementation.

2.1.d: Capillary pressure and Bubbling Pressure

The concept of capillary pressure (P_c) is a characteristic of a porous medium evolved from the representation of capillary phenomena in capillary tubes. An oil-water interface or an air-water interface in a large tube is flat because the wetting forces at the walls of the tube are distributed over a large perimeter and do not penetrate into the interior to any extent. Because of this, the pressure of the fluids at the interface are equal. Pores in reservoir rocks are analogous to capillary tubes in that the diameter are small. When diameters are small, surface forces induced by preferential wetting of the solid by one of the fluids extend over the entire interface causing measureable pressure differences between the two fluid phases across the interface.

If we consider an air-water interface in a capillary tube as shown in Figure 2.1. In this case water is a wetting phase and air is a non-wetting phase. The equilibrium of forces at the contact line between interface and solid surface of tube can be expressed as:

$$P_{nw}(\pi r^2) + \sigma_{ws}(2\pi r) = P_w(\pi r^2) + \sigma_{nws}(2\pi r^{\cancel{2}}) \qquad (2.5a)$$

or

$$P_{nw} - P_w = \frac{2(\sigma_{nws} - \sigma_{ws})}{r} \qquad (2.5b)$$

where P_w = pressure of wetting phase (F/L^2)

P_{nw} = pressure of non-wetting phase (F/L^2)

σ_{ws} = interfacial tension between wetting phase and solid surface (F/L)

σ_{nws} = interfacial tension between non-wetting phase and solid surface (F/L)

r = radius of capillary tube (L)

The difference in interfacial tensions in equation 2.5b is actually equal to $\sigma_{nww} \cdot \cos\theta_w$, where σ_{nww} is the interfacial tension between wetting and non-wetting phases and θ_w is the contact angle of wetting phase with the solid surface. Hence, the equation 2.5b can be written as

$$P_{nw} - P_w = \frac{2\sigma_{nww} \cos\theta_w}{r} \qquad (2.5c)$$

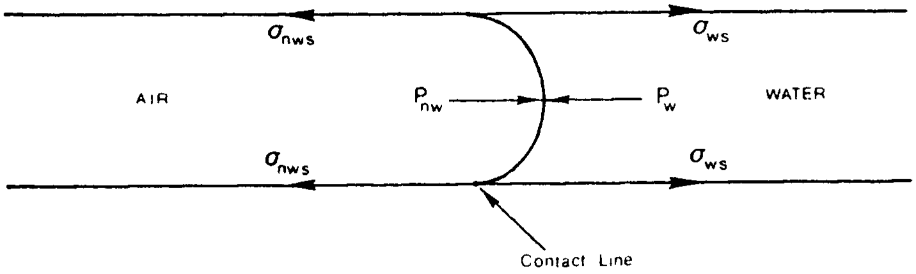


Figure 2.1: Force balance across an air-water interface at static equilibrium.

The pressure difference in equation 2.5c is defined as capillary pressure P_c.

Bubbling pressure (P_b) is approximately the minimum capillary pressure at which a continuous non-wetting phase exists in a porous media during its desaturation. In petroleum engineering, this critical P_c is called displacement pressure and is denoted by P_d. When non-wetting phase is air, then this critical pressure is generally termed as air entry pressure P_e.

2.1.e: Capillary Pressure - Saturation Relationship

A functional relationship between capillary pressure (P_c) and saturation (S) (also known as water retention or water-characteristic curves) can be visualized by considering a model, proposed by Carey (1977), of a cross-section of an element of pore space as illustrated in Figure 2.2. In this case, the pore space contains a mixture of water and air.

As P_c is increased from P_{c1} to P_{c2}, either by increasing the air pressure or decreasing the water pressure, a volume of water is removed from the pore space. In the process, the interfaces retreat to portions of pore space having smaller dimensions so that the radii of curvature are smaller. In other words,

$$S = f(P_c) \qquad (2.6)$$

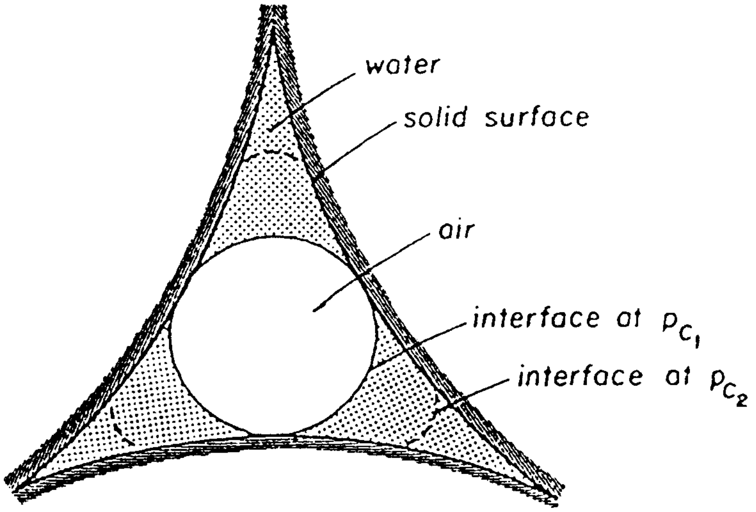


Figure 2.2: Model of pore cross-section with varying saturation of water.

However, if the pore space initially is fully occupied with water, a finite value of P_c must be exceeded before air can intrude into this element of the pore volume. This value of P_c (denoted as P_b) is called air entry pressure or bubbling pressure, and it depends on the dimensions of the largest opening in the particular element of pore volume considered. If the pore volume considered contains some portion of pore space with dimensions larger than the largest "opening" that portion of the pore space will immediately desaturate. Consequently, the desaturation of pore space with increasing P_c, in its initial stages, does not occur smoothly but proceeds in jumps.

If a laboratory sample of porous medium is caused to desaturate by increments of P_c and allowed to arrive at a static state with each increment, the value of S determined for the corresponding values of P_c will provide a curve as shown in Figure 2.3. Such curves are called "desaturation curves" or "water characteristic curves".

The capillary pressure vs. saturation data are highly useful in characterizing the pore size distribution of porous media and predicting its permeability.

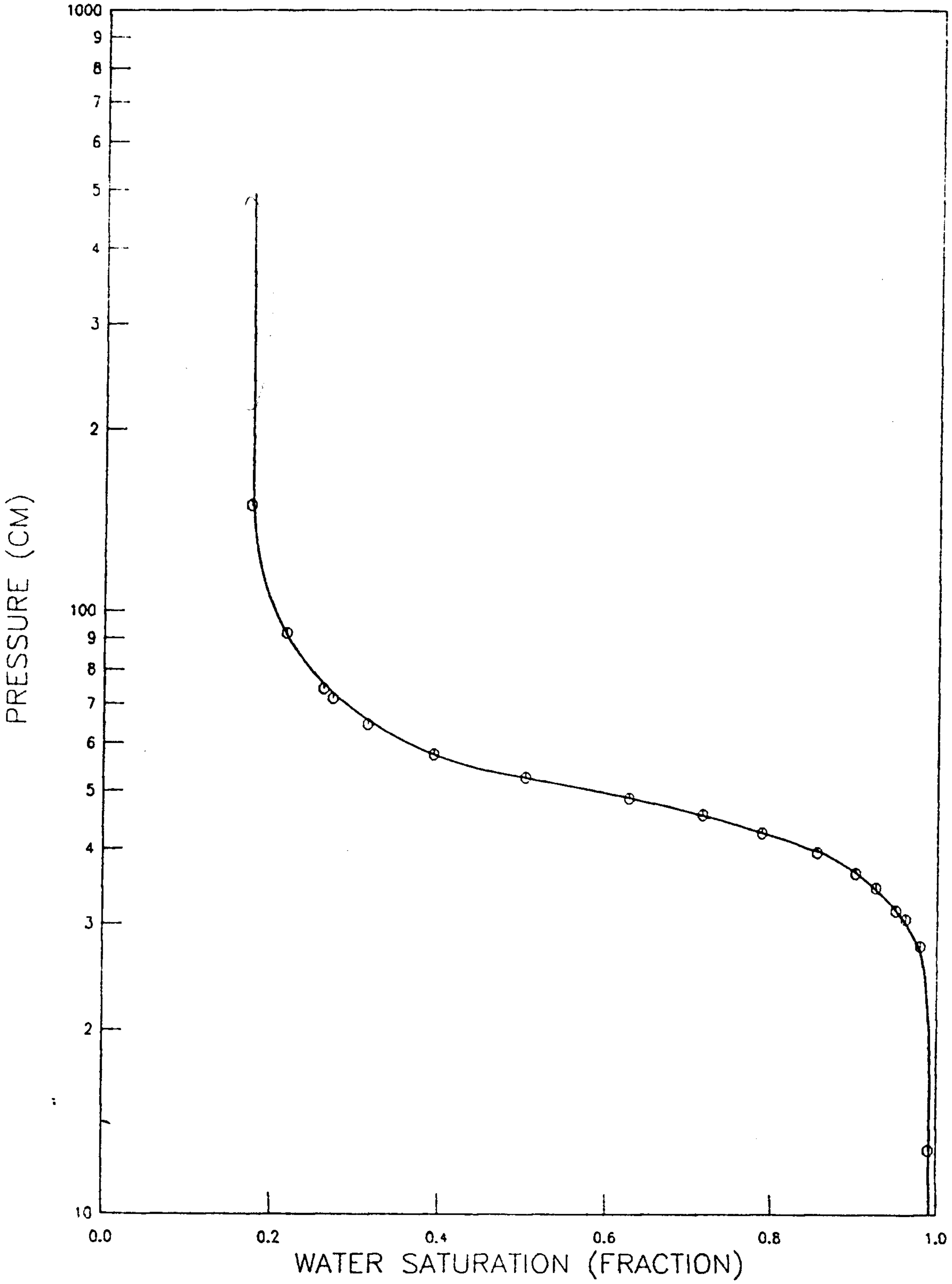


Figure 2.3: Plot of water saturation as a function of pressure.

2.1.f: Pore Size Distribution

2.1.f.a: Pore Size

No one has been able to give a unique definition of "pore diameter" or "pore size" as yet. Every method of "pore size" determination defines a pore size in terms of a pore model which is best suited to the quantity measured in the particular experiment. These operational definitions of pore size apply reasonably well only to portions of the entire pore size range in the porous sample.

Scheidegger (1960) proposed a way of defining the pore diameter. According to him, the pore diameter at any one point within the space is the diameter of the largest sphere which contains this point and remains wholly within the pore space.

Pore size has the dimenions of length and is physically analogous to hydraulic radius which is a ratio of the cross-sectional area of conducting pore channel to its wetted parameter. Clearly, pore size is associated with grain size and grain size distribution. The smaller the grains the smaller is the pore size. However, materials with structure may have some large pore sizes associated with the secondary pore space (i.e., fissures, fractures, etc.), even though the primary pore space is characterized by a small pore size.

2.1.f.b: Pore Size Distribution

Pore size distribution is one of the ways to characterize the intricate geometry of the flow channels in a porous medium. The pore size diameter is difficult to measure directly, but there is a way of defining and measuring an index of pore size distribution.

Corey (1977) explained the concept of pore size distribution by a balance of forces across a particular section. A sketch of a pore space is shown in Figure 2.4. As the pore space is not analogous to a capillary tube with constant radius 'r', so the 'hydraulic radius' of the pore channel is used, while balancing the forces across the interface of wetting and non-wetting fluids. Thus at equilibrium of forces

$$P_{nw}(A) + \sigma_{ws}(W_p) = P_w(A) + \sigma_{nws}(W_p) \qquad (2.7a)$$

or

$$(P_{nW} - P_W)\, A = (\sigma_{nws} - \sigma_{ws})\, W_p \qquad (2.7b)$$

or

$$P_c \cdot \frac{A}{W_p} = \sigma_{nw \cdot w} \mathrm{Cos}\ \theta_w \qquad (2.7c)$$

or

$$\frac{A}{W_p} = \frac{\sigma_{nw \cdot w}\ \mathrm{Cos}\ \theta_w}{P_c} \qquad (2.7d)$$

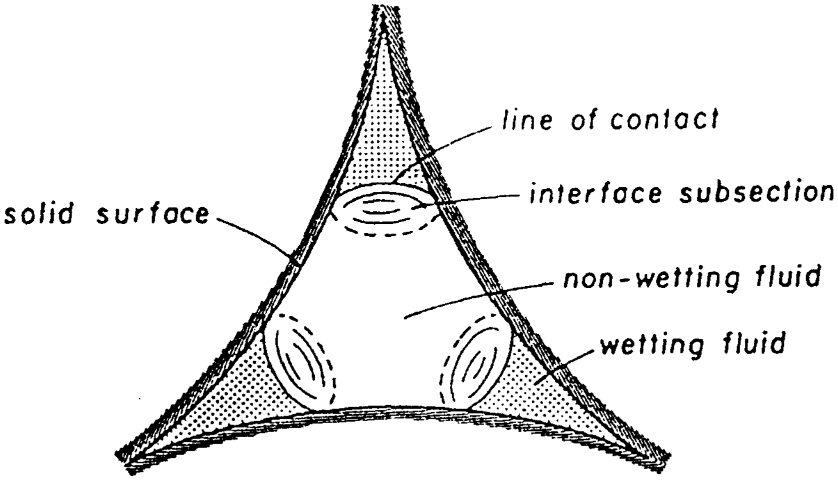


Figure 2.4: Cross-section of pore space with several interface sections.

Here A is the cross-sectional area of the pore channel and W_p is its wetted parimeter across the interface of wetting and non-wetting phase. Other parameter are predefined. The quantity A/W_p (hydraulic radius) has the dimensions of length and can be used to characterize the "size" of the section of pore space across which the interfaces are positioned. If P_c is increased within the reference element, the value of A/W_p will decrease. In the process, a portion of the pore space will lose its wetting phase (i.e., saturation 'S' will decrease). The increment of S is a measure of the fraction of the pore space characterized by the corresponding increment of A/W_p. The ratio of change in S to change in A/W_p is dependent on the frequency of pore sizes, which have values of A/W_p within the increment of P_c under consideration.

Equation 2.7d indicates that if $\sigma_{nw.w}$ Cos θ_w is essentially constant for a particular fluid system, A/W_p should be proportional to $1/P_c$. The quantity $1/P_c$, therefore should be a measure of the largest pore "size" (in that part of the pore space containing the wetting phase) at a particular value of P_c.

2.1.f.c: Pore Size Distribution Index

Brooks and Corey (1964) used a parameter λ as an index of pore size distribution. They reasoned that for media having a uniform pore size, the index would be a large number, which theoretically could apporach infinity. On the other hand, media with a very wide range of pore sizes should have a small value of λ , which theoretically could approach zero. They found that for a typical porous media, the usual value of λ is about 2. The undisturbed sands found in natural deposits usually have relatively high values of λ , 4 or 5. Brooks and Corey's method of calculating λ is reproduced in Appendix A.

Corey (1977) reports that the value of λ is affected by grain size distribution, structure and method of mixing.

All sands, regardless of grain size distribution, can be made to have a very uniform pore size (high) by thorough mixing and dense packing. Finer materials usually have somewhat smaller values of λ .

Structure increases the range of pore sizes and thus decreases λ . The degree and type of cementation may also have an effect on λ .

2.2. Literature Review

In this section, a number of studies conducted by various researchers for predicting hydraulic conductivity and correlating the physical properties of porous media are presented and discussed briefly.

2.2.A: Hyraulic Conductivity Problem

In recent years, several investigators have explored the possiboility of predicting the hydraulic conductivity of porous media from pore size distribution data. Interest in such predictions is warranted inasmuch as the hydraulic conductivity - water content relationship ($K(\theta)$) is relatively difficult to measure while the pore-size distribution is characterized relatively easily by the standard measurement of water content vs. pressure.

Several methods have been proposed for calculating hyraulic conductivities of porous media from moisture retention functions. Comparison of these methods with each other have also been published but no concrete decision has been made to establish the best one. Now there is a need to evaluate the validity of each method and to recommend the best one after comparison of these techniques with each other and with measured values.

Slichter (1899), Terzaghi (1925), Kozeny (1927), Zunker (1933), and Fair and Hatch (1933) derived expressions for permeability as a function of particle size to describe the porous medium in terms of particle size distribution, but the best known is perhaps that of Kozeny, i.e.,

$$k = Cd^2 \phi^3/(1-\phi)^2 \tag{2.8}$$

where k = permeability (L^2)

ϕ = porosity (fraction)

d = diameter of particle (L)

c = an empirical constant for size and shape of particle

In equation (2.8), 'd' is ill-defined in a sand with a wide range of particle sizes due to non-uniformity of particle diameters.

Fair and Hatch (1933) substituted for 'd', the factor V/A, where A is the total surface area of the representative sample whose volume is V, that is A/V is the specific surface. Fair and hatch's form is therefore

$$k = D\left(\frac{V}{A}\right)^2 \frac{\phi^3}{(1-\phi)^2} \qquad (2.9)$$

All the parameter in this equation are pre-defined except D, which is an empirical constant characterizing the size and shape of particles.

Tertaghi's expression was

$$k = B_T \quad \frac{1}{\mu} \left(\frac{\phi-0.13}{\sqrt[3]{1-\phi}}\right)^2 d^2 \qquad (2.10)$$

where d is the size of the grain, ϕ is the void volume, μ is the fluid viscosity and B_T is a constant for shape of grain and uniformity of sand.

Zunker's proposed form was

$$k = B_z \left(\frac{1}{A}\right) \phi_e^2/(1-\phi)^2 \qquad (2.11)$$

where B_z is Zunker's constant, and A and ϕ are the same as in equation (2.10), ϕ_e is the effective porosity, which is the ratio of the interconnected void space in the rock to the bulk volume of the rock.

Childs and Collis-George (1950) raised objections to the above-mentioned formulations on grounds that all these formulas fail to describe structured bodies, such as, for example, the 'stiff-fissured' clays. The structural fissures contribute in relative sence negligibly both to porosity ϕ and specific surface A/V and yet they determine the permeability k. The most evident drawback in the Kozeny-type formulas is the lack of a factor to take into account the tortuosity (actual flow path), and a means of evaluating this factor if it be needed.

Childs and Collis-George (1950) had sought to relate permeability more rationally with pore-size distribution rather than particle size. Their model is appropriate to a porous body in which the distribution of pores of various sizes in space is entirely random.

If one pays attention to a group of pores on one of the exposed surfaces of a broken unit cross-section of a porous body, this group of pores has an average size σ with size range δr, i.e., from $\rho - \delta r/2$ to $\rho + \delta r/2$. Similarly, a group of pores in the other exposed surface has an average size σ with range δr. The area devoted to a particular group in the exposure is the product of the concentration of pore volume about the chosen size and the width of the range δr. The concentration of the pore volume at a given pore size is a function of pore size, r, denoted as F(r) and is called distribution function.

Then the area (a_ρ) of exposure of pores of mean size is $F(\rho)\delta r$, while the area (a_σ) of exposure on the other surface of pores of mean size σ is $F(\sigma)\delta r$. The area of junction occupied by pore sequences characterized by a mean pore size ρ on the first side and pores of mean size σ on the second side is simply the product of a_ρ and a_σ.

Now, if one takes σ to be smaller than ρ in the sequence, the number of pore sequences occupying the area $a_{\rho\to\sigma}$ is proportional to $a_{\rho\to\sigma}/\sigma^2$, and by Poiseuille's equation, the rate of flow through each pore sequence per unit potential gradient is proportional to σ^4, so that the contribution δK of pore sequence to the total hydraulic conductivity

$$\delta K = M\sigma^2 \; F(\rho) \; \delta r \; . \; F(\sigma) \; \delta r \qquad (2.12)$$

and the total hydraulic conductivity is

$$K = M \sum_{\rho=0}^{\rho=P_c} \; \sum_{\sigma=0}^{\sigma=R} \sigma^2 \; F(\rho) \; \delta r \cdot F(\sigma)\delta r \qquad (2.13)$$

where M is a matching factor that forces the predicted curve to fit the experimental data at one point, and R is the upper pore size limit in the range.

A method of expanding equation (2.13) for many groups of pores is expalined in Childs and Collis-George (1950) original paper. The method describes how capillary pressure-desaturation data is used to calculate hydraulic conductivity with this approach.

The Childs and Collis-George theory has some limitations, which they themselves admitted in their original work (1950), i.e., "We have confined ourselves to a cross-sectional factor and have ignored the effect of the different lengths of cells of different sizes. A sequence of two small pores, for example, occupies a much smaller portion of the total volume than does a sequence of two larger pores and should presumably be weighted less on that account. This may well account for the relative over-estimate of permeability at low moisture contents, where the small pores become insignificant."

Marshall (1958) took a more random view of distribution of pores and derived an equation, similar in philosophy with that of Childs and Collis-George, but with a different procedure of summing up of pore sizes. Considering a relationship between permeability and size distribution of pores in isotropic materials, he gave

$$K(\theta)_i = 3600*24*\frac{\gamma^2}{2\rho g\mu}*\frac{\epsilon^P}{n^2}*\sum_{j=i}^{n}[(2j+1-2i)P_{cj}^{-2}] \qquad (2.14)$$

$$i=1,2,\ldots n$$

where $K(\theta)_i$ = the calculated hydraulic conductivity for a specified fluid content (cm/day)

θ = fluid content (cm^3/cm^3)

i = the last fluid content class on the wet end of porous media sample

γ = surface tension of permeating fluid (dynes/cm)

ρ = density of permeating fluid (g/cm^3)

g = gravitational constant (cm/sec^2)

μ = viscosity of permeating fluid (g/cm-sec)

ϵ = fluid filled porosity

p = a parameter that accounts for interaction of pore classes (2 for Marshall)

n = total number of pore classes

P_c = pressure, suction or head (cm)

24*3600 = multiplying factor to convert cm/sec into cm/day

According to Marshall, his equation appears to have a rather general application within the limits imposed, i.e., (i) the material should be isotropic and should contain no lengthy conducting channels, (ii) it is necessary to have a reliable measurement of size distribution of pores, and (iii) the accuracy of pore size measurement in swelling clay may limit the accuracy of calculation for media with moderate or high clay content.

Millington and Quirk (1960) termed Childs and Collis-George, and Marshall's approaches the "interaction models" in which only radius interactions have been considered. The

Millington and Quirk apporach is based on an interaction model which considers both radius and pore area interactions. They modified the Marshall equation with a change in the value of constant 'p' and fixed p = 4/3 based on the volume of the spherical pore spaces. They made this change with an idea that in a cut surface when ϵ cm^2/cm^2 are exposed for a medium of porosity ϵ cm^3/cm^3, this area contains some, but not all of the pore interaction governing flow normal to the cut surface. So their modified equation is

$$K(\theta)_i = 3600*24*\frac{\gamma^2}{2\rho g\mu}*\frac{\epsilon^{4/3}}{n^2}*\sum_{j=1}^{n}[(2j+1-2i)\overline{P}_{cj}^2] \qquad (2.15)$$

all the parameters are the same as in equation (2.14), except the change in exponential of ϵ .

Jackson, et al., (1965) compared the equations of Childs and Collis-George, Marshall and of Millington and Quirk for three porous media samples, and found that the Millington and Quirk method predicted K-values reasonably close to experimentally determined values only when matching factor was used. On the other hand, the Childs and Collis-George method with matching factor, and Marshall's method without matching factor did not predict the shape of the conductivity curve in contrast to Millington and Quirk method.

Kunze et al. (1968) tested the equation of Millington and Quirk with matching factor for some data and did not find best fit with experimental data. They used a 'p' value of unity in equation (2.14), neglecting the pore area interaction term, which produced a slightly higher conductivity at lower fluid contents, but it required a smaller matching factor. Their own comment about this change was that "changing the exponential of ϵ from 4/3 to unity was a step in the right direction but was not sufficient to correct the problem."

Green and Corey (1971) stressed over the use of matching factor for all the four methods, described above. They concluded that all methods of computation appeared sufficiently reliable to be used routinely for many field applications. Their conclusion was based on the comparison of calculated hydraulic conductivity and experimental data for glass beads and a number of soils.

Brooks and Corey (1964) presented a theory which developed the relationships among saturation, capillary pressure and permeabilities of air and water in terms of bubbling pressure and pore size distribution index.

They found that their measured curves of relative hydraulic conductivity as a function of capillary pressure, P_c, could be approximated by the empirical equations

$$\begin{aligned} K &= K_s && \text{for } P_c \leqslant P_b \\ k &= K_s\,(P_b/P_c)^{\eta} && \text{for } P_c \geqslant P_b \end{aligned} \qquad (2.16)$$

where K = relative hydraulic conductivity (L/T)

K_s = saturated hydraulic conductivity (L/T)

P_c = capillary pressure (L)

P_b = bubbling pressure approximately equal to the minimum P_c on the drainage cycle at which a continuous non-wetting phase exists

η = 2+3λ where is called the pore size distribution index a characteristic of particluar media The numbers 2 and 3 are empirical constants, established based on a series of experiments on porous media.

Brust *et al.* (1968) compared Millington and Quirk (M&Q) and Brooks and Corey (B&C) methods using six unconsolidated sand samples and found that M&Q gave less agreement with actual field measurements of hydraulic conductivity than did the B&C method.

Bruce (1972) made comparison of predicted values of hydraulic conductivity computed by Marshall, Childs and Collis-George (CCG), M&Q, and B&C methods for packed samples of sand, graded sand and fine sand (physical properties are listed in Table 2 in his original paper). He observed that eight measured values of sand fell on or very close to the predicted curves of Marshall and CCG methods. The B&C calculations were most closely related to measured values for graded sand, and Marshall calculations were most closely related to the values for fine sand. The M&Q method predicted a satisfactory match with the measured values for both materials, graded sand and fine sand.

Jackson (1972) studied the importance of exponential factor 'p' in the Marshall and M&Q equations. He compared the hydraulic conductivity values predicted by Marshall method (p=2) and M&Q method (p=4/3) with the experimental data for sand (1-0.5 mm), Botony sand. Sand (50-500 micron) and two samples of loam. He calculated the value of exponent 'p' by an iterative procedure for the best fit to the experimental data and found the value of 'p' ranged 0.74 to 1.24. Based on these results, he concluded that exponent of 1 adequately predicted the measured conductivities. In other works, he supported the method of Kunze et al. (1968), who proposed the value of 1 for exponent 'p'.

2.2.b: Correlation of Variables Affectingi Hydraulic Conductivity

Hydarulic conductivity or permeability are affected by a number of other characteristics of porous media, which include texture, porosity, density, structure, pore size distribution among others.

Attempts were made to correlate permeability with other properties to formulate functional relations of permeability with other properties of porous media, viz., porosity, capillary pressure curves, internal surface area, pore size distribution, etc. Fair and hatch (1933) related permeability with porosity including a factor of $(1-\phi)^2/\phi^3$

in his empirpical relationship based on his experiments for permeability through stratified and unstratified sand beds. Franzini (1951) tested and compared the porosity factor of Fair and Hatch (1933) with other porosity factors published in the literature and came up with the result that Fair and Hatch's porosity factor $(1-\phi)^2/\phi^3$ gave best results for calculation of permeability for laminar flow through granular media. Franzini's conclusion was based on permeability tests on Ottawa sand, lead shots, and a fine granular sand over normal porosity range of 0.34 to 0.42. Mavis and Wilsey (1936) claimed to have found that permeability k is proportional to ϕ^6 or ϕ^5 based on their permeability test on six unigranular sand samples from Iowa river, with porosities ranging from 0.385 to 0.435. Cloud (1941) found no sensible relationship after permeating equal amounts of 30.5 centipoise crude oil through equal weights of the same sand having different mesh sizes.

The next more involved correlation is between structure and permeability. The dependence of permeability on structural parameters of pore space has been discussed on experimental basis by Nelson and Baver (1940) and O'Neal (1949). O'Neal made permeability tests on samples of sands with different types of structures and concluded that structure was the most significant factor in evaluating permeability, but permeability could not be correctly evaluated on the basis of structure alone.

Correlation between permeability and grain size analysis have been attempted for unconsolidated porous media. Such correlations have been reported by Tickell (1935), Krumbein and Monk (1943) and Griffiths (1952). Most of these analyses were made on similar types of materials and therefore it was possible for the individual author to claim such correlations.

Martin _et al_. (1951) investigated the influences of roundness, orientation, and compaction of grains. They found that orientation of grains had a definite effect on pressure drop through stacked spheres. They used two sizes of brass ball bearings for different arrangements of stacking. Similar studies have been made by Tickell _et al_. (1933) and Tickell and Hiatt (1938), on lead shots, Ottawa silica sand and crushed quartz.

Douglas and Whiting (1967) correlated physical properties of 478 sandstone and 90 carbonate core samples through regression analysis and presented a number of equations for predicting porosity, formation factor and permeability. These correlations were claimed to be useful in understanding the relationships between the physical properties of porous media in formation evaluation.

Boyer (1978) studied the effects of texture, cation exchange capacity, pH, surface area of grains, sodium absorption ratio and $CaCO_3$ on a number of soil samples. He correlated these properties through regression analysis and formualted equations to predict hydraulic conductivity from these properties.

Recently, Swanson (1981) developed a correlation between brine and air permeabilities with capillary pressure data. It offers a ready application to improve estimation of permeability from capillary pressure measurements on small protions of sidewall core samples and cuttings.

CHAPTER 3

RESEARCH METHODS AND EXPERIMENTAL PROCEDURES

This chapter is divided into three sections. The first section describes the method of comparing different theoretical methods of predicting unsaturated hydraulic conductivity. In the second section, the experimental procedures for measuring physical properties of a number of unconsolidated sands are presented. The third section explains briefly a statistical method to correlate the physical properties of porous media for prediction of saturated hydraulic conductivity.

3.1. Comparison of methods of Predicting Hydraulic Conductivity

An extensive literature search was conducted to collect the information about the work done related to the subject under consideration. Five different theoretical methods of predicting hydraulic conductivity were selected for comparison, i.e., the methods of Childs and Collis-George (1950), Marshall (1958), Millington and Quirk (1960), Kunze et al. (1968), and Brooks and Corey (1964). The reason for selecting these methods is that all of these are based on pore size characterizations and other physical properties of porous media. The pore size distribution is determined from capillary pressure - saturation data.

The required data were available in the literature in the shape of capillary pressure - saturation curves or tabulated form for porous media. Fourteen samples were chosen for this study based on different pore size range, textural analysis, consolidation status, degree of compaction, porosity, and type of permeating fluid. The properties and source of the samples used in the analysis are summarized in Appendix C. The experimentally measured hyraulic conductivity (K) data at different degrees of saturation were also available to compare theoretically predicted values of K with the measured values. The data for some of these samples were lacking in pore size distribution index (λ) and bubbling pressure (P_b) determinations, which were necessary to predict K by the Brooks and Corey Method. These two properties for those samples were determined following the graphical method of Brooks and corey (1964), reproduced in Appendix A. The capillary pressure - saturation curves were converted into tabulated form very carefully for those samples that had data in graphic form.

All of the five equations (mentioned in Chapter 2) for the above mentioned five methods have been translated into the original FORTRAN IV computer program by Nielsen et al. (1973), which was modified and supplemented (i.e., B & C method) and named HYCOND. The program HYCOND reads the input data from a data file, which contains the properties of permeating fluid (inter-facial tension, viscosity, density and acceleration due to gravity), the value of saturated hydraulic conductivity, steady fluid content and pressure (where desaturation starts), pore size distribution index (λ), bubbling pressure and capillary pressure - saturation data. Three subroutines SUBD, SPLST, and SPLIN were used in this program. The subroutine SUBD calculates the matching factor which is a multiplier that forces the predicted curve towards the experimentally determined curve at a point where the sample is fully saturated. The subroutine SPLST has a capability of dividing the capillary pressure - saturation data in 4, 8, 16, 32, or 64 successive subdivisions. Subroutine SPLN is a curve-fitting routine that is used to fit a cubic spline curve to the data points. A complete FORTRAN listing of the program HYCOND is given in the Appendix B.

Using the computer program HYCOND on the Honeywell 66/60 system of The University of Kansas, the hyraulic conductivity values were computed at different intervals of capillary pressure (P_c) and volumetric fluid content (θ) for each of the five methods considered. The matching factor which was necessary for all the methods except Brooks and Corey's was also printed in the output. The resulting data were interpolated at 16 successive divisions for the whole capillary pressure range, as no better results were obtained by increasing these divisions.

The computed data of hydraulic conductivity at different fluid contents from minimum to maximum saturation are stored in the data files and transformed into plots of hyraulic conductivity (K) vs successive intervals of fluid content (θ). These data were plotted on the HP plotter 7221A using the EASY GRAPH plotting routine available at The University of Kansas Computing Center.

All of the five resulting curves of K vs θ for each method were compared with each other and with experimental data. The goodness of fit of each predicted curve to the experimental data for each sample was estimated using the multiple regression computer program RMULT from Davis (1973). The input data and the resulting output are presented in Appendix C. The plots of predicted curves and results are presented and discussed in Chapter 4.

3.2. Experimental Methods and Apparatus

The physical properties of a number of unconsolidated sands from southwestern Kansas were determined in the Porous Media Laboratory of the Kansas Geological Survey to supplement the literature data for regression analysis to correlate the properties of porous media. This section contains a description of experimental procedures and apparatus used during this work.

3.2.a: Hydraulic Conductivity Measurements

A diagram of the complete system for the constant-head method used in the determination of K is shown in Figure 3.1. Hydraulic conductivity is found using

$$K = \frac{L}{At(H)} \tag{3.1}$$

where K = hydraulic conductivity (L/T)

Q = volume of liquid discharge in time 't' (L^3/T)

L = length of the packed column of sample (L)

A = cross-sectional area of packed column (L^2)

H = hydraulic head difference across the sample (L)

Air dried sample, passed from the No. 200 sieve (0.074 mm) was compacted with a mechanical compression device, to its undisturbed bulk density in the brass ring of a Soilmoisture tempe cell. Construction details are shown in Figure 3.2. An individual tempe cell without its ceramic plates is used as a permeameter for each sample. A woolen cloth was used as a filter at both the ends of the sample. Then the sample was saturated with distilled water in a vacuum desicator as shown in Figure 3.3.

A constant-head (ΔH) of 33.66 cm was maintained, as shown in Figure 3.1. The length of the packed column (2.90 cm) and cross-sectional area (22.816 cm^2), restrained by the capped ends and brass ring interior, were assumed to remain constant for each test. The tap water at room temperature was directed upward through the sample column to minimize

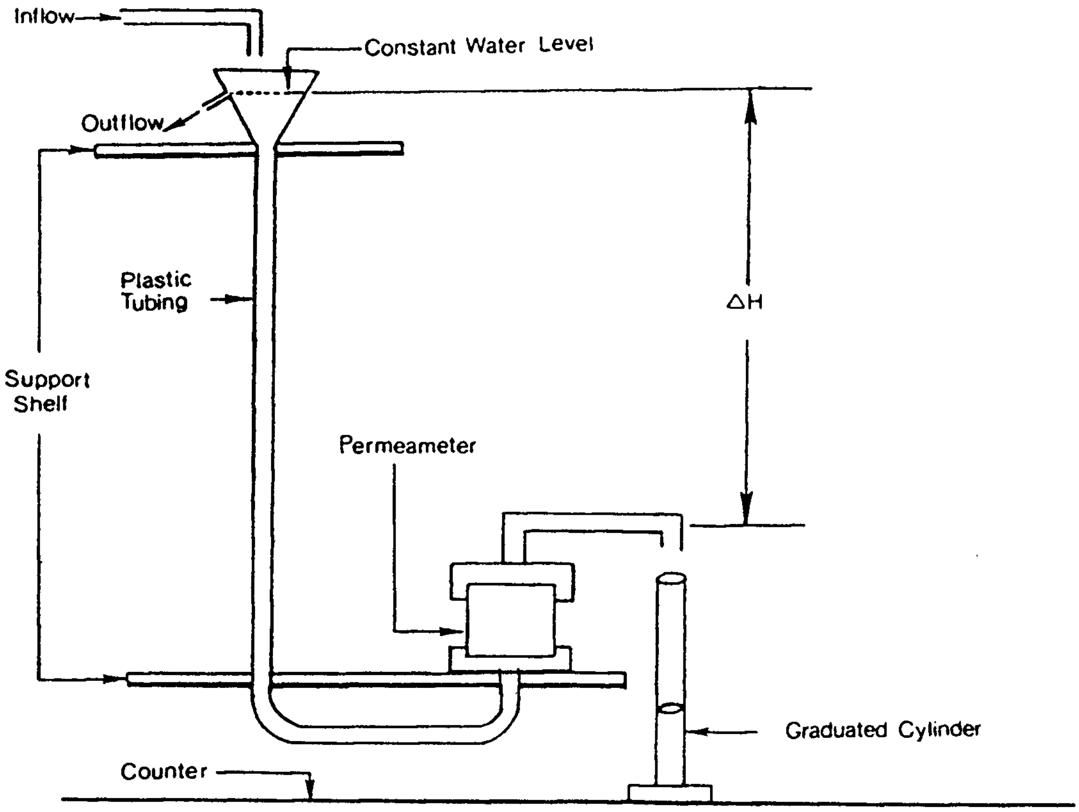


Figure 3.1: Arrangement of measurement of hydraulic conductivity.

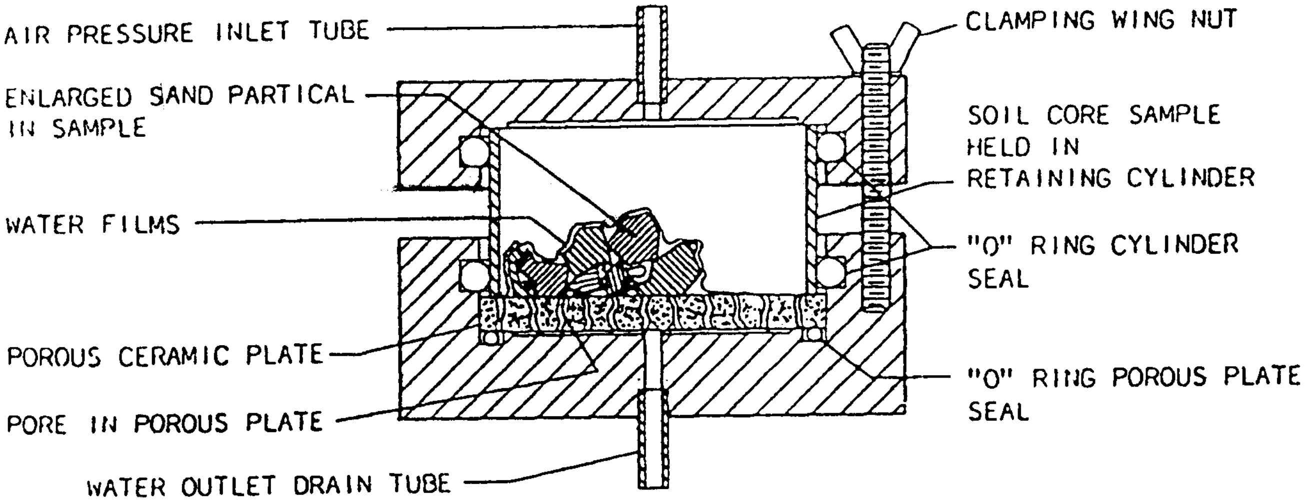


Figure 3.2: Cross-section view of pressure tempe cell.

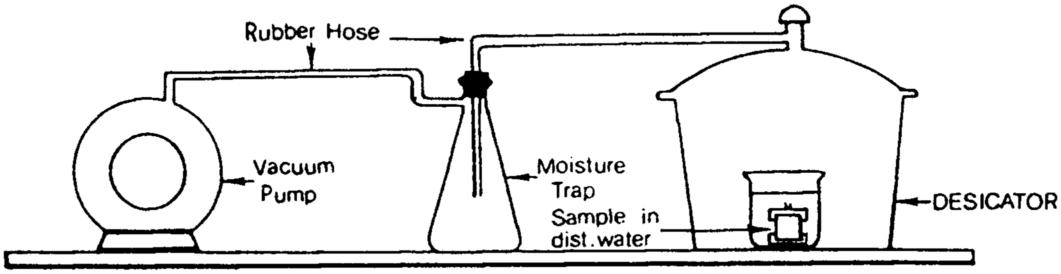


Figure 3.3: Desicator arrangement for water saturation.

entrapment of air in the sample pores. The flow of water was regulated into a constant-head funnel, such that a stable condition with flow from both the funnel overflow part and the chamber outflow line was achieved.

After equilibrium flow conditions were established, water permeated through the sample was collected in a graduated cylinder and permeating time was recorded. Finally, the calculations were made using equation 3.1 to determine hydraulic conductivity.

3.2.b: Grain Size Distribution Analysis

The Hydrometer method (Bowels, 1978) was used to find out the percentage of sand, silt, and clay in each sample. This procedure utilizes the relationship among the velocity of fall of spheres (V) in a fluid, the diameter of the sphere (D), unit weight of the sphere (γ_s) and of the fluid ($_f$) and viscosity of the fluid (μ_f), expressed as Stoke's law:

$$V = \frac{2}{9}\,\frac{\gamma_s - \gamma_f}{\mu_f}\left(\frac{D}{2}\right)^2 \qquad (3.2a)$$

Solving equation (3.2a) for D

$$D = \sqrt{\frac{18\ \mu_f V}{\gamma_s - \gamma_f}} \qquad (3.2b)$$

The equation (3.2b) is valid for solid particles of size range 0.0002 - 0.2 mm. A brief description of the method follows:

Fifty grams of air dried sample passed through #200 sieve was mixed with 125 ml of Calgon solution in a 500 ml beaker. The Calgon solution was prepared by mixing of 35.7 grams of soldium hexametaphosphate ($NaPO_3$) and 7.94 grams of sodium carbonate (Na_2CO_3) in 1000 ml of de-ionized water. $NaPO_3$ is a dispersing agent to neutrilize the particle charges in the samples. The mixture of sample and Calgon solution was left overnight for better results. The mixture was transferred to malt-mixture cup, added de-ionized water to two-thirds full of cup and stirred for 5-6 minutes.

All of the stirred mixture was transferred into the sedimentation cylinder, being careful not to lose any material. The de-ionized water was added to the cylinder to the 1000 ml mark with the hydrometer (152H) in it. Capping the cylinder with rubber stopper, the mixture was agitated for one minute with about 30 upside-down turns/minute.

As soon as the process was completed, the sedimentation cylinder was set down, stopper was removed and the hydrometer was inserted into the cylinder. The hydrometer readings at elapsed times of 40 secs, 1, 2, 3, 4, 8, 15, 30, 60 and 120 minutes were then recorded. The sedimentation cylinder was wrapped with insulating material to keep the temperature constant. The liquid temperature was also recorded periodically.

Sometimes the foam produced near the hydrometer stem, due to agitation, caused difficulty in taking the correct reading. This difficulty was removed by adding a few drops of Amyl Alcohol to disperse the foam.

Computations were made using the recorded data at 40 seconds and 120 minutes to find out the percentage of sand, silt, and clay in the sample. A sample calculation is shown in Appendix A.

3.2.c: Bulk Density

The bulk density was determined by the core method. The length and diameter of the cylinderical core sample was recorded as soon as it was drilled out to calculate its volume. The sample is dried in an oven (to 105°C) and weighed in the laboratory.

Bulk density was calculated by dividing the oven-dry mass with the field volume of the sample.

The samples were compacted to this original bulk density for hyraulic conductivity measurements and pressure-desaturation relationship experiments.

3.2.d: Particle Density

Particle density was determined by the Pycnometer method. This compares the weight of solid particles of sample to the weight of an equal volume of water displaced, since one cubic centimeter of water weighs approximately one gram.

First weighed an acid-washed air-dried pycrometer and recorded the weight. Then poured in about 10 grams of solid and weighed on a precision balance. Put about 10 ml of de-aired distilled water and corked it with thermometer stopper attached to it. The outside of the flask was wiped with cloth. When constant temperature was attained and the capillary tube of the pycnometer bottle was full, it was dried and weighed again. After this, removed the sample from the flask and weighed the pycrometer filled with fresh water. When temperature reached at the same point, weighed it.

Then particle density was calculated using the relationship:

$$\rho_s = \frac{d_w(W_s - W_a)}{(W_s - W_a) - (W_{sw} - W_w)} \quad \text{gm/cm}^3 \qquad (3.3)$$

where ρ_s = particle density (gm/cm^3)

d_w = density of water at temperature observed (gm/cm^3)

W_s = weight of pycrometer and sample (gm)

W_a = weight of pycrometer filled with air (gm)

W_{sw} = weight of pycrometer filled with sample and water (gm)

W_w = weight of pycrometer filled with water at temperature observed (gm)

3.2.e: Porosity

Porosity (ϕ) was determined by a simple relationship using bulk density ρ_b and particle density ρ_s measured in sections 3.3 and 3.4.

$$\phi = [1 - \frac{\rho_b}{\rho_s}]x100 \qquad (3.4)$$

3.2.f: Capillary pressure - Saturation Curves

3.2.f.1: Low Suction Range

The sample was prepared in a tempe cell with a similar procedure as was done during hyraulic conductivitiy measurements, and saturated with disinfectant Formaldehyde solution in a vacuum desicator and weighed.

Two plastic tubes one about 15 cm long and the other about 225 cm long were clamped at each end of the tempe cell, which was clamped with a hanger at about 215 cm height from the floor. The longer tube was filled with distilled water and the other end of the tube was connected to a measuring flask through a stopper and glass tube arrangement. The complete system of the experiment is shown in Figure 3.4.

The capillary pressure was changed in increments of 12.7 cm (5 inches) starting from zero elevation difference to 200 cm elevation difference from the center of the sample. The volume of water collected at each increment of pressure head provided a measure of the response of

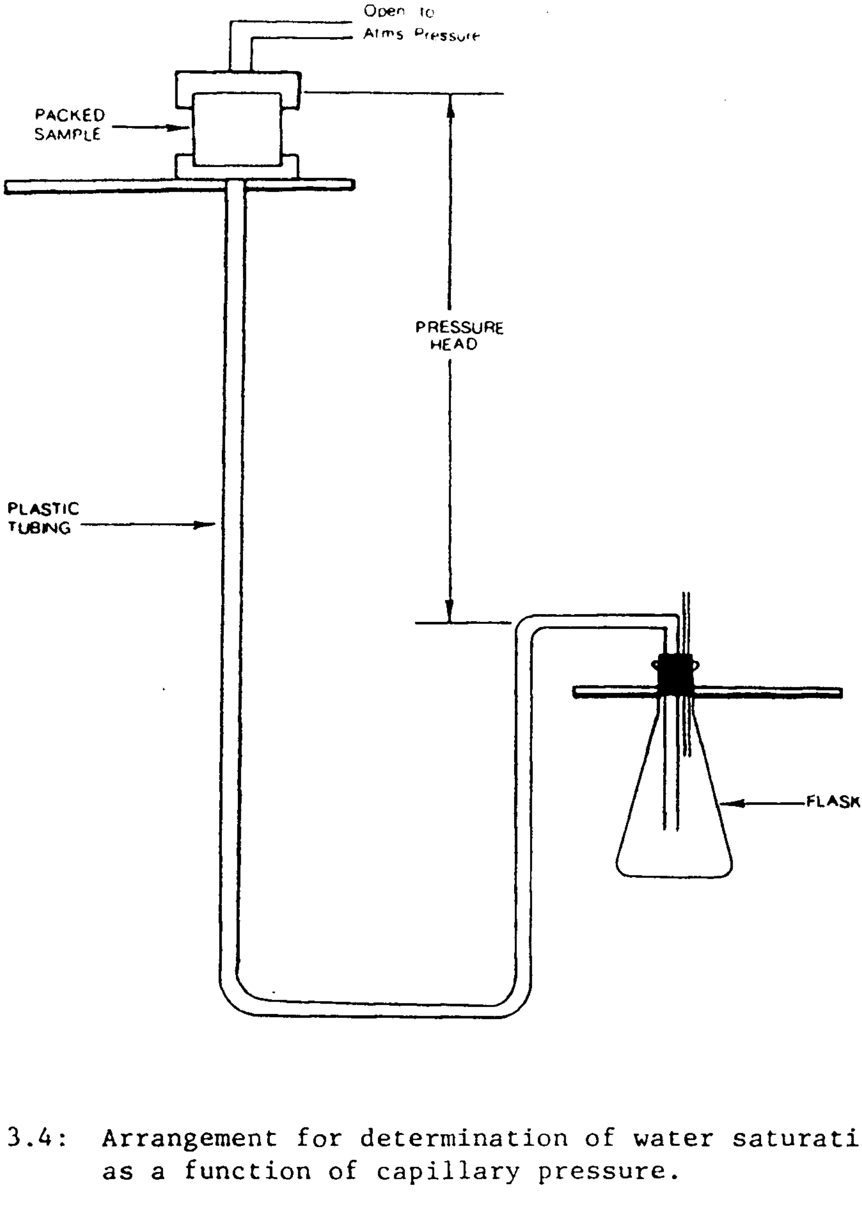


Figure 3.4: Arrangement for determination of water saturation as a function of capillary pressure.

saturation to change in capillary pressure. When no further flow of water from the sample was observed at each incremental change in capillary pressure, the system was considered to be in equilibrium (about 12 hours period was required to equilibrium) and capillary pressure and saturation measurements were made.

The volume of water collected at each increment of capillary pressure was converted into the saturation of the sample, and then capillary pressure - desaturation data were plotted. The sample calculations and the capillary pressure - saturation curve are shown in Appendix A.

3.2.f.2: High Suction Range

The samples were further desaturated by applying the higher pressures of 1, 3, 5, 10 and 15 bars. For this purpose '5 Bar Pressure Plate Extractor' (cat. no. 1600) for the pressure range of 1 to 5 bars, and 'Pressure Membrane Extractor' (cat. no. 1000) for the pressures of 10 and 15 bars were used. Both of these extractors were purchased from Soilmoisture Equipment Corporation, Santa Barbara, California.

Function of Pressure Plate Cells

A cross-section view of a ceramic pressure plate cell mounted in a pressure vessel with outflow tube running through the vessel wall to the atmosphere and a sand sample held on the porous ceramic surface of the cell is shown in Figure 3.5.

Each ceramic pressure plate cell consists of a porous ceramic plate covered on one side by a thin Neuprene diaphragm, sealed to the edges of the ceramic plate. An internal screen between the plate and the diaphragm provides a passage for flow of water. An outlet stem running through the plate connects this passage to an outflow tube fitting, which connects to the atmosphere outside of the extractor.

To use the ceramic pressure plate cell, porous media samples are placed on the porous ceramic surface, held in place by retaining rings of 1 cm height. The samples together with the porous ceramic plate are then saturated with water. This is done by allowing an excess of water to stand on the surface of the cell for several hours. After a complete saturation of samples and pressure plate cell, the cell is mounted in the pressure vessel, and air pressure used to effect extraction of moisture content from the samples under controlled conditions.

As soon as air pressure inside the chamber is raised above atmospheric pressure, the higher pressure inside the chamber forces excess water through the microscopic pores in the ceramic plate and out through the outlet stem via the passage afforded by the screen. The high pressure air, however, will not flow through the pores in the ceramic plate since the pores are filled with water, and the surface

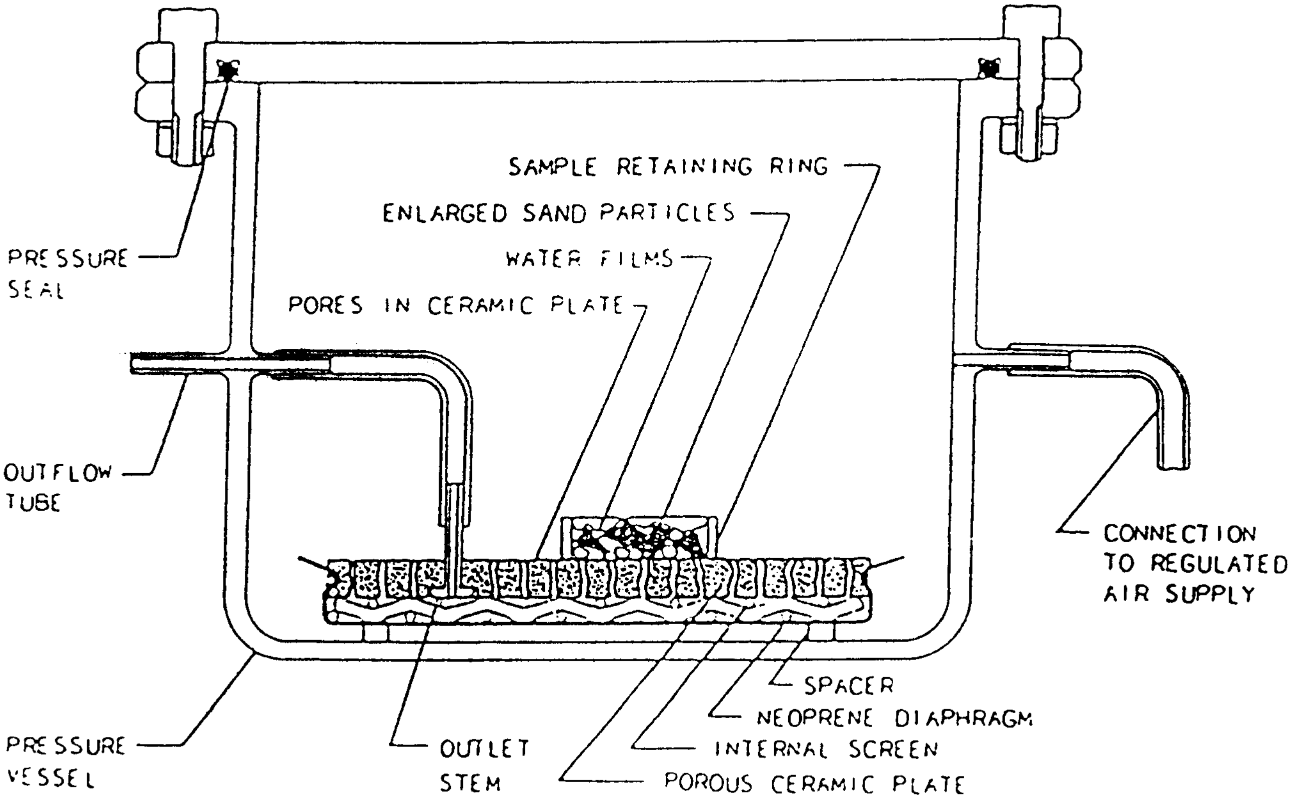


Figure 3.5: Cross-section view of ceramic pressure plate cell and sand sample in extractor.

tension of the water at the air-water interface at each of the pores support the pressure much the same as a flexible rubber diaphragm. To understand this phenomena more thoroughly, refer to Figure 3.6.

During a run at any fixed air pressure in the extractor, the sample moisture will flow from around each of the sample particles and out through the ceramic plate until such time as the effective curvature of the water films throughout the sample are the same as the pores in the plate. When this occurs, an equilibrium is reached and the flow of moisture is ceased. When the air pressure in the extractor is increased, flow of moisture from the sample starts again and continues until a new equilibrium is reached. At equilibrium, there is an exact relationship between air pressure in the extractor and the suction (and hence the moisture content) in the sample.

In pressure membrane extractor (cat. no. 1500), a cellulose membrane plate is used to withstand higher pressures above 5 bars, instead of the ceramic pressure plate. The mechanism of the moisture extraction for cellulose membrane plate is the same as that of ceramic pressure plate.

Capillary Pressure - Saturation Determination

The 1 bar and 5 bar 'Pressure Plate Extractor' (cat. no. 1600) and the 'Pressure Membrane Extractor' (cat, no. 1000) were used side by side with the same pressure source

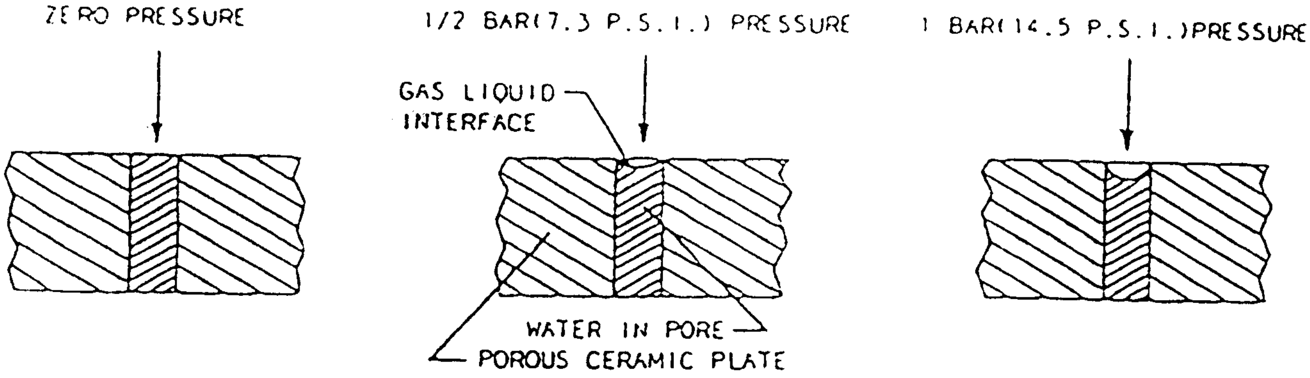


Figure 3.6: Changes in radius of curvature of air-water interface with pressure.

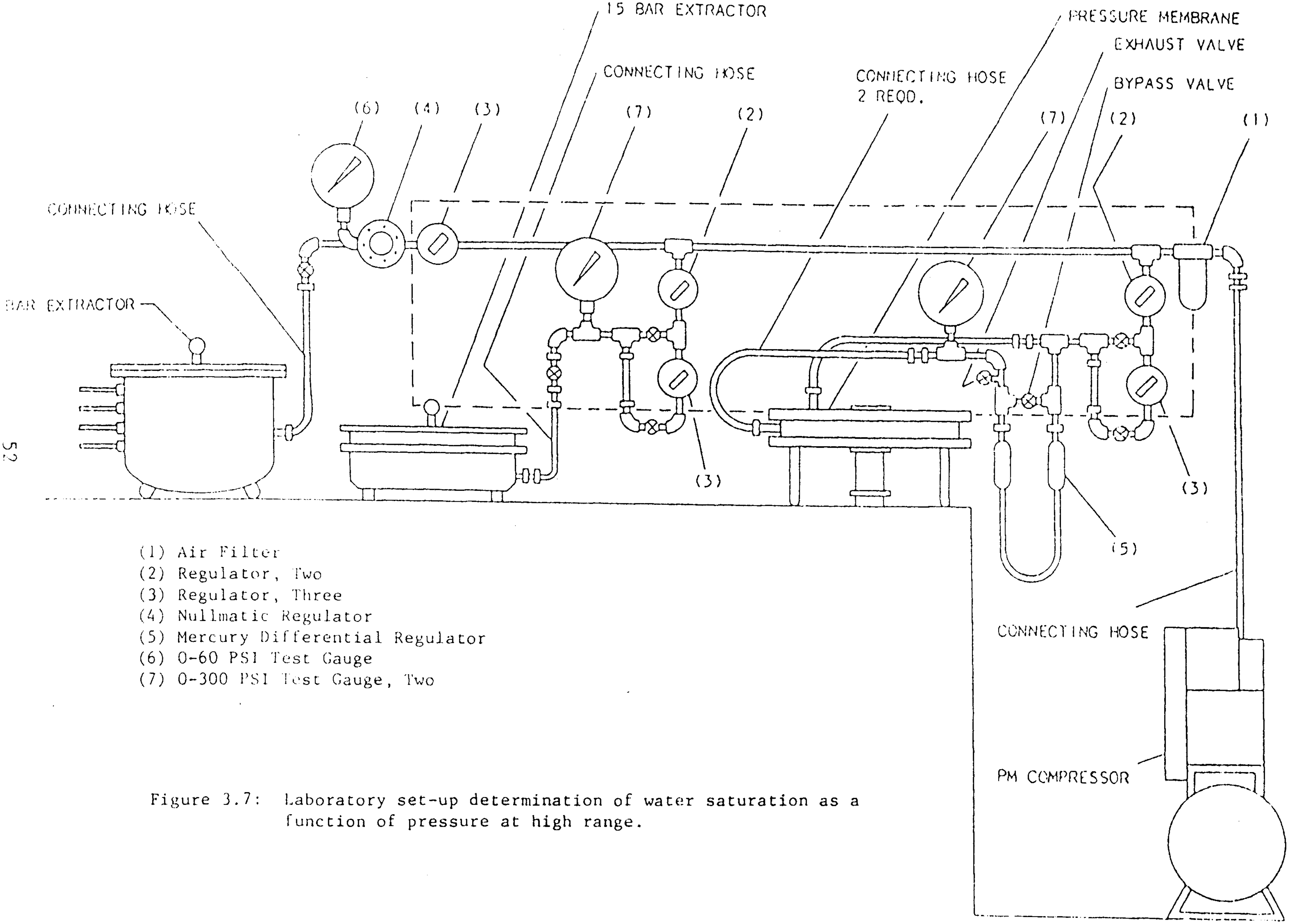
supplied by the same Compressor (cat. no. 500A). A laboratory set up for the whole equipment is shown in Figure 3.7.

Preparation of Samples

Duplicate 25 gm samples that have been passed through a 2 mm sieve were prepared for each sample (the same sample materials for which low suction pressure run was made). The sample-retaining rings were placed on the ceramic plate and on cellulose membrane to receive the group of samples. Each plate could accommodate 12 samples at a time when retained in the rings. The weighed quantity of each sample was poured into the rings and leveled the sample material. The samples along with the pressure plates were allowed to stand overnighit with an excess of water on the plate, so that the sample and pressure plates culd be fully saturated. When the samples were ready for the extractor, the excesss water from the pressure plates was removed with a pipette, mounted the plates in their respective extractors, connected up the outflow tubes and lids of the extractors were closed.

Maintenance of Pressure

It is desirable to provide a means for determining when equilibrium has been reached. This was done by connecting each outflow tube in the screen drain plate as shown in Figure 3.5 with a piece of small diameter plastic tubing for transporting the extracted water to the graduated



(1) Air Filter
(2) Regulator, Two
(3) Regulator, Three
(4) Nullmatic Regulator
(5) Mercury Differential Regulator
(6) 0-60 PSI Test Gauge
(7) 0-300 PSI Test Gauge, Two

Figure 3.7: Laboratory set-up determination of water saturation as a function of pressure at high range.

cylinder. The level of water collected in the cylinder is read periodically and when no measurable amount of change in the cylinder reading would be observed over a period of several hours, the equilibrium at that pressure was attained.

Removal of Samples

Samples were removed from the extractor usually after 48 hours from the commencement of extraction of moisture or earlier if the reading on the outflow graduated cylinder indicated that equilibrium has been attained. Each sample was transferred into a separate aluminum dish and weighed immediately after its removal from the extractor for moisture content determinations. Then, the samples were allowed to dry in the oven at temperature of 105°C over night. The oven dried sample were weighed and recorded.

Calculation of Saturation

The difference in the net weights of wet sample (when removed from extractor) and the oven-dried sample is the weight of the moistiure left in the sample. If this difference is divided by the net over-dried weight of the sample, we get the moisture content left in the sample in grams of water per gram of dry sample. This quantity was designated as 'WC' gm/gm. Then the water content was converted into volumetric content (θ) by multiplying 'WC' with previously calculated bulk density of the sample. The volumetric content 'θ' was further converted into saturation 'S' by dividing 'θ' with porosity of the sample. A sample calculation for one of these samples is presented in Appendix A.

The calculations for saturation of all the samples were made at all higher pressures of 1, 3, 5, 10 and 15 bars and the saturation vs capillary pressure curves (already plotted up to 200 cm of low pressure) were extended to pressure of 15 bars. The resulting curves are presented in Appendix A.

3.2.g: Pore Size Distribution Index (λ) and Bubbling Pressure (P_b)

Pore size distribution index (λ) and bubbling pressure (P_b) for these samples were determined graphically following the procedure proposed by Brooks and Corey (1964). The details of the procedure are reproduced in Appendix A.

3.3. Method of Statistical Analysis for Correlation of Physical Properties of Porous Media

Hydraulic conductivity K is affected by a number of other physical properties of porous media. Among these properties considered here are texture (relative amounts of sand, silt and clay), bulk density (ρ_b), porosity (ϕ), pore size distribution index (λ), and bubbling pressure (P_b). In a functional form these may be expressed as:

$$K = f(\text{texture}, \rho_b, \phi, \lambda, P_b) \qquad (3.5)$$

The physical properties of 48 samples of porous media including the 8 samples for which the properties were measured for this study were used to determine the effect of these parameters on the hyraulic conductivity individually or collectively. The data set of the properties includes the samples for which the properties were measured during this study, and from the published literature. The complete list of properties is listed in Appendix D.

The "BMDP, Biomedical Computer Program" (Dixon, et al., 1979) was used for regression analysis at the variables, because these programs were well tested and documented, used simplified data entry and allowed wide flexibility in the choice of the method analysis.

Stepwise Regression Program 'P2R' was used to observe the individual and combined effect of related properties on the dependent-variable K. In stepwise regression analysis the user has a choice of any number of variables to be used, F-levels to enter or remove variables, and tolerance levels. F-tests determine whether a particular variable is significant to the regression or if the regression as a whole is significant. The stepwise procedure used for entry of variables provides computer examination of F-levels of significance at each step for variables already in the equation as well as the variables about to enter. If a newly entered variable drops the significance of any variable already in the equation below a default value, the previously entered variable is automatically dropped on the next step. Before a variable is tested for selection during the stepwise procedure, its 'tolerance' level is checked. An extremely low tolerance level is a sign that the subprogram would have difficulty inverting the covariance matrix which includes this variable. If a variable with very low tolerance is used, large rounding errors may occur while computing the discriminant coefficients. This would lead to faulty estimates and inaccurate classifications. Here the default value with range of 0.01 to 1.0 is used for tolerance level.

At each step, the overall regression is checked for significance, the improvement in the R^2 value is noted, and the partial F-values for variable already in the equation are examined. The values of the partial F's is then compared with a pre-determined significance level of F-distribution and the corresponding variable is retained in the equation or rejected according to whether the test is significant or not significant. If the tested variable provides a non-significant contribution, it is removed from the model during backward stepping process and the appropriate fitted regression equation is then computed for all the remaining variable still in the model.

The BMDP output is complete, providing at each step coefficients of determination and correlation, regression coefficients, analysis of variance, the F-statistics, and level of significance for the total regression and each variable entered. Significance and tolerance levels for variables not entered into the regression equation are also listed. Options are available that provide for comparison of actual and predicted values with graphical plotting of the residuals, calculations and tabular presentation of 95 percent confidence intervals for regression coefficients and other desired statistical information. A table providing a summary of the entered variables, their correlation coefficients, F-level, and significance is a standard feature of the output.

A complete output is presented in Appendix D and results are discussed in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter is divided into two sections. In the first section, the results of the comparison study of various methods of predicting hydraulic conductivity are presented and discussed. The second section presents and discusses various correlations obtained as a result of statistical analysis of physical properties of porous media used during this study. In each part, the results will be presented first and then discussed separately.

4.1. Comparison of Hydraulic Conductivity Prediction Methods

As was mentioned earlier, fourteen samples of porous media ranging from narrow to wide pore size distribution, selected from the published literature were used to compare the validity and prediction level of each method of calculating hydraulic conductivity. The computed hydraulic conductivity (K) as a function of fluid content (θ) for each sample was compared with the experimental data in Figures 4.1 through 4.14. The predicted values of K for each sample were determined from the fitted curves at the fluid content (θ) corresponding to the one at which K values were determined experimentally. All these K values are shown in Appendix E. A "goodness of fit" test

$$\chi^2 = \frac{1}{n}\sum_{i=1}^{n}((P_i - E_i)^2 / E_i)$$

which compares the overall performance of the predicted K values (P_i) with the experimentally determined K values (E_i) for n number of observations, has been used for the comparison. A smaller value of χ^2 determines the closeness of the prediction with the experimental data. The calculated "goodness of fit" values for each sample are shown in Table 4.1. Moreover, the K vs θ curves for each sample were also analyzed graphically (Figures 4.1 to 4.14), to conclude which method predicted best over different ranges of fluid content. The following are the results based on the "goodness of fit" and graphical analyses.

(i) The Brooks and Corey (B&C) method predicted the values of hydraulic conductivity very close to the experimental data over the major range of fluid content for almost all samples, but the "goodness of fit" values are different for different samples. The smallest "goodness of fit" values were found for Glass Beads, Fine Sand 1, Graded Sand, Fragmented Mixture, Touchet Silt Loam 1, Touchet Silt Loam 2, Lakeland Fine Sand and Wide Range Sand, which determines the closeness of the B&C predictions to the experimental data. The "goodness of fit" values for Barea Sandstone and Hygiene Sandstone also not far from the smallest values for these samples. The K(θ) values predicted by the B&C method

Table 4.1. "Goodness of Fit" values for Different Hydraulic Conductivity Methods with Experimental Data.

Sample Name	CCG Method	KUG Method	MAR Method	M&Q Method	B&C Method
Glass Beads	18.703	8.092	5.607	7.075	3.565
Watson Sand	4.508	12.621	51.056	23.327	12.403
Fine Sand 1	7.767	5.442	7.545	5.978	0.890
Barea Sandstone	1.199	0.425	0.051	0.192	0.059
Hygiene Sandstone	0.196	0.054	0.013	0.054	0.016
Graded Sand	89.229	46.036	28.233	22.726	12.919
Volcanic Sand	7.869	8.061	15.533	10.273	12.512
Fragmented Mixture	7.306	10.778	20.336	14.650	4.091
Touchet Silt Loam 1	0.982	1.618	2.247	1.856	0.406
Touchet Silt Loam 2	0.236	0.216	0.366	0.271	0.201
Lakeland Fine Sand	0.581	0.293	2.129	1.517	0.517
Wide Range Sand	2.741	9.915	20.573	13.313	1.969
Bruce Sand	24.354	12.918	48.154	23.050	74.264
Fine Sand 2	85.578	20.250	8.209	121.688	93.920

underestimated the hydraulic conductivity at the lower range of fluid content for several samples such as Glass Beads (Fig. 4.1), Watson Sand (Fig. 4.2), Touchet Silt Loam 1 (Fig. 4.9), Touchet Silt Loam 2 (Fig. 4.10), Lakeland Fine Sand (Fig. 4.11) and Hygiene Sandstone (Fig. 4.5). However, it overestimated values of K in the lower range of fluid content for other samples such as Fine Sand 1 (Fig. 4.3) and Fine Sand 2 (Fig. 4.14).

(ii) The Childs and Collis-George (CCG) method generally predicted higher values of K than the experimentally determined values. Also, it predicted higher values than anyother method compared here, except for Touchet Silt Loam 1. This method showed some closeness with experimental data at higher ranges of fluid content near saturated hydraulic conductivity, but the values predicted were relatively lower than the experimental determinations in that range. This was observed in Fine Sand 1, Glass Beads, Fragmented Mixture, Touchet Silt Loam 1, and Wide Range Sand. Compared to all other methods, the CCG method predicted the best values for Watson Sand and Volcanic Sand.

(iii) The Marshall (MAR) method computed the lowest values of K as compared with other methods and experimental methods (Figures 4.1 - 4.14). However, it predicted the best values as evidenced by the lowest "goodness of fit" values relative to the experimental data.(see Table 4.1).

This method showed a reasonable match in moderately higher range of fluid content in the cases of Graded Sand (Fig. 4.6) and Glass Beads (Fig. 4.1).

(iv) The resulting curves of the Millington and Quirk (M&Q) method were somewhat higher than the resulting curves for the Marshall method. Reasonable match with experimental data was observed in the higher ranges of fluid content in Lakeland Fine Sand (Fig. 4.11), Wide Range Sand (Fig. 4.12) and in the middle range of fluid content in Graded Sand (Fig. 4.6), Volcanic Sand (Fig. 4.7) and in Fine Sand 2 (Fig. 4.14).

(v) The Kunze et al. (KUG) method predicted values of K very close to M&Q method but it gave the "goodness of fit" values smaller than all methods except B&C method for most of the samples (see Table 4.1).

All of the methods predicted K equally well for Barea sandstone (Figure 4.4) and Hygiene sandstone (Figure 4.5). Both of these materials are consolidated and undisturbed. The porosities are very low and the samples have higher amount of residual saturation. The higher residual saturations were attributed (Brooks and Corey, 1964) to alternate bands of finer and coarser beddings in Barea sandstone, and substantial amount of clay content in Hygiene sandstone. The reason for the closeness of all the resulting curves is the shorter span of fluid content range because the desaturation started at relatively high suction and stopped at high residual saturations. The pore size distribution index (λ) which determines the range of particles distribution, also is moderate (between 3 and 5).

The predicted curves for Glass beads and Watson sand showed approximately similar results. The B&C method computed K values very close to observed data in the higher range of fluid contents (θ), but again diverted down at very low range of θ . The Glass beads and Wtson sand had common properties of very narrow pore size range (high value of λ , 7.3 and 10.8 respectively) and both the samples were free of clay. The samples showed similar behavior during the desaturation process; that is, as soon as desaturation started, the Barea sandstone reached a saturation level of 9.90 percent at a suction of 53.5 cm and Watson sand reached 7.75 percent saturation at a suction of 50 cm (for reference, see the input data in Appendix C).

4.1.a: Discussion of Results

The Brooks and Corey method appears to be the best one in predicting unsaturated hydraulic conductivity for the overall range of saturation considered in the analyzed samples. The pore size distribution index (λ) seems to be a better way of determining the pore size distribution of porous media, as compared with the other methods in which lots of summations and calculation work are required. Those summations include that portion of the desaturation curve below P_b which makes the calculation more difficult and approximate.

The Childs and Collis-George method generally predicted K-values higher than the experimental data but showed some closeness with experimental data near relatively low saturations. This method has some limitations due to which the predicted curve (CCG-K) did not fit well to most of the experimental data. Childs and Collis-George confined themselves to a cross-sectional factor (refer to literature review in Chapter 2) and have ignored the effect of different lengths of pore cells of different sizes. A sequence of two small pores, for example, occupies a much smaller proportion of total volume than does a sequence of two large pores, and should presumably be weighted less on that account. This method also requires a high matching factor to force the predicted curve towards the saturated hydraulic conductivity point on the $K(\theta)$ plots. The high matching factors for this method are obvious from the computer outputs in Appendix B.

The methods of Marshall, Kunze, et al., and Millington and Quirk follow a similar methodology of predicting K but with different ideas of pore interaction. The Marshall method always computed lower K values than those of other methods in almost all the samples tested here, due to the use of higher exponent ($p=2$) of fluid filled porosity in his equation. The Kunze et al. and Millington and Quirk methods computed K-values very close to each other, but the latter was closer to the experimental data near the middle of the saturation range. The computed values by the Kunze, _et al_. and Millington and Quirk methods are higher than those of the Marshall method, as the first two methods use lower values of exponent of fluid filled porosity in their equations than Marshall used (M&Q used $p=4/3$, Kunze, _et al_. used $p=1$). The use of $p=4/3$ in M&Q equation takes care of the effective area of flow, which is the resulting interaction of two surfaces (refer to discussion in Chapter 2). Kunze, _et al_. did not take care of this factor and used $p=1$.

The shape of the $K(\theta)$ curve is another point to notice. The shape of the curves in Figures 4.1 through 4.14 is very similar for all methods except the Brooks and Corey method. A sharp bend in Brooks and Corey's curve in most of the $K(\theta)$ curves in Figures 4.1 to 4.14 near the 100 percent saturation point on the plot is not unexpected. The curve bends sharply towards the 100 percent saturation point, as this method assumes $K=K_s$ at $P_c \leqslant P_b$. The point at the bend is the bubbling pressure point and the sharpness of the bend is more intensive in those materials that have higher bubbling pressures. In several occasions, this curve showed some bends even for saturations beyond the bubbling pressure point. The reason is that the input P_c vs θ data for desaturation curves used only the experimentally determined data points, which were not sufficient to interpolate a smooth

P_c vs θ curve by subroutine SPLIN. Another reason for which the B&C curves have more bends as compared with $K(\theta)$ curves determined by other methods is that the B&C method has fewer data points available for plotting than the other methods within the same range of hydraulic conductivity (refer to computer output of any sample in Appendix C). The bends could be avoided if more data points on the desaturation curves were obtained and used as input data. Moreover, the K values in the B&C method increases exponentially as the pressure decreases.(refer to equation 2.16).

Another factor that can be considered while evaluating the predictability of these methods is the variation in the experimental procedures and the permeating fluid. The experimental methods and the $K(\theta)$ data obtained by these methods were considered reliable (for the experimental Procedures employed for each sample, see Table C.1 in Appendix C). The results could be more reliable if the capillary pressure - saturation data were obtained under the same experimentation and permeating fluid.

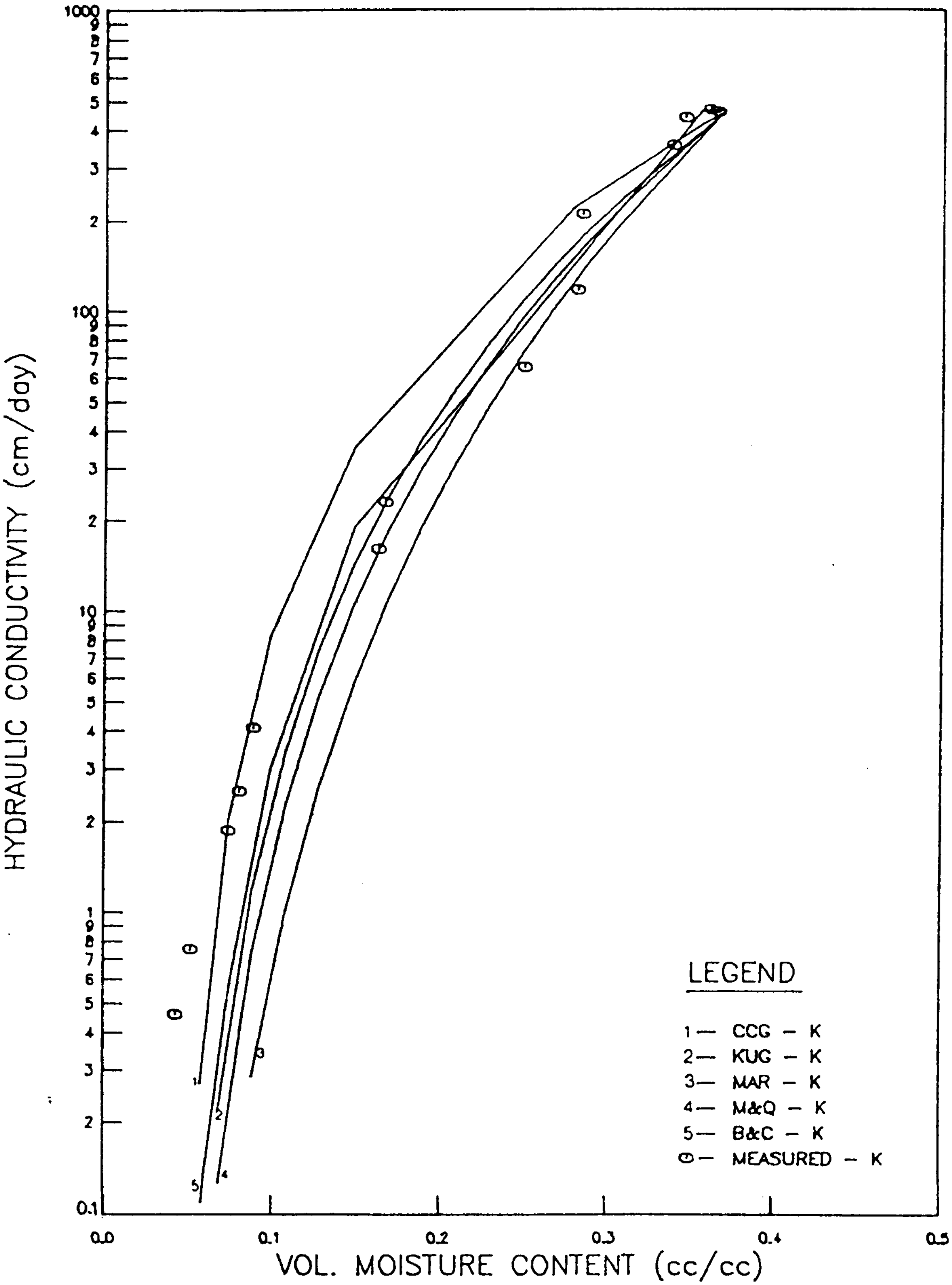


Figure 4.1: Comparison of computed K by different theoretical methods with experimentally measured K for Glass Beads.

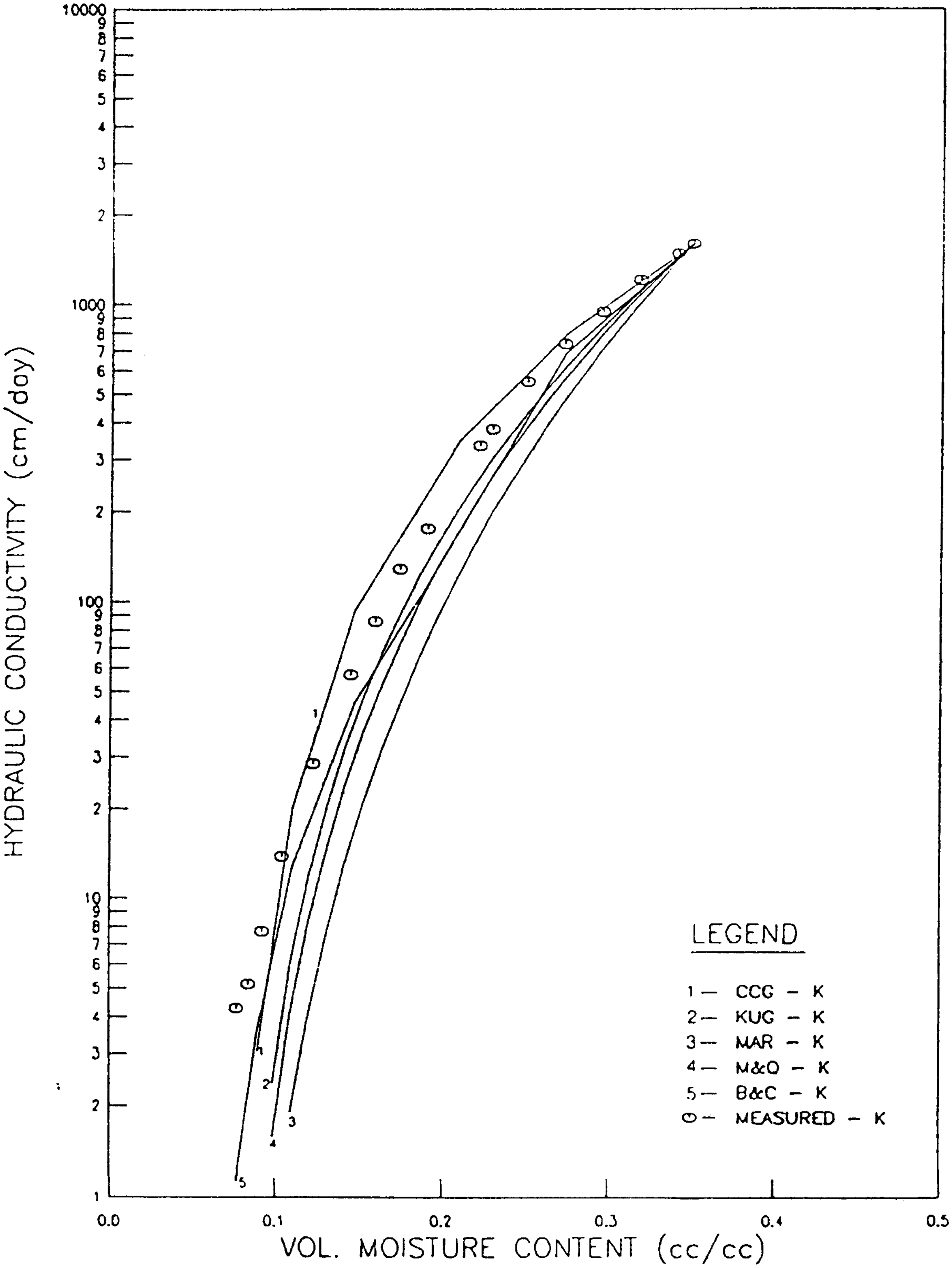


Figure 4.2: Comparison of computed K by different theoretical methods with experimentally measured K for Watson Sand.

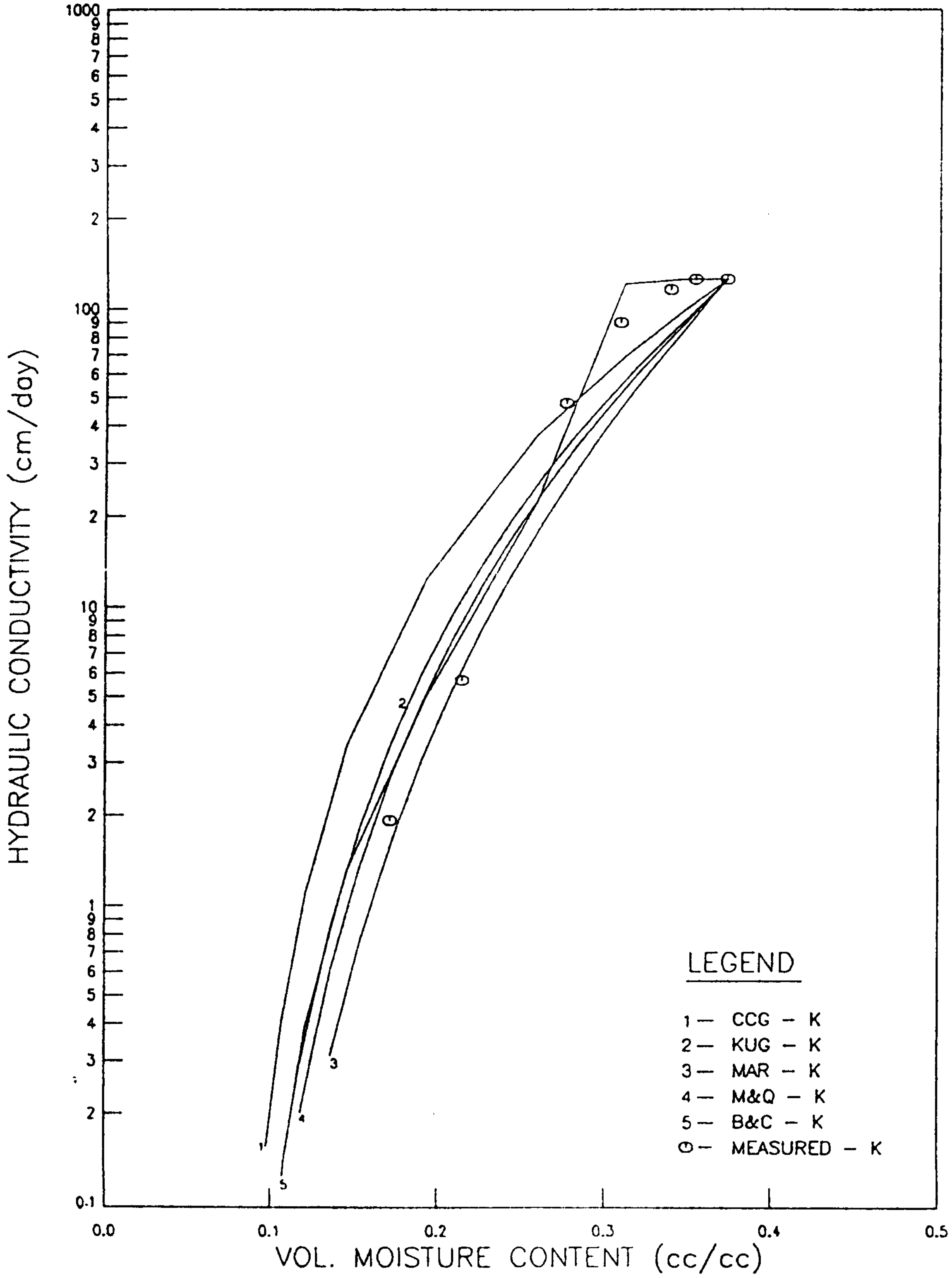


Figure 4.3: Comparison of computed K by different theoretical methods with experimentally measured K for Fine Sand 1.

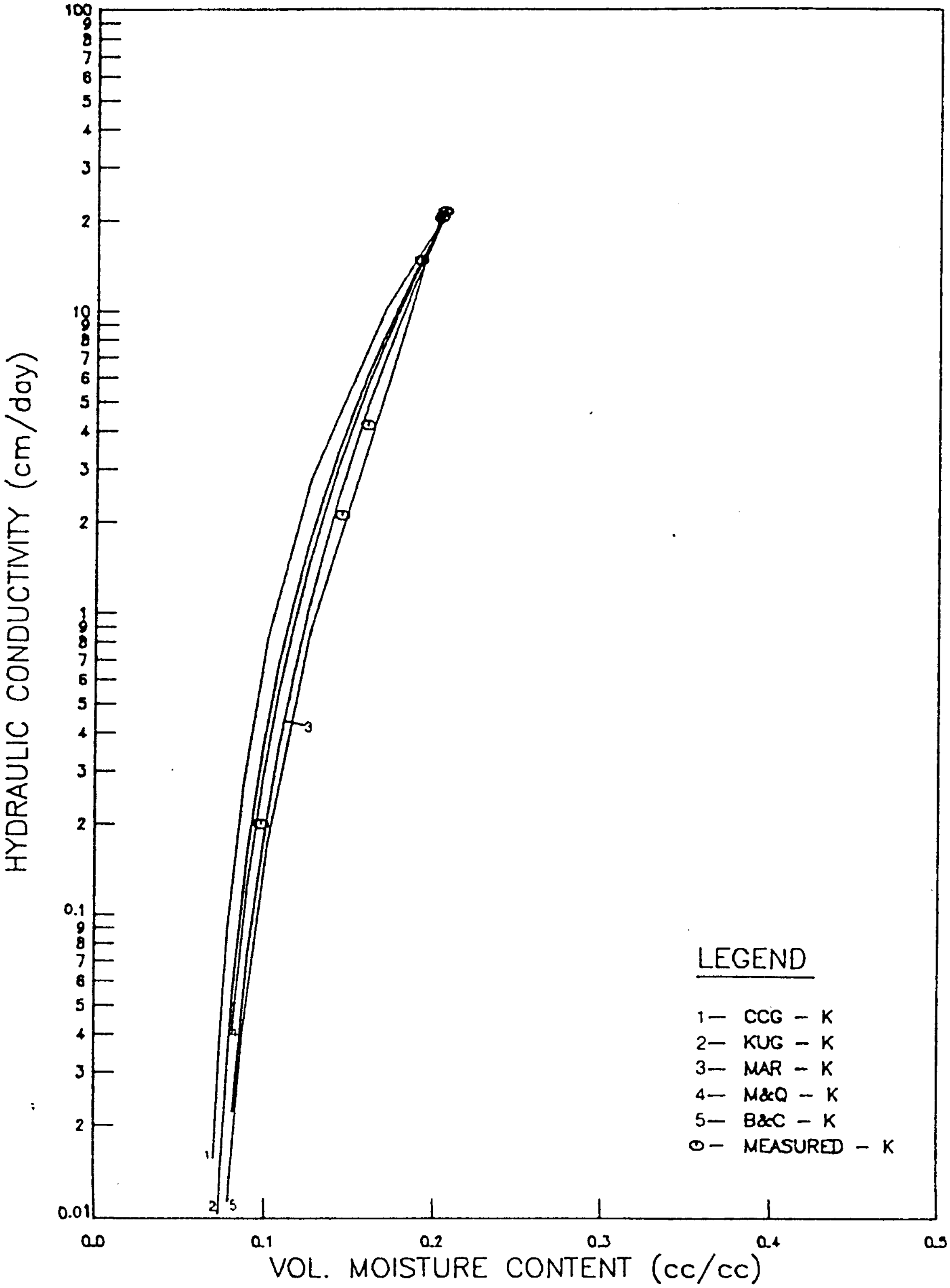


Figure 4.4: Comparison of computed K by different theoretical methods with experimentally measured K for Barea Sandstone.

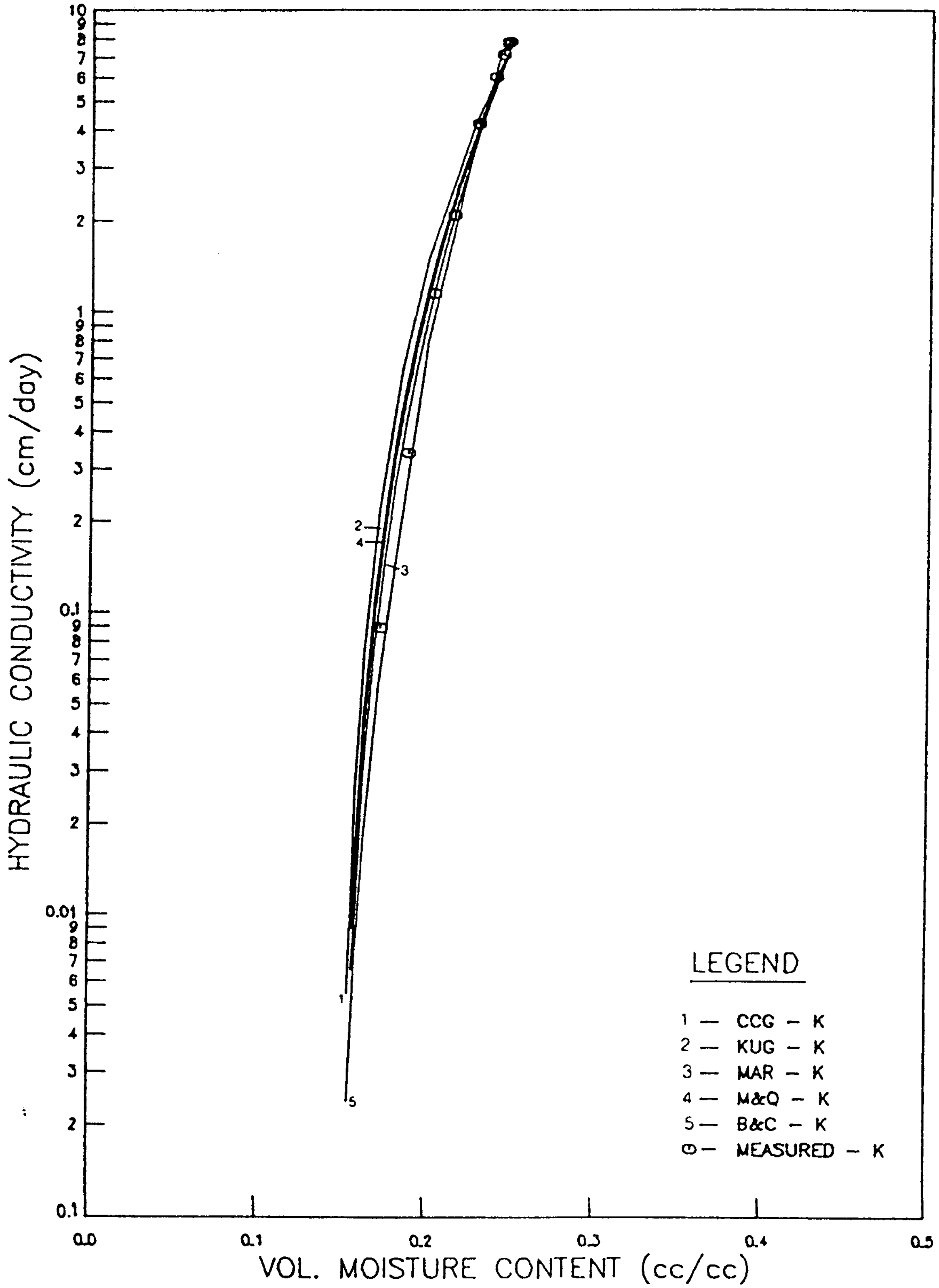


Figure 4.5: Comparison of computed K by different theoretical methods with experimentally measured K for Hygiene Sandstone.

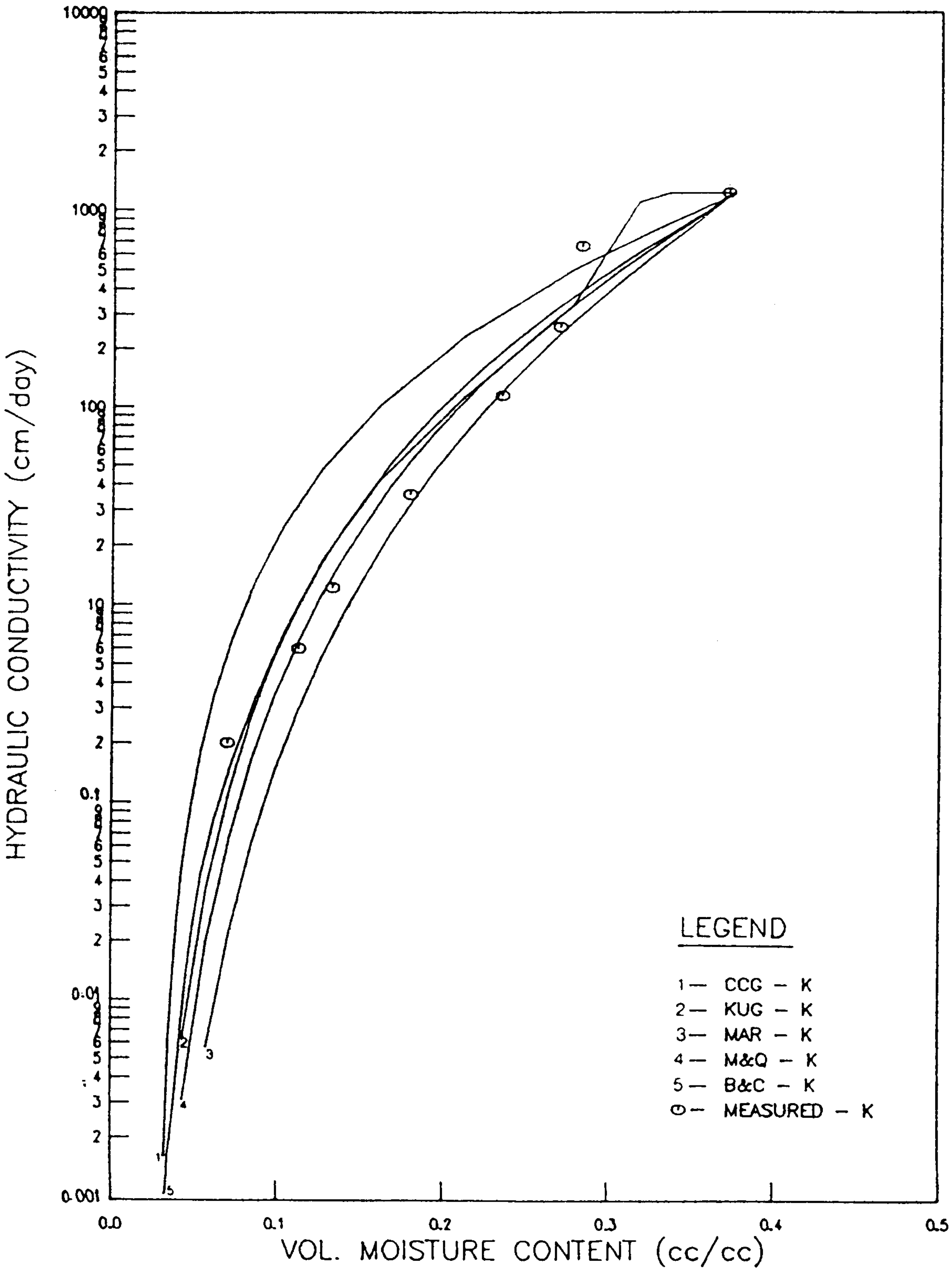


Figure 4.6: Comparison of computed K by different theoretical methods with experimentally measured K for Graded Sand.

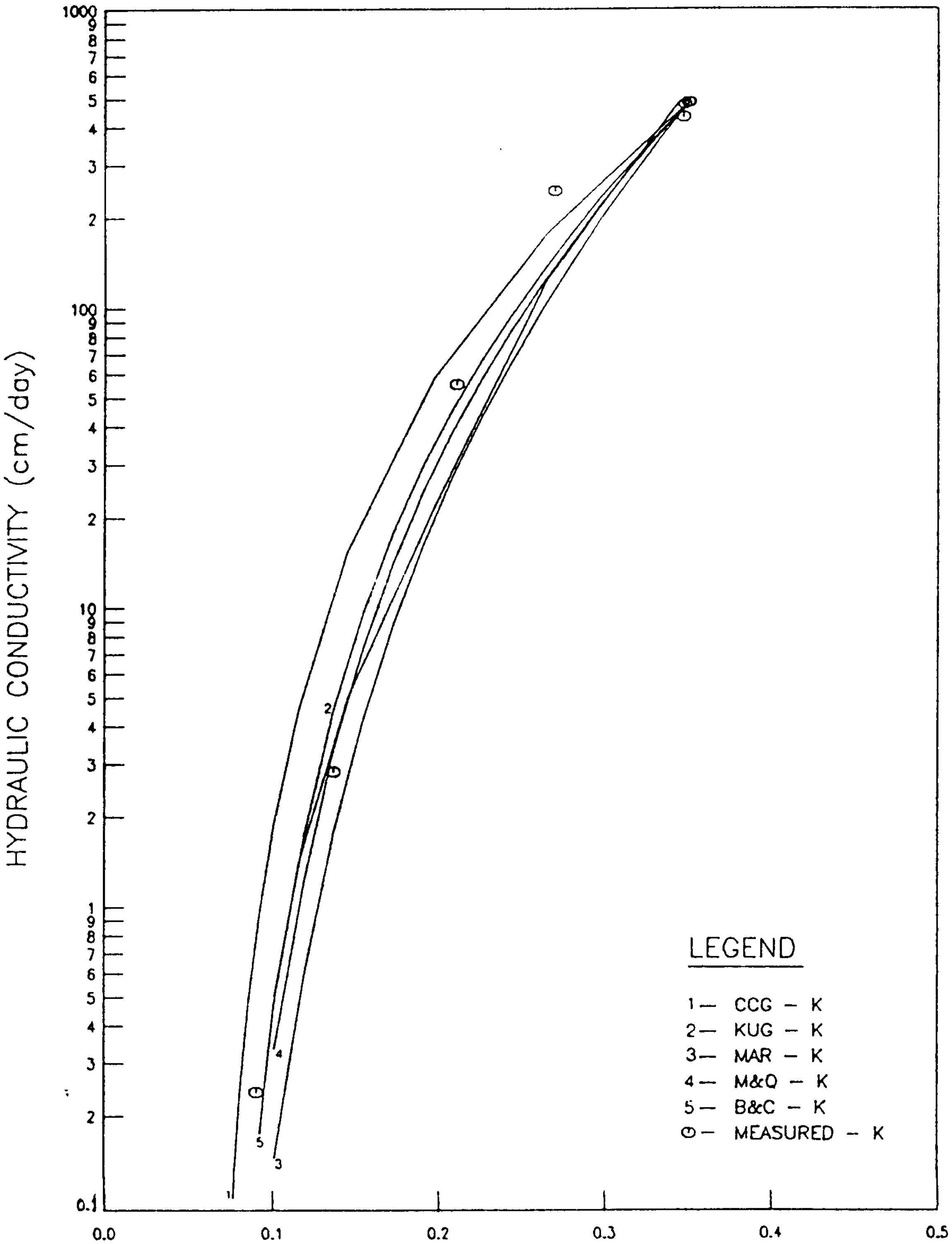


Figure 4.7: Comparison of computed K by different theoretical methods with experimentally measured K for Volcanic Sand.

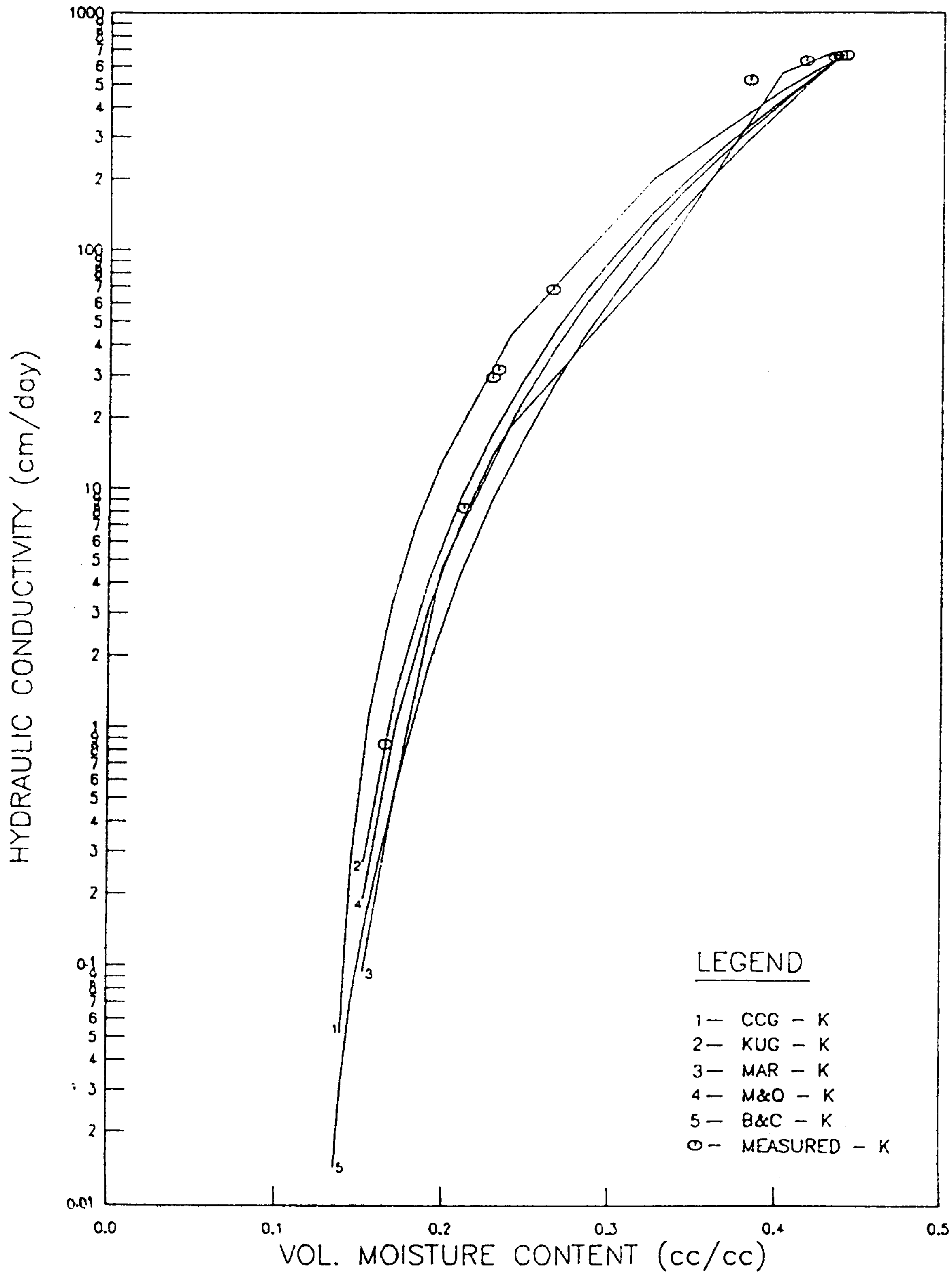


Figure 4.8: Comparison of computed K by different theoretical methods with experimentally measured K for Fragmented Mixture.

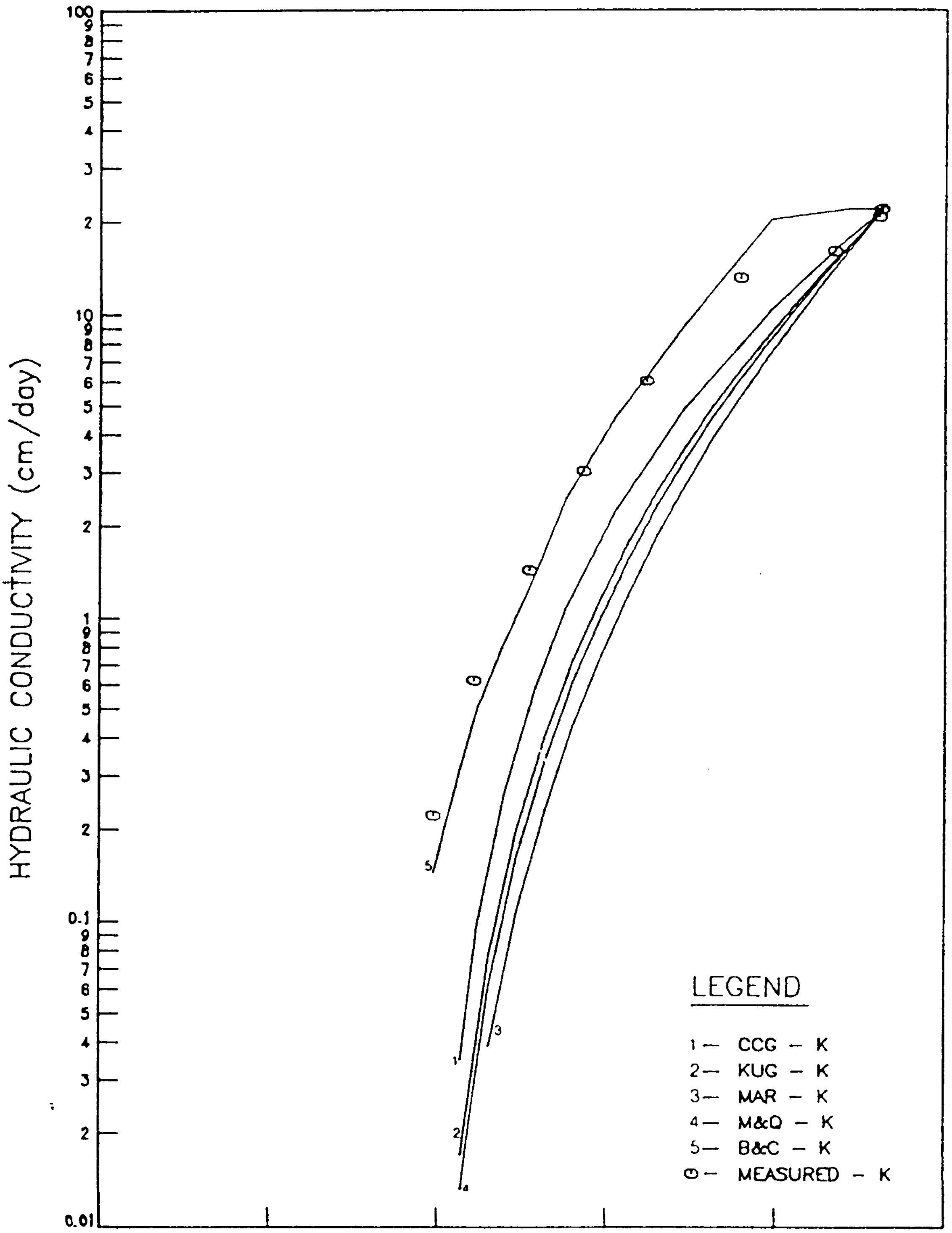


Figure 4.9: Comparison of computed K by different theoretical methods with experimentally measured K for Touchet Silt Loam 1.

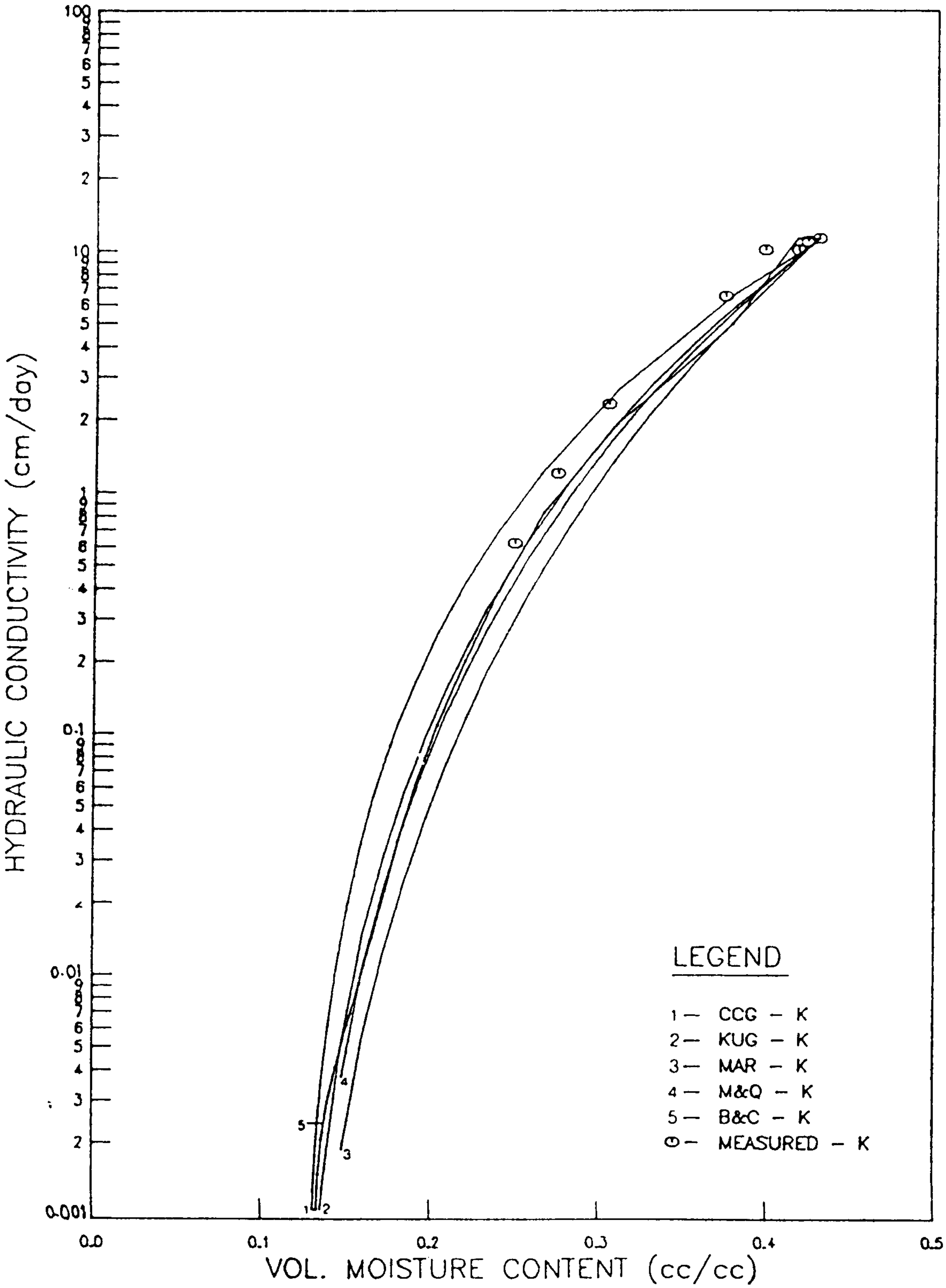


Figure 4.10: Comparison of computed K by different theoretical methods with experimentally measured K for Touchet Silt Loam 2.

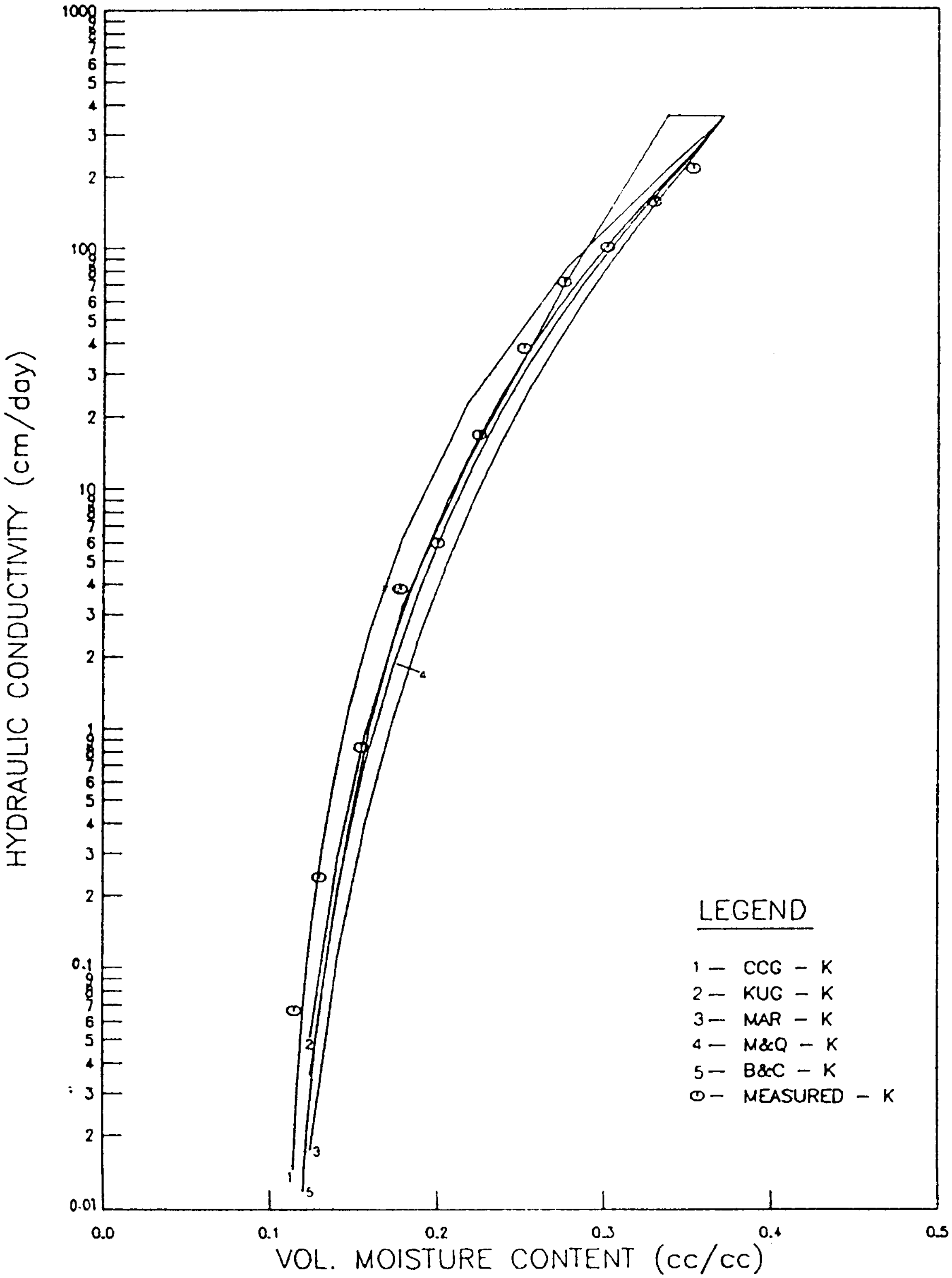


Figure 4.11: Comparison of computed K by different theoretical methods with experimentally measured K for Lakeland Fine Sand.

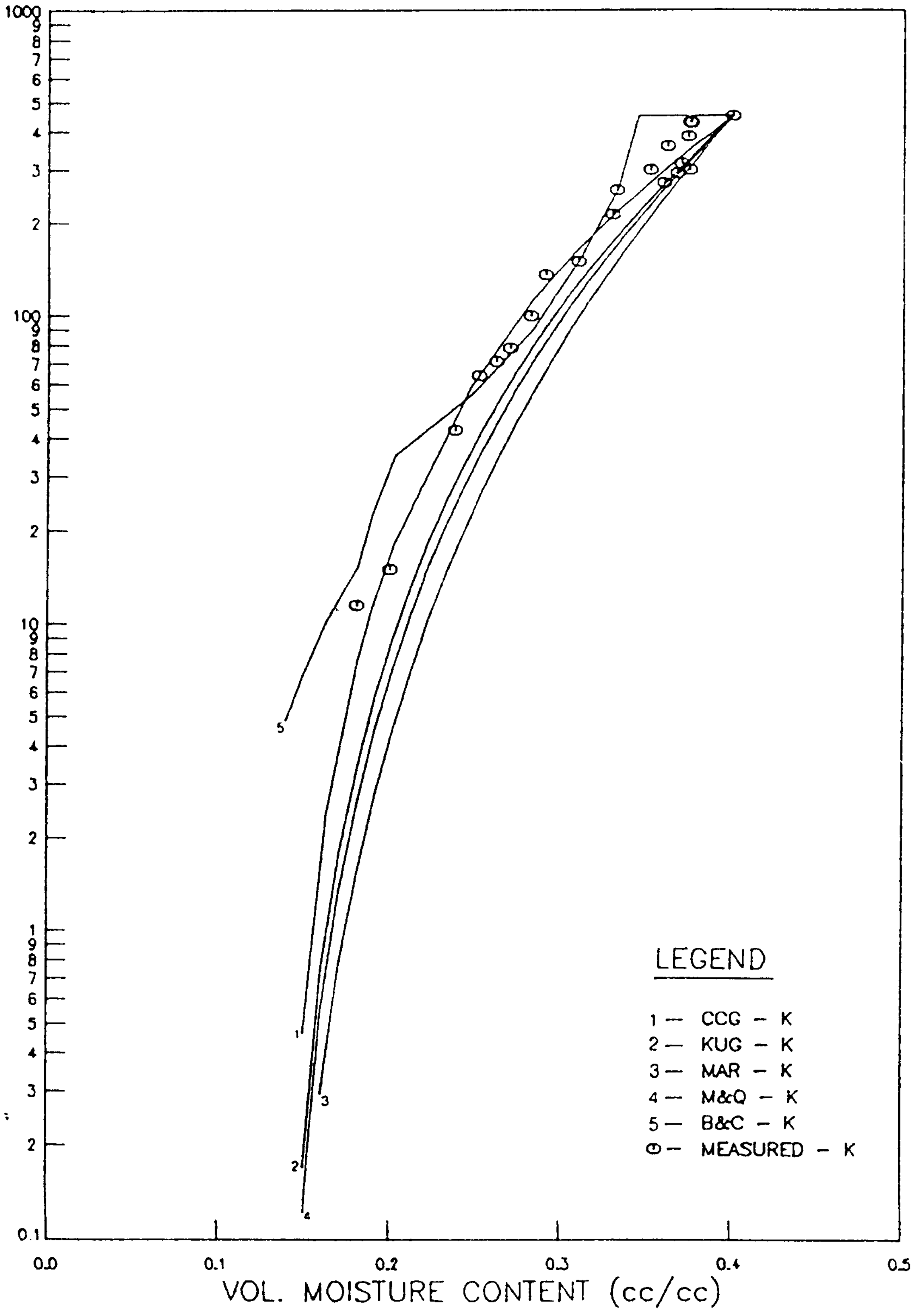


Figure 4.12: Comparison of computed K by different theoretical methods with experimentally measured K for Wide-Range Sand.

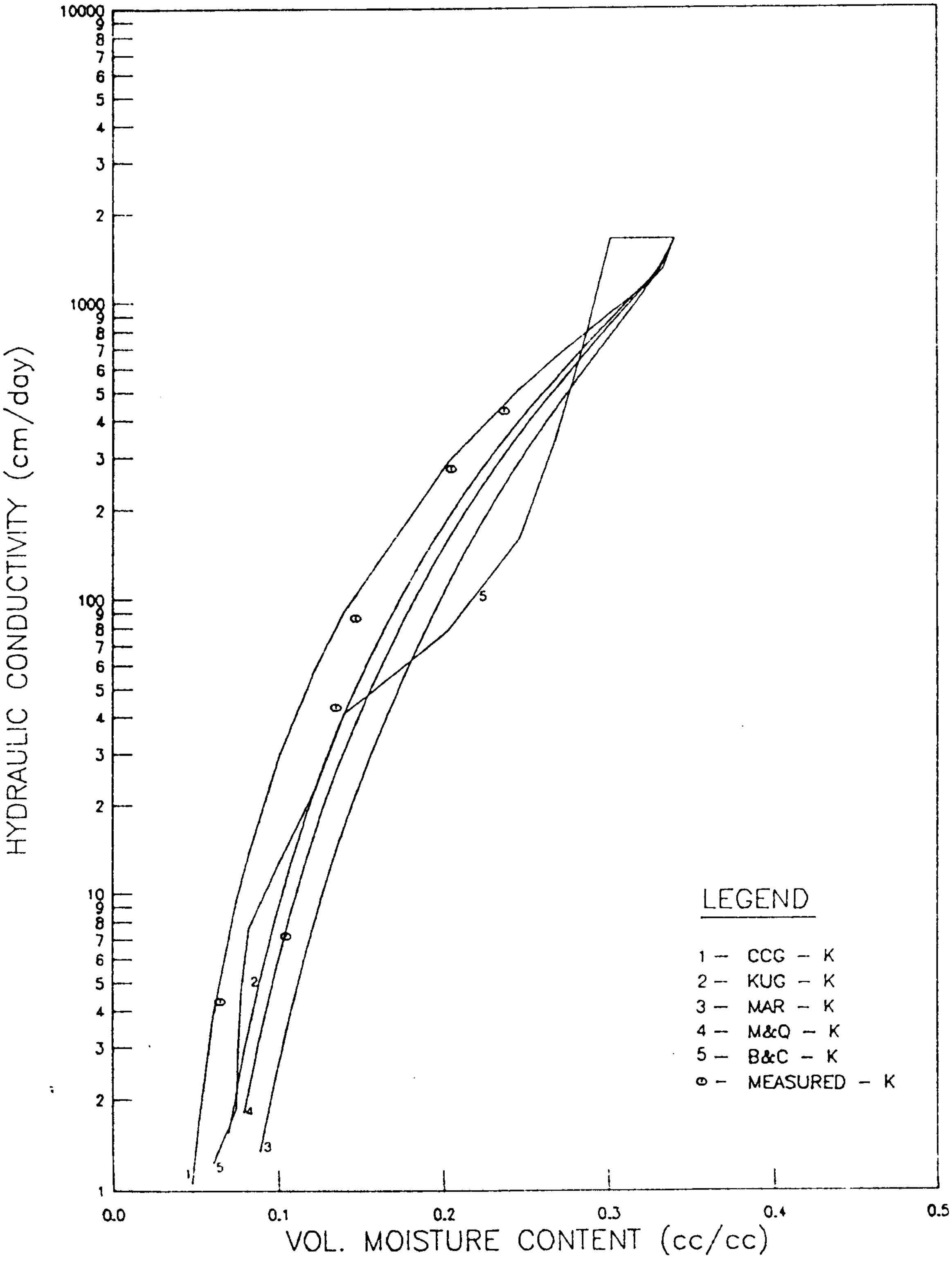


Figure 4.13: Comparison of computed K by different theoretical methods with experimentally measured K for Bruce Sand.

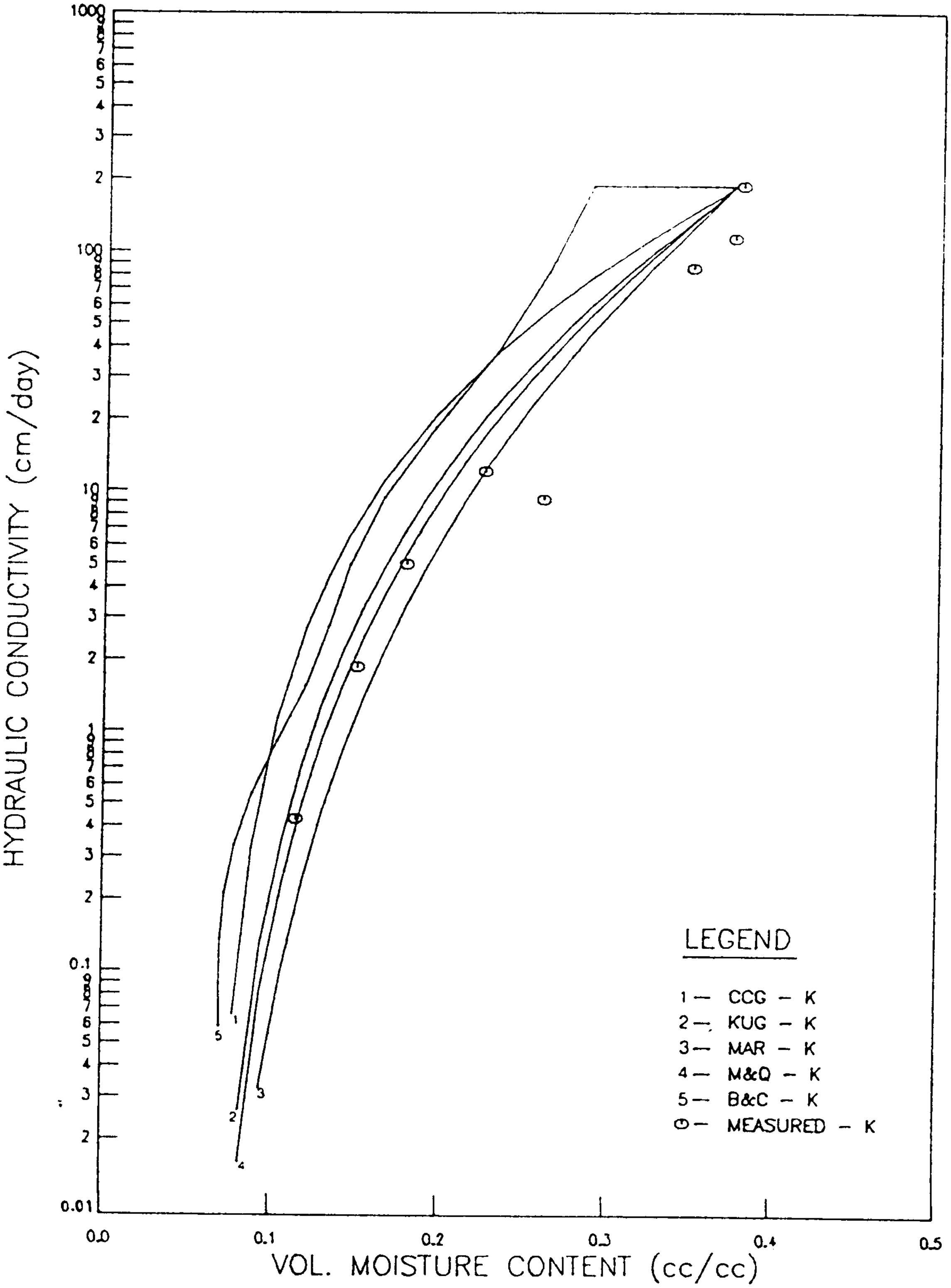


Figure 4.14: Comparison of computed K by different theoretical methods with experimentally measured K for Fine Sand 2.

4.2. Results of Regression Analysis

The physical properties of porous media that may effect the hyraulic conductivity and considered here are texture (relative amounts of sand, silt, and clay expressed as fractions), bulk density (ρ_b), porosity (ϕ), pore size distribution index (λ), and bubbling pressure (P_b). all of these properties are considered independent variables and regressed against hydraulic conductivity (K). The distribution of hydraulic conductivity and bubbling pressure data were tested and found to be log-normally distributed (see further discussion on this subject in Section 4.2.b). So these two variables were used as log-transformed. The silt, one of three components of textural analysis, was dropped and not used in regression analysis as the sum of the three components is one which creates the problems of multicollinearity. Thus, the final six variables considered in the regression against K are: 1) sand fraction; 2) clay fraction; 3) bulk density; 4) porosity, 5) pore size distribution index; and 6) log bubbling pressure. The independent variables were entered in regression equation step by step and their significance level was tested at 5 percent confidence level of F-distribution and/or tolerance level between 0.01 and 1.0. The first independent variable entered in the regression equation is that which has the highest correlation with the dependent variable. The results at each step are as following:

Step #1: The examination of correlation matrix (Appendix D) reveals that the variable sand with correlation coefficient of 0.9606 is highly correlated with the dependent variable log (K_s). Thus, sand is the first variable entered in the regression equation. The log (K_s) is regressed on variable sand and the least squares equation shown in Table 4.2(a). The overall F-test shows that regression equation is significant. The partial correlations of all variables not entered in the equation and the other statistics at Step #1 is shown in Table 4.2(a).

Step #2: The next variable to be entered in the regression is that with the highest partial correlation coefficient. This is variable clay with partial correlation coefficient of 0.51394. With clay as well as sand in the regression, the least square equation is shown in Table 4.2(b). This equation has the percentage R^2 of 94.36 percent and is significant, since the overall F = 335.03, which exceeds the critical value of $F_{crit}(2, 46, 0.95)$ = 3.206. Thus, the variable clay is also retained in the equation. The related statistics at the Step #2 is listed in Table 4.2(b).

Step #3: The stepwise method now selects as the next variable to enter the one most highly partially correlated with the dependent variable (given that variables sand and clay are already in the regression). This is seen to be variable log (P_b) with partial correlation coefficient of

-0.50738. The new equation with these three variables and the related statistics at this step is shown in Table 4.2(c). The percentage sequence of the multiple correlation coefficient, R^2 has increased from 94.36 percent to 95.81 percent. At this point, the three partial F-values for variables sand, clay, and log (P_b), which is higher than the critical value $F_{crit}(3, 45, 0.95) = 2.816$. Thus, log (P_b) is also accepted as a component of the regression equation as it is significant at 95 percent level of confidence.

Step #4: The variable porosity (ϕ) with the highest partial correlation coefficient of 0.6797 (Table 4.2(c)) is the next candidate to enter in the equation at this step. With this variable in the regression equation, the percentage R^2 of the equation is 97.75 percent, which is improved from the previous one, and is significant. The overall F-ratio is 477.48, which exceeds $F(4, 44, 0.95) = 2.594$. This shows that new variable provided a significant decrease in the residual sum of squares. the examination of partial F-values shows that the newly entered variable ϕ decreased the significance of variable clay (already in the equation). The clay has the lowest partial F-value of 2.60 which is not significant as compared with $F_{crit}(2, 44, 0.95) = 3.21$. The variable clay will be removed later in the backward stepping process, but is included in the regression equation for the ~~term~~ time being to see if the next variable to be entered can increase its significance. The standard deviation as percentage of dependent variable mean is 16.46 (Table 4.2(d)) shows that the regression equation at this step is more significaint than the equation at Step #3.

Steps #5, 6: The next variables entered are λ in Step #5 and ρ_b in Step #6. The statistics and regression equations at these steps are presented in Tables 4.2(e) and 4.2(f) respectively. The analysis of the statistics show that these variables did not increase the R^2 and the standard deviation as percentage of dependent variable mean is the same as was in Step #4. The partial F-levels are also lower than the F-distribution at 95 percent level of confidence. Therefore, ~~tehse~~ these two variables are not significant and will be removed in backward stepping.

Steps #7, #8: The lowest partial F-value of 1.22 (Table 4.2(F)) in Step #6 was for variable ρ_b. Thus, this variable is removed first in backward stepping. The next variable removed was in Step #8. The lowest partial F-value in Step #8 is that of clay (i.e., 2.60, and $F_{crit}(4, 44, 0.95) = 2.61$) which has increased from 2.44 after removal of ρ_b in Step #7. This means that the status of clay is right at the edge of the significance level of 95 percent, and is more significanit at a 90 percent level of F-distribution (i.e., $F_{crit}(4, 44, 0.90) = 2.07$). thus, clay is retained in the final regression equation. Another reason for retaining clay in the final equation is from the practical point of view as we know from experience the clay content affects hyraulic conductivity significantly. The related statistics at Steps #7 and 8 are shown in Tables 4.2(g) and 4.2(h) respectively.

The final regression equation contains the variables sand, clay, ϕ , and $\log(P_b)$. The R^2 of this equation is 97.75 percent and the total and partial F-values are significaint at F-distribution of 95 percent level of confidence. The average standard deviation as a percentage of the dependent variable mean is 16.46 (Table 4.2(h)). The resulting regression equation can be written as:

$$\log(K) = 2.5543 \text{ Sand} + 1.3633 \text{ Clay} + 4.2388\phi - 1.0613 \log(P_b) \qquad (4.1)$$

or

$$\log(K) + 1.0613 \log(P_b) = 2.5543 \text{ Sand} + 1.3633 \text{ Clay} + 4.2388\phi \qquad (4.2)$$

or

$$\log(K*P_b^{1.0613}) = 2.5543 \text{ Sand} + 1.3633 \text{ Clay} + 4.2388\phi \qquad (4.3)$$

or

$$K*P_b^{1.0613} = 10^{(2.5543 \text{ Sand} + 1.3633 \text{ Clay} + 4.2388\phi} \qquad (4.4)$$

or

$$K = \frac{10^{(2.5543 \text{ Sand} + 1.3633 \text{ Clay} + 4.2388\phi)}}{P_b^{1.0613}} \qquad (4.5)$$

where sand, clay and ϕ are fractions, bubbling pressure (P_b) has units of cm and K has units of cm/day.

Equation (4.5) has a R^2-value of 97.75 percent and a capability of predicting K-values with average accuracy of about 85.54 percent (i.e., 100-standard deviation 16.46) of experimentally determined K-values. The resulting equation can be useful for predicting hydraulic conductivity when basic properties of porous media involved in this equation are known.

The bubbling pressure (P_b) is determined from P_c vs S curve, which is relatively time consuming as compared with other physical properties included in equation (4.5). Another regression analysis was done excluding P_b and λ, and a regression equation was formulated using the same data used for previous regression analysis. The equation was not proved to be significa~~i~~nt as the R^2 for that equation was 95.36 percent and standard error was high (results not included here).

4.2.a: Discussion of Multiple Regression Analysis

A few points regarding the use of statistical techniques need atten~~d~~tion here.

Size of Data Set: The first, and the most important consideration is the number of data observations available for use in the regression. A very small number of observations will produce unrealistically high correlations with the use of multiple regression techniques. The analysis of m variables using only m+2 observations produces values of multiple correlation coefficients close to 1.0 and lowers the significance of the remaining unentered variables to zero, causing program default at that point. Hahn and Shapiro (1966) recommended the use of at least ten more data points than variables used, if possible, to assure sufficient degrees of freedom for statistical analysis. The data set used here, although not very big, meets the above criteria and covers a large variety of samples.

Transformations: Another point relates to the effect transformations themselves have on the regression. Taking the logarithm of the variable, for example, reduces the variance of the transformed data points. Inclusion of a transformed variable in a least squares regression provides assurance that the sum of squares of the deviations for the transformed variables is a minimum. Two variables, hydraulic conductivity (K) and bubbling pressure (P_b) were transformed. The distribution of K is known to be log-normal (Freeze, 1975). The values of P_b ranged from 3.4 cm to 89.5 cm, which have a large variance. The distribution of P_b values were tested and proved to be log-normal. the plot of log-normal distribution of P_b is present with other plots of predicted and observed values and plots of residuals in Appendix D.

Significance Levels: Significance levels are pre-selected as criteria is to admit or to reject the independent variable in the regression. It is possible to use different levels for entry and exit tests. If this is done however, it is not wise to set the 'exit level' smaller than the entry level or else one sometimes rejects independent variable just admitted (Draper and Smith, 1966). The F-distribution of significance level of 95 percent is conservative and the same is used at entry and exit levels in the above regression analysis. In this way, no variable was discriminated from entering or exiting from the regression by fixing different levels of significance.

Use of Stepwise Regression Analysis: This method is used when an optimal prediction equation with a few variables is required (Draper and Smith, ~~1966~~ 1981). Although all the suspected variables are allowed to be entered in the regression analysis, this method enters and removes the variables at pre-determined levels of significance. Also, it tells the significance of the regression equation at inclusion and removal of all the variables.

Table 4.2(a): Statistics of Multiple Regression Analysis at Step #1.

No. of Observations:	48
Dependent variable name:	log(K)
Level of significance for F-distribution:	95%
Variable not entered:	clay, ρ_b, ϕ, λ, log(P_b)
Variable entering:	Sand
Total F-ratio:	566.56
Percent variation explained R^2:	92.34
Standard deviation of residuals:	0.6429
Mean of dependent variable log(K):	2.1885
Std. dev. as % of dependent variable mean:	29.37
Degrees of freedom:	47

ANOVA

Source	d.f.	sums sq.	mean sq.	overall F
Total	48	253.6024		
Regression	1	234.1760	234.1760	566.56
Residuals	47	19.4264	0.413327	

Regression Coefficients and Confidence Limits

Var. Name	Mean	Reg. Coeff.	Std. Error	Partial F-Test
Sand	0.5504	3.85172	0.1618	566.56

Regression Equation: Log(K) = 3.85172 Sand

Partial Correlation Coeff. of Variables not in Regression

Variable	Partial Corr. Coeff.	Sq. Partial Corr. Coeff.
Clay	0.51394	0.26413
ρ_b	0.27149	0.07371
ϕ	0.48318	0.23346
λ	-0.38061	0.14486
Log(P_b)	-0.17085	0.02919

Table 4.2(b): Statistics of Multiple Regression Analysis at Step #2.

No. of Observations: 48
Dependent variable name: log(K)
Level of significance for F-distribution: 95%
Variable not entered: ρ_b, ϕ, λ, $\log(P_b)$

Variable entering: Clay
Total F-ratio: 335.03
Percent variation explained R^2: 94.36
Standard deviation of residuals: 0.5575
Mean of dependent variable log(K): 2.1885
Std. dev. as % of dependent variable mean: 25.47
Degrees of freedom: 46

ANOVA

Source	d.f.	sums sq.	mean sq.	overall F
Total				
Regression	2	239.30718	119.6536	335.03
Residuals	46	14.29523	0.3108	

Regression Coefficients and Confidence Limits

Var. Name	Mean	Reg. Coeff.	Std. Error	Partial F-Test
Sand	0.5504	2.78270	0.2982	87.10
Clay	0.1892	3.49838	0.8609	16.51

Regression Equation: log(K) = 2.78270 Sand + 3.49838 Clay

Partial Correlation Coeff. of Variables not in Regression

Variable	Partial Corr. Coeff.	Sq. Partial Corr. Coeff.
ρ_b	-0.21686	0.04703
ϕ	0.17450	0.03045
λ	-0.32124	0.10320
$\log(P_b)$	-0.50738	0.25743

Table 4.2(c): Statistics of Multiple Regression Analysis at Step #3.

No. of Observations:	48
Dependent variable name:	log(K)
Level of significance for F-distribution:	95%
Variable not entered:	b, ϕ, λ
Variable entering:	Log(P_b)
Total F-ratio:	343.36
Percent variation explained R^2:	95.81%
Standard deviation of residuals:	0.4857
Mean of dependent variable log(K):	2.1885
Std. dev. as % of dependent variable mean:	22.19%
Degrees of freedom:	45

ANOVA

Source	d.f.	sums sq.	mean sq.	overall F
Total	48	253.6024		
Regression	3	242.9873	80.9958	343.36
Residuals	45	10.6151	0.23589	

Regression Coeffs. and Confidence Limits

Var. Name	Mean	Reg. Coeff.	Std. Error	Partial F-Test
Sand	0.5504	3.6628	0.3422	114.54
Clay	0.1892	4.9157	0.8315	34.95
log(P_b)	1.3630	-0.5764	0.1459	15.60

Regression Equation: log(K) = 3.6628 Sand + 4.9157 clay
- 0.5764 log(P_b)

Partial Correlation Coeff. of Variables not in Regression

Variable	Partial Corr. Coeff.	Sq. Partial Corr. Coeff.
ρ_b	0.12639	0.01674
ϕ	0.67971	0.46201
λ	-0.19938	0.03975

Table 4.2(d): Statistics of Multiple Regression Analysis at Step #4.

No. of Observations:	48
Dependent variable name:	log(K)
Level of significance for F-distribution:	95%
Variable not entered:	ρ_b, λ
Variable entering:	ϕ
Total F-ratio:	477.48
Percent variation explained R^2:	97.75%
Standard deviation of residuals:	0.36027
Mean of dependent variable log(K):	2.1885
Std. dev. as % of dependent variable mean:	16.46%
Degrees of freedom:	44

ANOVA

Source	d.f.	sums sq.	mean sq.	overall F
Total	48	253.6024		
Regression	4	247.8916	61.9729	477.48
Residuals	44	5.7108	0.12979	

Regression Coefficients and Confidence Limits

Var. Name	Mean	Reg. Coeff.	Std. Error	Partial F-Test
Sand	0.5504	2.5543	0.3114	67.28
Clay	0.1892	1.3633	0.8452	2.60
ϕ	0.4657	4.2388	0.6896	37.79
$\log(P_b)$	1.3630	-1.0613	0.1339	62.79

Regression Equation: $\log(K) = 2.5543\ \text{Sand} + 1.3633\ \text{Clay} + 4.2388\,\phi - 1.06131\ \log(P_b)$

Partial Correlation Coeff. of Variables not in Regression

Variable	Partial Corr. Coeff.	Sq. Partial Corr. Coeff.
ρ_b	-0.14323	0.02051
λ	0.15136	0.02291

Table 4.2(e): Statistics of Multiple Regression Analysis at Step #5.

No. of Observations: 48
Dependent variable name: log(K)
Level of significance for F-distribution: 95%
Variable not entered: ρ_b

Variable entering: λ
Total F-ratio: 382.26
Percent variation explained R^2: 97.80%
Standard deviation of residuals: 0.36023
Mean of dependent variable log(K): 2.1885
Std. dev. as % of dependent variable mean: 16.46%
Degrees of freedom: 43

ANOVA

Source	d.f.	sums sq.	mean sq.	overall F
Total	48	253.60242		
Regression	5	248.02244	49.60448	382.26
Residuals	43	5.57998	0.1297670	

Regression Coefficients and Confidence Limits

Var. Name	Mean	Reg. Coeff.	Std. Error	Partial F-Test
Sand	0.5504	2.2355	0.4446	25.28
Clay	0.1892	1.3221	0.8461	2.44
ϕ	0.4657	4.5780	0.7678	35.55
λ	1.8277	0.07255	0.0723	1.01
$\log(P_b)$	1.3630	-1.1397	0.1551	54.03

Regression Equation: $\log(K) = 2.2355 \text{ Sand} + 1.3221 \text{ Clay} + 4.5780\, \phi + 0.07255\, \lambda - 1.1397 \log(P_b)$

Partial Correlation Coeff. of Variables not in Regression

Variable	Partial Corr. Coeff.	Sq. Partial Corr. Coeff.
ρ_b	-0.16812	0.02826

Table 4.2(f): Statistics of Multiple Regression Analysis at Step #6.

No. of Observations:	48
Dependent variable name:	log(K)
Level of significance for F-distribution:	95%
Variable not entered:	none left

Variable entering:	ρ_b
Total F-ratio:	320.39
Percent variation explained R^2:	97.86%
Standard deviation of residuals:	0.35931
Mean of dependent variable log(K):	2.1885
Std. dev. as % of dependent variable mean:	16.42%
Degrees of freedom:	42

ANOVA

Source	d.f.	sums sq.	mean sq.	overall F
Total	48	248.6024		
Regression	6	243.1801	41.3634	320.39
Residuals	42	5.4223	0.12910	

Regression Coefficients and Confidence Limits

Var. Name	Mean	Reg. Coeff.	Std. Error	Partial F-Test
Sand	0.5504	2.3395	0.4534	26.63
Clay	0.1892	1.8209	0.9570	3.62
ρ_b	1.3971	-0.2850	0.2578	1.22
ϕ	0.4657	4.9010	0.8197	35.75
λ	1.8277	0.0839	0.0728	1.33
$\log(P_b)$	1.3630	-1.0872	0.1618	45.16

Regression Equation: $\log(K) = 2.3395\ \text{Sand} + 1.8209\ \text{Clay} - 0.2850\ \rho_b + 4.9010\ \phi + 0.0839\lambda - 1.0872 \log(P_b)$

Partial Correlation Coeff. of Variables not in Regression

Variable	Partial Corr. Coeff.	Sq. Partial Corr. Coeff.

no variable is left outside the regression.

Table 4.2(g): Statistics of Multiple Regression Analysis at Step #7.

No. of Observations: 48
Dependent variable name: log(K)
Level of significance for F-distribution: 95%
Variable not entered: ρ_b

Variable removed: ρ_b
Total F-ratio: 382.26
Percent variation explained R^2: 97.80%
Standard deviation of residuals: 0.36023
Mean of dependent variable log(K): 2.1885
Std. dev. as % of dependent variable mean: 16.46%
Degrees of freedom: 43

Source	d.f.	ANOVA sums sq.	mean sq.	overall F
Total	48	254.60240		
Regression	5	248.02242	49.6045	382.26
Residuals	43	5.57998	0.12977	

Regression Coefficients and Confidence Limits

Var. Name	Mean	Reg. Coeff.	Std. Error	Partial F-Test
Sand	0.5504	2.2355	0.4446	25.28
Clay	0.1892	1.3221	0.8461	2.44
ϕ	0.4657	4.5780	0.7628	35.55
λ	1.8277	0.0725	0.0723	1.01
$\log(P_b)$	1.3630	-1.1397	0.1551	54.03

Regression Equation: log(K) = 2.2355 Sand + 1.3221 Clay +
4.5780 + 0.0725 -
1.1397 $\log(P_b)$

Partial Correlation Coeff. of Variables not in Regression

Variable	Partial Corr. Coeff.	Sq. Partial Corr. Coeff.
ρ_b	-0.16812	0.02826

a

Table 4.2(h): Statistics of Multiple Regression Analysis at Step #8.

No. of Observations: 48
Dependent variable name: log(K)
Level of significance for F-distribution: 95%
Variable not entered: ρ_b, λ

Variable removed:
Total F-ratio: 477.48
Percent variation explained R^2: 97.75%
Standard deviation of residuals: 0.36027
Mean of dependent variable log(K): 2.1885
Std. dev. as % of dependent variable mean: 16.46%
Degrees of freedom:

		ANOVA		
Source	**d.f.**	**sums sq.**	**mean sq.**	**overall F**
Total	48	253.6024		
Regression	4	247.8916	61.97290	477.48
Residuals	44	5.71082	0.12979	

Regression Coefficients and Confidence Limits

Var. Name	Mean	Reg. Coeff.	Std. Error	Partial F-Test
Sand	0.5504	2.5543	0.3114	67.28
Clay	0.1892	1.3633	0.8452	2.60
ϕ	0.4657	4.2388	0.6896	37.79
$\text{Log}(P_b)$	1.3630	-1.0613	0.1339	62.29

Regression Equation: $\log(K) = 2.5543\,\text{Sand} + 1.3633\,\text{Clay} + 4.2388\phi - 1.0613\log(P_b)$

Partial Corr. Coeff. of Variables not in Regression

Variable	Partial Corr. Coeff.	Sq. Partial Corr. Coeff.
ρ_b	-0.14323	0.02051
λ	0.15136	0.02291

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

A. A comparitive study of a number of theoretical methods for predicting unsaturated hydraulic conductivity was made, and the accuracy of the different methods under different conditions of porous media were studied. The Brooks and Corey method best predicted unsaturated K for almost all kinds of proous media used during this study and the whole range of moisture content considered. The conclusion supports the results of the study conducted by Bruce (1972). The Childs and Collis-George method always predicted higher K values, but that method was close to experimental values near lower saturations. The Marshall method usually computed lower K values. Kunze, et al. and Millington & Quirk method predicted K values close to each other, but the latter matched well with experimental data at the middle range of saturations for the samples considered. Kunze's method predicted values of K next to that of M&Q method.

B. A computer program was modified and supplemented with a computation of hydraulic conductivity values based on the Brooks and Corey method.

C. A relationship between saturated hydraulic conductivity (K_s) and four properties of porous media (i.e., sand fraction, clay, porosity, and bubbling pressure) was developed. A stepwise regression analysis was used to correlate these properties and the resulting regression equation has the R^2 value of 97.75% which is highly significant for predicting the hydraulic conductivity value close to experimentally determined K values.

5.2. Recommendations

A. A large set of samples of the porous media with large pore size range is needed for the most accurate validity of each theoretical prediction method of unsaturated hydraulic conductivity. The study will be more effective if capillary pressure - desaturation data for all of the samples were obtained under the same conditions using the same fluid.

B. More data should be accumulated in order to study the correlations between the parameters measured here. Other physical properties (i.e., formation factor and surface area of the particles) should be included in view of the importance to flow through porous media.

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APPENDIX A

THIS APPENDIX PRESENTS ~~THE~~ SAMPLE CALCULATIONS
FOR DETERMINING~~I~~ BUBBLING PRESSURE,
PORE SIZE DISTRIBUTION INDEX,
TEXTURAL ANALYSIS AND
SATURATION AS A FUNCTION OF PRESSURE.
THE RESULTING PLOTS OF P_c VS. S ARE
ALSO PRESENTED HERE.

Determiination of P_b and

To determine the bubbling pressure (P_b) and pore size distribution index (λ), it is necessary to plot $\log S_e$ versus $\log P_c$, which necessitates determining the residual saturation (S_r). Since the saturation (S) is related to S_e by the relation

$$S_e = \frac{S - S_r}{1 - S_r} \qquad \text{for } S_r < S \quad 1.0$$

it is necessary to have measured values of S as a function of P_c to determine S_r. The P_c and S value for Fine Sand 1 are shown in Table A.1 and the P_c Vs. S data are plotted in Figure A.1.

An approximate value of S_r is obtained by selecting a value of S at which the curve P_c vs. S appears to approach a vertical asymtote as shown in Figure A.1. With this estimate of S_r, tentative value of $\log S_e$ are computed. the computed values with first estimate of $S_r = 1.70$ (Table A.1) are plotted as a function of P_c on a log-log axes. Usually the plot will not be a straight line, but an intermediate portion of the computed values will fall on a straight line as shown in Figure A.2.

A second estimate of S_r is then obtained such that a value of S_e in the high capillary pressure range which does not lie on a straight line will fall on a straignt line as shown in Figure A.2. The second estimate of S_r is usually adequate, and all of the points will lie suficiently close to a straight line when the points are recomputed using the new value of S_r. If that is not the case, the process is repeated until a value of S_r is obtained that results in a straight line for most values of $P_c > P_b$.

The value of P_b is the intercept on $\log P_c$ vs $\log S_e$ plot in Figure A.2, where the straight line meets the ordinate representing $S_e = 1.0$, and the negative slope of the straight line is the value of pore size index (λ).

Table A.1: Capillary pressure - saturation data for Fine Sand 1.

Pressure (cm)	Saturation (fraction)	Effective Saturation (fraction)
12.8	0.990	0.988
27.8	0.980	0.976
30.8	0.962	0.954
31.8	0.950	0.940
34.8	0.926	0.911
36.8	0.901	0.881
39.8	0.855	0.825
42.8	0.788	0.745
45.8	0.716	0.658
48.8	0.627	0.551
52.8	0.503	0.401
57.7	0.393	0.269
64.8	0.314	0.173
71.7	0.273	0.124
74.4	0.262	0.111
92.1	0.217	0.057
150.1	0.174	0.005

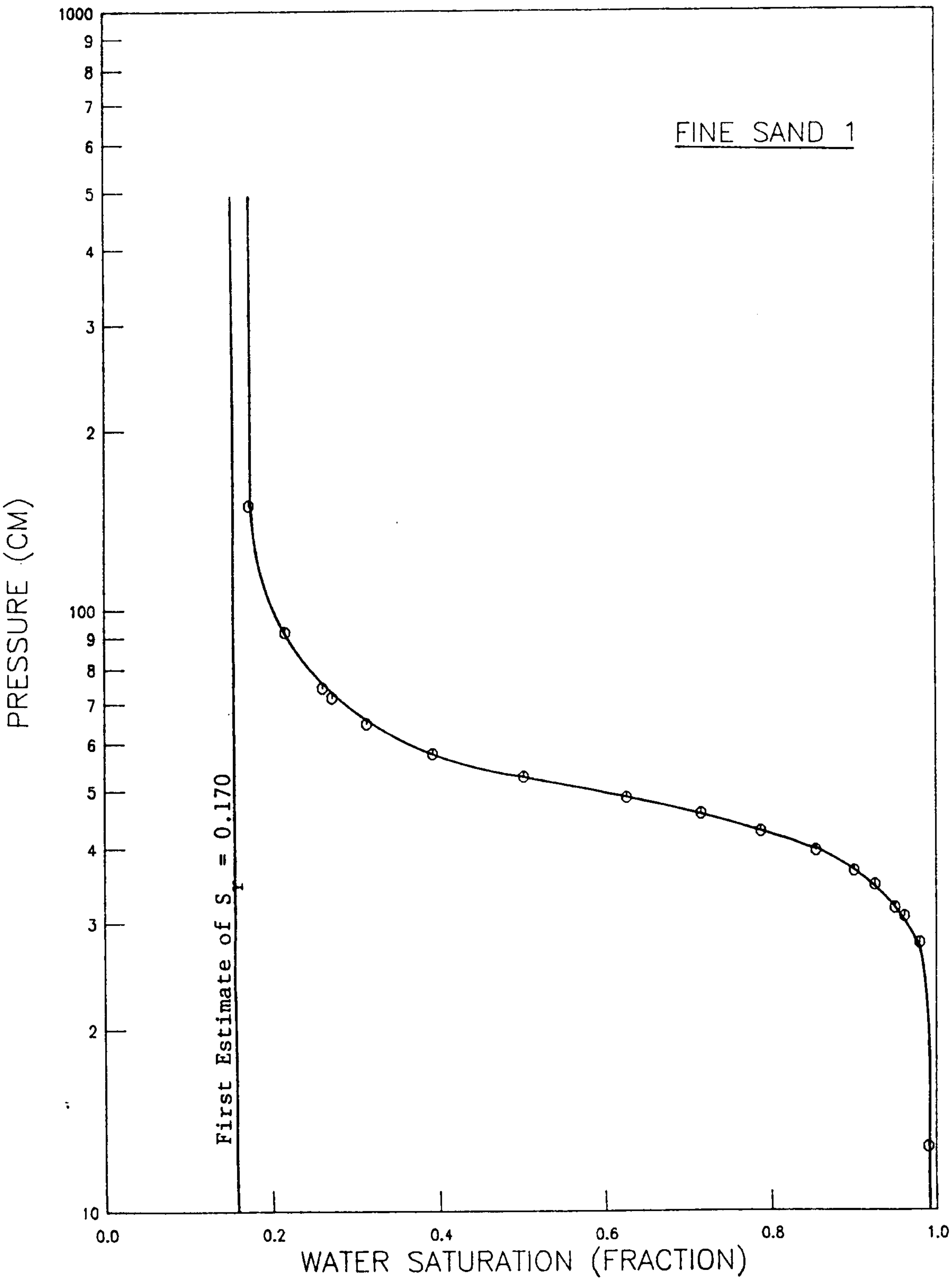

Figure A.1: Capillary pressure head as a function of saturation.

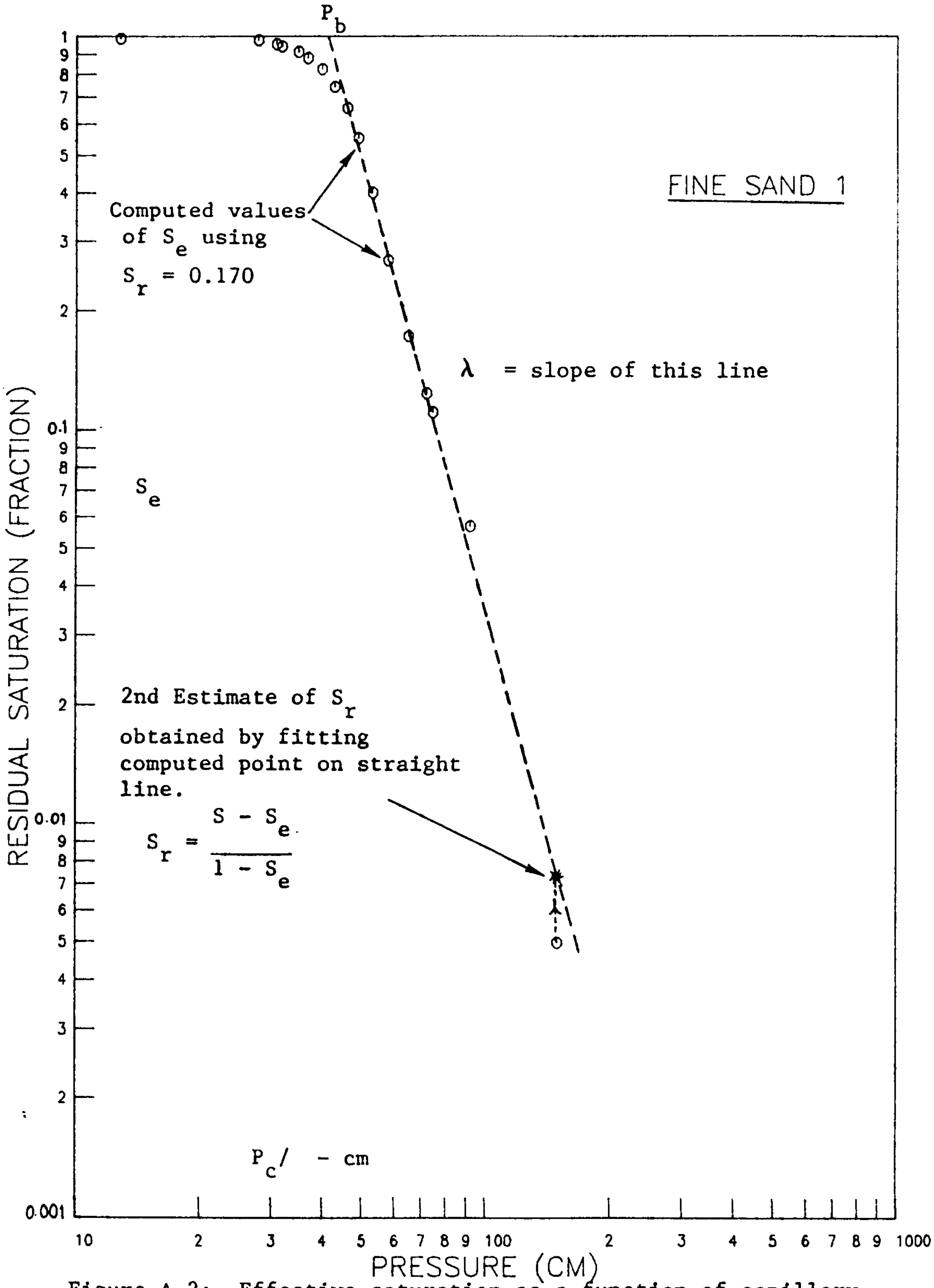

Figure A.2: Effective saturation as a function of capillary pressure head.

Textural Analysis

Sample Zenith #2

Weight of sample (W_s) = 50 gm

Hydrometer corrected reading at 40 seconds;

$$R_{c_{40}} = R_{a_{40}} - \text{zero correction} + C_T$$

$$= 22.8 - 5 + 0.97 = 18.77$$

$$\text{Finer percent} = \frac{R_{c_{40}}}{W_s} = \frac{18.77}{50} \times 100 = 37.54\%$$

$$\text{Coarse percent} = 100 - 37.54 = 62.46\% \qquad \underline{\text{SAND}}$$

Hydrometer corrected reading at 2 hours;

$$R_{c_{2hrs}} = R_{a_{2hrs}} - \text{zero correction} + C_T$$

$$= 16 - 5 + 0.82 = 11.82$$

$$\text{Finer percent} = \frac{R_{c_{2\,hrs}}}{W_s} = \frac{11.82}{100} \times 100 = 23.64\% \ \underline{\text{CLAY}}$$

$$100 - (\%\ \text{Sand} + \%\ \text{Clay}) = 100 - (62.46 + 23.64)$$

$$= 13.90\% \qquad \underline{\text{SILT}}$$

Here

R_c = corrected reading of Hydrometer

R_a = observed reading on Hydrometer

C_T = correction for temperature

and zero correction is for the use of Amyl Alcohol as foam dispenying agent

Determination of Water Saturation at Low Pressure Range

Sample Zenith #2

Wt. of dry sample (W_d) $= 85.25$ gm

Bulk density (ρ_b) $= 1.25$ gm/cm^3

Particle density (ρ_s) $= 2.484$ gm/cm^3

Total volume of sample (V_t) $= \frac{W_d}{\rho_b} = 68.40$ cm^3

Volume of solid particles (V_s) $= \frac{W_d}{\rho_s} = 34.3196$ cm^3

Void ($V_t - V_s$) $= 34.0804$

Porosity (ϕ) $= 1 - \frac{\rho_b}{\rho_s} = 0.496$

Pressure (cm)	Water Released (cm^3)	Cumulative Water Released (cm^3)	Saturation*
10.0	0	0	1.0000
12.7	0.54	0.54	0.9842
25.4	0.60	1.14	0.9665
38.1	3.10	4.24	0.8756
50.8	1.99	6.23	0.8172
63.5	1.91	8.14	0.7612
77.5	3.39	11.53	0.6617
88.9	1.61	13.14	0.6144
101.6	1.80	14.94	0.5616
114.3	1.12	16.06	0.5288
127.0	1.16	17.22	0.4947
139.7	0.91	18.13	0.4680
152.4	0.59	18.72	0.4507
165.1	0.48	19.20	0.4366
177.8	0.58	19.78	0.4196
190.5	0.40	20.18	0.4079
203.2	0.23	20.41	0.4011

---

*Saturation $= 1 - \frac{\text{Comm. water released}}{\text{Void}}$

Determination of Water Saturation at High Pressure

The sample calculations for sample Zenith #2 for determination of water saturation at pressure of 1 bar are shown here. The duplicate samples were used and the results were averaged.

Sample #	W_{wet} (gm)	W_{dry} (gm)	W_{water} (gm)	WC (gm/gm)
Zenith #2a	24.36	21.82	2.54	0.1164
Zenith #2b	24.88	22.03	2.85	0.1215

$$\text{Average WC} = \frac{(0.1164 + 0.1215)}{2} = 0.1229 \text{ gm/gm}$$

Porosity of the sample ( ) = 0.496

Bulk density of the sample ($_b$) = 1.25 gm/cm^2

$$\text{Volumetric water content ( )} = \text{WC} \times {}_b$$

$$= 0.1229 \times 1.25$$

$$= 0.1536 \text{ cm}^3/\text{cm}^3$$

$$\text{Saturation of the sample (S)} = -$$

$$= \frac{0.1536}{0.496} = 0.3097$$

or S = 30.97%

Here

W_{wet} = weight of the wet sample when removed from pressure chamber (gm)

W_{dry} = weight of the oven dry sample (gm)

W_{water} = (W_{wet} - W_{dry}) i.e., the weight of water left in the sample at 1 bar pressure

WC = water content per unit weight of oven dry weight

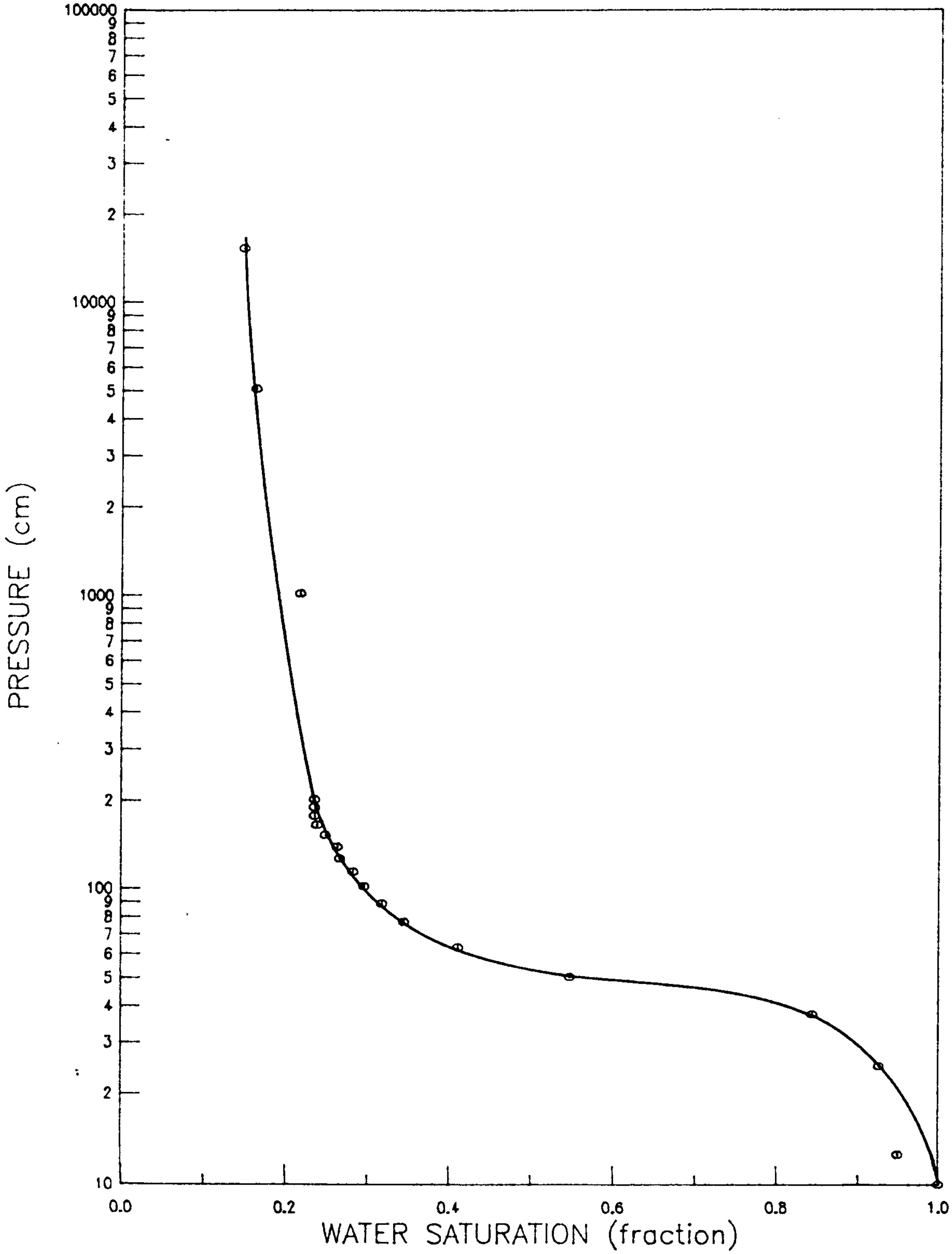

Figure A.3: Plot of Pressure Vs Saturation data for sample Zenith #1.

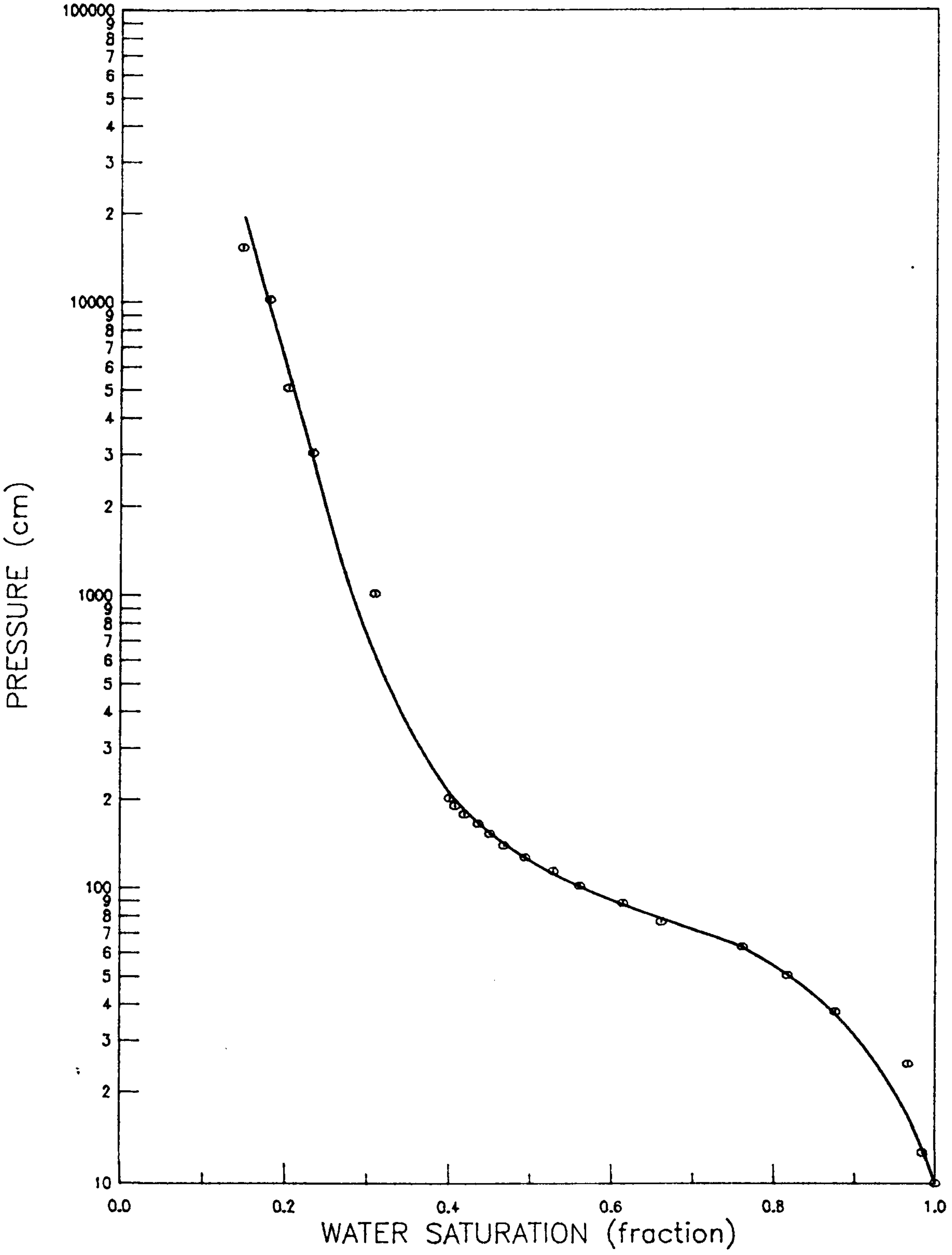

Figure A.4: Plot of Pressure Vs Saturation data for sample Zenith #2.

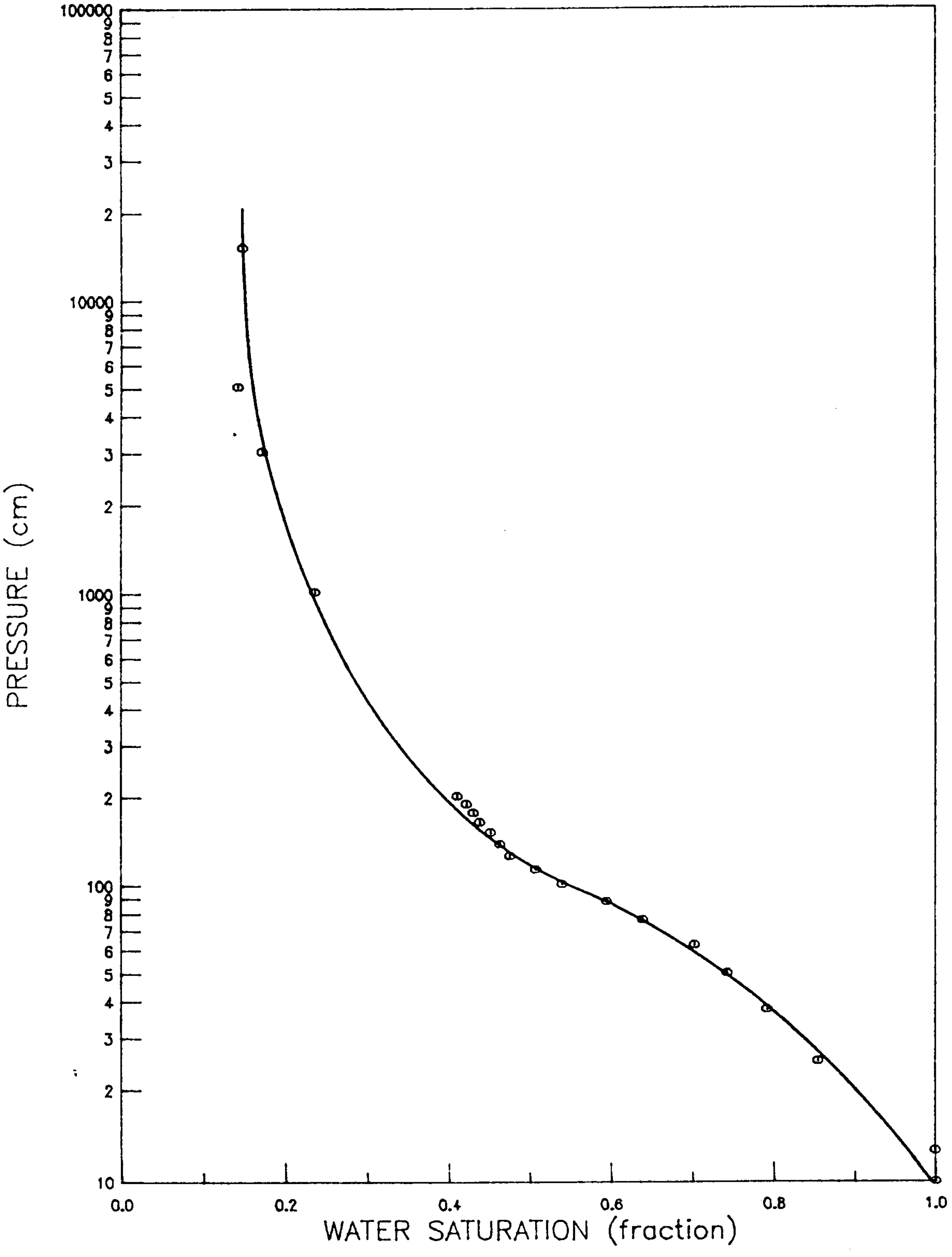

Figure A.5: Plot of Pressure Vs Saturation data for sample Zenith #3.

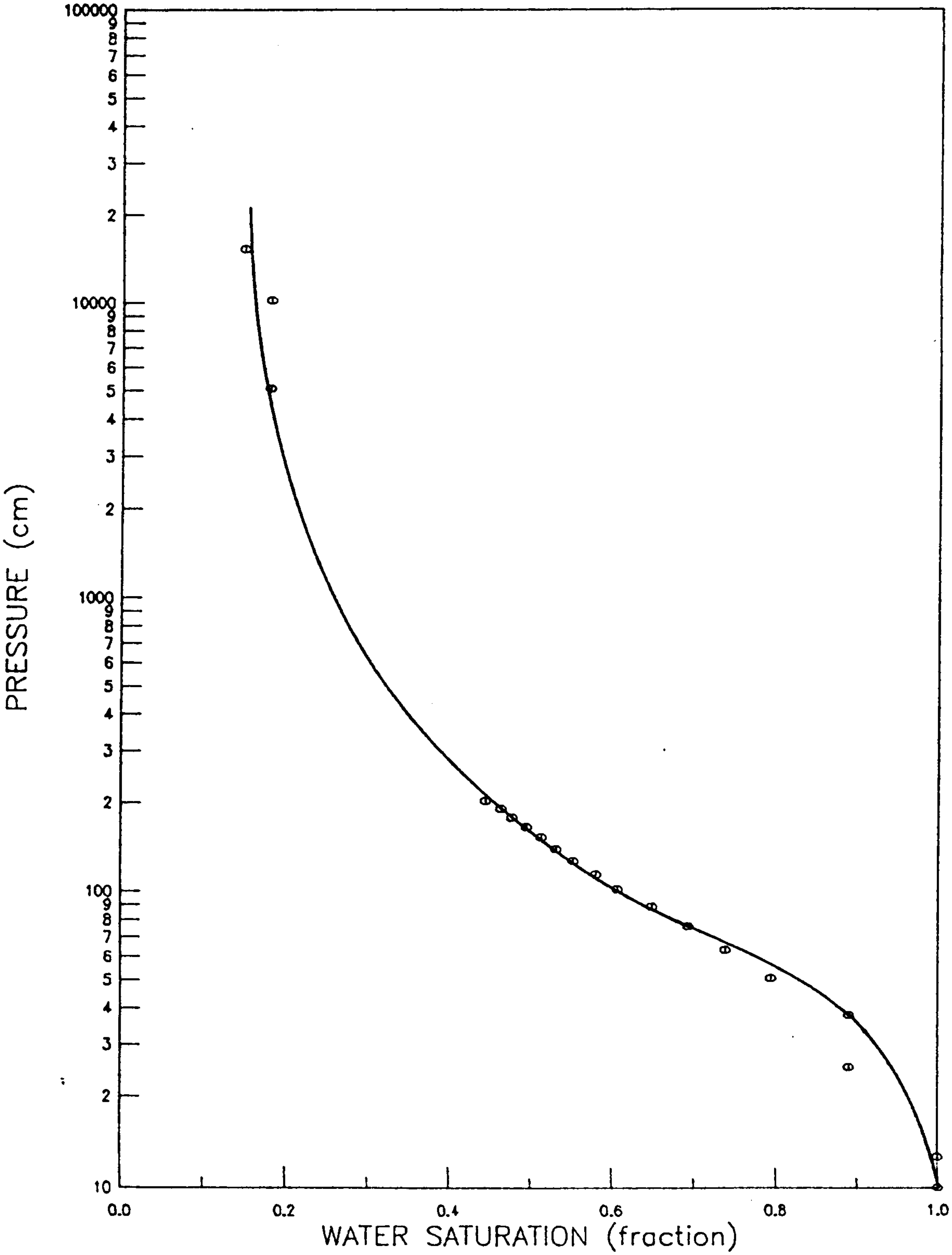

Figure A.6: Plot of Pressure Vs Saturation data for sample Zenith #4.

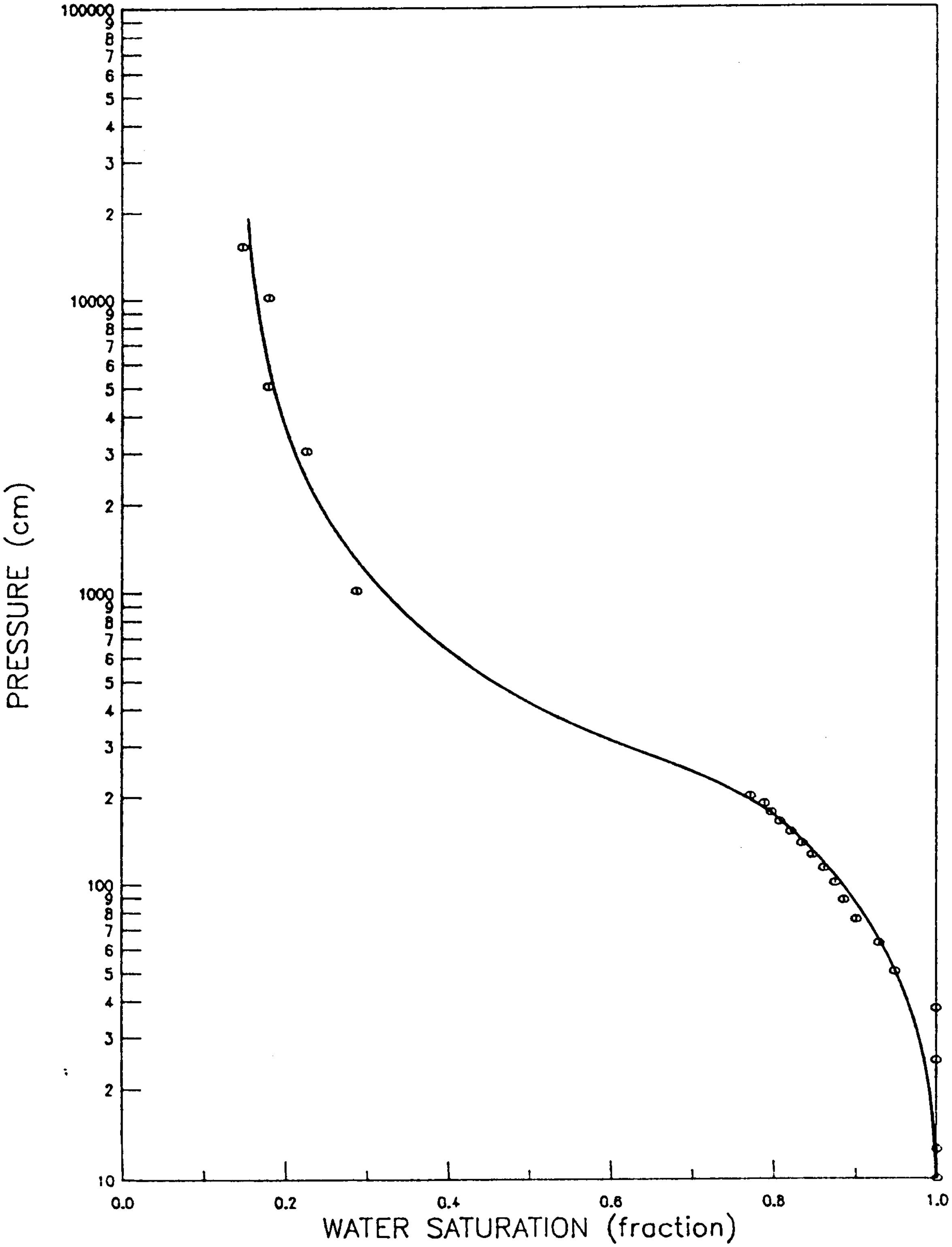

Figure A.7: Plot of Pressure Vs Saturation data for sample Zenith #5.

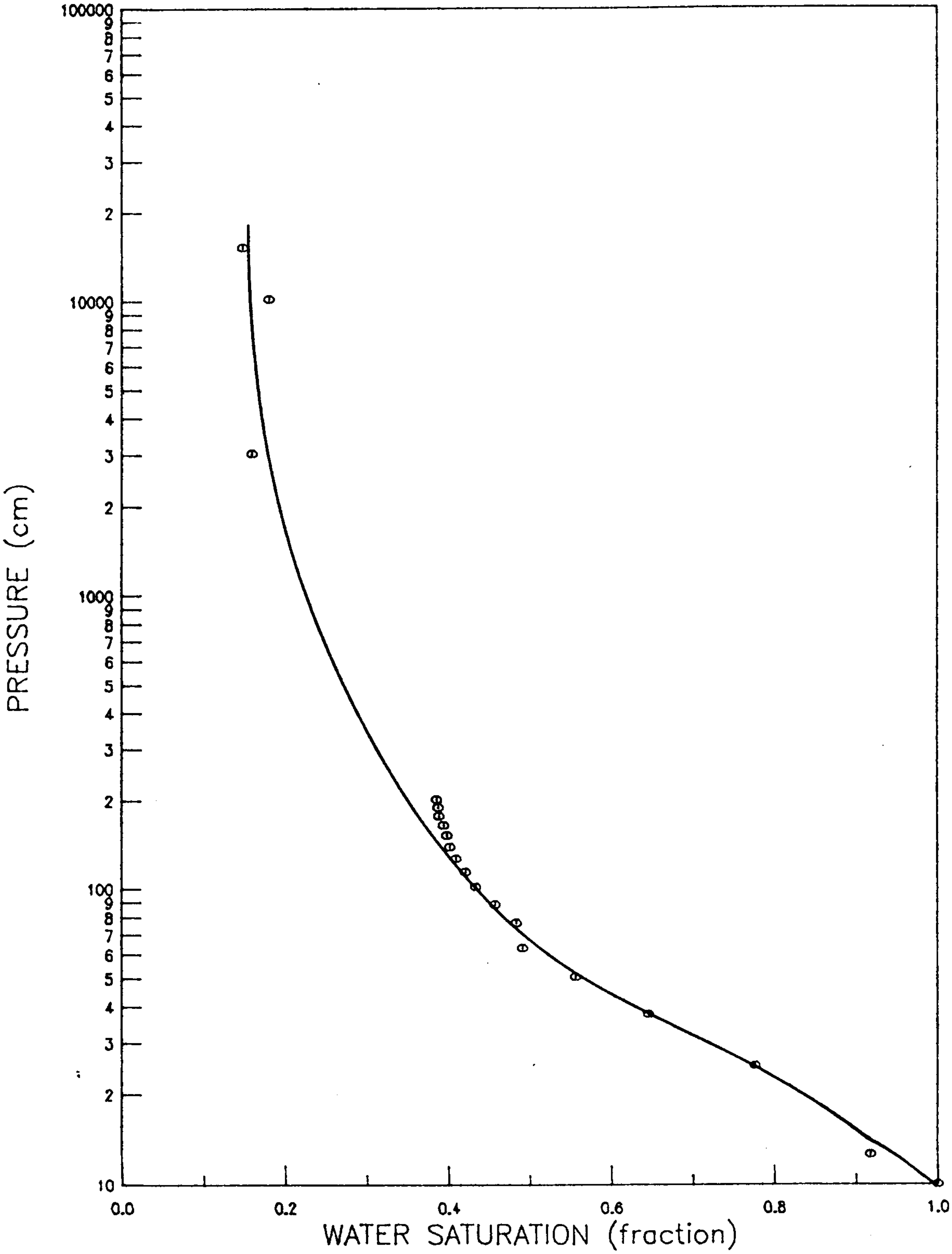

Figure A.8: Plot of Pressure Vs Saturation data for sample Burrton #1.

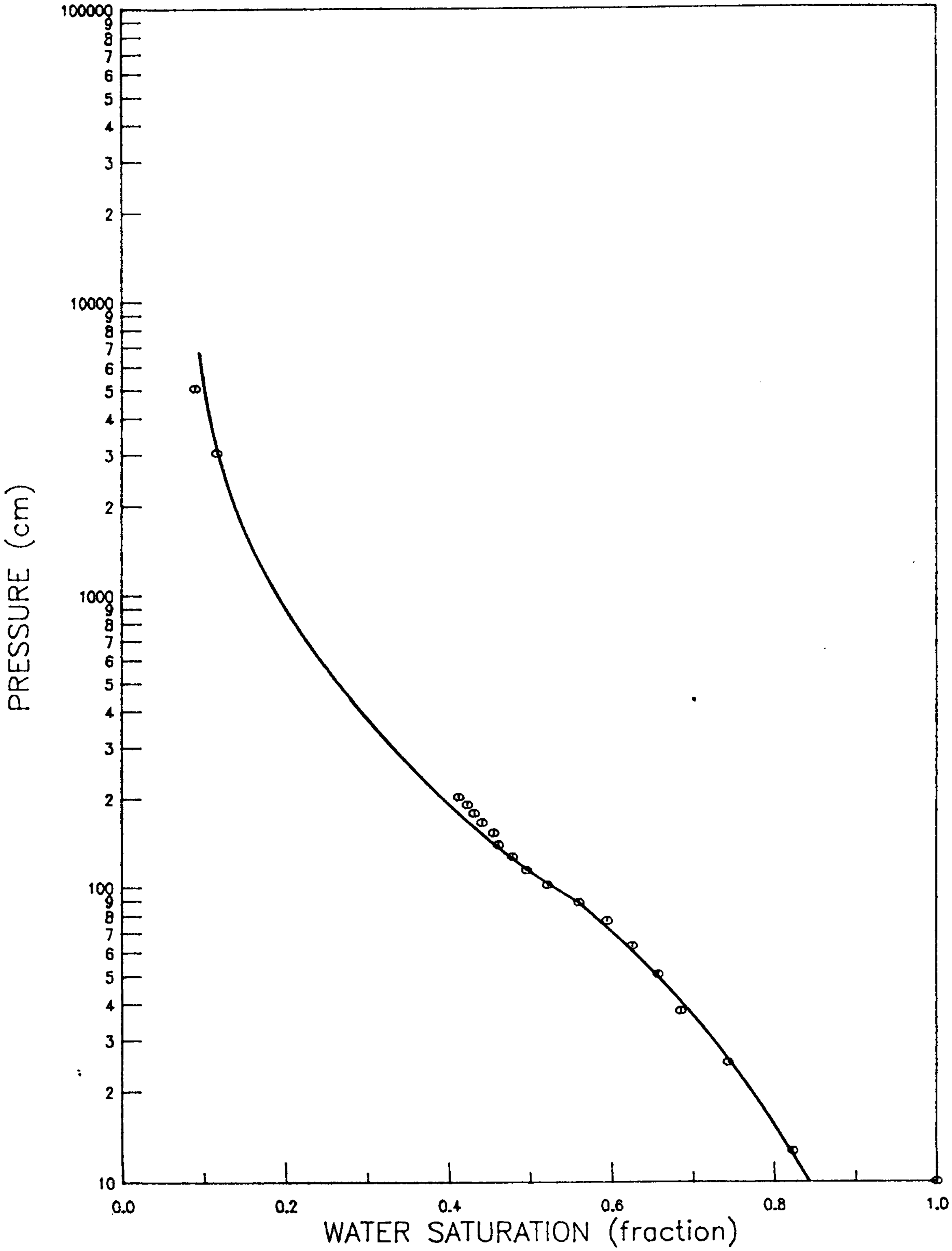

Figure A.9: Plot of Pressure Vs Saturation data for sample Burrton #2.

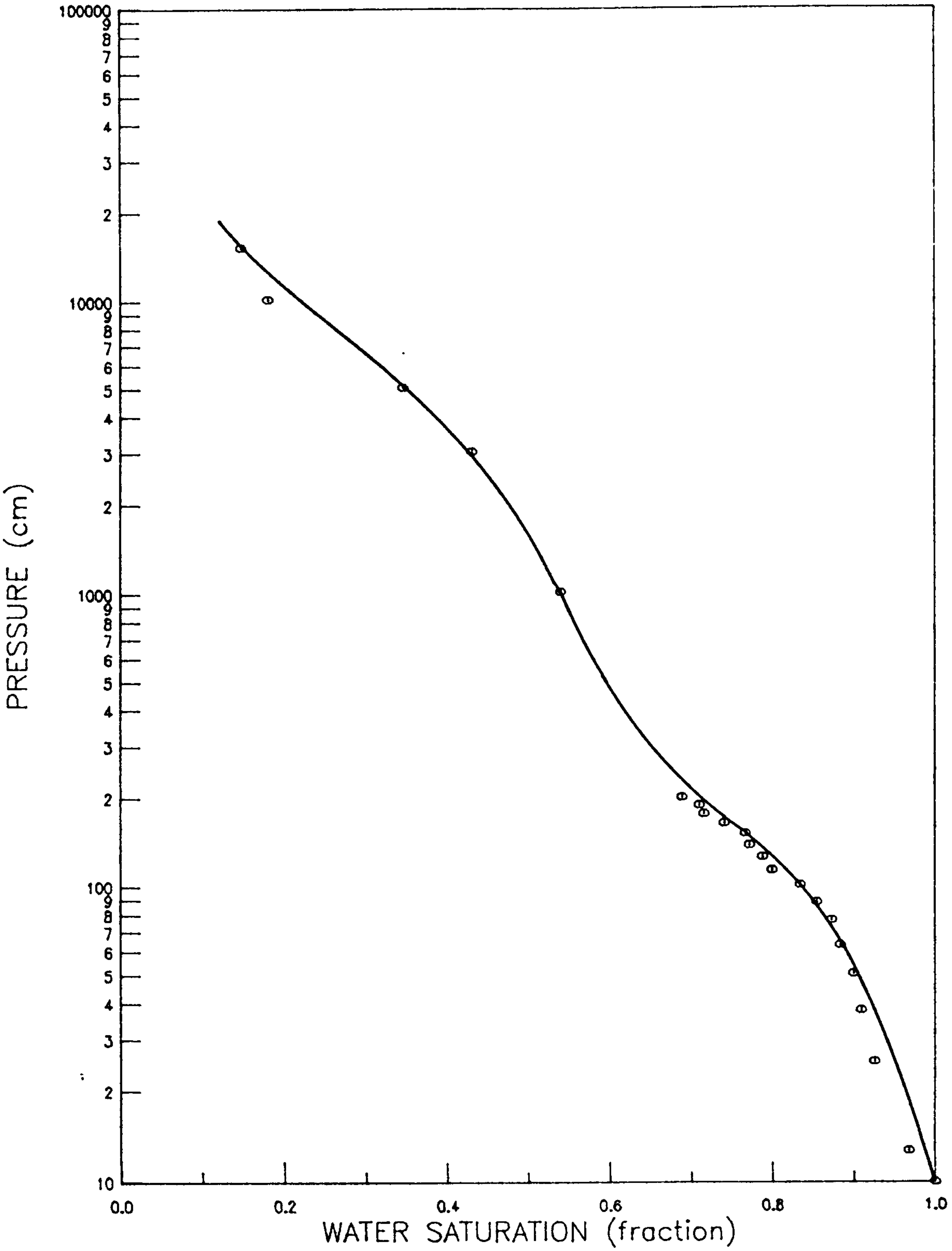

Figure A.10: Plot of Pressure Vs Saturation data for sample Burrton #3.

APPENDIX B

THIS APPENDIX CONTAINS THE COMPUTER PROGRAM 'HYCOND' WHICH COMPUTES HYDRAULIC CONDUCTIVITY BY FIVE DIFFERENT METHODS USED FOR COMPARISON STUDY WITH EXPERIMENTAL DATA

COMPUTER PROGRAM 'HYCOND'

```
10C     *****************************************************************
20C     THIS PROGRAM CALCULATES THE HYDRAULIC CONDUCTIVITIES  OF
30C     POROUS MATERIAL SAMPLES THEORETICALLY BY FIVE DIFFERENT METHODS.
40C     *****************************************************************
50C
60C     CCG = CHILDS AND COLLIS-GEORGE    M = MARSHALL
70C     MQ = MILLINGTON AND QUIRK    KUG = KUNZE ET AL
80C     CFMK = MATCH FACTOR * MARSHALL-K
90C     CFMQK = MATCH FACTOR * MQ-K
100C     BCK = BROOKS AND COREY
110      REAL LAMDA
120      DIMENSION CCGP(100),CCGC(100),CCGKM(100),H(100),SMC(100),CMK(100),
130     &CMQK(100),CKUGK(100),SWC(100),SWP(100),X(100),Y(100),RP(100),
140     &PR(100),DCCGC(100),CFMK(100),CFMQK(100),SWCC(100),STDEV(100),
150     &BCK(100),PC(100),S(100),SE(100),WC(100)
160      CHARACTER*20 SAMPLE
170      CALL FMEDIA (08,6)
180      CALL FMEDIA (09,6)
190      CALL FMEDIA (11,6)
200      CALL FMEDIA (12,6)
210      CALL FMEDIA (13,6)
220C
230C     ********************
240C     READ THE INPUT DATA;
250C     ********************
260C
270      READ(10,100)GAMMA,VIS,RHO,G
280      READ(10,200)N
290      READ(10,300)NPLOT
300      READ(10,400)SAMPLE
310      READ(10,500)STK,STWC,STWP,PB,LAMDA
320      READ(10,600)(SWP(I),I=1,N)
330      READ(10,700)(SWC(I),I=1,N)
340#100   FORMAT(4F10.0)
350#200   FORMAT(I2)
360#300   FORMAT(I1)
370#400   FORMAT(V)
380#500   FORMAT(5F10.0)
390#600   FORMAT(10F7.0)
400#700   FORMAT(10F6.0)
410C
420C     **************************
430C     ECHO PRINT THE INPUT DATA;
440C     **************************
450C
460      WRITE(6,301)
470#301   FORMAT(1X,//////,24X,'I N P U T  D A T A',/,24X,
480     &'-------------------',//)
490      WRITE(6,302)GAMMA,VIS,RHO,G
500#302   FORMAT(15X,'SURFACE TENSION (Dynes/cm)  =',F10.4/15X,
510     &'VISCOSITY (Poise)            =',F10.4/15X,'DENSITY (gm/cc)
520     &     =',F10.4/15X,'GRAVITY FORCE (cm/sq.sec)   =',F10.4/)
```

```
530        WRITE(6,303)STK,STWC,STWP
540#303     FORMAT(15X,'SAT. HYD. COND. (cm/day)     =',F10.4/15X,
550        &'STEADY WATER CONTENT (cc/cc)=',F10.4/15X,'STEADY WATER PRESSURE
560        &(cm) =',F10.4/)
570        WRITE(6,304)PB
580#304     FORMAT(15X,'BUBBLING PRESSURE (cm)       =',F10.4/)
590        WRITE(6,305)LAMDA
600#305     FORMAT(15X,'PORE SIZE DIST. INDEX(LAMDA)=',F10.4/)
610        WRITE(6,306)N
620#306     FORMAT(15X,'NUMBER OF DATA POINTS        =',I10,///)
630        WRITE(6,307)
640#307     FORMAT(15X,'PRESSURE (cm)',5X,'WATER CONTENT (cc/cc)',/15X,
650        &'-------------',5X,'---------------------',/)
660        DO 55 I=1,N
670        WRITE(6,308)SWP(I),SWC(I)
680#55      CONTINUE
690#308     FORMAT(14X,F10.3,16X,F6.4)
700C
710C       ***************************************
720C        CALCULATION OF HYDRAULIC CONDUCTIVITY BY
730C        CHILDS AND COLLIS-GEORGE METHOD.
740C       ***************************************
750C
760        CKUG=((3600.*24.)*(GAMMA**2.0))/(2.0*RHO*G*VIS)
770        DO 12 NP=1,NPLOT
780        NA=N+1
790        DO 1 J=1,N
800        X(J)=SWC(NA-1)
810        Y(J)=SWP(NA-1)
820#1       NA=NA-1
830        PMAX=SWP(N)
840        CMAX=SWC(1)
850        CMIN=SWC(N)
860        CALL SPLST(SWP,SWC,N)
870        CALL SPLST(X,Y,N)
880        NUMB=5
890        DO 2 J=2,NUMB
900        D=2.0**J
910        IB=D
920        IA=IB+1
930        IB=IA+1
940        IF(STWP.LE.0.0)STWP=2.0
950        CALL SUBD(PMAX,STWP,D,MF,DUMX,DX,CMIN)
960        DO 3 JA=1,IA
970        CALL SPLIN(SWP,SWC,DUMX,YO)
980        CCGP(JA)=DUMX
990        CCGC(JA)=YO
1000        RP(JA)=1.0/DUMX
1010#3       DUMX=DUMX-DX
1020        DO 4 JA=1,IB
1030        RP(JA)=(RP(JA)+RP(JA+1))/2.0
1040        DCCGC(JA)=CCGC(JA+1)-CCGC(JA)
1050        DUMX1=(RP(JA)*DCCGC(JA))**2
1060        IF(JA.EQ.1)GO TO 52
1070        DUMX2=0.0
1080        DO 5 JC=2,JA
1090#5       DUMX2=DUMX2+2.0*RP(JC-1)**2*DCCGC(JC-1)*DCCGC(JA)
1100        DUMX1=DUMX1+DUMX2+CCGKM(JA-1)
1110#52      CCGKM(JA)=DUMX1
1120#4       CONTINUE
```

```
1130      FM=STK/CCGKM(MF)
1140      DO 6 JE=1,IB
1150#6     CCGKM(JE)=FM*CCGKM(JE)
1160C
1170C     ****************************************
1180C     CALCULATION OF HYDRAULIC CONDUCTIVITY BY
1190C     KUNZE ET AL,  MARSHALL, AND MILLINGTON & QUIRK METHODS.
1200C     *******************************************************
1210C
1220      CALL SUBD(CMAX,STWC,D,MFF,DUMY,DY,CMIN)
1230      DO 7 K=1,IA
1240      CALL SPLIN(X,Y,DUMY,YY)
1250      H(K)=YY
1260      SMC(K)=DUMY
1270#7     DUMY=DUMY+DY
1280      DO 14 K=1,IA
1290#14    PR(K)=2./(H(K)+H(K+1))
1300      DO 11 KA=1,IA
1310      CL=KA
1320      SUM=0.0
1330      KD=2*KA-1
1340      DO 8 KC=1,KA
1350      F=KD
1360      SUM=SUM+F*PR(KC)**2
1370#8     KD=KD-2
1380      CMK(KA)=CKUG/D**2.*SMC(KA+1)**2.*SUM
1390      CMQK(KA)=CKUG/D**2.*SMC(KA+1)**(4./3.)*SUM
1400      CKUGK(KA)=CKUG/D**2.*SMC(KA+1)*SUM
1410#11    CONTINUE
1420      FMK=STK/CKUGK(MFF)
1430      FMM=STK/CMK(MFF)
1440      FMMQ=STK/CMQK(MFF)
1450      DO 9 JF =1,IA
1460      CFMK(JF)=FMM*CMK(JF)
1470      CFMQK(JF)=FMMQ*CMQK(JF)
1480#9     CKUGK(JF)=FMK*CKUGK(JF)
1490C
1500C     ******************************************
1510C     CALCULATION  OF  HYDRAULIC CONDUCTIVITY BY
1520C     BROOKS AND COREY METHOD.
1530C     ******************************************
1540C
1550      ETA=2.0+3.0*LAMDA
1560      CALL SUBD(PMAX,STWP,D,MF,DUMX,DX,CMIN)
1570      DO 61 K=1,IA
1580      CALL SPLIN(SWP,SWC,DUMX,YO)
1590      PC(K)=DUMX
1600      WC(K)=YO
1610#61    DUMX=DUMX-DX
1620      DO 62 K=1,IB
1630      IF (PC(K).LE.PB)GO TO 63
1640      BCK(K)=STK*((PB/PC(K))**ETA)
1650      GO TO 62
1660#63    BCK(K)=STK
1670#62    CONTINUE
1680#2     CONTINUE
1690#12    CONTINUE
1700C
1710C     ************************************************
1720C     PRINTING OF CALCULATED HYDRAULIC CONDUCTIVITIES.
```

```
1730C     ********************************************
1740C
1750      WRITE(6,501)
1760#501   FORMAT(1H1,////,25X,'O U T P U T',/,25X,'-----------'//)
1770      WRITE(6,502)SAMPLE
1780#502   FORMAT(15X,A20,//)
1790      WRITE(6,503)
1800#503   FORMAT(15X,'CHILDS AND COLLIS-GEORGE - K',/,15X,
1810     &'____________________________',//)
1820      WRITE(6,504)MF
1830#504   FORMAT(15X,'MATCHING POINT NUMBER=',I10/)
1840      WRITE(6,505)FM
1850#505   FORMAT(15X,'MATCHING FACTOR      =',E10.4/)
1860      WRITE(6,506)
1870#506   FORMAT(1X,//,15X,'PRESSURE',6X,'WATER CONTENT',5X,'CCGS - K',
1880     &/,17X,'(cm)',11X,'(cc/cc)',8X,'(cm/day)',//)
1890      DO 81 IZ=1,IA-1
1900      WRITE(6,507)CCGP(IZ+1),CCGC(IZ+1),CCGKM(IZ)
1910      WRITE(08,91)CCGC(IZ+1),CCGKM(IZ)
1920#81    CONTINUE
1930#91    FORMAT(2F10.4)
1940#507   FORMAT(13X,F10.4,F15.4,1PE18.4)
1950      WRITE(6,508)
1960#508   FORMAT(1H1,/////,15X,'KUNZE - K, MARSHALL - K,',
1970     &2X,'MILLINGTON AND QUIRK - K',/,15X,
1980     &'--------------------------------------------------',//)
1990      WRITE(6,509)MFF
2000#509   FORMAT(15X,'MATCHING POINT NUMBER            =',I10/)
2010      WRITE(6,510)FMK,FMM,FMMQ
2020#510   FORMAT(15X,'KUNZE-K MATCHING FACTOR          =',E10.4,/,
2030     &15X,'MARSHALL-K MATCHING FACTOR       =',E10.4,/,
2040     &15X,'MILL. AND QUIRK-K MATCHING FACTOR=',E10.4,////)
2050      WRITE(6,511)
2060#511   FORMAT(51X,'WITH  MATCHING FACTOR',10X,
2070     &'WITHOUT MATCHING FACTOR',/,51X,
2080     &'--------------------',10X,'-----------------------')
2090      WRITE(6,512)
2100#512   FORMAT(15X,'PRESSURE',3X,'WATER CONTENT',5X,
2110     &'KUNZE- K',4X,'MARSHALL-K',5X,'M-Q-K',6X,'MARSHALL-K',5X,
2120     &'M-Q-K',/,17X,'(cm)',8X,'(cc/cc)',8x,'(cm/day)',5X,
2130     &'(cm/day)',5X,'(cm/day)',5X,'(cm/day)',5X,'(cm/day)',//)
2140      DO 82 IZ=1,IA-1
2150      WRITE(6,513)H(IZ+1),SMC(IZ+1),CKUGK(IZ),CFMK(IZ),CFMQK(IZ),
2160     &CMK(IZ),CMQK(IZ)
2170      WRITE(09,91)SMC(IZ+1),CKUGK(IZ)
2180      WRITE(13,91)SMC(IZ+1),CFMK(IZ)
2190      WRITE(11,91)SMC(IZ+1),CFMQK(IZ)
2200#82    CONTINUE
2210#513   FORMAT(13X,F10.4,F12.4,1PE18.4,1P4E13.4)
2220      WRITE(6,514)
2230#514   FORMAT(1H1,/////,15X,'BROOKS AND COREY - K',/,15X,
2240     &'--------------------',///)
2250      WRITE(6,515)
2260#515   FORMAT(15X,'PRESSURE',6X,'WATER CONTENT',5X,
2270     &'BROOKS AND COREY-K',/,17X,'(cm)',11X,'(cc/cc)',13X,
2280     &'(cm/day)',//)
2290      DO 83 K=2,IA
2300      WRITE(6,516)PC(K),WC(K),BCK(K)
2310      WRITE(12,91)WC(K),BCK(K)
2320#83    CONTINUE
```

```
2330#516  FORMAT(13X,F10.4,F15.4,1PE23.4)
2340      STOP
2350      END
2360C
2370C     ***************
2380C     SUBROUTINE SUBD
2390C     ***************
2400C
2410      SUBROUTINE SUBD(PMAX,STWP,D,MF,DUMY,DX,CMIN)
2420      DX1=PMAX/D
2430      IF(STWP .LT. 1.0)GO TO 51
2440      IF(DX1 .GT. STWP)GO TO 50
2450      IC=STWP/DX1
2460      D1=IC
2470      DX=(PMAX-STWP)/(D-D1)
2480      MF=D-D1
2490      DUMY=PMAX
2500      RETURN
2510#50    DX=(PMAX-STWP)/D
2520      DUMY=PMAX
2530      MF=D
2540      RETURN
2550#51    IF(DX1 .GT. (PMAX-STWP))GO TO 52
2560      IC=(PMAX-STWP)/DX1
2570      D1=IC
2580      DX=(STWP-CMIN)/(D-D1)
2590      MF=D-D1
2600      DUMY=CMIN
2610      RETURN
2620#52    DX=(STWP-CMIN)/D
2630      DUMY=CMIN
2640      MF=D
2650      RETURN
2660      END
2670C
2680C     ****************
2690C     SUBROUTINE SPLST
2700C     ****************
2710C
2720      SUBROUTINE SPLST(X,Y,N)
2730      DIMENSION X(50),Y(200)
2740      IF(N-50)1,1,2
2750#1     IF(N-2)7,8,3
2760#2     N=50
2770#3     DO 4 I=2,N
2780      J=N-I+2
2790#4     Y(4*J-3)=Y(J)
2800      DX1=X(2)-X(1)
2810      DY1=Y(5)-Y(1)
2820      Y(2)=N
2830      Y(3)=0.0
2840      Y(4)=0.0
2850      DO 5 I=3,N
2860      DX2=X(I)-X(I-1)
2870      J=4*I-3
2880      DY2=Y(J)-Y(J-4)
2890      B=2.0*(DX1+DX2)
2900      Y(J-3)=DX1*Y(J-6)+B
2910      Y(J-2)=-DX2/Y(J-3)
2920      D=6.0*(DY2/DX2-DY1/DX1)
```

```
2930         Y(J-1)=(D-DX1*Y(J-5))/Y(J-3)
2940         DX1=DX2
2950#5        DY1=DY2
2960         Y(J+3)=0.0
2970C        BACK SUBSTITUTION
2980         DO 6 I=4,N
2990         J=J-4
3000#6        Y(J-1)=Y(J-1)+Y(J-2)*Y(J+3)
3010         RETURN
3020#7        Y(4)=0.0
3030         Y(2)=1.0
3040         RETURN
3050#8        Y(4)=(Y(2)-Y(1))/(X(2)-X(1))
3060         Y(2)=2.0
3070         RETURN
3080         END
3090C
3100C        ****************
3110C        SUBROUTINE SPLIN
3120C        ****************
3130C
3140         SUBROUTINE SPLIN(X,Y,XN,YO)
3150         DIMENSION X(50),Y(200)
3160         IF(Y(2)-2.0)13,13,14
3170#13       DY=Y(4)
3180         DX=XN-X(1)
3190         YO=DY*DX+Y(1)
3200         RETURN
3210#14       N=Y(2)
3220         DO 15 I=2,N
3230         IF(XN-X(I))10,10,15
3240#15       CONTINUE
3250#10       DX=X(I)-X(I-1)
3260         J=4*I-3
3270         DYY=Y(J)-Y(J-4)
3280         DELX=XN-X(I-1)
3290         B=3.0*DX*Y(J-1)
3300         A=6.0*DYY-DX*DX*(2.0*Y(J-1)+Y(J+3))
3310         C=Y(J+3)-Y(J-1)
3320         YO=Y(J-4)+(A+(B+C*DELX)*DELX)*DELX/(6.0*DX)
3330         RETURN
3340         END
```

APPENDIX C

THIS APPENDIX CONTAINS THE PROPERTIES OF 14 SAMPLES OF POROUS MEDIA USED FOR COMPARING DIFFERENT METHODS OF COMPUTING THEIR HYDRAULIC CONDUCTIVITY VALUES.

THE INPUT DATA AND THE COMPUTED VALUES OF HYDRAULIC CONDUCTIVITY BY COMPUTER PROGRAM 'HYCOND' ARE ALSO PRESENTED.

Table C.1: Properties of the 16 samples of porous media used for comparing different methods of computing their hydraulic conductivity values.

# Name	K_s (cm/day)	ϕ (frac.)	λ	P_b	Permeating Fluid	Source
Glass Beads	466.410	0.379	7.30	29.00	Soltrol 'C'	Brooks & Corey (1964)
Watson Sand	1607.040	0.350	10.81	40.50	Water	Brooks & Corey (1964)
Fine Sand 1	126.597	0.377	3.70	41.00	Soltrol 'C'	Watson (1966)
Barea Sandstone	21.360	0.206	3.69	42.00	Soltrol 'C'	Brooks & Corey (1964)
Hygiene Sandstone	7.907	0.250	4.17	54.00	Soltrol 'C'	Brooks & Corey (1964)
Graded Sand	1211.120	0.375	3.05	42.00	Water	Bruce (1972)
Volcanic Sand	488.620	0.351	2.29	16.00	Soltrol 'C'	Brooks & Corey (1964)
Fragmented Mixture	666.300	0.443	2.89	17.20	Soltrol 'C'	Brooks & Corey (1964)
Touchet Silt Loam 1	22.210	0.463	1.48	68.00	Soltrol 'C'	Brooks & Corey (1964)
Touchet Silt Loam 2	11.41	0.430	1.67	72.80	Soltrol 'C'	Brooks & Corey (1964)
Lakeland Fine Sand	355.200	0.371	1.59	33.00	0.01N $CaSO_4$ Soln.	Elzeft. & Mansell (1975)
Wide-Range Sand	453.60	0.400	2.30	60.10	Water	Jackson (1965)
Bruce Sand	1641.60	0.349	2.15	33.00	Water	Bruce (1972)
Fine Sand 2	188.64	0.375	2.82	164.00	Water	Bruce (1972)

GLASS BEADS

```
                 I N P U T   D A T A
                 -----------------

SURFACE TENSION (DYNES/CM)    =    22.9000
VISCOSITY (POISE)             =     0.0144
DENSITY (GM/CC)               =     0.7549
GRAVITY FORCE (CM/SQ.SEC)     =   981.0000
SAT. HYD. COND. (CM/DAY)      =   466.4100
STEADY WATER CONTENT (CC/CC)=       0.3700
STEADY WATER PRESSURE  (CM) =       3.8000
BUBBLING PRESSURE (CM)        =    29.0000
PCRE SIZE DIST. INDEX(LAMDA)=       7.3000
NUMBER OF DATA POINTS         =         16

PRESSURE (CM)      WATER CONTENT (CC/CC)
-------------      ---------------------
     3.800                  0.370
     5.900                  0.368
    11.800                  0.366
    17.800                  0.364
    23.800                  0.363
    26.900                  0.359
    28.800                  0.347
    29.300                  0.337
    30.400                  0.283
    31.000                  0.252
    32.100                  0.214
    32.700                  0.172
    33.900                  0.125
    35.700                  0.100
    39.000                  0.070
    43.800                  0.048
```

```
               O U T P U T
               -----------

GLASS-BEADS

CHILD AND COLLIS-GEORGE - K
---------------------------

MATCHING POINT NUMBER=        15
MATCHING FACTOR      =0.5106E 07


PRESSURE       WATER CONTENT      CCGS - K
  (CM)            (CC/CC)        (CM/DAY)

 41.1333          0.0578        2.7084E-01
 38.4667          0.0741        2.0353E 00
 35.8000          0.0990        8.3456E 00
 33.1333          0.1484        3.5939E 01
 30.4667          0.2791        2.2346E 02
 27.8000          0.3560        4.2024E 02
 25.1333          0.3619        4.3841E 02
 22.4667          0.3636        4.4362E 02
 19.8000          0.3639        4.4455E 02
 17.1333          0.3641        4.4541E 02
 14.4667          0.3650        4.4831E 02
 11.8000          0.3660        4.5138E 02
  9.1333          0.3666        4.5324E 02
  6.4667          0.3676        4.5678E 02
  3.8000          0.3700        4.6641E 02
```

```
KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER            =        16
KUNZE-K MATCHING FACTOR          =0.3365E 00
MARSHALL-K MATCHING FACTOR       =0.1373E 01
MILL. AND QUIRK-K MATCHING FACTOR=0.7077E 00


                                    WITH  MATCHING FACTOR          WITHOUT MATCHING FACTOR
                                    ---------------------          -----------------------
PRESSURE   WATER CONTENT     KUNZE- K    MARSHALL-K     M-Q-K      MARSHALL-K     M-Q-K
 (CM)         (CC/CC)        (CM/DAY)     (CM/DAY)     (CM/DAY)     (CM/DAY)     (CM/DAY)

 39.3337      0.0681        2.2020E-01   4.0544E-02   1.2527E-01   2.9527E-02   1.7702E-01
 36.6852      0.0883        1.1969E 00   2.8548E-01   7.4228E-01   2.0791E-01   1.0489E 00
 35.0403      0.1084        3.4790E 00   1.0190E 00   2.3104E 00   7.4212E-01   3.2648E 00
 33.7144      0.1285        7.6725E 00   2.6646E 00   5.3931E 00   1.9406E 00   7.6207E 00
 33.0201      0.1486        1.4425E 01   5.7944E 00   1.0643E 01   4.2199E 00   1.5040E 01
 32.7303      0.1687        2.4399E 01   1.1128E 01   1.8781E 01   8.1042E 00   2.6539E 01
 32.5395      0.1889        3.8253E 01   1.9527E 01   3.0572E 01   1.4221E 01   4.3200E 01
 32.2213      0.2090        5.6649E 01   3.1999E 01   4.6828E 01   2.3304E 01   6.6170E 01
 31.6311      0.2291        8.0278E 01   4.9712E 01   6.8425E 01   3.6204E 01   9.6689E 01
 31.0508      0.2492        1.0988E 02   7.4022E 01   9.6325E 01   5.3908E 01   1.3611E 02
 30.7916      0.2694        1.4623E 02   1.0646E 02   1.3155E 02   7.7534E 01   1.8589E 02
 30.0334      0.2895        1.9013E 02   1.4876E 02   1.7520E 02   1.0834E 02   2.4757E 02
 28.7091      0.3096        2.4248E 02   2.0292E 02   2.2850E 02   1.4778E 02   3.2289E 02
 28.6366      0.3298        3.0430E 02   2.7120E 02   2.9284E 02   1.9751E 02   4.1380E 02
 27.1680      0.3499        3.7663E 02   3.5614E 02   3.6967E 02   2.5937E 02   5.2236E 02
  3.8000      0.3700        4.6641E 02   4.6641E 02   4.6641E 02   3.3967E 02   6.5906E 02
```

```
BROOK AND COREY - K
-------------------


PRESSURE        WATER CONTENT        BROOK AND COREY-K
  (CM)             (CC/CC)               (CM/DAY)

 43.8000           0.0480              2.4482E-02
 41.1333           0.0578              1.0986E-01
 38.4667           0.0741              5.4520E-01
 35.8000           0.0990              3.0358E 00
 33.1333           0.1484              1.9308E 01
 30.4667           0.2791              1.4344E 02
 27.8000           0.3560              4.6641E 02
 25.1333           0.3619              4.6641E 02
 22.4667           0.3636              4.6641E 02
 19.8000           0.3639              4.6641E 02
 17.1333           0.3641              4.6641E 02
 14.4667           0.3650              4.6641E 02
 11.8000           0.3660              4.6641E 02
  9.1333           0.3666              4.6641E 02
  6.4667           0.3676              4.6641E 02
  3.8000           0.3700              4.6641E 02
```

WATSON SAND

```
                I N P U T   D A T A
                -------------------

SURFACE TENSION (DYNES/CM)   =    72.7500
VISCOSITY (POISE)            =     0.0100
DENSITY (GM/CC)              =     0.9982
GRAVITY FORCE (CM/SQ.SEC)    =   981.0000
SAT. HYD. COND. (CM/DAY)     =  1607.0400
STEADY WATER CONTENT (CC/CC)=      0.3500
STEADY WATER PRESSURE  (CM)  =    39.8000
BUBBLING PRESSURE (CM)       =    40.5000
PORE SIZE DIST. INDEX(LAMDA)=     10.8145
NUMBER OF DATA POINTS        =         17

PRESSURE (CM)        WATER CONTENT (CC/CC)
-------------        ---------------------
    39.800                   0.350
    40.000                   0.341
    40.500                   0.318
    41.000                   0.295
    41.500                   0.273
    42.000                   0.250
    42.500                   0.229
    43.000                   0.221
    43.500                   0.190
    44.000                   0.174
    44.500                   0.159
    45.000                   0.145
    46.000                   0.122
    47.000                   0.104
    48.000                   0.093
    49.000                   0.084
    50.000                   0.077
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                 O U T P U T
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WATSON-SAND

CHILDS AND COLLIS-GEORGE - K
----------------------------

MATCHING POINT NUMBER=        4
MATCHING FACTOR      =0.4262E 08


PRESSURE          WATER CONTENT        CCGS - K
  (CM)               (CC/CC)           (CM/DAY)

 47.4500              0.0984          8.2647E 00
 44.9000              0.1476          9.4586E 01
 42.3500              0.2335          4.9554E 02
 39.8000              0.3500          1.6070E 03
 37.2500              0.5203          4.5684E 03
 34.7000              1.0257          2.4272E 04
 32.1500              2.2016          1.4264E 05
 29.6000              4.3831          6.7388E 05
 27.0500              7.9054          2.5382E 06
 24.5000             13.1037          8.0084E 06
 21.9500             20.3133          2.2143E 07
 19.4000             29.8692          5.5530E 07
 16.8500             42.1068          1.2965E 08
 14.3000             57.3612          2.8796E 08
 11.7500             75.9676          6.2027E 08
```

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KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER              =      16
KUNZE-K MATCHING FACTOR            =0.1959E 00
MARSHALL-K MATCHING FACTOR         =0.1118E 01
MILL. AND QUIRK-K MATCHING FACTOR=0.5551E 00


                                                 WITH  MATCHING FACTOR           WITHOUT MATCHING FACTOR
                                                 ---------------------           -----------------------
PRESSURE     WATER CONTENT         KUNZE- K       MARSHALL-K        M-Q-K        MARSHALL-K       M-Q-K
  (CM)          (CC/CC)           (CM/DAY)        (CM/DAY)       (CM/DAY)        (CM/DAY)       (CM/DAY)

 47.8940        0.0941          1.4005E 00     3.7638E-01     9.0377E-01     3.3676E-01     1.6282E 00
 46.5321        0.1111          6.7418E 00     2.1405E 00     4.5993E 00     1.9152E 00     8.2859E 00
 45.7196        0.1282          1.7846E 01     6.5360E 00     1.2768E 01     5.8480E 00     2.3003E 01
 44.9902        0.1453          3.6584E 01     1.5182E 01     2.7288E 01     1.3584E 01     4.9161E 01
 44.3912        0.1623          6.4881E 01     3.0088E 01     5.0220E 01     2.6921E 01     9.0474E 01
 43.8058        0.1794          1.0472E 02     5.3667E 01     8.3800E 01     4.8018E 01     1.5097E 02
 43.4304        0.1964          1.5812E 02     8.8744E 01     1.3043E 02     7.9402E 01     2.3497E 02
 43.2881        0.2135          2.2712E 02     1.3854E 02     1.9262E 02     1.2396E 02     3.4702E 02
 42.4190        0.2306          3.1381E 02     2.0672E 02     2.7305E 02     1.8496E 02     4.9192E 02
 42.0303        0.2476          4.2041E 02     2.9744E 02     3.7461E 02     2.6613E 02     6.7488E 02
 41.7049        0.2647          5.4918E 02     4.1532E 02     5.0035E 02     3.7160E 02     9.0140E 02
 41.2940        0.2818          7.0239E 02     5.6542E 02     6.5339E 02     5.0590E 02     1.1771E 03
 40.9168        0.2988          8.8236E 02     7.5331E 02     8.3706E 02     6.7401E 02     1.5080E 03
 40.5460        0.3159          1.0915E 03     9.8507E 02     1.0548E 03     8.8137E 02     1.9003E 03
 40.1766        0.3329          1.3322E 03     1.2673E 03     1.3102E 03     1.1339E 03     2.3604E 03
 39.8000        0.3500          1.6070E 03     1.6070E 03     1.6070E 03     1.4379E 03     2.8952E 03
```

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BROOKS AND COREY - K
--------------------

PRESSURE        WATER CONTENT       BROOKS AND COREY-K
  (CM)             (CC/CC)              (CM/DAY)

 50.0000           0.0770              1.1322E 00
 47.4500           0.0984              6.8701E 00
 44.9000           0.1476              4.6053E 01
 42.3500           0.2335              3.4505E 02
 39.8000           0.3500              1.6070E 03
 37.2500           0.5203              1.6070E 03
 34.7000           1.0257              1.6070E 03
 32.1500           2.2016              1.6070E 03
 29.6000           4.3831              1.6070E 03
 27.0500           7.9054              1.6070E 03
 24.5000          13.1037              1.6070E 03
 21.9500          20.3133              1.6070E 03
 19.4000          29.8692              1.6070E 03
 16.8500          42.1068              1.6070E 03
 14.3000          57.3612              1.6070E 03
 11.7500          75.9676              1.6070E 03
```

FINE SAND 1

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                   I N P U T   D A T A
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SURFACE TENSION (DYNES/CM)      =    22.9000
VISCOSITY (POISE)               =     0.0144
DENSITY (GM/CC)                 =     0.7549
GRAVITY FORCE (CM/SQ.SEC)       =   981.0000
SAT. HYD. COND. (CM/DAY)        =   126.5970
STEADY WATER CONTENT (CC/CC)=         0.3730
STEADY WATER PRESSURE  (CM) =        12.8000
BUBBLING PRESSURE (CM)          =    41.0000
PORE SIZE DIST. INDEX(LAMDA)=         3.7000
NUMBER OF DATA POINTS           =         16

PRESSURE (CM)         WATER CONTENT (CC/CC)
-------------         ---------------------
    12.800                   0.373
    27.800                   0.369
    30.800                   0.363
    31.800                   0.358
    34.800                   0.349
    36.800                   0.340
    39.800                   0.322
    42.800                   0.297
    45.800                   0.270
    48.800                   0.236
    52.800                   0.190
    57.800                   0.148
    64.800                   0.118
    71.700                   0.103
    74.400                   0.099
    92.100                   0.082
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                O U T P U T
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FINE-SAND1

CHILDS AND COLLIS-GEORGE - K
-----------------------------

MATCHING POINT NUMBER=        14
MATCHING FACTOR       =0.4371E 07

PRESSURE          WATER CONTENT        CCGS - K
  (CM)               (CC/CC)           (CM/DAY)

 86.4357              0.0864          1.0719E-02
 80.7714              0.0915          5.1975E-02
 75.1071              0.0981          1.5612E-01
 69.4429              0.1070          4.0894E-01
 63.7786              0.1210          1.1037E 00
 58.1143              0.1460          3.4283E 00
 52.4500              0.1937          1.2537E 01
 46.7857              0.2595          3.7371E 01
 41.1214              0.3115          6.9275E 01
 35.4571              0.3465          9.8549E 01
 29.7929              0.3665          1.1905E 02
 24.1286              0.3709          1.2415E 02
 18.4643              0.3724          1.2593E 02
 12.8000              0.3730          1.2660E 02
  7.1357              0.3736          1.2729E 02
```

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KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER            =        16
KUNZE-K MATCHING FACTOR          =0.2340E 00
MARSHALL-K MATCHING FACTOR       =0.9470E 00
MILL. AND QUIRK-K MATCHING FACTOR=0.4907E 00


                                    WITH  MATCHING FACTOR          WITHOUT MATCHING FACTOR
                                    ---------------------          -----------------------
PRESSURE   WATER CONTENT     KUNZE- K    MARSHALL-K     M-Q-K      MARSHALL-K     M-Q-K
  (CM)        (CC/CC)       (CM/DAY)      (CM/DAY)    (CM/DAY)      (CM/DAY)     (CM/DAY)

 73.5333      0.1002        5.6723E-02   1.5236E-02   3.6598E-02   1.6083E-02   7.4580E-02
 64.6704      0.1184        2.9732E-01   9.4359E-02   2.0281E-01   9.9635E-02   4.1328E-01
 59.8285      0.1366        8.5660E-01   3.1362E-01   6.1280E-01   3.3116E-01   1.2488E 00
 56.7918      0.1548        1.8845E 00   7.8183E-01   1.4055E 00   8.2555E-01   2.8641E 00
 54.5277      0.1729        3.5414E 00   1.6419E 00   2.7410E 00   1.7338E 00   5.5855E 00
 52.6936      0.1911        5.9981E 00   3.0734E 00   4.7997E 00   3.2453E 00   9.7808E 00
 51.0460      0.2093        9.4363E 00   5.2953E 00   7.7833E 00   5.5914E 00   1.5861E 01
 49.5012      0.2275        1.4051E 01   8.5698E 00   1.1916E 01   9.0491E 00   2.4282E 01
 48.0033      0.2457        2.0051E 01   1.3207E 01   1.7446E 01   1.3946E 01   3.5551E 01
 46.4030      0.2639        2.7654E 01   1.9570E 01   2.4649E 01   2.0665E 01   5.0230E 01
 44.4961      0.2821        3.7143E 01   2.8088E 01   3.3840E 01   2.9659E 01   6.8958E 01
 42.4376      0.3003        4.8781E 01   3.9267E 01   4.5378E 01   4.1463E 01   9.2470E 01
 40.2892      0.3184        6.2916E 01   5.3712E 01   5.9685E 01   5.6716E 01   1.2163E 02
 37.4250      0.3366        7.9957E 01   7.2160E 01   7.7269E 01   7.6195E 01   1.5746E 02
 32.9443      0.3548        1.0048E 02   9.5578E 01   9.8817E 01   1.0092E 02   2.0137E 02
 12.8000      0.3730        1.2660E 02   1.2660E 02   1.2660E 02   1.3368E 02   2.5798E 02
```

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BROOKS AND COREY - K
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PRESSURE        WATER CONTENT       BROOKS AND COREY-K
  (CM)             (CC/CC)              (CM/DAY)

 92.1000           0.0820               3.1484E-03
 86.4357           0.0864               7.2312E-03
 80.7714           0.0915               1.7572E-02
 75.1071           0.0981               4.5548E-02
 69.4429           0.1070               1.2722E-01
 63.7786           0.1210               3.8784E-01
 58.1143           0.1460               1.3116E 00
 52.4500           0.1937               5.0260E 00
 46.7857           0.2595               2.2450E 01
 41.1214           0.3115               1.2179E 02
 35.4571           0.3465               1.2660E 02
 29.7929           0.3665               1.2660E 02
 24.1286           0.3709               1.2660E 02
 18.4643           0.3724               1.2660E 02
 12.8000           0.3730               1.2660E 02
  7.1357           0.3736               1.2660E 02
```

BAREA SANDSTONE

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                 I N P U T   D A T A
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SURFACE TENSION (DYNES/CM)    =    22.9000
VISCOSITY (POISE)             =     0.0144
DENSITY (GM/CC)               =     0.7549
GRAVITY FORCE (CM/SQ.SEC)     =   981.0000
SAT. HYD. COND. (CM/DAY)      =    21.3660
STEADY WATER CONTENT (CC/CC)=       0.2060
STEADY WATER PRESSURE  (CM) =      11.5000
BUBBLING PRESSURE (CM)        =    42.0000
PORE SIZE DIST. INDEX(LAMDA)=       3.6900
NUMBER OF DATA POINTS         =         10

PRESSURE (CM)       WATER CONTENT (CC/CC)
-------------       ---------------------
    11.500                  0.206
    20.500                  0.205
    31.900                  0.204
    35.900                  0.203
    43.700                  0.191
    48.000                  0.160
    50.200                  0.145
    62.400                  0.098
    88.400                  0.071
   116.900                  0.064
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             O U T P U T
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BEREA-SANDSTONE

CHILD AND COLLIS-GEORGE - K
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MATCHING POINT NUMBER=        15
MATCHING FACTOR       =0.3665E 07

PRESSURE       WATER CONTENT       CCGS - K
  (CM)            (CC/CC)          (CM/DAY)

109.8733           0.0654         5.3457E-04
102.8467           0.0669         2.4497E-03
 95.8200           0.0687         6.7777E-03
 88.7933           0.0709         1.5671E-02
 81.7667           0.0738         3.4946E-02
 74.7400           0.0789         9.1215E-02
 67.7133           0.0878         2.7333E-01
 60.6867           0.1021         8.4256E-01
 53.6600           0.1264         2.7831E 00
 46.6333           0.1706         1.0405E 01
 39.6067           0.2024         1.9997E 01
 32.5800           0.2038         2.0506E 01
 25.5533           0.2049         2.0923E 01
 18.5267           0.2051         2.1015E 01
 11.5000           0.2060         2.1366E 01
```

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KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER                =        16
KUNZE-K MATCHING FACTOR              =0.8563E-01
MARSHALL-K MATCHING FACTOR           =0.6276E 00
MILL. AND QUIRK-K MATCHING FACTOR=0.2189E 00


                                                  WITH  MATCHING FACTOR               WITHOUT MATCHING FACTOR
                                                  ---------------------               -----------------------
PRESSURE        WATER CONTENT         KUNZE- K       MARSHALL-K       M-Q-K           MARSHALL-K        M-Q-K
  (CM)             (CC/CC)           (CM/DAY)        (CM/DAY)        (CM/DAY)         (CM/DAY)         (CM/DAY)

 82.5060           0.0729           1.0418E-02      3.6855E-03      7.3681E-03       5.8728E-03       3.3661E-02
 65.9004           0.0818           5.6160E-02      2.2287E-02      4.1270E-02       3.5513E-02       1.8854E-01
 61.9332           0.0906           1.6647E-01      7.3235E-02      1.2661E-01       1.1670E-01       5.7841E-01
 62.4609           0.0995           3.6836E-01      1.7792E-01      2.8902E-01       2.8351E-01       1.3204E 00
 61.6641           0.1084           6.8315E-01      3.5940E-01      5.5149E-01       5.7270E-01       2.5194E 00
 59.3817           0.1173           1.1329E 00      6.4480E-01      9.3884E-01       1.0275E 00       4.2890E 00
 56.2975           0.1261           1.7447E 00      1.0682E 00      1.4815E 00       1.7022E 00       6.7681E 00
 53.0953           0.1350           2.5520E 00      1.6725E 00      2.2167E 00       2.6650E 00       1.0127E 01
 50.4591           0.1439           3.5940E 00      2.5101E 00      3.1887E 00       3.9998E 00       1.4568E 01
 48.8873           0.1528           4.9128E 00      3.6428E 00      4.4466E 00       5.8048E 00       2.0314E 01
 47.7911           0.1616           6.5504E 00      5.1394E 00      6.0415E 00       8.1894E 00       2.7600E 01
 46.5153           0.1705           8.5492E 00      7.0759E 00      8.0268E 00       1.1275E 01       3.6670E 01
 45.1754           0.1794           1.0955E 01      9.5387E 00      1.0461E 01       1.5200E 01       4.7789E 01
 43.9971           0.1882           1.3816E 01      1.2625E 01      1.3407E 01       2.0118E 01       6.1249E 01
 42.2611           0.1971           1.7187E 01      1.6447E 01      1.6937E 01       2.6207E 01       7.7374E 01
 41.5000           0.2060           2.1366E 01      2.1366E 01      2.1366E 01       3.4046E 01       9.7609E 01
```

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BROOK AND COREY - K
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PRESSURE          WATER CONTENT          BROOK AND COREY-K
  (CM)               (CC/CC)                 (CM/DAY)

116.9000              0.0640                3.3056E-05
109.8733              0.0654                7.4324E-05
102.8467              0.0669                1.7631E-04
 95.8200              0.0687                4.4459E-04
 88.7933              0.0709                1.2030E-03
 81.7667              0.0738                3.5336E-03
 74.7400              0.0789                1.1435E-02
 67.7133              0.0878                4.1560E-02
 60.6867              0.1021                1.7401E-01
 53.6600              0.1264                8.6907E-01
 46.6333              0.1706                5.4416E 00
 39.6067              0.2024                2.1366E 01
 32.5800              0.2038                2.1366E 01
 25.5533              0.2049                2.1366E 01
 18.5267              0.2051                2.1366E 01
 11.5000              0.2060                2.1366E 01
```

HYGIENE SANDSTONE

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          I N P U T   D A T A
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SURFACE TENSION (DYNES/CM)    =   22.9000
VISCOSITY (POISE)             =    0.0144
DENSITY (GM/CC)               =    0.7549
GRAVITY FORCE (CM/SQ.SEC)     =  981.0000
SAT. HYD. COND. (CM/DAY)      =    7.9070
STEADY WATER CONTENT (CC/CC)=      0.2500
STEADY WATER PRESSURE  (CM) =     13.3000
BUBBLING PRESSURE (CM)        =   54.0000
PORE SIZE DIST. INDEX(LAMDA)=      4.1700
NUMBER OF DATA POINTS         =        13

PRESSURE (CM)      WATER CONTENT (CC/CC)
-------------      ---------------------
    13.300                0.250
    18.400                0.249
    27.400                0.248
    44.900                0.247
    51.300                0.244
    54.100                0.240
    56.600                0.230
    59.300                0.216
    62.100                0.204
    67.700                0.189
    75.100                0.173
    85.200                0.161
   100.600                0.151
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            O U T P U T
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HYGIEN-SANDSTONE

CHILD AND COLLIS-GEORGE - K
---------------------------

MATCHING POINT NUMBER=        14
MATCHING FACTOR      =0.3960E 07

PRESSURE       WATER CONTENT      CCGS - K
  (CM)            (CC/CC)         (CM/DAY)

 94.3643          0.1546         5.5355E-03
 88.1286          0.1588         2.6165E-02
 81.8929          0.1639         7.6646E-02
 75.6571          0.1720         2.2119E-01
 69.4214          0.1851         6.4921E-01
 63.1857          0.2004         1.5164E 00
 56.9500          0.2282         4.3346E 00
 50.7143          0.2444         6.8275E 00
 44.4786          0.2471         7.3168E 00
 38.2429          0.2480         7.4752E 00
 32.0071          0.2480         7.4803E 00
 25.7714          0.2481         7.5002E 00
 19.5357          0.2488         7.6430E 00
 13.3000          0.2500         7.9070E 00
  7.0643          0.2512         8.2594E 00
```

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KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER              =        16
KUNZE-K MATCHING FACTOR            =0.3663E-01
MARSHALL-K MATCHING FACTOR         =0.2212E 00
MILL. AND QUIRK-K MATCHING FACTOR=0.8780E-01


                                         WITH  MATCHING FACTOR             WITHOUT MATCHING FACTOR
                                         --------------------             ------------------------
PRESSURE     WATER CONTENT      KUNZE- K      MARSHALL-K      M-Q-K         MARSHALL-K     M-Q-K
  (CM)          (CC/CC)        (CM/DAY)       (CM/DAY)      (CM/DAY)       (CM/DAY)      (CM/DAY)

 90.5039        0.1572        1.0468E-02     6.5815E-03    8.9676E-03     2.9748E-02    1.0214E-01
 82.4873        0.1634        4.5916E-02     3.0006E-02    3.9846E-02     1.3563E-01    4.5383E-01
 77.2433        0.1696        1.1396E-01     7.7295E-02    1.0013E-01     3.4937E-01    1.1404E 00
 73.5997        0.1758        2.2238E-01     1.5634E-01    1.9774E-01     7.0664E-01    2.2522E 00
 70.6722        0.1819        3.7885E-01     2.7571E-01    3.4077E-01     1.2462E 00    3.8813E 00
 68.0643        0.1881        5.9119E-01     4.4487E-01    5.3772E-01     2.0108E 00    6.1244E 00
 65.4882        0.1943        8.6768E-01     6.7441E-01    7.9778E-01     3.0483E 00    9.0863E 00
 63.1572        0.2005        1.2174E 00     9.7632E-01    1.1310E 00     4.4129E 00    1.2882E 01
 61.4551        0.2067        1.6496E 00     1.3638E 00    1.5483E 00     6.1645E 00    1.7634E 01
 60.1350        0.2129        2.1739E 00     1.8511E 00    2.0605E 00     8.3669E 00    2.3468E 01
 58.2688        0.2191        2.7999E 00     2.4534E 00    2.6793E 00     1.1089E 01    3.0516E 01
 56.4915        0.2253        3.5383E 00     3.1880E 00    3.4174E 00     1.4410E 01    3.8923E 01
 57.0303        0.2314        4.3993E 00     4.0726E 00    4.2876E 00     1.8408E 01    4.8834E 01
 57.0143        0.2376        5.3904E 00     5.1236E 00    5.3000E 00     2.3159E 01    6.0365E 01
 50.8808        0.2438        6.5236E 00     6.3621E 00    6.4693E 00     2.8757E 01    7.3683E 01
 13.3000        0.2500        7.9070E 00     7.9070E 00    7.9070E 00     3.5739E 01    9.0057E 01
```

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BROOK AND COREY - K
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PRESSURE        WATER CONTENT        BROOK AND COREY-K
  (CM)             (CC/CC)               (CM/DAY)

100.6000            0.1510              9.4918E-04
 94.3643            0.1546              2.4021E-03
 88.1286            0.1588              6.4774E-03
 81.8929            0.1639              1.8786E-02
 75.6571            0.1720              5.9283E-02
 69.4214            0.1851              2.0653E-01
 63.1857            0.2004              8.0922E-01
 56.9500            0.2282              3.6545E 00
 50.7143            0.2444              7.9070E 00
 44.4786            0.2471              7.9070E 00
 38.2429            0.2480              7.9070E 00
 32.0071            0.2480              7.9070E 00
 25.7714            0.2481              7.9070E 00
 19.5357            0.2488              7.9070E 00
 13.3000            0.2500              7.9070E 00
  7.0643            0.2512              7.9070E 00
```

GRADED SAND

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                 I N P U T   D A T A
                 -------------------

SURFACE TENSION (DYNES/CM)      =    71.9700
VISCOSITY (POISE)               =     0.0086
DENSITY (GM/CC)                 =     0.9970
GRAVITY FORCE (CM/SQ.SEC)       =   981.0000
SAT. HYD. COND. (CM/DAY)        =  1221.1200
STEADY WATER CONTENT (CC/CC)=         0.3750
STEADY WATER PRESSURE  (CM)     =     4.0000
BUBBLING PRESSURE (CM)          =    42.0000
PORE SIZE DIST. INDEX(LAMDA)=         3.0509
NUMBER OF DATA POINTS           =         11

PRESSURE (CM)      WATER CONTENT (CC/CC)
-------------      ---------------------
     4.000                 0.375
    20.000                 0.365
    30.000                 0.348
    42.000                 0.320
    47.000                 0.280
    51.000                 0.225
    58.000                 0.151
    67.000                 0.102
    82.000                 0.060
   100.000                 0.043
   124.000                 0.030
```

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               O U T P U T
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GRADED-SAND

CHILDS AND COLLIS-GEORGE - K
-----------------------------

MATCHING POINT NUMBER=        16
MATCHING FACTOR      =0.3527E 08

PRESSURE       WATER CONTENT       CCGS - K
  (CM)            (CC/CC)          (CM/DAY)

116.5000           0.0341         4.0154E-02
109.0000           0.0381         1.6640E-01
101.5000           0.0422         3.9186E-01
 94.0000           0.0465         7.5964E-01
 86.5000           0.0534         1.6539E 00
 79.0000           0.0658         4.4458E 00
 71.5000           0.0859         1.2779E 01
 64.0000           0.1147         3.4774E 01
 56.5000           0.1635         1.0608E 02
 49.0000           0.2534         3.8422E 02
 41.5000           0.3225         7.6040E 02
 34.0000           0.3427         9.0581E 02
 26.5000           0.3537         9.9505E 02
 19.0000           0.3664         1.1146E 03
 11.5000           0.3727         1.1874E 03
  4.0000           0.3750         1.2211E 03
```

```
KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
-----------------------------------------------------

MATCHING POINT NUMBER              =       16
KUNZE-K MATCHING FACTOR            =0.4175E 00
MARSHALL-K MATCHING FACTOR         =0.1113E 01
MILL. AND QUIRK-K MATCHING FACTOR=0.5789E 00


                                                WITH  MATCHING FACTOR            WITHOUT MATCHING FACTOR
                                                ---------------------            -----------------------
PRESSURE     WATER CONTENT       KUNZE- K      MARSHALL-K      M-Q-K          MARSHALL-K      M-Q-K
  (CM)          (CC/CC)         (CM/DAY)       (CM/DAY)      (CM/DAY)         (CM/DAY)      (CM/DAY)

 89.1811         0.0516         1.9791E-01    2.7213E-02    1.0215E-01      2.4446E-02    1.7646E-01
 74.6474         0.0731         1.3173E 00    2.5687E-01    7.6388E-01      2.3075E-01    1.3195E 00
 68.4054         0.0947         4.4705E 00    1.1238E 00    2.8256E 00      1.0140E 00    4.8310E 00
 64.2369         0.1162         1.1026E 01    3.4182E 00    7.4626E 00      3.0706E 00    1.2891E 01
 60.1630         0.1378         2.2556E 01    8.2895E 00    1.6157E 01      7.4465E 00    2.7910E 01
 56.8365         0.1594         4.0882E 01    1.7375E 01    3.0737E 01      1.5608E 01    5.3096E 01
 54.4867         0.1809         6.8064E 01    3.2841E 01    5.3384E 01      2.9501E 01    9.2218E 01
 52.7140         0.2025         1.0633E 02    5.7418E 01    8.6587E 01      5.1579E 01    1.4957E 02
 51.0751         0.2241         1.5805E 02    9.4433E 01    1.3312E 02      8.4829E 01    2.2995E 02
 49.2698         0.2456         2.2577E 02    1.4788E 02    1.9607E 02      1.3284E 02    3.3870E 02
 47.6517         0.2672         3.1231E 02    2.2252E 02    2.7894E 02      1.9789E 02    4.8185E 02
 45.6992         0.2888         4.2063E 02    3.2388E 02    3.8553E 02      2.9095E 02    6.6593E 02
 44.5855         0.3103         5.5394E 02    4.5839E 02    5.2006E 02      4.1177E 02    8.9837E 02
 37.0185         0.3319         7.1706E 02    6.3460E 02    6.8844E 02      5.7006E 02    1.1892E 03
 28.1300         0.3534         9.2015E 02    8.6724E 02    9.0217E 02      7.7905E 02    1.5584E 03
  4.0000         0.3750         1.2211E 03    1.2211E 03    1.2211E 03      1.0969E 03    2.1094E 03
```

```
BROOKS AND COREY - K
--------------------

PRESSURE        WATER CONTENT        BROOKS AND COREY-K
  (CM)            (CC/CC)               (CM/DAY)

124.0000           0.0300              6.9673E-03
116.5000           0.0341              1.3972E-02
109.0000           0.0381              2.9347E-02
101.5000           0.0422              6.4992E-02
 94.0000           0.0465              1.5299E-01
 86.5000           0.0534              3.8673E-01
 79.0000           0.0658              1.0634E 00
 71.5000           0.0859              3.2348E 00
 64.0000           0.1147              1.1132E 01
 56.5000           0.1635              4.4699E 01
 49.0000           0.2534              2.1884E 02
 41.5000           0.3225              1.2211E 03
 34.0000           0.3427              1.2211E 03
 26.5000           0.3537              1.2211E 03
 19.0000           0.3664              1.2211E 03
 11.5000           0.3727              1.2211E 03
```

VOLCANIC SAND

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                I N P U T   D A T A
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SURFACE TENSION (DYNES/CM)   =   22.9000
VISCOSITY (POISE)            =    0.0144
DENSITY (GM/CC)              =    0.7549
GRAVITY FORCE (CM/SQ.SEC)    =  981.0000
SAT. HYD. COND. (CM/DAY)     =  488.6200
STEADY WATER CONTENT (CC/CC)=     0.3510
STEADY WATER PRESSURE  (CM) =    10.5000
BUBBLING PRESSURE (CM)       =   16.0000
PORE SIZE DIST. INDEX(LAMDA)=     2.2900
NUMBER OF DATA POINTS        =        12

PRESSURE (CM)       WATER CONTENT (CC/CC)
-------------       ---------------------
   10.500                   0.351
   12.000                   0.347
   13.500                   0.346
   14.500                   0.344
   15.500                   0.342
   16.000                   0.333
   17.000                   0.314
   17.200                   0.307
   21.000                   0.224
   24.800                   0.168
   36.900                   0.097
   67.700                   0.066
```

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                    O U T P U T
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VOLCANIC-SAND

CHILDS AND COLLIS-GEORGE - K
-------------------------------

MATCHING POINT NUMBER=          14
MATCHING FACTOR       =0.3791E 07

PRESSURE           WATER CONTENT        CCGS - K
  (CM)                (CC/CC)           (CM/DAY)

 63.6143               0.0680          3.5717E-03
 59.5286               0.0703          1.6539E-02
 55.4429               0.0729          4.6477E-02
 51.3571               0.0763          1.0947E-01
 47.2714               0.0806          2.3702E-01
 43.1857               0.0860          4.8849E-01
 39.1000               0.0927          9.7335E-01
 35.0143               0.1012          1.9099E 00
 30.9286               0.1157          4.5990E 00
 26.8429               0.1450          1.5456E 01
 22.7571               0.1970          5.8635E 01
 18.6714               0.2648          1.7323E 02
 14.5857               0.3441          4.5560E 02
 10.5000               0.3510          4.8862E 02
  6.4143               0.3410          4.4489E 02
```

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KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER              =          16
KUNZE-K MATCHING FACTOR            =0.2038E 00
MARSHALL-K MATCHING FACTOR         =0.8764E 00
MILL. AND QUIRK-K MATCHING FACTOR=0.4361F 00


                                             WITH  MATCHING FACTOR              WITHOUT MATCHING FACTOR
                                             ---------------------              -----------------------
PRESSURE    WATER CONTENT        KUNZE- K       MARSHALL-K       M-Q-K          MARSHALL-K        M-Q-K
  (CM)         (CC/CC)          (CM/DAY)        (CM/DAY)       (CM/DAY)         (CM/DAY)        (CM/DAY)

 48.3996        0.0838         8.4110E-02      2.0084E-02     5.2181E-02       2.2915E-02      1.1965E-01
 33.8183        0.1016         5.0932E-01      1.4746E-01     3.3694E-01       1.6825E-01      7.7260E-01
 26.3546        0.1194         1.7625E 00      5.9975E-01     1.2305F 00       6.8429E-01      2.8215E 00
 24.0174        0.1372         4.6074E 00      1.8016E 00     3.3692E 00       2.0556E 00      7.7254E 00
 24.3276        0.1551         9.8465E 00      4.3499E 00     7.4992F 00       4.9631E 00      1.7196E 01
 24.8165        0.1729         1.8121E 01      8.9248E 00     1.4310E 01       1.0183E 01      3.2813E 01
 24.0528        0.1907         3.0015E 01      1.6306E 01     2.4491E 01       1.8605E 01      5.6158E 01
 22.4933        0.2085         4.6265E 01      2.7482E 01     3.8891E 01       3.1356E 01      8.9178E 01
 20.7945        0.2263         6.7860E 01      4.3754E 01     5.8625E 01       4.9921E 01      1.3443E 02
 19.4423        0.2441         9.6033E 01      6.6793E 01     8.5086E 01       7.6208E 01      1.9510E 02
 18.4562        0.2619         1.3219E 02      9.8652E 01     1.1991E 02       1.1256E 02      2.7494E 02
 17.7776        0.2798         1.7784E 02      1.4174E 02     1.6488E 02       1.6172E 02      3.7808E 02
 17.3474        0.2976         2.3448E 02      1.9878E 02     2.2192E 02       2.2680E 02      5.0885E 02
 16.9033        0.3154         3.0364E 02      2.7282E 02     2.9299E 02       3.1128E 02      6.7183E 02
 16.0193        0.3332         3.8702E 02      3.6738E 02     3.8036E 02       4.1917E 02      8.7216E 02
 10.5000        0.3510         4.8862E 02      4.8862E 02     4.8862E 02       5.5750E 02      1.1204E 03
```

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BROOKS AND COREY - K
--------------------

PRESSURE         WATER CONTENT       BROOKS AND COREY-K
  (CM)              (CC/CC)               (CM/DAY)

 67.7000            0.0660               1.3553E-03
 63.6143            0.0680               2.3550E-03
 59.5286            0.0703               4.2433E-03
 55.4429            0.0729               7.9727E-03
 51.3571            0.0763               1.5721E-02
 47.2714            0.0806               3.2796E-02
 43.1857            0.0860               7.3122E-02
 39.1000            0.0927               1.7657E-01
 35.0143            0.1012               4.6996E-01
 30.9286            0.1157               1.4126E 00
 26.8429            0.1450               4.9637E 00
 22.7571            0.1970               2.1472E 01
 18.6714            0.2648               1.2421E 02
 14.5857            0.3441               4.8862E 02
 10.5000            0.3510               4.8862E 02
  6.4143            0.3410               4.8862E 02
```

FRAGMENTED MIXTURE

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                I N P U T   D A T A
                -------------------

SURFACE TENSION (DYNES/CM)    =    22.9000
VISCOSITY (POISE)             =     0.0144
DENSITY (GM/CC)               =     0.7549
GRAVITY FORCE (CM/SQ.SEC)     =   981.0000
SAT. HYD. COND. (CM/DAY)      =   666.3000
STEADY WATER CONTENT (CC/CC)=       0.4390
STEADY WATER PRESSURE  (CM) =      10.9000
BUBBLING PRESSURE (CM)        =    17.2000
PORE SIZE DIST. INDEX(LAMDA)=       2.8900
NUMBER OF DATA POINTS         =         11

PRESSURE (CM)      WATER CONTENT (CC/CC)
-------------      ---------------------
   10.900                 0.439
   13.000                 0.433
   14.100                 0.429
   15.000                 0.426
   16.000                 0.421
   17.000                 0.409
   18.400                 0.386
   23.600                 0.249
   30.500                 0.184
   37.700                 0.154
   53.700                 0.134
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                 O U T P U T
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FRAGMENTED-MIXTURE

CHILDS AND COLLIS-GEORGE - K
----------------------------

MATCHING POINT NUMBER=         13
MATCHING FACTOR      =0.4472E 07

PRESSURE           WATER CONTENT        CCGS - K
  (CM)                (CC/CC)          (CM/DAY)

 50.4077              0.1344          3.0282E-04
 47.1154              0.1358          6.0205E-03
 43.8231              0.1392          5.3130E-02
 40.5308              0.1455          2.8728E-01
 37.2385              0.1557          1.1382E 00
 33.9462              0.1695          3.3905E 00
 30.6538              0.1834          7.1600E 00
 27.3615              0.1984          1.3311E 01
 24.0692              0.2392          4.4768E 01
 20.7769              0.3254          2.0200E 02
 17.4846              0.4019          4.7314E 02
 14.1923              0.4287          6.0668E 02
 10.9000              0.4390          6.6630E 02
  7.6077              0.4498          7.3876E 02
  4.3154              0.4752          1.0185E 03
```

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KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER                =        16
KUNZE-K MATCHING FACTOR              =0.2275E 00
MARSHALL-K MATCHING FACTOR           =0.7826E 00
MILL. AND QUIRK-K MATCHING FACTOR=0.4520E 00

                                                  WITH  MATCHING FACTOR                         WITHOUT MATCHING FACTOR
                                                  ---------------------                         -----------------------
PRESSURE      WATER CONTENT          KUNZE- K       MARSHALL-K        M-Q-K             MARSHALL-K        M-Q-K
  (CM)           (CC/CC)            (CM/DAY)        (CM/DAY)         (CM/DAY)           (CM/DAY)        (CM/DAY)

 38.2515          0.1531            2.7347E-01     9.5349E-02      1.9248E-01         1.2184E-01      4.2580E-01
 31.7419          0.1721            1.4533E 00     5.6983E-01      1.0637E 00         7.2814E-01      2.3532E 00
 29.8338          0.1912            4.2333E 00     1.8458E 00      3.2126E 00         2.3586E 00      7.1069E 00
 27.7781          0.2103            9.3410E 00     4.4737E 00      7.3083E 00         5.7165E 00      1.6168E 01
 25.5955          0.2293            1.7552E 01     9.1684E 00      1.4136E 01         1.1716E 01      3.1271E 01
 23.6553          0.2484            2.9851E 01     1.6889E 01      2.4690E 01         2.1581E 01      5.4618E 01
 22.2485          0.2674            4.7398E 01     2.8875E 01      4.0180E 01         3.6896E 01      8.8886E 01
 21.3206          0.2865            7.1452E 01     4.6631E 01      6.1978E 01         5.9586E 01      1.3711E 02
 20.7219          0.3056            1.0330E 02     7.1902E 01      9.1549E 01         9.1878E 01      2.0252E 02
 20.3025          0.3246            1.4422E 02     1.0665E 02      1.3042E 02         1.3627E 02      2.8851E 02
 19.9126          0.3437            1.9548E 02     1.5304E 02      1.8017E 02         1.9556E 02      3.9856E 02
 19.4025          0.3628            2.5842E 02     2.1354E 02      2.4250E 02         2.7286E 02      5.3646E 02
 18.6224          0.3818            3.3456E 02     2.9098E 02      3.1936E 02         3.7182E 02      7.0648E 02
 17.4910          0.4009            4.2578E 02     3.8880E 02      4.1308E 02         4.9682E 02      9.1382E 02
 16.1433          0.4199            5.3456E 02     5.1135E 02      5.2670E 02         6.5341E 02      1.1652E 03
 10.9000          0.4390            6.6630E 02     6.6630E 02      6.6630E 02         8.5141E 02      1.4740E 03
```

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BROOKS AND COREY - K
--------------------

PRESSURE        WATER CONTENT        BROOKS AND COREY-K
  (CM)             (CC/CC)               (CM/DAY)

 53.7000           0.1340               3.5313E-03
 50.4077           0.1344               6.9361E-03
 47.1154           0.1358               1.4260E-02
 43.8231           0.1392               3.0888E-02
 40.5308           0.1455               7.1071E-02
 37.2385           0.1557               1.7550E-01
 33.9462           0.1695               4.7122E-01
 30.6538           0.1834               1.3995E 00
 27.3615           0.1984               4.7040E 00
 24.0692           0.2392               1.8474E 01
 20.7769           0.3254               8.8750E 01
 17.4846           0.4019               5.5927E 02
 14.1923           0.4287               6.6630E 02
 10.9000           0.4390               6.6630E 02
  7.6077           0.4498               6.6630E 02
  4.3154           0.4752               6.6630E 02
```

TOUCHET SILT LOAM 1

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                 I N P U T   D A T A
                 -------------------

SURFACE TENSION (DYNES/CM)    =    22.9000
VISCOSITY (POISE)             =     0.0144
DENSITY (GM/CC)               =     0.7549
GRAVITY FORCE (CM/SQ.SEC)     =   981.0000
SAT. HYD. COND. (CM/DAY)      =    22.2100
STEADY WATER CONTENT (CC/CC)=       0.4630
STEADY WATER PRESSURE  (CM)  =      6.4000
BUBBLING PRESSURE (CM)        =    68.0000
PORE SIZE DIST. INDEX(LAMDA)=       1.4700
NUMBER OF DATA POINTS         =         12

PRESSURE (CM)      WATER CONTENT (CC/CC)
-------------      ---------------------
     6.400                0.463
    17.100                0.462
    36.400                0.460
    49.300                0.457
    62.600                0.433
    71.300                0.382
    81.400                0.329
    94.300                0.280
   104.100                0.259
   116.400                0.234
   131.600                0.214
   149.100                0.198
```

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                O U T P U T
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TCUCHET-SILT-LOAM |

CHILD AND COLLIS-GEORGE - K
---------------------------

MATCHING POINT NUMBER=        16
MATCHING FACTOR      =0.2660E 07

PRESSURE        WATER CONTENT       CCGS - K
  (CM)             (CC/CC)          (CM/DAY)

140.1812            0.2058         7.8070E-03
131.2625            0.2143         3.5278E-02
122.3437            0.2247         9.9235E-02
113.4250            0.2397         2.6035E-01
104.5062            0.2582         5.9015E-01
 95.5875            0.2766         1.0866E 00
 86.6687            0.3061         2.3044E 00
 77.7500            0.3465         4.9984E 00
 68.8313            0.3975         1.0515E 01
 59.9125            0.4430         1.7946E 01
 50.9938            0.4563         2.0656E 01
 42.0750            0.4590         2.1259E 01
 33.1563            0.4604         2.1572E 01
 24.2375            0.4614         2.1788E 01
 15.3188            0.4622         2.1980E 01
```

```
KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER            =         16
KUNZE-K MATCHING FACTOR          =0.9397E-01
MARSHALL-K MATCHING FACTOR       =0.3064E 00
MILL. AND QUIRK-K MATCHING FACTOR=0.1834E 00


                                    WITH  MATCHING FACTOR          WITHOUT MATCHING FACTOR
                                    ---------------------          -----------------------
PRESSURE   WATER CONTENT    KUNZE- K    MARSHALL-K     M-Q-K      MARSHALL-K     M-Q-K
 (CM)         (CC/CC)       (CM/DAY)     (CM/DAY)     (CM/DAY)     (CM/DAY)     (CM/DAY)

131.0606      0.2146       1.7053E-02   7.9026E-03   1.3196E-02   2.5790E-02   7.1960E-02
118.1516      0.2311       7.8323E-02   3.9098E-02   6.2131E-02   1.2760E-01   3.3880E-01
109.3155      0.2477       2.0293E-01   1.0856E-01   1.6473E-01   3.5428E-01   8.9828E-01
101.5976      0.2643       4.1236E-01   2.3535E-01   3.4205E-01   7.6806E-01   1.8652E 00
 93.9617      0.2808       7.3153E-01   4.4368E-01   6.1922E-01   1.4479E 00   3.3766E 00
 88.1941      0.2974       1.1897E 00   7.6413E-01   1.0265E 00   2.4938E 00   5.5974E 00
 84.1400      0.3139       1.8191E 00   1.2334E 00   1.5981E 00   4.0254E 00   8.7145E 00
 81.1571      0.3305       2.6528E 00   1.8936E 00   2.3708E 00   6.1798E 00   1.2928E 01
 78.5859      0.3471       3.7245E 00   2.7918E 00   3.3833E 00   9.1113E 00   1.8449E 01
 75.7141      0.3636       5.0699E 00   3.9818E 00   4.6776E 00   1.2995E 01   2.5507E 01
 71.8192      0.3802       6.7304E 00   5.5266E 00   6.3025E 00   1.8036E 01   3.4367E 01
 66.6233      0.3967       8.7582E 00   7.5050E 00   8.3188E 00   2.4493E 01   4.5362E 01
 62.3236      0.4133       1.1220E 01   1.0016E 01   1.0804E 01   3.2688E 01   5.8912E 01
 61.9733      0.4299       1.4185E 01   1.3171E 01   1.3839E 01   4.2983E 01   7.5462E 01
 63.6016      0.4464       1.7701E 01   1.7068E 01   1.7488E 01   5.5702E 01   9.5360E 01
  6.4001      0.4630       2.2210E 01   2.2210E 01   2.2210E 01   7.2483E 01   1.2111E 02
```

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BROOK AND COREY - K
-------------------

PRESSURE          WATER CONTENT         BROOK AND COREY-K
  (CM)               (CC/CC)               (CM/DAY)

149.1000             0.1980               1.4486E-01
140.1812             0.2058               2.1510E-01
131.2625             0.2143               3.2783E-01
122.3437             0.2247               5.1467E-01
113.4250             0.2397               8.3608E-01
104.5062             0.2582               1.4133E 00
 95.5875             0.2766               2.5036E 00
 86.6687             0.3061               4.6906E 00
 77.7500             0.3465               9.4089E 00
 68.8313             0.3975               2.0546E 01
 59.9125             0.4430               2.2210E 01
 50.9938             0.4563               2.2210E 01
 42.0750             0.4590               2.2210E 01
 33.1563             0.4604               2.2210E 01
 24.2375             0.4614               2.2210E 01
 15.3188             0.4622               2.2210E 01
```

TOUCHET SILT LOAM 2

```
                 I N P U T   D A T A
                 -------------------

SURFACE TENSION (DYNES/CM)   =    22.9000
VISCOSITY (POISE)            =     0.0144
DENSITY (GM/CC)              =     0.7549
GRAVITY FORCE (CM/SQ.SEC)    =   981.0000
SAT. HYD. COND. (CM/DAY)     =    11.4160
STEADY WATER CONTENT (CC/CC)=      0.4300
STEADY WATER PRESSURE  (CM) =     34.2000
BUBBLING PRESSURE (CM)       =    72.8000
PORE SIZE DIST. INDEX(LAMDA)=      1.6700
NUMBER OF DATA POINTS        =         15

PRESSURE (CM)      WATER CONTENT (CC/CC)
-------------      ---------------------
    34.200               0.430
    36.900               0.423
    59.600               0.420
    71.000               0.415
    82.100               0.377
    93.000               0.314
   104.100               0.271
   120.800               0.234
   142.000               0.203
   160.300               0.184
   181.600               0.171
   202.200               0.157
   240.300               0.138
   276.600               0.132
   307.900               0.123
```

```
                    O U T P U T
                    -----------

TOUCHET-SILT-LOAM2

CHILDS AND COLLIS-GEORGE - K
----------------------------

MATCHING POINT NUMBER=        15
MATCHING FACTOR       =0.1824E 07


PRESSURE        WATER CONTENT        CCGS - K
  (CM)             (CC/CC)          (CM/DAY)

289.6533           0.1292          6.9421E-04
271.4067           0.1333          2.0476E-03
253.1600           0.1358          3.2735E-03
234.9133           0.1402          6.3910E-03
216.6667           0.1487          1.6018E-02
198.4200           0.1598          3.7358E-02
180.1733           0.1716          7.2389E-02
161.9267           0.1832          1.2282E-01
143.6800           0.2010          2.3711E-01
125.4333           0.2266          5.0546E-01
107.1867           0.2625          1.1486E 00
 88.9400           0.3375          3.9507E 00
 70.6933           0.4150          9.7343E 00
 52.4467           0.4160          9.8264E 00
 34.2000           0.4300          1.1416E 01
 15.9533           0.3480          2.6801E 01
```

```
KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER               =       16
KUNZE-K MATCHING FACTOR             =0.1929E 00
MARSHALL-K MATCHING FACTOR          =0.4486E 00
MILL. AND QUIRK-K MATCHING FACTOR=0.2556E 00


                                                 WITH  MATCHING FACTOR                WITHOUT MATCHING FACTOR
                                                 ---------------------                -----------------------
PRESSURE       WATER CONTENT          KUNZE- K       MARSHALL-K        M-Q-K          MARSHALL-K       M-Q-K
  (CM)            (CC/CC)            (CM/DAY)        (CM/DAY)        (CM/DAY)          (CM/DAY)       (CM/DAY)

223.0462          0.1426            3.2384E-03      1.0737E-03      2.2414E-03      2.3931E-03      8.7692E-03
196.7879          0.1617            1.6897E-02      6.3549E-03      1.2197E-02      1.4165E-02      4.7718E-02
165.2275          0.1809            4.9099E-02      2.0654E-02      3.6789E-02      4.6037E-02      1.4393E-01
144.4071          0.2001            1.1084E-01      5.1565E-02      8.5883E-02      1.1493E-01      3.3601E-01
130.1030          0.2192            2.1668E-01      1.1046E-01      1.7309E-01      2.4621E-01      6.7721E-01
118.6364          0.2384            3.8409E-01      2.1292E-01      3.1552E-01      4.7459E-01      1.2345E 00
109.5079          0.2575            6.3372E-01      3.7955E-01      5.3418E-01      8.4598E-01      2.0899E 00
101.9236          0.2767            9.8958E-01      6.3678E-01      8.5434E-01      1.4193E 00      3.3425E 00
 95.9135          0.2959            1.4790E 00      1.0176E 00      1.3057E 00      2.2682E 00      5.1084E 00
 92.9634          0.3150            2.1310E 00      1.5612E 00      1.9211E 00      3.4798E 00      7.5160E 00
 93.3710          0.3342            2.9723E 00      2.3100E 00      2.7327E 00      5.1488E 00      1.0692E 01
 92.6926          0.3533            4.0258E 00      3.3081E 00      3.7707E 00      7.3735E 00      1.4753E 01
 85.4263          0.3725            5.3191E 00      4.6080E 00      5.0706E 00      1.0271E 01      1.9838E 01
 69.1120          0.3917            6.9071E 00      6.2915E 00      6.6954E 00      1.4023E 01      2.6195E 01
 66.8517          0.4108            8.8761E 00      8.4806E 00      8.7423E 00      1.8902E 01      3.4204E 01
 34.1999          0.4300            1.1416E 01      1.1416E 01      1.1416E 01      2.5445E 01      4.4664E 01
```

```
BROOKS AND COREY - K
--------------------

PRESSURE       WATER CONTENT       BROOKS AND COREY-K
  (CM)            (CC/CC)              (CM/DAY)

307.9000          0.1234              4.6484E-04
289.6533          0.1292              7.1332E-04
271.4067          0.1333              1.1256E-03
253.1600          0.1358              1.8334E-03
234.9133          0.1402              3.0974E-03
216.6667          0.1487              5.4595E-03
198.4200          0.1598              1.0115E-02
180.1733          0.1716              1.9891E-02
161.9267          0.1832              4.2047E-02
143.6800          0.2010              9.7209E-02
125.4333          0.2266              2.5187E-01
107.1867          0.2625              7.5817E-01
 88.9400          0.3375              2.8047E 00
 70.6933          0.4150              1.1416E 01
 52.4467          0.4160              1.1416E 01
 34.2000          0.4300              1.1416E 01
```

```
                  I N P U T   D A T A
                  -------------------

SURFACE TENSION (DYNES/CM)   =    22.9000
VISCOSITY (POISE)            =     0.0144
DENSITY (GM/CC)              =     0.7549
GRAVITY FORCE (CM/SQ.SEC)    =   981.0000
SAT. HYD. COND. (CM/DAY)     =    11.4160
STEADY WATER CONTENT (CC/CC)=      0.4300
STEADY WATER PRESSURE  (CM) =     34.2000
BUBBLING PRESSURE (CM)       =    72.8000
PORE SIZE DIST. INDEX(LAMDA)=      1.6700
NUMBER OF DATA POINTS        =         15

PRESSURE (CM)      WATER CONTENT (CC/CC)
-------------      ---------------------
    34.200                  0.430
    36.900                  0.423
    59.600                  0.420
    71.000                  0.415
    82.100                  0.377
    93.000                  0.314
   104.100                  0.271
   120.800                  0.234
   142.000                  0.203
   160.300                  0.184
   181.600                  0.171
   202.200                  0.157
   240.300                  0.138
   276.600                  0.132
   307.900                  0.123
```

```
                 O U T P U T
                 -----------

         TOUCHET-SILT-LOAM2

         CHILDS AND COLLIS-GEORGE - K
         ----------------------------

         MATCHING POINT NUMBER=       15
         MATCHING FACTOR      =0.1824E 07

         PRESSURE       WATER CONTENT      CCGS - K
           (CM)            (CC/CC)         (CM/DAY)

         289.6533          0.1292         6.9421E-04
         271.4067          0.1333         2.0476E-03
         253.1600          0.1358         3.2735E-03
         234.9133          0.1402         6.3910E-03
         216.6667          0.1487         1.6018E-02
         198.4200          0.1598         3.7358E-02
         180.1733          0.1716         7.2389E-02
         161.9267          0.1832         1.2282E-01
         143.6800          0.2010         2.3711E-01
         125.4333          0.2266         5.0546E-01
         107.1867          0.2625         1.1486E 00
          88.9400          0.3375         3.9507E 00
          70.6933          0.4150         9.7343E 00
          52.4467          0.4160         9.8264E 00
          34.2000          0.4300         1.1416E 01
          15.9533          0.3480         2.6801E 01
```

```
KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER              =        16
KUNZE-K MATCHING FACTOR            =0.1929E 00
MARSHALL-K MATCHING FACTOR         =0.4486E 00
MILL. AND QUIRK-K MATCHING FACTOR=0.2556E 00


                                            WITH  MATCHING FACTOR                   WITHOUT MATCHING FACTOR
                                            ---------------------                   -----------------------
PRESSURE    WATER CONTENT       KUNZE- K      MARSHALL-K       M-Q-K           MARSHALL-K       M-Q-K
  (CM)         (CC/CC)          (CM/DAY)       (CM/DAY)       (CM/DAY)          (CM/DAY)       (CM/DAY)

223.0462       0.1426          3.2384E-03     1.0737E-03     2.2414E-03        2.3931E-03     8.7692E-03
196.7879       0.1617          1.6897E-02     6.3549E-03     1.2197E-02        1.4165E-02     4.7718E-02
165.2275       0.1809          4.9099E-02     2.0654E-02     3.6789E-02        4.6037E-02     1.4393E-01
144.4071       0.2001          1.1084E-01     5.1565E-02     8.5883E-02        1.1493E-01     3.3601E-01
130.1030       0.2192          2.1668E-01     1.1046E-01     1.7309E-01        2.4621E-01     6.7721E-01
118.6364       0.2384          3.8409E-01     2.1292E-01     3.1552E-01        4.7459E-01     1.2345E 00
109.5079       0.2575          6.3372E-01     3.7955E-01     5.3418E-01        8.4598E-01     2.0899E 00
101.9236       0.2767          9.8958E-01     6.3678E-01     8.5434E-01        1.4193E 00     3.3425E 00
 95.9135       0.2959          1.4790E 00     1.0176E 00     1.3057E 00        2.2682E 00     5.1084E 00
 92.9634       0.3150          2.1310E 00     1.5612E 00     1.9211E 00        3.4798E 00     7.5160E 00
 93.3710       0.3342          2.9723E 00     2.3100E 00     2.7327E 00        5.1488E 00     1.0692E 01
 92.6926       0.3533          4.0258E 00     3.3081E 00     3.7707E 00        7.3735E 00     1.4753E 01
 85.4263       0.3725          5.3191E 00     4.6080E 00     5.0706E 00        1.0271E 01     1.9838E 01
 69.1120       0.3917          6.9071E 00     6.2915E 00     6.6954E 00        1.4023E 01     2.6195E 01
 66.8517       0.4108          8.8761E 00     8.4806E 00     8.7423E 00        1.8902E 01     3.4204E 01
 34.1999       0.4300          1.1416E 01     1.1416E 01     1.1416E 01        2.5445E 01     4.4664E 01
```

```
BROOKS AND COREY - K
--------------------

PRESSURE        WATER CONTENT       BROOKS AND COREY-K
  (CM)             (CC/CC)              (CM/DAY)

307.9000            0.1234             4.6484E-04
289.6533            0.1292             7.1332E-04
271.4067            0.1333             1.1256E-03
253.1600            0.1358             1.8334E-03
234.9133            0.1402             3.0974E-03
216.6667            0.1487             5.4595E-03
198.4200            0.1598             1.0115E-02
180.1733            0.1716             1.9891E-02
161.9267            0.1832             4.2047E-02
143.6800            0.2010             9.7209E-02
125.4333            0.2266             2.5187E-01
107.1867            0.2625             7.5817E-01
 88.9400            0.3375             2.8047E 00
 70.6933            0.4150             1.1416E 01
 52.4467            0.4160             1.1416E 01
 34.2000            0.4300             1.1416E 01
```

LAKELAND FINE SAND

```
                 I N P U T   D A T A
                 -------------------

SURFACE TENSION (DYNES/CM)    =    72.7500
VISCOSITY (POISE)             =     0.0100
DENSITY (GM/CC)               =     0.9982
GRAVITY FORCE (CM/SQ.SEC)     =   981.0000
SAT. HYD. COND. (CM/DAY)      =   355.2000
STEADY WATER CONTENT (CC/CC)=       0.3710
STEADY WATER PRESSURE  (CM) =       5.0000
BUBBLING PRESSURE (CM)        =    33.0000
PORE SIZE DIST. INDEX(LAMDA)=       1.5877
NUMBER OF DATA POINTS         =         12

PRESSURE (CM)       WATER CONTENT (CC/CC)
-------------       ---------------------
      5.000                0.371
     10.000                0.370
     15.000                0.368
     20.000                0.363
     25.000                0.352
     30.000                0.335
     45.000                0.260
     60.000                0.195
     80.000                0.158
    100.000                0.140
    150.000                0.120
    200.000                0.108
```

```
          O U T P U T
          -----------

LAKELAND-FINE-SAND

CHILDS AND COLLIS-GEORGE - K
----------------------------

MATCHING POINT NUMBER=        16
MATCHING FACTOR      =0.1537E 08


PRESSURE      WATER CONTENT     CCGS - K
  (CM)           (CC/CC)        (CM/DAY)

187.8125         0.1109        3.4745E-03
175.6250         0.1138        1.4405E-02
163.4375         0.1168        3.3948E-02
151.2500         0.1197        6.3589E-02
139.0625         0.1227        1.0657E-01
126.8750         0.1264        1.7821E-01
114.6875         0.1314        3.1700E-01
102.5000         0.1383        6.0996E-01
 90.3125         0.1478        1.2490E 00
 78.1250         0.1601        2.6031E 00
 65.9375         0.1792        6.3099E 00
 53.7500         0.2183        2.2881E 01
 41.5625         0.2782        8.3621E 01
 29.3750         0.3374        2.1401E 02
 17.1875         0.3664        3.2730E 02
  5.0000         0.3710        3.5520E 02
```

```
KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER               =      16
KUNZE-K MATCHING FACTOR             =0.1295E 00
MARSHALL-K MATCHING FACTOR          =0.3489E 00
MILL. AND QUIRK-K MATCHING FACTOR=0.1802E 00


                                           WITH  MATCHING FACTOR            WITHOUT MATCHING FACTOR
                                           --------------------            -----------------------
PRESSURE    WATER CONTENT        KUNZE- K     MARSHALL-K      M-Q-K        MARSHALL-K      M-Q-K
  (CM)         (CC/CC)          (CM/DAY)      (CM/DAY)      (CM/DAY)       (CM/DAY)      (CM/DAY)

135.1708        0.1244        5.2210E-02    1.7512E-02    3.6276E-02    5.0186E-02    2.0135E-01
 98.6398        0.1409        2.9878E-01    1.1345E-01    2.1636E-01    3.2514E-01    1.2009E 00
 80.5508        0.1573        9.6785E-01    4.1039E-01    7.2711E-01    1.1761E 00    4.0359E 00
 69.4653        0.1738        2.3884E 00    1.1186E 00    1.8548E 00    3.2056E 00    1.0295E 01
 61.8006        0.1902        4.9772E 00    2.5515E 00    3.9834E 00    7.3121E 00    2.2110E 01
 56.2061        0.2066        9.2390E 00    5.1456E 00    7.6014E 00    1.4746E 01    4.2192E 01
 51.9272        0.2231        1.5765E 01    9.4784E 00    1.3306E 01    2.7164E 01    7.3853E 01
 48.5538        0.2395        2.5227E 01    1.6285E 01    2.1803E 01    4.6671E 01    1.2102E 02
 45.6801        0.2559        3.3382E 01    2.6478E 01    3.3915E 01    7.5883E 01    1.8824E 02
 42.9184        0.2724        5.6086E 01    4.1177E 01    5.0597E 01    1.1801E 02    2.8084E 02
 40.0371        0.2888        7.9342E 01    6.1765E 01    7.2988E 01    1.7701E 02    4.0512E 02
 36.8844        0.3053        1.0938E 02    8.9997E 01    1.0250E 02    2.5792E 02    5.6891E 02
 33.3091        0.3217        1.4781E 02    1.2816E 02    1.4095E 02    3.6730E 02    7.8234E 02
 29.1594        0.3381        1.9688E 02    1.7944E 02    1.9089E 02    5.1424E 02    1.0595E 03
 24.1215        0.3546        2.6016E 02    2.4863E 02    2.5626E 02    7.1255E 02    1.4224E 03
  4.9999        0.3710        3.5520E 02    3.5520E 02    3.5520E 02    1.0179E 03    1.9716E 03
```

```
BROOKS AND COREY - K
--------------------

PRESSURE        WATER CONTENT        BROOKS AND COREY-K
  (CM)             (CC/CC)                (CM/DAY)

200.0000           0.1080                1.8123E-03
187.8125           0.1109                2.7727E-03
175.6250           0.1138                4.3649E-03
163.4375           0.1168                7.0993E-03
151.2500           0.1197                1.1990E-02
139.0625           0.1227                2.1164E-02
126.8750           0.1264                3.9354E-02
114.6875           0.1314                7.7915E-02
102.5000           0.1383                1.6657E-01
 90.3125           0.1478                3.9212E-01
 78.1250           0.1601                1.0452E 00
 65.9375           0.1792                3.2912E 00
 53.7500           0.2183                1.3110E 01
 41.5625           0.2782                7.4627E 01
 29.3750           0.3374                3.5520E 02
 17.1875           0.3664                3.5520E 02
```

WIDE-RANGE SAND

```
                 I N P U T   D A T A
                 -------------------

SURFACE TENSION (DYNES/CM)   =    71.6500
VISCOSITY (POISE)            =     0.0086
DENSITY (GM/CC)              =     0.9965
GRAVITY FORCE (CM/SQ.SEC)    =   981.0000
SAT. HYD. COND. (CM/DAY)     =   453.6000
STEADY WATER CONTENT (CC/CC)=      0.4000
STEADY WATER PRESSURE  (CM)  =    28.0000
BUBBLING PRESSURE (CM)       =    60.1000
PORE SIZE DIST. INDEX(LAMDA)=      2.3000
NUMBER OF DATA POINTS        =         22

PRESSURE (CM)        WATER CONTENT (CC/CC)
-------------        ---------------------
    28.000                  0.400
    29.000                  0.400
    32.000                  0.399
    37.000                  0.398
    42.000                  0.396
    46.000                  0.390
    49.000                  0.383
    52.000                  0.376
    56.000                  0.365
    59.000                  0.350
    62.000                  0.336
    65.000                  0.330
    68.000                  0.310
    71.000                  0.290
    73.000                  0.275
    75.000                  0.255
    77.000                  0.240
    78.000                  0.230
    80.000                  0.203
    85.000                  0.190
    90.000                  0.172
   100.000                  0.140
```

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                 O U T P U T
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WIDE-RANGE-SAND

CHILDS AND COLLIS-GEORGE - K
-----------------------------

MATCHING POINT NUMBER=          12
MATCHING FACTOR       =0.4018E 08

PRESSURE        WATER CONTENT       CCGS - K
  (CM)             (CC/CC)          (CM/DAY)

 94.0000            0.1566         1.1846E 00
 88.0000            0.1812         7.6333E 00
 82.0000            0.1908         1.1767E 01
 76.0000            0.2474         6.0082E 01
 70.0000            0.2964         1.3806E 02
 64.0000            0.3328         2.2118E 02
 58.0000            0.3555         2.8623E 02
 52.0000            0.3760         3.5555E 02
 46.0000            0.3900         4.1003E 02
 40.0000            0.3970         4.4010E 02
 34.0000            0.3985         4.4650E 02
 28.0000            0.4000         4.5360E 02
 22.0000            0.3923         4.2170E 02
 16.0000            0.3186         7.9022E 02
 10.0000            0.1128         1.4829E 04
  4.0000           -0.2911         2.6516E 05
```

```
KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER             =       16
KUNZE-K MATCHING FACTOR           =0.2568E 00
MARSHALL-K MATCHING FACTOR        =0.6420E 00
MILL. AND QUIRK-K MATCHING FACTOR=0.3485E 00


                                               WITH  MATCHING FACTOR                WITHOUT MATCHING FACTOR
                                               -------------------                  ----------------------
PRESSURE     WATER CONTENT      KUNZE- K      MARSHALL-K       M-Q-K            MARSHALL-K       M-Q-K
 (CM)          (CC/CC)          (CM/DAY)       (CM/DAY)       (CM/DAY)           (CM/DAY)      (CM/DAY)

 94.5758        0.1563        4.3924E-01     1.7158E-01     3.2109E-01       2.6728E-01     9.2133E-01
 89.8731        0.1725        1.9944E 00     8.6003E-01     1.5068E 00       1.3398E 00     4.3236E 00
 85.4506        0.1887        5.0779E 00     2.3962E 00     3.9533E 00       3.7326E 00     1.1344E 01
 79.4759        0.2050        1.0172E 01     5.2131E 00     8.1402E 00       8.1208E 00     2.3358E 01
 78.1448        0.2212        1.7818E 01     9.3555E 00     1.4626E 01       1.5352E 01     4.1968E 01
 77.3153        0.2375        2.8532E 01     1.6941E 01     2.3981E 01       2.6389E 01     6.8810E 01
 75.1514        0.2537        4.2812E 01     2.7159E 01     3.6786E 01       4.2306E 01     1.0555E 02
 73.4994        0.2700        6.1207E 01     4.1315E 01     5.3691E 01       6.4359E 01     1.5406E 02
 71.5863        0.2862        8.4313E 01     6.0337E 01     7.5415E 01       9.3939E 01     2.1640E 02
 68.8684        0.3025        1.1279E 02     8.5294E 01     1.0276E 02       1.3287E 02     2.9485E 02
 67.5487        0.3187        1.4735E 02     1.1742E 02     1.3660E 02       1.8290E 02     3.9197E 02
 62.4697        0.3350        1.8884E 02     1.5815E 02     1.7800E 02       2.4636E 02     5.1075E 02
 58.8439        0.3512        2.3837E 02     2.0932E 02     2.2827E 02       3.2607E 02     6.5499E 02
 55.1704        0.3675        2.9732E 02     2.7316E 02     2.8904E 02       4.2551E 02     8.2936E 02
 48.5424        0.3837        3.6743E 02     3.5251E 02     3.6239E 02       5.4912E 02     1.0398E 03
 28.0000        0.4000        4.5360E 02     4.5360E 02     4.5360E 02       7.0654E 02     1.3016E 03
```

```
BROOKS AND COREY - K
--------------------

PRESSURE         WATER CONTENT       BROOKS AND COREY-K
  (CM)              (CC/CC)              (CM/DAY)

100.0000            0.1400              4.8827E 00
 94.0000            0.1566              8.4687E 00
 88.0000            0.1812              1.5232E 01
 82.0000            0.1908              2.8557E 01
 76.0000            0.2474              5.6159E 01
 70.0000            0.2964              1.1676E 02
 64.0000            0.3328              2.5921E 02
 58.0000            0.3555              4.5360E 02
 52.0000            0.3760              4.5360E 02
 46.0000            0.3900              4.5360E 02
 40.0000            0.3970              4.5360E 02
 34.0000            0.3985              4.5360E 02
 28.0000            0.4000              4.5360E 02
 22.0000            0.3923              4.5360E 02
 16.0000            0.3186              4.5360E 02
 10.0000            0.1128              4.5360E 02
```

BRUCE SAND

```
                  I N P U T   D A T A
                  -------------------

SURFACE TENSION (DYNES/CM)    =    71.9700
VISCOSITY (POISE)             =     0.0086
DENSITY (GM/CC)               =     0.9970
GRAVITY FORCE (CM/SQ.SEC)     =   981.0000
SAT. HYD. COND. (CM/DAY)      =  1641.6000
STEADY WATER CONTENT (CC/CC)=       0.3400
STEADY WATER PRESSURE  (CM) =       2.1420
BUBBLING PRESSURE (CM)        =    33.0000
PORE SIZE DIST. INDEX(LAMDA)=       2.1537
NUMBER OF DATA POINTS         =         15

PRESSURE (CM)       WATER CONTENT (CC/CC)
-------------       ---------------------
     2.142                 0.340
     5.304                 0.334
     9.380                 0.330
    20.400                 0.318
    32.640                 0.300
    42.840                 0.250
    46.920                 0.209
    48.960                 0.167
    55.080                 0.121
    61.200                 0.086
    73.400                 0.075
    77.520                 0.060
    87.720                 0.048
   102.000                 0.037
   122.400                 0.031
```

```
                O U T P U T
                -----------

BRUCE-SAND

CHILDS AND COLLIS-GEORGE - K
-----------------------------

MATCHING POINT NUMBER=        16
MATCHING FACTOR      =0.3793E 08

PRESSURE        WATER CONTENT      CCGS - K
  (CM)            (CC/CC)          (CM/DAY)

114.8839           0.0318         1.5526E-03
107.3678           0.0339         2.4192E-02
 99.8516           0.0387         1.9028E-01
 92.3355           0.0453         7.0551E-01
 84.8194           0.0489         1.1467E 00
 77.3033           0.0608         3.6338E 00
 69.7871           0.0787         1.0903E 01
 62.2710           0.0821         1.2817E 01
 54.7549           0.1223         5.4596E 01
 47.2388           0.2028         2.7012E 02
 39.7226           0.2678         6.0686E 02
 32.2065           0.3014         8.5931E 02
 24.6904           0.3144         9.7851E 02
 17.1743           0.3214         1.0517E 03
  9.6581           0.3298         1.1618E 03
  2.1420           0.3400         1.6416E 03
```

```
KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER               =      16
KUNZE-K MATCHING FACTOR             =0.4772E 00
MARSHALL-K MATCHING FACTOR          =0.1403E 01
MILL. AND QUIRK-K MATCHING FACTOR=0.6837E 00


                                               WITH  MATCHING FACTOR            WITHOUT MATCHING FACTOR
                                               ---------------------            -----------------------
PRESSURE     WATER CONTENT        KUNZE- K      MARSHALL-K      M-Q-K           MARSHALL-K      M-Q-K
  (CM)          (CC/CC)          (CM/DAY)        (CM/DAY)      (CM/DAY)          (CM/DAY)      (CM/DAY)

 85.6696         0.0503          2.3172E-01    3.4290E-02    1.2256E-01      2.4432E-02    1.7927E-01
 75.5804         0.0696          1.4959E 00    3.0633E-01    8.8174E-01      2.1827E-01    1.2897E 00
 58.4271         0.0889          5.0816E 00    1.3293E 00    3.2499E 00      9.4712E-01    4.7535E 00
 53.2691         0.1083          1.2976E 01    4.1314E 00    8.8607E 00      2.9437E 00    1.2960E 01
 55.3311         0.1276          2.7490E 01    1.0314E 01    1.9827E 01      7.3487E 00    2.9000E 01
 52.8450         0.1469          5.0682E 01    2.1894E 01    3.8313E 01      1.5600E 01    5.6039E 01
 49.0789         0.1662          8.4901E 01    4.1498E 01    6.6878E 01      2.9568E 01    9.7821E 01
 47.5423         0.1855          1.3305E 02    7.2588E 01    1.0871E 02      5.1721E 01    1.5901E 02
 47.1072         0.2048          1.9809E 02    1.1933E 02    1.6730E 02      8.5025E 01    2.4471E 02
 45.6444         0.2241          2.8298E 02    1.8654E 02    2.4628E 02      1.3291E 02    3.6023E 02
 43.4761         0.2434          3.9103E 02    2.7998E 02    3.4982E 02      1.9949E 02    5.1167E 02
 41.8375         0.2628          5.2615E 02    4.0661E 02    4.8283E 02      2.8972E 02    7.0623E 02
 39.1323         0.2821          6.9288E 02    5.7481E 02    6.5105E 02      4.0956E 02    9.5227E 02
 31.9018         0.3014          8.9822E 02    7.9618E 02    8.6283E 02      5.6729E 02    1.2620E 03
 18.1860         0.3207          1.1620E 03    1.0960E 03    1.1395E 03      7.8089E 02    1.6667E 03
  2.1420         0.3400          1.6416E 03    1.6416E 03    1.6416E 03      1.1697E 03    2.4011E 03
```

```
BROOKS AND COREY - K
--------------------

PRESSURE          WATER CONTENT        BROOKS AND COREY-K
  (CM)               (CC/CC)               (CM/DAY)

122.4000             0.0310               2.5040E-02
114.8839             0.0318               4.2806E-02
107.3678             0.0339               7.5882E-02
 99.8516             0.0387               1.4022E-01
 92.3355             0.0453               2.7188E-01
 84.8194             0.0489               5.5767E-01
 77.3033             0.0608               1.2227E 00
 69.7871             0.0787               2.9053E 00
 62.2710             0.0821               7.6196E 00
 54.7549             0.1223               2.2625E 01
 47.2388             0.2028               7.8915E 01
 39.7226             0.2678               3.4194E 02
 32.2065             0.3014               1.6416E 03
 24.6904             0.3144               1.6416E 03
 17.1743             0.3214               1.6416E 03
  9.6581             0.3298               1.6416E 03
```

FINE SAND 2

```
                 I N P U T   D A T A
                 -------------------

SURFACE TENSION (DYNES/CM)    =     71.9700
VISCOSITY (POISE)             =      0.0086
DENSITY (GM/CC)               =      0.9970
GRAVITY FORCE (CM/SQ.SEC)     =    981.0000
SAT. HYD. COND. (CM/DAY)      =    188.6400
STEADY WATER CONTENT (CC/CC)=        0.3750
STEADY WATER PRESSURE  (CM) =       27.0000
BUBBLING PRESSURE (CM)        =    164.0000
PORE SIZE DIST. INDEX(LAMDA)=        2.8191
NUMBER OF DATA POINTS         =          12

PRESSURE (CM)        WATER CONTENT (CC/CC)
-------------        ---------------------
    27.000                  0.375
    56.000                  0.370
    92.000                  0.364
   120.000                  0.350
   150.000                  0.320
   168.000                  0.280
   183.000                  0.252
   200.000                  0.208
   225.000                  0.155
   255.000                  0.125
   280.000                  0.095
   355.000                  0.070
```

```
                    O U T P U T
                    -----------

FINE-SAND2

CHILDS AND COLLIS-GEORGE - K
----------------------------

MATCHING POINT NUMBER=         15
MATCHING FACTOR       =0.9012E 08

PRESSURE       WATER CONTENT      CCGS - K
  (CM)            (CC/CC)         (CM/DAY)

333.1333          0.0697         7.1807E-05
311.2667          0.0736         1.1652E-02
289.4000          0.0860         2.4446E-01
267.5333          0.1101         1.6753E 00
245.6667          0.1336         4.4801E 00
223.8000          0.1568         8.8892E 00
201.9333          0.2029         2.3662E 01
180.0667          0.2579         5.3886E 01
158.2000          0.3021         9.0426E 01
136.3333          0.3388         1.3156E 02
114.4667          0.3531         1.5098E 02
 92.6000          0.3638         1.6734E 02
 70.7333          0.3684         1.7514E 02
 48.8667          0.3710         1.7986E 02
 27.0000          0.3750         1.8864E 02
  5.1333          0.3790         2.1802E 02
```

```
KUNZE - K, MARSHALL - K,  MILLINGTON AND QUIRK - K
--------------------------------------------------

MATCHING POINT NUMBER            =        16
KUNZE-K MATCHING FACTOR          =0.8416E 00
MARSHALL-K MATCHING FACTOR       =0.2244E 01
MILL. AND QUIRK-K MATCHING FACTOR=0.1167E 01


                                    WITH  MATCHING FACTOR         WITHOUT MATCHING FACTOR
                                    ---------------------         -----------------------
PRESSURE   WATER CONTENT     KUNZE- K    MARSHALL-K    M-Q-K      MARSHALL-K     M-Q-K
  (CM)        (CC/CC)        (CM/DAY)     (CM/DAY)     (CM/DAY)    (CM/DAY)     (CM/DAY)

293.4443      0.0891        7.4488E-02   1.7691E-02   4.6129E-02  7.8827E-03   3.9525E-02
264.0531      0.1081        3.9363E-01   1.1350E-01   2.6005E-01  5.0572E-02   2.2282E-01
253.4439      0.1272        1.1306E 00   3.8347E-01   7.8847E-01  1.7087E-01   6.7560E-01
234.1573      C.1463        2.4761E 00   9.6568E-01   1.8091E 00  4.3028E-01   1.5501E 00
216.5984      0.1653        4.6588E 00   2.0537E 00   3.5457E 00  9.1511E-01   3.0381E 00
206.9086      0.1844        7.9510E 00   3.9093E 00   6.2755E 00  1.7419E 00   5.3771E 00
201.2304      0.2034        1.2641E 01   6.8579E 00   1.0310E 01  3.0558E 00   8.8341E 00
195.6003      0.2225        1.9023E 01   1.1287E 01   1.5985E 01  5.0293E 00   1.3697E 01
188.1484      0.2416        2.7412E 01   1.7658E 01   2.3674E 01  7.8680E 00   2.0285E 01
178.1622      0.2606        3.8173E 01   2.6530E 01   3.3813E 01  1.1821E 01   2.8973E 01
168.1312      0.2797        5.1745E 01   3.8593E 01   4.6926E 01  1.7196E 01   4.0208E 01
161.6288      0.2988        6.8628E 01   5.4674E 01   6.3620E 01  2.4361E 01   5.4513E 01
151.7802      0.3178        8.9382E 01   7.5751E 01   8.4585E 01  3.3753E 01   7.2477E 01
132.3739      0.3369        1.1477E 02   1.0310E 02   1.1074E 02  4.5941E 01   9.4891E 01
114.9190      0.3559        1.4603E 02   1.3861E 02   1.4351E 02  6.1760E 01   1.2297E 02
 27.0000      0.3750        1.8864E 02   1.8864E 02   1.8864E 02  8.4054E 01   1.6164E 02
```

```
BROOKS AND COREY - K
--------------------

PRESSURE        WATER CONTENT       BROOKS AND COREY-K
  (CM)             (CC/CC)              (CM/DAY)

355.0000           0.0700              5.8670E-02
333.1333           0.0697              1.1406E-01
311.2667           0.0736              2.3200E-01
289.4000           0.0860              4.9693E-01
267.5333           0.1101              1.1301E 00
245.6667           0.1336              2.7565E 00
223.8000           0.1568              7.3068E 00
201.9333           0.2029              2.1413E 01
180.0667           0.2579              7.0987E 01
158.2000           0.3021              1.8864E 02
136.3333           0.3388              1.8864E 02
114.4667           0.3531              1.8864E 02
 92.6000           0.3638              1.8864E 02
 70.7333           0.3684              1.8864E 02
 48.8667           0.3710              1.8864E 02
 27.0000           0.3750              1.8864E 02
```

APPENDIX D

THIS APPENDIX CONTAINS A DATA SET OF PROPERTIES OF POROUS MEDIA USED FOR REGRESSION ANALYSIS, THE OUTPUT FOR REGRESSION ANALYSIS, AND PLOT OF LOG NORMAL DISTRIBUTION OF BUBBLING PRESSURE.

Table D.1: Properties of porous media samples used for multiple regression analysis.

#	K(cm/sec)	Sand	Silt	Clay	ρ_b	ρ_s	ϕ	λ	P_b
1	0.00009	0.32	0.53	0.15	1.57	2.599	0.395	1.70	89.5
2	0.00013	0.32	0.53	0.15	1.50	2.599	0.423	1.64	75.6
3	0.00017	0.32	0.53	0.15	1.43	2.599	0.449	1.59	63.5
4	0.00029	0.32	0.53	0.15	1.36	2.599	0.478	1.47	50.7
5	0.00036	0.32	0.53	0.15	1.29	2.599	0.503	1.02	41.3
6	0.00026	0.32	0.53	0.15	1.40	2.599	0.469	1.20	64.0
7	0.00021	0.54	0.35	0.11	1.47	2.664	0.449	1.70	58.7
8	0.00032	0.54	0.35	0.11	1.41	2.664	0.471	1.81	50.7
9	0.00042	0.54	0.35	0.11	1.37	2.664	0.485	1.50	45.2
10	0.00082	0.54	0.35	0.11	1.26	2.664	0.527	1.49	33.4
11	0.00127	0.54	0.35	0.11	1.18	2.664	0.559	1.27	26.5
12	0.01419	0.44	0.26	0.30	1.40	2.568	0.454	0.50	3.4
13	0.00673	0.44	0.26	0.30	1.38	2.568	0.463	0.23	4.2
14	0.00205	0.44	0.26	0.30	1.36	2.568	0.472	1.60	20.0
15	0.00081	0.44	0.26	0.30	1.36	2.568	0.469	2.47	38.1
16	0.00972	0.55	0.24	0.21	1.29	2.596	0.504	1.97	15.4
17	0.00530	0.55	0.24	0.21	1.29	2.596	0.504	2.07	19.8
18	0.00313	0.55	0.24	0.21	1.34	2.596	0.483	3.63	27.1
19	0.00247	0.55	0.24	0.21	1.30	2.596	0.502	3.33	27.2
20	0.00679	0.80	0.04	0.16	1.58	2.632	0.398	2.767	13.8
21	0.00684	0.80	0.04	0.16	1.62	2.632	0.383	3.000	13.8
22	0.00493	0.80	0.04	0.16	1.59	2.632	0.396	4.533	19.0
23	0.00347	0.80	0.04	0.16	1.63	2.632	0.382	4.433	21.3
24	0.00012	0.73	0.14	0.13	1.81	2.601	0.304	4.800	59.3
25	0.00405	0.73	0.14	0.13	1.29	2.601	0.505	2.067	19.9
26	0.00478	0.73	0.14	0.13	1.19	2.601	0.543	3.133	20.3
27	0.00415	0.64	0.20	0.16	1.45	2.625	0.446	1.600	17.2
28	0.00823	0.64	0.20	0.16	1.37	2.625	0.477	1.833	13.5
29	0.01393	0.66	0.18	0.16	1.43	2.663	0.463	1.267	9.1
30	0.01347	0.66	0.18	0.16	1.41	2.663	0.471	1.267	9.1
31	0.00766	0.66	0.18	0.16	1.40	2.663	0.473	1.500	10.0
32	0.00291	0.66	0.18	0.16	1.41	2.663	0.469	1.867	18.1
33	0.03609	0.64	0.18	0.18	1.28	2.671	0.520	1.100	6.0
34	0.02072	0.64	0.18	0.18	1.35	2.671	0.496	1.833	8.7
35	0.00031	0.34	0.43	0.23	1.53	2.720	0.437	0.520	14.0
36	0.00264	0.34	0.42	0.24	1.49	2.720	0.452	0.460	9.0
37	0.00147	0.35	0.35	0.30	1.46	2.720	0.463	0.770	9.0
38	0.00008	0.30	0.47	0.23	1.51	2.720	0.445	0.530	11.0
39	0.00347	0.32	0.42	0.26	1.47	2.720	0.459	0.710	12.0
40	0.00061	0.32	0.40	0.28	1.46	2.720	0.463	0.450	6.0
41	0.00496	0.6935	0.1101	0.1964	1.25	2.417	0.4828	1.6583	28.0
42	0.00283	0.6082	0.1363	0.2555	1.25	2.484	0.4960	2.9667	72.0
43	0.00496	0.7649	0.0747	0.1604	1.27	2.488	0.4895	2.2651	63.5
44	0.00146	0.6627	0.1295	0.2078	1.37	2.563	0.465	0.8230	39.0
45	0.00246	0.4971	0.2114	0.2915	1.35	2.445	0.4530	0.8998	63.5
46	0.00432	0.7481	0.1237	0.1282	1.25	2.571	0.5138	1.7296	30.0
47	0.00494	0.7123	0.1213	0.1664	1.25	2.517	0.5033	3.5993	76.5
48	0.000058	0.5921	0.1104	0.2975	1.38	2.483	0.4443	1.1555	72.0

Source #1 to #34: Laliberte *et al*. (1966)
#35 to #39: Jackson *et al*. (1965)
#41 to #48: This study

COMPUTER OUTPUT FOR MULTIPLE REGRESSION ANALYSIS

```
            CORRELATION OF CHARACTERISTICS OF POROUS MEDIA

  VARIABLE                    STANDARD    COEFFICIENT                                 SMALLEST       LARGEST      SMALLEST      LARGEST
NO.    NAME          MEAN     DEVIATION   OF VARIATION    SKEWNESS      KURTOSIS        VALUE         VALUE      STD SCORE     STD SCORE
 10   LOGK          2.1885       2.2986      1.050289     -0.0133       -2.9807        0.6999        3.4939      -0.6476        0.5679
  2   SAND          0.5504       0.5735      1.041892     -0.0035       -2.9890        0.3000        0.8000      -0.4366        0.4353
  4   CLAY          0.1892       0.1986      1.049427      0.0182       -2.9813        0.1100        0.3000      -0.3990        0.5577
  5   RHOB          1.3971       1.4026      1.003962      0.0006       -2.9998        1.1800        1.8100      -0.1548        0.2944
  7   PHI           0.4657       0.4678      1.004582     -0.0009       -2.9996        0.3040        0.5590      -0.3456        0.1995
  8   LAMDA         1.8277       2.1278      1.164239      0.1351       -2.7570        0.2300        4.8000      -0.7508        1.3969
 11   LOGPB         1.3630       1.4109      1.035183     -0.0039       -2.9904        0.5315        1.9518      -0.5893        0.4174

NOTE - KURTOSIS VALUES GREATER THAN ZERO INDICATE A
       DISTRIBUTION WITH HEAVIER TAILS THAN NORMAL
       DISTRIBUTION.
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            CORRELATION OF CHARACTERISTICS OF POROUS MEDIA

COVARIANCE MATRIX

                LOGK        SAND        CLAY        RHOB         PHI       LAMDA       LOGPB
                    10           2           4           5           7           8          11

LOGK      10   5.233
SAND       2   1.267      0.3288
CLAY       4  0.4176      0.1005      0.3944E-01
RHOB       5   3.031      0.7682      0.2644       1.967
PHI        7   1.029      0.2559      0.8798E-01  0.6453      0.2188
LAMDA      8   4.086       1.115      0.3232       2.583      0.8361      4.528
LOGPB     11   2.828      0.7492      0.2504       1.901      0.6336      2.624        1.991
```

```
            CORRELATION OF CHARACTERISTICS OF POROUS MEDIA

CORRELATION MATRIX

                LOGK        SAND        CLAY        RHOB         PHI       LAMDA       LOGPB
                    10           2           4           5           7           8          11

LOGK      10      1.0000
SAND       2      0.9609      1.0000
CLAY       4      0.9148      0.8823      1.0000
RHOB       5      0.9400      0.9551      0.9491      1.0000
PHI        7      0.9568      0.9540      0.9470      0.9834      1.0000
LAMDA      8      0.8354      0.9139      0.7649      0.8655      0.8400      1.0000
LOGPB     11      0.8720      0.9260      0.8937      0.9604      0.9599      0.8739      1.0000
```

```
             CORRELATION OF CHARACTERISTICS OF POROUS MEDIA

  REGRESSION TITLE. . . . . . .
CORRELATION OF CHARACTERISTICS OF POROUS MEDIA


  STEPPING ALGORITHM. . . . . . . . . . . . . . .F
  MAXIMUM NUMBER OF STEPS . . . . . . . . . . . .      22
  DEPENDENT VARIABLE. . . . . . . . . . . . . . .      10 LOGK
  MINIMUM ACCEPTABLE F TO ENTER . . . . . . . . .   1.000,  50.000
  MAXIMUM ACCEPTABLE F TO REMCVE. . . . . . . . .   0.   ,  49.000
  MINIMUM ACCEPTABLE TOLERANCE. . . . . . . . . . 0.01000
  SUBSCRIPTS OF THE INDEPENDENT VARIABLES . . . .   2    4    5     7    8    11


 STEP NO.    0

STD. ERROR OF EST.     2.2986

ANALYSIS OF VARIANCE
                      SUM OF SQUARES     DF    MEAN SQUARE
         RESIDUAL     253.60240          48   5.283383

                         VARIABLES IN EQUATION                                  .              VARIABLES NOT IN EQUATION
                              STD. ERROR  STD REG               F TO            .               PARTIAL              F TO
    VARIABLE     COEFFICIENT   OF COEFF    COEFF   TOLERANCE   REMOVE    LEVEL.   VARIABLE    CORR.  TOLERANCE   ENTER  LEVEL
                                                                                . SAND        2  0.96094  1.00000    566.56   1
                                                                                . CLAY        4  0.91482  1.00000    241.16   1
                                                                                . RHOB        5  0.94002  1.00000    356.92   1
                                                                                . PHI         7  0.95685  1.00000    509.61   1
                                                                                . LAMDA       8  0.83542  1.00000    108.59   1
                                                                                . LOGPB      11  0.87201  1.00000    149.16   1


 STEP NO.    1
VARIABLE ENTERED    2 SAND

MULTIPLE R             0.9609
MULTIPLE R-SQUARE      0.9234
STD. ERROR OF EST.     0.6429

ANALYSIS OF VARIANCE
                      SUM OF SQUARES     DF    MEAN SQUARE      F RATIO
         REGRESSION   234.176C2           1   234.1760           566.56
         RESIDUAL     19.426381          47  0.4133273

                         VARIABLES IN EQUATION                                  .              VARIABLES NOT IN EQUATION
                              STD. ERROR  STD REG               F TO            .               PARTIAL              F TO
    VARIABLE     COEFFICIENT   OF COEFF    COEFF   TOLERANCE   REMOVE    LEVEL.   VARIABLE    CORR.  TOLERANCE   ENTER  LEVEL
SAND        2       3.85172       0.1618    0.961   1.00000     566.56       1  . CLAY        4  0.51394  0.22146     16.51   1
                                                                                . RHOB        5  0.27149  0.08787      3.66   1
                                                                                . PHI         7  0.48318  0.08980     14.01   1
                                                                                . LAMDA       8 -0.38061  0.16482      7.79   1
                                                                                . LOGPB      11 -0.17085  0.14247      1.38   1


 STEP NO.    2
```

```
VARIABLE ENTERED     4 CLAY

MULTIPLE R             0.9714
MULTIPLE R-SQUARE      0.9436
STD. ERROR OF EST.     0.5575

ANALYSIS OF VARIANCE
                       SUM OF SQUARES     DF     MEAN SQUARE      F RATIO
         REGRESSION    239.30718           2    119.6536           385.03
         RESIDUAL      14.295226          46   0.3107658

                          VARIABLES IN EQUATION                                  .              VARIABLES NOT IN EQUATION
                               STD. ERROR  STD REG                F TO           .               PARTIAL               F TO
    VARIABLE      COEFFICIENT   OF COEFF    COEFF    TOLERANCE    REMOVE    LEVEL.    VARIABLE    CORR.   TOLERANCE    ENTER  LEVEL
SAND         2       2.78270       0.2982    0.694   0.22146       87.10      1  . RHOB        5 -0.21686  0.03679       2.22   1
CLAY         4       3.49833       0.8609    0.302   0.22146       16.51      1  . PHI         7  0.17450  0.03979       1.41   1
                                                                                 . LAMDA       8 -0.32124  0.15704       5.18   1
                                                                                 . LOGPB      11 -0.50738  0.11594      15.60   1


 STEP NO.    3
VARIABLE ENTERED   11 LOGPB

MULTIPLE R             0.9788
MULTIPLE R-SQUARE      0.9581
STD. ERROR OF EST.     0.4857

ANALYSIS OF VARIANCE
                       SUM OF SQUARES     DF     MEAN SQUARE      F RATIO
         REGRESSION    242.98731           3    80.99577           343.36
         RESIDUAL      10.615087          45   0.2358903

                          VARIABLES IN EQUATION                                  .              VARIABLES NOT IN EQUATION
                               STD. ERROR  STD REG                F TO           .               PARTIAL               F TO
    VARIABLE      COEFFICIENT   OF COEFF    COEFF    TOLERANCE    REMOVE    LEVEL.    VARIABLE    CORR.   TOLERANCE    ENTER  LEVEL
SAND         2       3.66279       0.3422    0.914   0.12759      114.54      1  . RHOB        5  0.12639  0.02358       0.71   1
CLAY         4       4.91567       0.8315    0.425   0.18022       34.95      1  . PHI         7  0.67971  0.02599      37.79   1
LOGPB       11      -0.57636       0.1459   -0.354   0.11594       15.60      1  . LAMDA       8 -0.19938  0.14182       1.82   1


 STEP NO.    4
VARIABLE ENTERED    7 PHI

MULTIPLE R             0.9887
MULTIPLE R-SQUARE      0.9775
STD. ERROR OF EST.     0.3603

ANALYSIS OF VARIANCE
                       SUM OF SQUARES     DF     MEAN SQUARE      F RATIO
         REGRESSION    247.89158           4    61.97290           477.48
         RESIDUAL      5.7108195          44   0.1297914

                          VARIABLES IN EQUATION                                  .              VARIABLES NOT IN EQUATION
                               STD. ERROR  STD REG                F TO           .               PARTIAL               F TO
    VARIABLE      COEFFICIENT   OF COEFF    COEFF    TOLERANCE    REMOVE    LEVEL.    VARIABLE    CORR.   TOLERANCE    ENTER  LEVEL
SAND         2       2.55426       0.3114    0.637   0.08480       67.28      1  . RHOB        5 -0.14323  0.02098       0.90   1
CLAY         4       1.36329       0.8452    0.118   0.09597        2.60      1  . LAMDA       8  0.15136  0.11436       1.01   1
PHI          7       4.23879       0.6896    0.863   0.02599       37.79      1  .
```

```
LOGPB       11       -1.06123        0.1339   -0.651   0.07572       62.79       1  .


 STEP NO.     5
VARIABLE ENTERED      8 LAMDA

MULTIPLE R               0.9889
MULTIPLE R-SQUARE        0.9780
STD. ERROR OF EST.       0.3602

ANALYSIS OF VARIANCE
                        SUM OF SQUARES      DF     MEAN SQUARE       F RATIO
             REGRESSION   248.02242          5    49.60448           382.26
             RESIDUAL     5.5799817         43   0.1297670

                          VARIABLES IN EQUATION                            .                    VARIABLES NOT IN EQUATION
                               STD. ERROR  STD REG                F TO     .                       PARTIAL                 F TO
         VARIABLE      COEFFICIENT   OF COEFF    COEFF    TOLERANCE   REMOVE      LEVEL.      VARIABLE      CORR.  TOLERANCE     ENTER  LEVEL
SAND            2        2.23555      0.4446     0.558    0.04158     25.28        1  . RHOB            5 -0.16812  0.02057       1.22    1
CLAY            4        1.32213      0.8461     0.114    0.09574      2.44        1  .
PHI             7        4.57803      0.7678     0.932    0.02095     35.55        1  .
LAMDA           8        0.07255      0.0723     0.067    0.11436      1.01        1  .
LOGPB          11       -1.13973      0.1551    -0.700    0.05649     54.03        1  .


 STEP NO.     6
VARIABLE ENTERED      5 RHOB

MULTIPLE R               0.9893
MULTIPLE R-SQUARE        0.9786
STD. ERROR OF EST.       0.3593

ANALYSIS OF VARIANCE
                        SUM OF SQUARES      DF     MEAN SQUARE       F RATIO
             REGRESSION   248.18014          6    41.36336           320.39
             RESIDUAL     5.4222587         42   0.1291014

                          VARIABLES IN EQUATION                            .                    VARIABLES NOT IN EQUATION
                               STD. ERROR  STD REG                F TO     .                       PARTIAL                 F TO
         VARIABLE      COEFFICIENT   OF COEFF    COEFF    TOLERANCE   REMOVE      LEVEL.      VARIABLE      CORR.  TOLERANCE     ENTER  LEVEL
SAND            2        2.33951      0.4534     0.584    0.03979     26.63        1  .
CLAY            4        1.82087      0.9570     0.157    0.07446      3.62        1  .
RHOB            5       -0.28498      0.2578    -0.174    0.02057      1.22        1  .
PHI             7        4.90098      0.8197     0.997    0.01829     35.75        1  .
LAMDA           8        0.08388      0.0728     0.078    0.11210      1.33        1  .
LOGPB          11       -1.08724      0.1618    -0.667    0.05162     45.16        1  .

* * * * * F-LEVELS(    1.000,    0.    ) OR TOLERANCE INSUFFICIENT FOR FURTHER STEPPING

* * * * * BACKWARD STEPPING BEGINS NOW * * * * *


 STEP NO.     7
VARIABLE REMOVED      5 RHOB

MULTIPLE R               0.9889
MULTIPLE R-SQUARE        0.9780
```

```
STD. ERROR OF EST.      0.3602

ANALYSIS OF VARIANCE
                    SUM OF SQUARES      DF    MEAN SQUARE       F RATIO
         REGRESSION  248.02242           5    49.60448           382.26
         RESIDUAL    5.5799817          43  0.1297670

                         VARIABLES IN EQUATION                                  .   .             .  VARIABLES NOT IN EQUATION
                             STD. ERROR  STD REG                  F TO              .                  PARTIAL                  F TO
    VARIABLE       COEFFICIENT   OF COEFF     COEFF     TOLERANCE     REMOVE      LEVEL.    VARIABLE       CORR.   TOLERANCE      ENTER  LEVEL
SAND         2       2.23555      0.4446     0.558    0.04158       25.28        1  . RHOB            5 -0.16812  0.02057         1.22    1
CLAY         4       1.32213      0.8461     0.114    0.09574        2.44        1  .
PHI          7       4.57803      0.7678     0.932    0.02095       35.55        1  .
LAMDA        8       0.07255      0.0723     0.067    0.11436        1.01        1  .
LOGPB       11      -1.13973      0.1551    -0.700    0.05649       54.03        1  .


 STEP NO.    8
VARIABLE REMOVED     8 LAMDA

MULTIPLE R              0.9887
MULTIPLE R-SQUARE       0.9775
STD. ERROR OF EST.      0.3603

ANALYSIS OF VARIANCE
                    SUM OF SQUARES      DF    MEAN SQUARE       F RATIO
         REGRESSION  247.89153           4    61.97290          477.48
         RESIDUAL    5.7108195          44  0.1297914

                         VARIABLES IN EQUATION                                  .                    VARIABLES NOT IN EQUATION
                             STD. ERROR  STD REG                  F TO              .                  PARTIAL                  F TO
    VARIABLE       COEFFICIENT   OF COEFF     COEFF     TOLERANCE     REMOVE      LEVEL.    VARIABLE       CORR.   TOLERANCE      ENTER  LEVEL
SAND         2       2.55426      0.3114     0.637    0.08480       67.28        1  . RHOB            5 -0.14323  0.02098         0.90    1
CLAY         4       1.36329      0.8452     0.118    0.09597        2.60        1  . LAMDA           8  0.15136  0.11436         1.01    1
PHI          7       4.23879      0.6896     0.363    0.02599       37.79        1  .
LOGPB       11      -1.06128      0.1339    -0.651    0.07572       62.79        1  .


 STEP NO.    9
VARIABLE REMOVED     4 CLAY

MULTIPLE R              0.9880
MULTIPLE R-SQUARE       0.9761
STD. ERROR OF EST.      0.3666

ANALYSIS OF VARIANCE
                    SUM OF SQUARES      DF    MEAN SQUARE       F RATIO
         REGRESSION  247.55392           3    82.51797          613.92
         RESIDUAL    6.0484864          45  0.1344108

                         VARIABLES IN EQUATION                                  .                    VARIABLES NOT IN EQUATION
                             STD. ERROR  STD REG                  F TO              .                  PARTIAL                  F TO
    VARIABLE       COEFFICIENT   OF COEFF     COEFF     TOLERANCE     REMOVE      LEVEL.    VARIABLE       CORR.   TOLERANCE      ENTER  LEVEL
SAND         2       2.45195      0.3102     0.612    0.08847       62.46        1  . CLAY            4  0.23628  0.09597         2.60    1
PHI          7       4.99927      0.5121     1.017    0.04880       95.31        1  . RHOB            5 -0.01088  0.02703         0.01    1
LOGPB       11      -1.09330      0.1348    -0.671    0.07742       65.79        1  . LAMDA           8  0.15835  0.11463         1.13    1

* * * * * F-LEVELS(  50.000,  49.000) OR TOLERANCE INSUFFICIENT FOR FURTHER STEPPING
```

```
              CORRELATION OF CHARACTERISTICS OF POROUS MEDIA
                          STEPWISE REGRESSION COEFFICIENTS

 VARIABLES    2 SAND      4 CLAY      5 RHOB      7 PHI       8 LAMDA    11 LOGPB
STEP
    0         3.8517     10.5881      1.5405      4.7016      0.9025      1.4206
    1         3.8517*     3.4984      0.4154      2.1927     -0.2803     -0.2041
    2         2.7827*     3.4984*    -0.4399      1.0206     -0.2079     -0.5764
    3         3.6628*     4.9157*     0.2760      4.2388     -0.1170     -0.5764*
    4         2.5543*     1.3633*    -0.2432      4.2388*     0.0726     -1.0613*
    5         2.2355*     1.3221*    -0.2850      4.5780*     0.0726*    -1.1397*
    6         2.3395*     1.8209*    -0.2850*     4.9010*     0.0839*    -1.0872*
    7         2.2355*     1.3221*    -0.2850      4.5780*     0.0726*    -1.1397*
    8         2.5543*     1.3633*    -0.2432      4.2388*     0.0726     -1.0613*
    9         2.4520*     1.3633     -0.0167      4.9993*     0.0780     -1.0933*

NOTE - 1) REGRESSION COEFFICIENTS FOR VARIABLE IN THE
          EQUATION ARE INDICATED BY AN ASTERISK
       2) THE REMAINING COEEFICIENTS ARE THOSE WHICH WOULD
          BE OBTAINED IF THAT VARIABLE WERE TO ENTER IN THE
          NEXT STEP
```

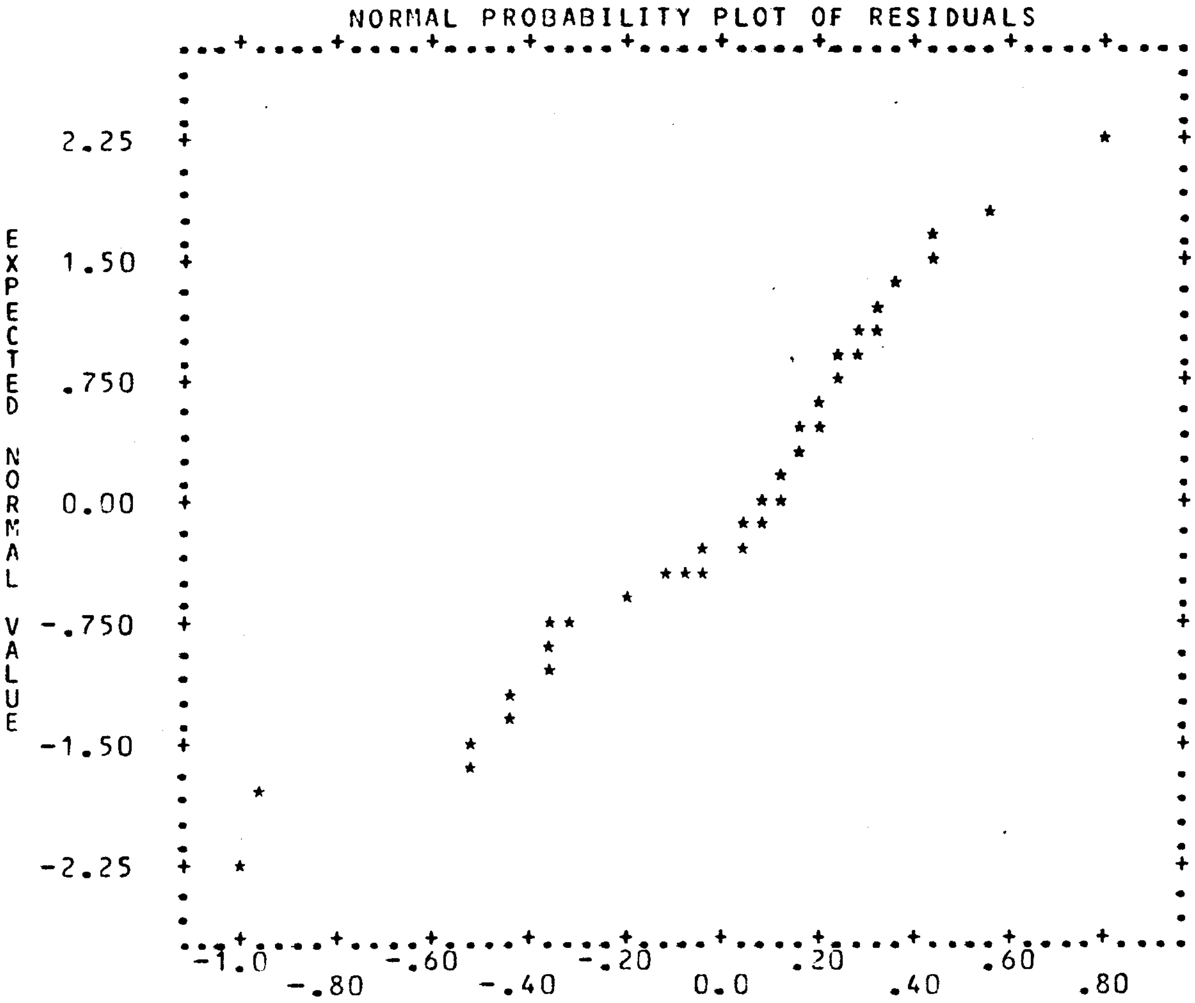
```
              CORRELATION OF CHARACTERISTICS OF POROUS MEDIA
                                   F-TO-ENTER OR F-TO-REMOVE OF EACH VARIABLE AT EACH STEP

 VARIABLES    2 SAND      4 CLAY      5 RHOB      7 PHI       8 LAMDA    11 LOGPB
STEP
    0       566.5632    241.1608    356.9236    509.6112    108.5895    149.1567
    1       566.5632*    16.5113      3.6602     14.0103      7.7924      1.3831
    2        87.1015*    16.5113*     2.2207      1.4134      5.1781     15.6010
    3       114.5399*    34.9494*     0.7142     37.7858      1.8216     15.6010*
    4        67.2823*     2.6016*     0.9007     37.7858*     1.0083     62.7861*
    5        25.2792*     2.4416*     1.2217     35.5492*     1.0083*    54.0333*
    6        26.6300*     3.6201*     1.2217*    35.7485*     1.3276*    45.1645*
    7        25.2792*     2.4416*     1.2217     35.5492*     1.0083*    54.0333*
    8        67.2823*     2.6016*     0.9007     37.7858*     1.0083     62.7861*
    9        62.4611*     2.6016      0.0052     95.3112*     1.1317     65.7873*
```

```
              CORRELATION OF CHARACTERISTICS OF POROUS MEDIA
                                    PARTIAL CORRELATIONS

 VARIABLES    2 SAND      4 CLAY      5 RHOB      7 PHI       8 LAMDA    11 LOGPB
STEP
    0         0.9609      0.9148      0.9400      0.9568      0.8354      0.8720
    1         0.9609*     0.5139      0.2715      0.4832     -0.3806     -0.1708
    2         0.8089*     0.5139*    -0.2169      0.1745     -0.3212     -0.5074
    3         0.8473*     0.6612*     0.1264      0.6797     -0.1994     -0.5074*
    4         0.7776*     0.2363*    -0.1432      0.6797*     0.1514     -0.7668*
    5         0.6085*     0.2318*    -0.1681      0.6727*     0.1514*    -0.7462*
    6         0.6229*     0.2817*    -0.1681*     0.6781*     0.1750*    -0.7198*
    7         0.6085*     0.2318*    -0.1681      0.6727*     0.1514*    -0.7462*
    8         0.7776*     0.2363*    -0.1432      0.6797*     0.1514     -0.7668*
    9         0.7624*     0.2363     -0.0109      0.8242*     0.1584     -0.7706*
```

```
             CORRELATION OF CHARACTERISTICS OF POROUS MEDIA
SUMMARY TABLE
STEP          VARIABLE                MULTIPLE     INCREASE        F-TO-       F-TO-  NUMBER OF INDEPENDENT
 NO.    ENTERED      REMOVED        R       RSQ    IN RSQ          ENTER       REMOVE   VARIABLES INCLUDED
   1    2 SAND                     0.9609   0.9234   0.9234     566.5632                        1
   2    4 CLAY                     0.9714   0.9436   0.0202      16.5113                        2
   3   11 LOGPB                    0.9788   0.9581   0.0145      15.6010                        3
   4    7 PHI                      0.9887   0.9775   0.0193      37.7858                        4
   5    8 LAMDA                    0.9889   0.9780   0.0005       1.0083                        5
   6    5 RHOB                     0.9893   0.9786   0.0006       1.2217                        6
   7                  5 RHOB       0.9889   0.9780  -0.0006                    1.2217           5
   8                  8 LAMDA      0.9887   0.9775  -0.0005                    1.0083           4
   9                  4 CLAY       0.9880   0.9761  -0.0013                    2.6016           3
```

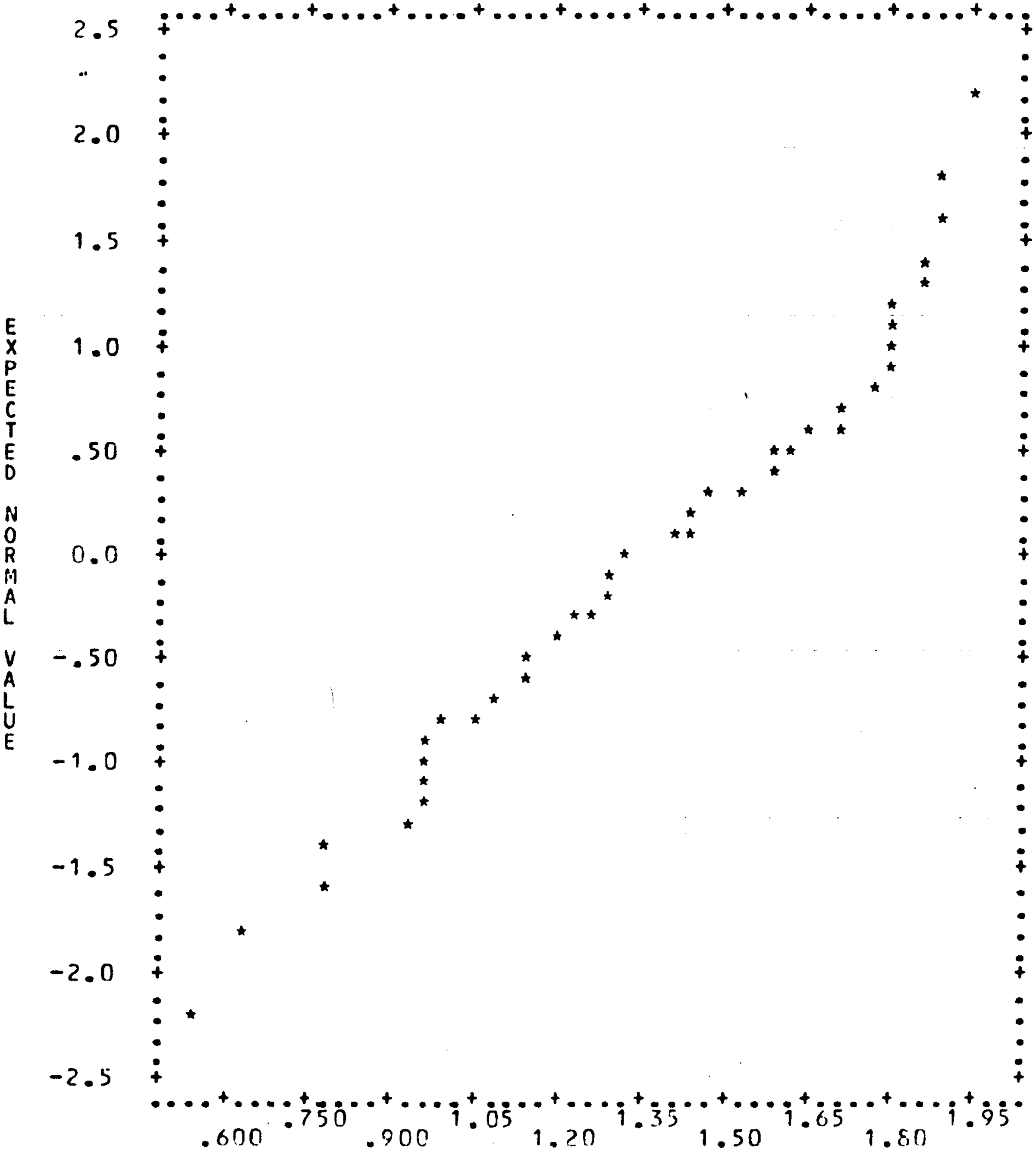

NORMAL PROBABILITY PLOT OF RESIDUALS
EXPECTED NORMAL VALUE
2.25
1.50
.750
0.00
-.750
-1.50
-2.25
-1.0
-.80
-.60
-.40
-.20
0.0
.20
.40
.60
.80

```
             CORRELATION OF CHARACTERISTICS OF POROUS MEDIA
HISTOGRAM OF VARIABLE      LPB
                                  SYMBOL  COUNT     MEAN     ST.DEV.
                                    X        48      1.363       0.369
                        EACH SYMBOL REPRESENTS         1 OBSERVATIONS
INTERVAL                                                      FREQUENCY PERCENTAGE
NAME          5   10   15   20   25   30   35   40   45   50  INT. CUM. INT.  CUM.
         +----+----+----+----+----+----+----+----+----+----+
*.560000 +X                                                    1    1   2.1   2.1
*.600000 +                                                     0    1   0.    2.1
*.640000 +X                                                    1    2   2.1   4.2
*.680000 +                                                     0    2   0.    4.2
*.720000 +                                                     0    2   0.    4.2
*.760000 +                                                     0    2   0.    4.2
*.800000 +XX                                                   2    4   4.2   8.3
*.840000 +                                                     0    4   0.    8.3
*.880000 +                                                     0    4   0.    8.3
*.920000 +                                                     0    4   0.    8.3
*.960000 +XXXXX                                                5    9  10.4  18.8
*1.00000 +X                                                    1   10   2.1  20.8
*1.04000 +                                                     0   10   0.   20.8
*1.08000 +XX                                                   2   12   4.2  25.0
*1.12000 +                                                     0   12   0.   25.0
*1.16000 +XXXX                                                 4   16   8.3  33.3
*1.20000 +X                                                    1   17   2.1  35.4
*1.24000 +X                                                    1   18   2.1  37.5
*1.28000 +XX                                                   2   20   4.2  41.7
*1.32000 +XXXX                                                 4   24   8.3  50.0
*1.36000 +X                                                    1   25   2.1  52.1
*1.40000 +                                                     0   25   0.   52.1
*1.44000 +XXX                                                  3   28   6.3  58.3
*1.48000 +XX                                                   2   30   4.2  62.5
*1.52000 +                                                     0   30   0.   62.5
*1.56000 +X                                                    1   31   2.1  64.6
*1.60000 +XX                                                   2   33   4.2  68.8
*1.64000 +X                                                    1   34   2.1  70.8
*1.68000 +X                                                    1   35   2.1  72.9
*1.72000 +XX                                                   2   37   4.2  77.1
*1.76000 +                                                     0   37   0.   77.1
*1.80000 +XX                                                   2   39   4.2  81.3
*1.84000 +XXXX                                                 4   43   8.3  89.6
*1.88000 +XXX                                                  3   46   6.3  95.8
*1.92000 +X                                                    1   47   2.1  97.9
*1.96000 +X                                                    1   48   2.1 100.0
*2.00000 +                                                     0   48   0.  100.0
*2.04000 +                                                     0   48   0.  100.0
         +----+----+----+----+----+----+----+----+----+----+
              5   10   15   20   25   30   35   40   45   50
```

CORRELATION OF CHARACTERISTICS OF POROUS MEDIA

NORMAL PLOT OF VARIABLE LPB

```
SYMBOL   COUNT      MEAN      ST.DEV.
  *        48       1.363      0.369
```



APPENDIX E

THIS APPENDIX CONTAINS THE HYDRAULIC CONDUCTIVITY VALUES PREDICTED BY DIFFERENT METHODS AND EXPERIMENTAL PROCEDURES AT THE CORRESPONDING LEVELS OF FLUID CONTENT

Hydraulic Conductivity (cm/day) values predicted by different methods and experimental procedures at the corresponding levels of fluid content.

GLASS BEADS

EXP-K	CCG-K	KUG-K	MAR-K	M&Q-K	B&C-K
461.968	461.968	461.968	461.968	461.968	461.968
470.852	450.000	400.000	400.000	400.000	470.852
440.646	385.000	360.000	350.000	360.000	392.000
358.914	358.914	310.000	304.000	308.000	358.914
213.216	217.000	180.000	165.000	170.000	175.000
118.601	225.000	175.000	122.000	168.000	160.000
65.964	125.000	108.000	75.000	98.000	90.500
23.232	48.000	24.000	10.700	18.000	27.000
16.124	42.000	20.300	9.000	16.000	22.500
4.109	4.800	1.060	0.285	0.770	1.600
2.532	2.850	0.570	0.175	0.330	0.800
1.866	1.600	0.280	0.100	0.160	0.410

WATSON SAND

1607.04	1607.04	1607.04	1607.04	1607.04	1607.04
1494.72	1494.72	1494.72	1494.72	1494.72	1494.72
1218.24	1200.00	1100.00	1050.00	1070.00	1200.00
950.40	950.40	840.00	710.00	795.00	940.00
743.04	753.00	610.00	490.00	580.00	690.00
552.96	560.00	420.00	310.00	385.00	430.00
384.48	460.00	310.00	205.00	270.00	270.00
336.96	390.00	265.00	165.00	225.00	225.00
177.12	210.00	130.00	72.00	110.00	110.00
129.60	150.00	86.40	42.00	70.00	78.00
86.64	120.00	58.00	26.00	42.00	58.00
57.02	84.00	37.00	15.00	27.00	41.00
28.51	28.50	11.00	4.50	9.20	22.00

FINE SAND 1

126.597	126.597	126.597	126.597	126.597	126.597
126.597	110.000	102.000	96.000	102.000	126.597
116.380	90.173	82.000	77.000	80.000	122.000
90.173	68.000	56.000	45.500	51.000	108.000
47.752	44.000	34.000	26.000	30.500	40.500
5.686	18.000	11.000	6.100	9.100	8.100
1.928	7.100	3.500	1.700	2.800	2.700

BAREA SANDSTONE

21.4990	21.4990	21.4990	21.4990	21.4990	21.4990
21.3660	21.3660	21.3660	21.3660	21.3660	21.3660
14.7920	16.0000	15.5000	14.0000	15.5000	13.0000
4.2200	7.8000	6.5000	5.0000	5.8500	3.6500
2.1100	4.7000	3.7000	2.6000	3.1000	1.8500
0.2000	0.6200	0.3300	0.1650	0.2700	0.1250

HYGIENE SANDSTONE

7.90700	7.90700	7.90700	7.90700	7.90700	7.90700
7.15200	6.80000	6.80000	6.80000	6.80000	7.15200
5.99700	5.99000	5.99000	5.99000	5.99000	5.99000
4.22000	4.35000	3.95000	3.95000	3.95000	3.95000
2.08800	2.70000	2.40000	2.08800	2.40000	1.80000
1.15500	1.70000	1.40000	1.15500	1.40000	0.91000
0.34200	0.83000	0.61500	0.48000	0.61500	0.29800
0.08900	0.28000	0.17500	0.12000	0.17500	0.06000

GRADED SAND

1221.12	1221.12	1221.12	1221.12	1221.12	1221.12
650.00	520.00	380.00	295.00	360.00	380.00
270.00	470.00	320.00	240.00	280.00	280.00
120.00	280.00	185.00	120.00	170.00	170.00
38.00	150.00	68.00	35.00	55.00	62.00
0.62	35.00	10.00	0.29	0.65	10.00
0.20	0.54	0.12	0.20	0.62	0.16

VOLCANIC SAND

433.090	460.000	450.000	450.000	450.000	480.000
246.970	190.000	150.000	115.000	140.000	140.000
55.970	72.000	48.000	38.000	40.500	31.000
2.884	10.200	4.000	1.600	3.200	3.200
0.242	0.820	0.220	0.055	0.120	0.170

FRAGMENTED MIXTURE

666.300	666.300	666.300	666.300	666.300	666.300
661.858	661.858	661.858	661.858	661.858	663.000
630.764	550.000	505.000	490.000	505.000	660.000
524.156	395.000	360.000	300.000	325.000	480.000
69.295	73.000	45.000	28.000	39.000	39.000
32.027	38.000	18.000	10.200	17.000	17.000
29.850	33.000	17.000	9.000	12.000	12.000
8.395	20.500	10.050	4.950	8.000	7.000
0.848	2.800	0.848	0.360	0.530	0.170

TOUCHET SILT LOAM 1

16.1690	16.1690	16.0000	14.5000	16.0000	20.6000
13.2370	8.1000	6.8000	5.5000	6.3000	16.5000
6.1300	3.2000	2.3000	1.6500	2.0000	6.1500
3.0650	1.4000	0.8400	0.5100	0.7000	3.0650
1.4440	0.5000	0.2700	0.1600	0.2200	1.3000

TOUCHET SILT LOAM 2

10.0000	9.50000	9.50000	9.50000	9.50000	10.0000
9.2000	8.90000	8.90000	8.90000	8.90000	9.5000
10.2000	8.00000	7.80000	6.80000	7.80000	7.8000
6.7000	6.20000	5.10000	4.70000	4.90000	4.7000
2.3000	2.30000	1.80000	1.40000	1.60000	1.8000
1.4000	1.60000	1.00000	0.82000	0.54000	1.0000
0.6300	0.85000	0.55000	0.27000	0.42000	0.5500

LAKELAND FINE SAND

100.800	98.0000	101.000	84.0000	98.0000	140.000
72.000	61.0000	61.000	55.0000	45.0000	72.000
38.400	38.4000	35.000	24.0000	30.5000	37.000
16.800	19.0000	16.800	10.5000	14.0000	16.000
6.000	9.1000	7.200	4.0000	6.0000	6.000
3.840	4.8000	3.200	1.5000	2.4000	2.800
0.840	1.6000	0.850	0.3800	0.6800	0.830
0.240	0.3500	0.160	0.0520	0.1200	0.065

WIDE RANGE SAND

453.600	453.600	453.600	453.600	453.600	453.600
432.000	355.000	315.000	302.400	315.000	440.000
388.000	355.000	315.000	302.400	315.000	470.000
302.400	355.000	315.000	302.400	315.000	460.000
273.600	220.000	180.000	155.000	170.000	273.000
216.000	216.000	175.000	150.000	165.000	225.000
151.200	165.000	120.000	99.000	110.000	151.000
136.800	125.000	91.000	65.000	81.000	105.000
100.800	104.000	77.000	52.000	69.000	90.000
79.200	89.000	60.050	40.000	52.000	78.000
72.000	76.000	49.000	31.500	42.000	70.000
64.800	64.800	39.500	25.000	33.000	62.000
43.200	45.000	28.000	16.000	22.000	51.000
15.120	15.120	7.900	4.000	6.600	32.000
11.520	7.800	3.400	1.500	2.700	13.500

BRUCE SAND

440.000	450.	350.	250.000	310.000	140.
280.000	300.	190.	120.000	170.000	80.
85.000	110.	52.	24.000	40.000	47.
45.000	78.	34.	14.000	24.000	34.
7.400	33.	11.	3.400	7.400	13.

FINE SAND 2

90.000	170.000	160.000	150.000	160.000	200.000
140.000	350.000	220.000	140.000	190.000	350.000
5.200	15.000	7.000	3.400	58.000	13.000
1.900	7.500	2.800	1.200	2.000	5.600
0.450	2.200	0.580	0.180	0.380	1.200