Effect of Clay Percentage in Sandy Clay Soil on Saturated Hydraulic Conductivity

Dr. Khitam Abdulhussein Saeed

Iraq-Baghdad Al-Mustansiriya University-College of Engineering

Email: khitamhussein@yahoo.com

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ABSTRACT:

Hydraulic properties of sandy clay soil are very important for filtration, seepage and irrigation; so set of experiments were carried out for different samples of sandy clay in Baghdad. Measurements include bulk density, particle size distribution, clay percentage and hydraulic conductivity using constant head system. The aims of this study were to estimate equivalent saturated hydraulic conductivity (Ks) for different clay percentages and predict porosity of sandy clay as function of clay percentage and porosity of sand and clay. Nine samples of sandy clay soil have been tested in a hydraulic and soil laboratory (Mustansiriya University). Semi-empirical model was correlated to evaluate saturated hydraulic conductivity from clay percentage and results were compared with five empirical models selected from published literature were also used to predict Ks. These empirical models were (Puckett ,1985) , (Ryjov and Sudoplatov,1990), (Dane ,1992), (Dheyaa ,2001)and (Shevnin.et al, 2006).

Keywords: soil, sandy clay, hydraulic conductivity, porosity

اثر نسبة الطين في الترب الرملية الطينية على التوصيل الهيدروليكي المشبع

د. ختام عبد الحسين

الملخص :

تعتبر الخواص الهيدروليكية للترب الرملية الطينية مهمة جدا للترشيح,الجريان والري لذلك اجريت مجموعة من التجارب لنماذج مختلفة من الترب الرملية الطينية في بغداد .شملت القياسات الكثافة الظاهرية,التوزيع الحجمي للحبيبات,نسبة الطين والموصلية الهيدروليكية مستعملين نظام الارتفاع الثابت. ان الهدف من الدراسة هو لتقييم الموصلية الهيدروليكية المشبعة المكافئة لنسب مختلفة من الطين وكذلك التنبا بالمسامية للترب الطينية الرملية كدالة لنسبة الطين والمسامية لكل من الطين والرمل. تم فحص تسع نماذج من الترب الرملية الطينية في مختبري الموائع والتربة في الجامعة المستنصرية.أعتمد في معالجة النتائج على نموذج شبه تجريبي لتقييم الموصلية الهيدروليكية المشبعة من نسبة الطين وتمت مقارنته مع خمس موديلات تطبيقية مختارة من منشورات سابقة التي ايضا قيمت الموصلية الهيدروليكية المشبعة وهذه الموديلات لكل من

(Puckett, et al,1985: Ryjov and Sudoplatov,1990: Dane,1992: Dheyaa ,2001 : Shevnin,2006)

1. INTRODUCTION

Hydraulic conductivity (K) is the constant of proportionality in Darcy's Law and as such is defined as defines the rate of movement of water through a porous medium such as a soil or aquifer or the flow volume per unit cross-sectional area of porous medium under the influence of a unit hydraulic gradient (m/d) commonly used units for hydraulic conductivity shown in (Table 1) (Puckett et al, 1985) and (Nakhaei, 2005).

Soil water potential is the driving force behind water movement. The main advantage of the "potential" concept is that it provides a unified measure by which the water state can be evaluated at any time and everywhere within the soil-plant-atmosphere continuum (Hillel, 1980).

The forces subject soil water include gravity, hydraulic pressure, the attraction of the soil matrix for water, the presence of solutes, and the action of external gas pressure .At any point in the soil, total soil water potential is the sum of all of the contributing forces(Hillel, 1980).

Measurement of hydraulic conductivity is problematic, considering the parameter can differ over several orders of magnitude across the spectrum of sediments and rock types, as indicated in (Table 2). The parameter can also vary markedly in space, even with apparently minor changes in sediment characteristics. Hydraulic conductivity is influenced by the properties of the fluid being transmitted (such as viscosity) as well as the porous medium (Ranieri et al, 2012). Hydraulic conductivity is also scale dependent, so that measurements taken at the core sample level may not be directly extrapolated to the aquifer scale. It is also direction dependent, so that hydraulic conductivity can be markedly different in the vertical from the horizontal. Hydraulic conductivity cannot be directly measured but inferred from field, laboratory or modeled data.

2. THEORETICAL APPROACH

In Darcy's law, saturated hydraulic conductivity is a constant (or proportionality constant) that defines the linear relationship between the two variables J and i (figure 1). It is the slope of the line (J/i) showing the relationship between flux and hydraulic gradient. Solving Darcy's equation for K yields J/i (see equation 1).

$$K = J/i \tag{1}$$

Flux (J) is commonly expressed on a volume basis, and the units simplify to m/s. The hydraulic head difference (ΔH) is commonly expressed on a weight basis. It simplifies to centimeters of head, and the hydraulic gradient (i) becomes unit less (e.g., cm/cm) (Ranieri et al, 2010). Then, K_s takes the same units as flux (m/s). Flux represents the quantity of water moving in the direction of, and at a rate proportional to, the hydraulic gradient. If the same hydraulic gradient is applied to two soils, the soil from which the greater quantity of water is discharged (i.e., highest flux) is the more conductive (greatest flow rate). The sandy soil yields a higher flux (is more conductive) than the clayey soil at the same hydraulic gradient as shown in Figure (1). The soil with the steeper slope (the sandy soil in figure 1) has the higher hydraulic conductivity. Hydraulic conductivity (or slope "K") defines the proportional relationship between flux and hydraulic gradient, or in this case, of unidirectional flow in saturated soil. Saturated hydraulic conductivity ("K_s") is a quantitative expression of the soil's ability to transmit water under a given hydraulic gradient (Mason et al, 1957).

The hydraulic conductivity for a given soil becomes lower when the fluid is more viscous than water. Hydraulic conductivity (or *Ks*) is expressed using various units. The units and dimensions depend on those that are used to measure the hydraulic gradient (mass, volume, or weight) and flux (mass or volume). To provide national consistency in defining permeability classes in soil surveys, Uhland and O'Neal (1951) evaluated percolation rates of about 900 soils. They defined "permeability" classes by distributing the percolation data equally among seven tentative classes (Table 2). Along with percolation data, they also studied 14 soil morphologic characteristics that affect water movement and that could be used to make predictions regarding permeability class. Because of management effects on surface horizons, they confined their study to horizons below the surface layer. These classes were published in the 1951 *Soil Survey Manual* (Soil Survey Staff, 1951).

Mason et al. (1957) statistically analyzed Uhland and O'Neal's data. They concluded that it was overly optimistic that one could correctly place a given soil into one of seven permeability classes on the basis of percolation rates of five core samples taken at one site (the probability of being correct was 30%). A reasonable degree of reliability could be achieved if either more sites per soil were sampled or fewer classes were used. The study suggested that a 95% probability of making a correct placement could occur by using three to five permeability classes. In 1963, the NCSS National Soil Moisture Committee proposed a class/subclass "choice schema" with five to seven classes (Table 2) (Soil Survey Division, 1997). The proposal was provisionally accepted, pending the outcome of discussions comparing auger-hole percolation tests with the Uhland core method and pending additional information on critical limits.

When the Soil Survey Division converted its previous database to the National Soil Information System (NASIS) in 1994, saturated hydraulic conductivity replaced permeability. Only the name was changed at this time. The values from the previous database were imported directly into NASIS without modification.

Krumbein and Monk (1943) proposed the equation:

$$K=b(d_m)^2 \exp(-\sigma\Phi) \quad (2)$$

Where k is in darcies (1 darcy = $9.87E^{-09}$ cm^2), dm is the geometric mean grain-size diameter (mm), σΦ is the geometric standard deviation (in Φ units, where Φ is –ln(d) and d is the grain-size diameter in mm), and a and b are empirical constants. This equation was based on experiments performed with sieved glacial outwash sands that were recombined to obtain various grain-size distributions.

Kozeny (1953) proposed an equation based on porosity and specific surface that may be written as (Marshall 1958):

$$K=n^3/(S^2 p \quad (3)$$

Where k is in cm^2, S is the soil surface area of the medium per volume (cm^2/cm^3), and p is an empirical constant. Marshall (1958) went on to derive an equation for an isotropic material in which the mean radius of pores for each of ‘m’ equal fractions of the total pore space are represented by the corresponding mean radii ($r_1, r_2, \ldots, r_m$):

$$K=1/8\{n^2m^{-2}[r1^2+3r2^2+5r3^2+\ldots\ldots(2n-1)rn^2]\} \quad (4)$$

Where k is in cm^2, ri (cm) is the mean radius of the ith fraction, and r decreases in size from r1 to r_m.

Shepherd (1989) extended Hazen's work by performing power regression analysis on 19 sets of published data for unconsolidated sediments.

$$K_s=cD^2_{10} \quad (5)$$

The data sets ranged in size from 8 to 66 data pairs. He found that the exponent in Equation 8 varies from 1.11 to 2.05 with an average value of 1.72, and that the value of the constant c is most often between 0.05 and 1.18 but can reach a value of 9.85. Values for both c and the exponent are typically higher for well-sorted samples with uniformly sized particles and highly spherical grains.

3. EXPERIMENTAL WORK

There are relatively simple and inexpensive laboratory tests that may be run to determine the hydraulic conductivity of a soil: constant-head method and falling-head method. The constant-head method is typically used on granular soil as shown in figure (2). This procedure allows water to move through the soil under a steady state head condition while the quantity (volume) of water flowing through the soil specimen is measured over a period of time. By knowing the quantity *Q* of water measured, length *L* of specimen, cross-sectional area *A* of the specimen, time *t* required for the quantity of water *Q* to be discharged, and head *h*, the hydraulic conductivity can be calculated:

$$K=V\ L\ /[A\ t\ (H_2-H_1)] \quad (6)$$

The total head loss through the permeameter is indicated by the difference in elevation between the inflow and outflow water levels.

3.1 Laboratory Methods

Constant-head methods are primarily used in samples of soil materials with an estimated *K* above 1.0×10^2 m/yr, which corresponds to water filters medias. Important considerations regarding the laboratory methods for measuring *K* are related to the soil sampling procedure and preparation of the test specimen and circulating liquid. The sampling process, if not properly conducted, usually disturbs the matrix structure of the soil and results in a misrepresentation of the actual field conditions.

3.2 Materials and Methods

Samples were classified according to particle size using a standard *British Soil Classification System*, detailed in *BS 5930: Site Investigation*.

The samples were classified, diameters of soil particles at 10%, 20% and 50% cumulative weight determined, and the coefficients of uniformity, intercepts and porosity values were calculated. Since the kinematic coefficient of viscosity is also necessary for the estimation of hydraulic conductivity, a value of $0.0874 m^2/day$ ($0.897 * 10^{-6}$ m^2/s) derived for a water temperature of (24-26^oC) is measured in the laboratory.

4. RESULTS

4.1 Prediction of Porosity of Sandy Clay Soil

The total porosity n_{sc} of the sandy clay soil is calculated from two empirical forms, the first is (Ryjov and Sudoplatov,1990) equation as following expressions:

$$n_{sc} = (ns - C) + nc.C, \text{ when } C < ns \quad (7)$$

$$n_{sc} = = C.nc, \text{ when } C \geq ns \quad (8)$$

Where C is clay content, nc is clay porosity and n_s is sand porosity.

The second empirical equation is (Dheyaa, 2001) model as following expression:

$$n_{sc} = ns\,(1- C) + nc.C \quad (9)$$

Clay and sand porosities are considered as constant; therefore, soil porosity is a function of clay content.

Thus, porosity, grain size (or capillary radius) and tortuosity are not independent parameters. Rather, they are interrelated in the sand-clay soil model. In this work clay content as the main factor was considered, as a function of other parameters such as soil porosity, tortuosity and formation factor. Measurements for different porosities (0 to 1) were graphed and correlated as follow (R^2=0.879):

$$n_{sc} = 0.244+0.036C \quad (10)$$

Comparison between measured values of porosities and empirical equations of (Ryjov and Sudoplatov, 1990), (Dheyaa, 2001) and (Masch. et al, 1966) were shown in figure(3).

4.2 Effect of clay percentage on hydraulic conductivity of sandy clay soil

Filtration coefficient of soil depends on many factors, like clay content, grain size, type of clay, anisotropy of layered sediments, and two types of capillaries in clay. As a result, dependence of filtration coefficient from clay content is scattered. The scatter can be diminished with the help of calibration by using direct Ks measurements.

Puckett et al. (1985) sampled six soils at seven different locations in the Alabama lower coastal plain containing 34.6% to 88.5% sand-sized particles and 1.4% to 42.1% clay-sized particles, and used regression analysis to determine that percentage of clay sized particles was the best predictor of Ks (R^2 = 0.77):

$$Ks=4.36*10^{-3}\exp(-0.1975\,C) \quad (11)$$

Where Ks is expressed in cm/sec and C is the clay-sized particles (in percent) in the soil sample. Bulk density and porosity, often used in other pedotransfer functions, were not highly correlated with Ks for this data set of sandy soils.

Dane and Puckett (1992) expanded the work of Puckett et al. (1985) with two more data sets from the lower coastal plain of Alabama. One set consisted of 577 Ks and grain-size data pairs from 60 locations in a 0.5-ha agricultural field in south central Alabama. Nonlinear regression analysis yielded the equation ($R^2 = 0.453$):

$$Ks=8.44*10^{-5}\exp(-0.144\ C) \quad (12)$$

The form of Equation 6 that worked well for the previous data set yielded a significantly poorer fit for this data set. Another set of data consisting of 130 pairs of Ks and grain-size data from nine different soil series from the Florida Panhandle was also analyzed.

Nonlinear regression analysis resulted in the equation ($R^2 = 0.443$):

$$Ks=7.77*10^{-5}\exp(-0.116\ C) \quad (13)$$

Which also displayed a poorer fit than their previous study (Puckett et al, 1985). Comparison between measured values of hydraulic conductivity and empirical models of (Puckett, 1985) and (Dane and puckett 1992) for different clay percentages is shown in Figure (4).

5. CONCLUSIONS

Nine samples of sandy clay soil have been tested in a hydraulic and soil laboratory (Mustansiriya University). The major conclusions can be drawn as follow:

1. Filtration coefficient of sandy clay soil extremely depends on clay content,
2. Measurements for different porosities (0 to 1) were correlated as (R^2=0.879):

   $n_{sc} = 0.244+0.036C$

3. Empirical equation of hydraulic conductivity for different percentages of clay sized particles was correlated with the best predictor of Ks ($R^2 = 0.897$) as:

   $Ks=0.019\exp(-0.11\ C)$

6.REFERENCES:

[1] Dheyaa, W. (2001)"Hydrodynamic Modeling of laminar flow in porous media".19 – 20 march, Water resource, Baghdad.

[2] Dane, J.H. and W.E. Puckett. 1992. Field soil hydraulic properties based on physical and mineralogical information. In Proceedings of an international workshop: Indirect methods for estimating the hydraulic properties of unsaturated soils.

[3] Hillel, D. 1980. Fundamentals of soil physics. Academic Press. New York, NY.

[4] Krumbein, W. C. and G. D. Monk. 1943. Permeability as a function of the size parameters of unconsolidated sands. *Transaction of the American Institute of Mining, Metallurgical and Petroleum Engineers,* 151, 153-163.

[5] Kozeny, J. 1953. Das wasser in boden, grundwasserbewegung. Hydraulik, 280-445.(In German).

[6] Mason, D.D., J.F. Lutz, and R.G. Petersen. 1957. Hydraulic conductivity as related to certain soil properties in a number of great soil groups—Sampling errors involved. Soil Science Society of America Proceedings 21:554–561 Marshall, T.J. 1958. A relation between permeability and size distribution of pores.Journal of Soil Science 9, 1-8.

[7] Masch, F. D. and K. J. Denny. 1966. Grain-size distribution and its effect on the permeability of unconsolidated sands. Water Resources Research 2, no. 4: 665–677.

[8] Marshall, J. J. (1958). A relation between permeability and size distribution of pores. Journal of soil science ,9 :1-8.

[9] Nakheai, M. (2005). Estimating the saturated hydraulic conducting of granular material using artificial neural network based on grain size distribution curve. Journal of Science, 16(1) :55-62.

[10] Puckett, W.E., J.H. Dane, and B.F. Hajek. 1985. Physical and mineralogical data to determine soil hydraulic properties. Soil Science Society of America Journal 49, no. 4:831-836

[11] RYJOV, A. A. and A. D. SUDOPLATOV, 1990. The calculation of specific electrical conductivity for sandy - clayed rocks and the usage of functional cross-plots for the decision of hydrogeological problems. *In:* Scientific and technical achievements and advanced experience in the field of geology and mineral deposits research. Moscow, pp. 27-41.

[12] Ranieri, V., Antonacci, M. C., Ying, G and Sansalone, J. J. (2010). Application of kozeny-kovacs model to predict the hydraulic conductivity of permeable pavement. Transportation research record, 2195: 168-176.

[13] Ranieri, V., Ying, G. and Sansalone, J. (2012). Drainage modeling of roadway systems with porous frication courses. Journal of transportation engineering, 138(4) : 395-405.

[14] Shevnin, V., O. Delgado-Rodríguez, A. Mousatov and A. Ryjov, 2006. Estimation of soil superficial conductivity in a zone of mature oil contamination using DC resistivity. SAGEEP-2006, Seattle. P.1514-1523.

[15] Shepherd R. G. (1989). Correlation with permeability and grain size. Ground water,27(5): 633-638.

[16] Site investigation: A Guide to BS 5930 : 1999 : Code of practice for site investigations for higher education, 593.

[17] United State Department of Agriculture, (1951). Soil Survey Manual. U. S. Dept. Agr. Hanb, 1

[18] Uhland, R.E. and A.M. O'Neal. 1951. Soil permeability determination for use in soil and water conservation. SCS–TP–101. United States Department of Agriculture, Soil Conservation Service, Washington, D.C.

[19] Uma, K.O., B.C.E. Egboka, and K.M. Onuoha. 1989. New statistical grain-size method for evaluating the hydraulic conductivity of sandy aquifers. Journal of Hydrology 108, 343-366.

Table (1): Commonly used units for hydraulic conductivity (K)(Hillel, 1980)

Description	**(m/d)**	**(m/s)**	**(mm/d)**	**(mm/hr)**
Extremely slow	0.000001	$1.5741x10^{-11}$	0.001	0.000041667
Very Slow	0.0001	$1.5741x10^{-9}$	0.1	0.0041667
Slow	0.01	$1.5741x10^{-7}$	10	0.41667
Moderate	1	$1.5741x10^{-5}$	1000	41.667
Fast	10	$1.5741x10^{-4}$	10000	416.667
Very Fast	100	$1.5741x10^{-3}$	100000	4166.667

Table (2): Indicative hydraulic conductivities of some rock types (Uhland and O'neal 1951)

Rock Type	**Grain size (mm)**	**Hydraulic Conductivity K (m/d)**
Clay	0.0005-0.002	10^{-2}-10^{-8}
Silt	0.002-0.06	10^{-2} - 1
Fine Sand	0.06 -0.25	1-5
Medium Sand	0.25-0.50	5-20
Coarse Sand	0.50-2	20-100
Gravel	2-64	100-1000
Shale	Small	$5x10^{-6}$ - $5x10^{-8}$
Sandstone	Medium	10^{-3}-1
Limestone	Variable	10^{-5}-1
Basalt	Small	0.0003-3
Granite	Large	0.0003-0.03
Slate	Small	10^{-5}-10^{-8}
Schist	Medium	10^{-4}-10^{-7}

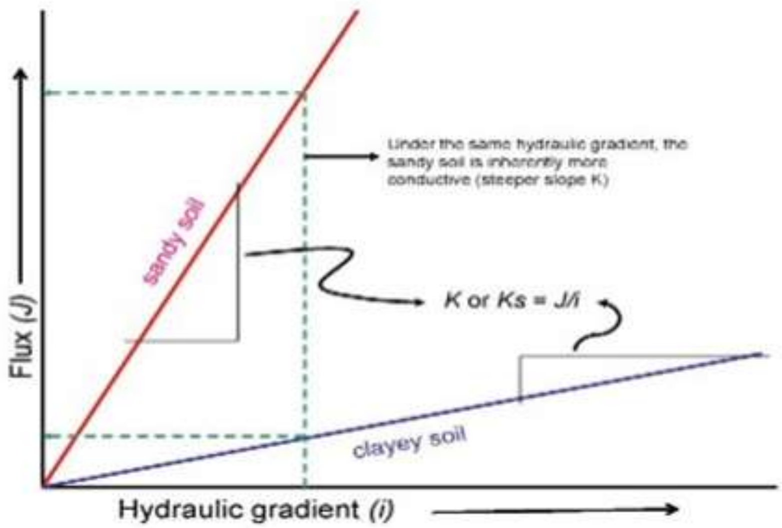

Figure (1): The relationship between flux and hydraulic gradient density.

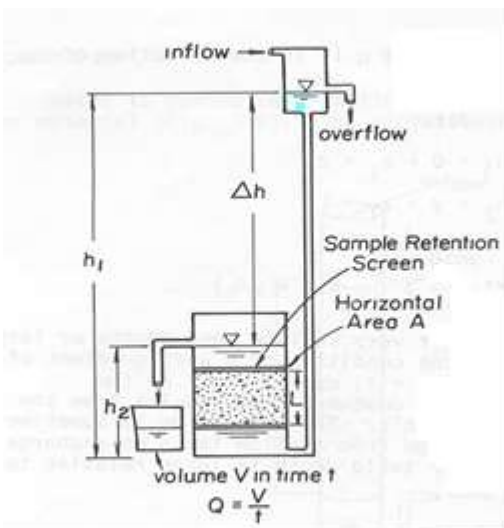

Figure (2): Constant head permeameter
(After Todd, 1959)

Plate 1: The Constant Head Parameter Test

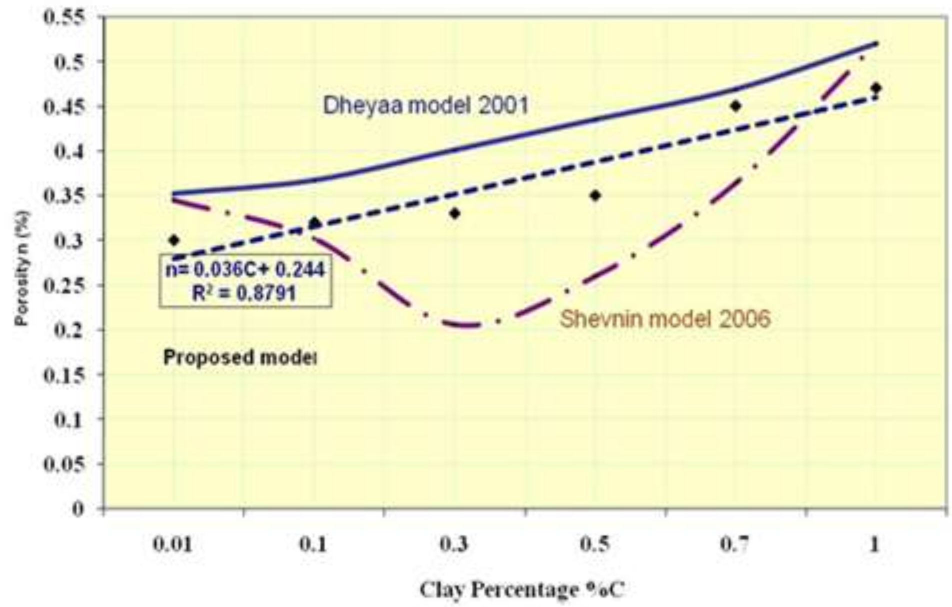

Fig. (3): Comparison between experimental results and empirical models of (Shevnin, 2006) and (Dheya, 2001)

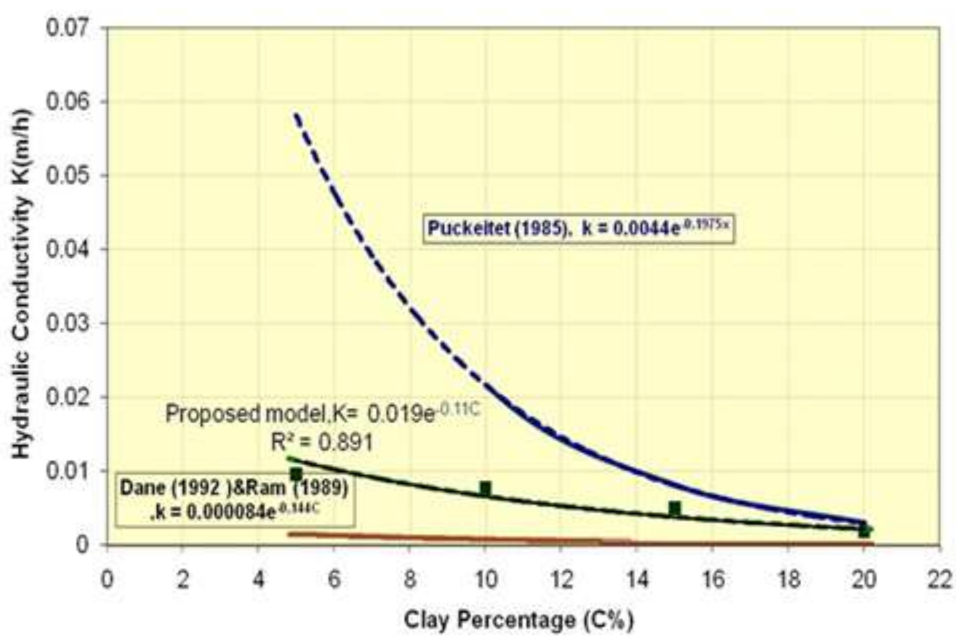

Fig. (4): Comparison between measured of hydraulic and empirical models of (Puckett, 1985) and (Dane, 1992) for different clay percentages.