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Prediction of Permeability Characteristics of Fine Grained Soils and its Validation

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Abstract— **Permeability of soils forms one of the important soil parameters required in the design of water retaining structures like Dams. Grain size distribution and density are known to influence the permeability of soils. It is one of the most important physical properties of soil used in geotechnical engineering. Though many correlations have been developed by many researchers in the past, the applicability of these correlations to the real practice have been always doubtful. Also these studies have concentrated on mostly the coarse grained soils only. Fine grained soils are complex in itself with the presence of finer particles. The behavior of the fine grained soil depends mostly on the clay and silt contents. The present study focuses on the applicability of the existing empirical relationship to the permeability of fine grained soils. The data obtained from the investigations carried out by CSMRS for various river valley projects is used in the present study. An attempt is also made to develop correlation/empirical relations between k and grain sizes, index properties, and compaction characteristics. Attempts are also made to validate the equations thus obtained.**

Keywords—**Coefficient of Permeability, Grain Sizes, Void Ratio, Maximum Dry Density, Atterberg Limits, Specific Gravity.**

I. INTRODUCTION

Geotechnical Engineers often have to solve complex problems involving a number of the interacting factors. The engineering properties of soil exhibit varied and uncertain behavior due to the complex and imprecise physical process associated with the formation of these materials which is a matter of concern for a Geotechnical Engineer. Permeability is a very important engineering property of soils. Determination of permeability is essential in a number of soil engineering problems, such as settlement of buildings, yield of wells, seepage through and below the earth structures etc. It controls the hydraulic stability of soil masses. The permeability of soils is also required in the design of filters used to prevent the piping in hydraulic structures.

The rate of settlement of saturated soils under load, the stability of slopes and retaining structures, the design of filters made of soil, and the design of earthen dams are some of the examples of applications of permeability in geotechnical engineering (Das, 2008). Although the relationships between grain size distribution and permeability has been quantified in previous studies, the influence of density has not been quantified. The accuracy of permeability test results for such soils depends on how well the soil structure and density of laboratory samples represent the natural state of soil in the field (DeGroot et al., 2012). An Empirical relationship were developed by many researchers such as Hazen, 1892; Kozeny, 1927 and Carmen, 1956; Terzaghi and Peck, 1964; Kenney et al., 1984; for predicting permeability from physical and engineering properties.

Permeability of soils is influenced by various factors such as Particle Size, Structure of soils, Shape of Particles, Void ratio, Properties of water and degree of saturation. Several methods are adopted for determining the coefficient of permeability in the field and laboratory generally depending upon the site conditions and type of soils. Indirect methods are also used to evaluate the coefficient of permeability of soils without conducting any test. With the limitation of the analytical approaches for evaluating the coefficient of permeability, it is difficult to correlate more than one factor in the approach, the present study focuses on the applicability of the existing empirical relationships such as Allen Hazen's formula and Kozeny – Carman equation to the permeability of fine grained soils. An attempt is also made to correlate permeability with grain sizes, index properties, and compaction characteristics. Attempts are also made to validate the equations developed through the present study through a new set of data and presented in this paper.

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II. Permeability Of Soils

The permeability tests are used to determine the coefficient of permeability (k) of a particular soil. The results of permeability tests on the construction materials of earth and rockfill dams are useful in selecting the type of soil for various zones of the dam. The value of coefficient of permeability is used in drawing the flow nets in the body of the dam which leads to the design of appropriate filter systems. The coefficient of permeability (k) of a soil is determined using field and laboratory methods. The permeability of a soil deposit at its in-situ conditions are determined by (i) Pumping-out tests – influences a large area around the pumping well and give an overall value of the soil deposit and (ii) Pumping-in tests - influences a small area around the hole and give a value of the surrounding hole. Depending on the type of soils two types of laboratory permeability tests are carried out on the construction materials (i) Constant Head test – For more pervious soils and (ii) Falling head test – For impervious soils.

Factors Affecting Permeability

Permeability is a complex property that is controlled by physical properties of both the soil and the permeating fluid. At a constant temperature of 20°C, the common room temperature, the viscosity and unit weight of water remain constant. Therefore, physical properties such as grain size distribution, density, void ratio, and soil texture and structure affect the magnitude of permeability.

Effect of Grain Size and Grain Size Distribution

Grain size distribution of granular soils affects their permeability. Poorly graded soils have higher porosity and permeability values than well graded soils in which smaller grains tend to fill the voids between larger grains.

Effect of Density and Void Ratio

Dry density is the ratio of the mass of the solids in a soil to its total volume, the sum of volume of solids and volume of voids. Void ratio (e) is defined as the ratio of the volume of voids to the volume of solids. Density and void ratio are inversely related. Permeability decreases as density increases or void ratio decreases.

Effect of Soil Texture and Structure

Texture and structure relate to size, shape, and arrangement of particles in a soil mass. Particle shape has an important effect on permeability as it influences the size and shape of interconnection between particles.

The more angular the grains are, the smaller the voids and more tortuous the flow paths will be. This is because edges and corners of angular grains can fit into voids which means there is a greater degree of interlocking.

Correlations on Coefficient of Permeability

Attempts were made by many researchers to predict permeability empirically from grain size distribution indices, void ratio, porosity, viscosity etc. Computation from the particle size or its specific surface and computation from the consolidation test data are the most common among them. Some of the correlations are given below.

Allen Hazen's Formula:

$$k = C.D_{10}^2$$

Where k = Coefficient of permeability, cm/sec
D_{10} = Effective size, cm
C = Constant with a value 100 and 150

Kozeny – Carman equation:

$$k = \frac{g\rho_w}{(C_s \mu S^2)T^2} \cdot \frac{e_3}{1+e}$$

Where k = Coefficient of permeability, cm/sec
ρ_w = Mass density of water, g/cc
C_s = Shape factor which can be taken as 2.5 for granular soils
μ = Coefficient of viscosity, poise
e = Void ratio
g = 9.81 cm.sec^2
T = Tortuosity, with a value of √2 for granular soils and
S = Surface area per unit volume (Specific area), cm^2/ cm^3

Terzaghi and Peck (1964) equation:

$$k = \frac{g}{v} C_t \left[\frac{n - 0.13}{(1-n)^{1/3}} \right]^2 D_{10}^{\,2}$$

Where k = Coefficient of permeability, cm/sec
g = the acceleration due to gravity, cm/sec^2
v = kinematic viscosity, mm^2/sec
C_t = sorting coefficient, ranging between 6.1× 10^{-3} and 10.7× 10^{-3}
n = porosity
D_{10} = grain size corresponding to 10% passing, mm

Figure 1 shows the correlation between the coefficient of permeability and the D_{10} for the sands and gravels. The correlations for clays are difficult due to the clay mineralogy present in clays.

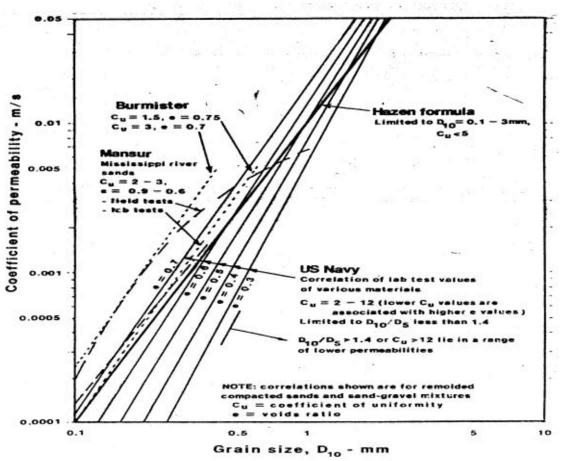

Figure 1 Correlation - k and D_{10}

Figure 2 shows the correlation between the coefficient of permeability and the water content in dry soil mass which depicts the effect of physically mixing or blending of a soil on permeability.

Figure 3 shows the correlations between the coefficient of permeability and the dry density and molding water content in dry soil mass and depict the effect of dispersion on permeability.

Figure 4 presents the correlations between the coefficient of permeability (k) and the degree of saturation (S) on permeability. The typical ranges of permeability for different soil types are presented in Table 1.

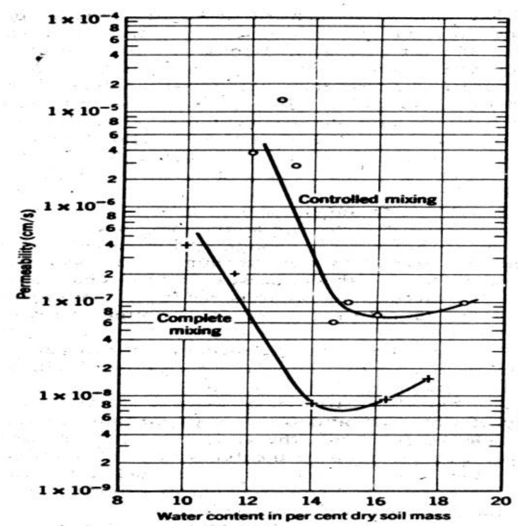

Figure 2 Effect of water content on k

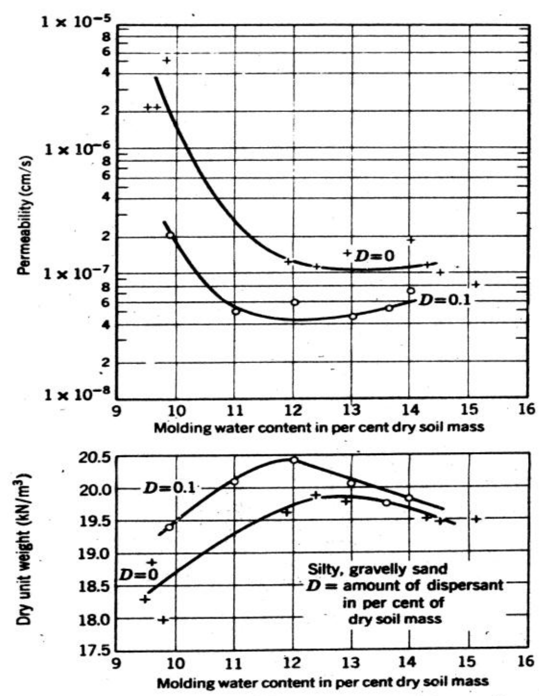

Figure 3 Effect of γ_d and w on k

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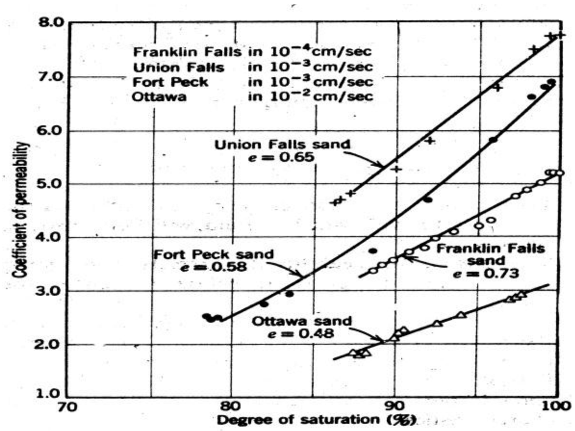

Figure 4 Effect of S on k

Table 1
Typical Ranges of Permeability

Soil type	Degree of Permeability	k cm/sec	Drainage Characteristics
Clean Gravel	High	1 – 10	Good
Clean Sand, Sand with gravel mix	Medium	$1 - 10^{-3}$	Good
Fine sand, Silt	Low	$10^{-3} - 10^{-5}$	Fair - Poor
Sand – Silt – Clay mixture	Very low	$10^{-4} - 10^{-7}$	Poor - Impervious
Homogeneous Clay	Very low impermeable	Less than 10^{-7}	Impervious

III. The Study

The data used for the present study is taken from a large data bank exists in Central Soil and Materials Research Station from the investigations carried out for the various river valley projects located in various parts of India. The focus on this study is the fine grained soils. The fine grained soils are not classified on the basis of grain size distribution only, but according to plasticity and compressibility. The classification criteria as per the Bureau of Indian Standard Classification system are also based on the relationship between liquid limit and plasticity index.

There are three major groups in the fine grained soils: the 'H' groups, which have liquid limits more than 50, the 'I' groups, which have liquid limits between 35 and 50, and the 'L' groups, which have liquid limits less than 35. The symbols H, I and L have general meanings of high, intermediate and low compressibility respectively.

Fine grained soils are further divided with relation to their position above or below the A-line of the plasticity chart.

For the present study, a total of 36 soil data, 12 soil data each from the fine grained soils, CH (Clays with High Compressibility), CI (Clays with Medium Compressibility), and CL (Clays with Low Compressibility) groups of the Bureau of Indian Standard Classification system were used. These soil data are the original data from the tests carried out at CSMRS on the soil samples collected from various projects within India. The Grain Size Distribution curves of the selected soil samples representing each from the three soil types CH, CI and CL are present in Figure 5.

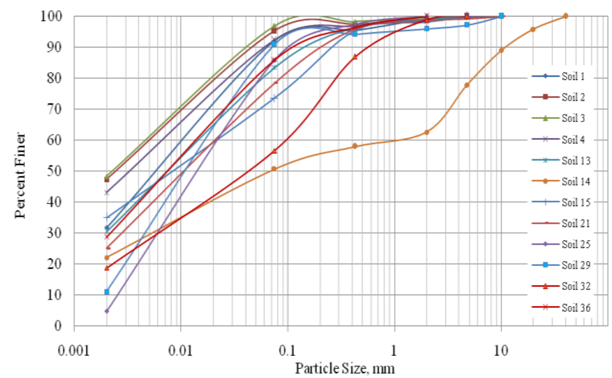

Figure 5 - Grain Size Distribution Curves

The applicability of the Allen Hazen's Formula, Kozeny – Carman equation and the Terzaghi and Peck equation were studied with the data set considered for the present study. It is seen that these equations are not valid for the fine grained soils and they may be valid only for the coarse grained soils.

As may be seen from the grain size distribution curves, the clay sizes present in the CH, CI and CL soils vary from 13.5 % to 48.4 %, 22.2 % to 35.0 % and 4.8 % to 28.8 % respectively. Determining the D_{10} for the CH and CI soils are meaningless for the study on the applicability of these equations. Though the D_{10} could be determined for some of the CL soils, the applicability of the three equations under study was seen to be highly bleak. Therefore, the applicability of the three equations is to be studied with the fresh data set of the coarse grained soils only.

IV. Results And Discussion

Figure 6 presents the variation of coefficient of permeability with clay sizes for the three different types of fine grained soils considered for the present study.

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The coefficient of permeability (k) of the CH, CI and CL groups soils vary from 1.87×10^{-8} cm/sec to 7.31×10^{-7} cm/sec, 1.85×10^{-7} cm/sec to 9.08×10^{-7} cm/sec and 2.89×10^{-6} cm/sec to 1.01×10^{-5} cm/sec respectively. From this graph, it may be seen that as the clay sizes increases, the coefficient of permeability decreases.

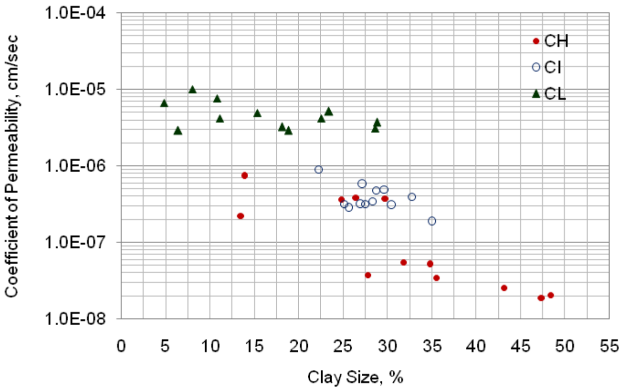

Figure 6 - Different Soil Types taken for Study

Figure 7 shows the correlation between the coefficient of permeability and % clay size. As the % of clay size increases, the coefficient of permeability decreases. From the correlation graphs, it can be seen that the value of R^2 obtained is 0.642. The correlation equation obtained can be written as:

$$k = 2\times10^{-5}e^{-0.14a} \qquad (1)$$

where k = coefficient of permeability and a = percentage of clay sizes.

Figure 8 shows the correlation between the coefficient of permeability and liquid limit. As the liquid limit increases, the coefficient of permeability decreases. From the correlation graphs, it can be seen that the value of R2 obtained is 0.793. The correlation equation obtained can be written as:

$$k = 0.0005e-0.15\ LL \qquad (2)$$

where k = coefficient of permeability and LL = Liquid Limit

Figure 9 shows the correlation between the coefficient of permeability and plastic limit. As the plastic limit increases, the coefficient of permeability decreases. From the correlation graphs, it can be seen that the value of R^2 obtained is 0.407. The correlation equation obtained can be written as:

$$k = 0.001e^{-0.34\ PL} \qquad (3)$$

where k = coefficient of permeability and PL = Plastic Limit

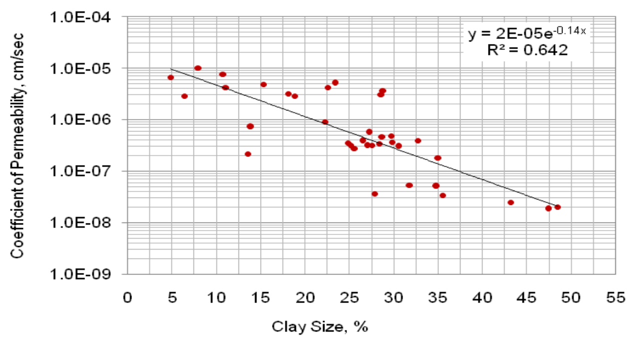

Figure 7- Effect of clay sizes on k

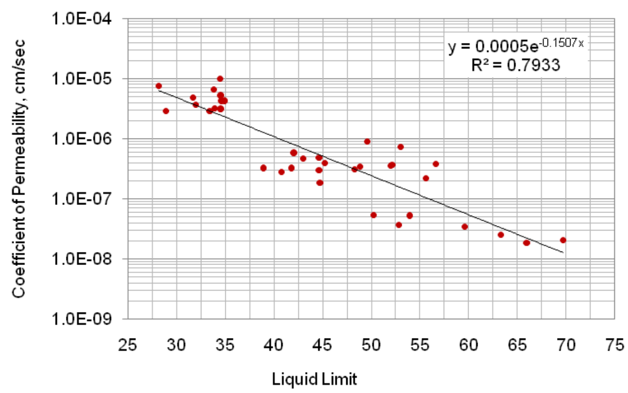

Figure 8- Correlation b/w LL & k

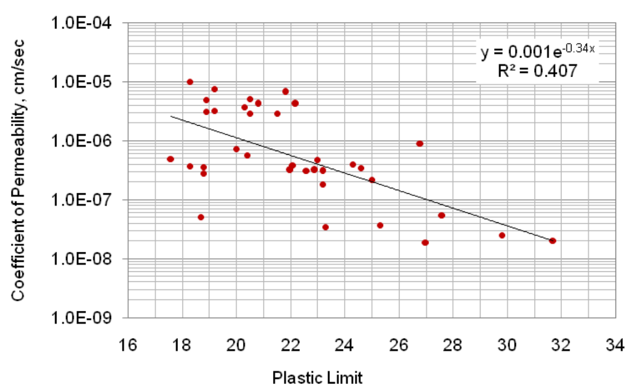

Figure 9- Correlation b/w PL & k

Figure 10 shows the correlation between the coefficient of permeability and plasticity index. As the plasticity index increases, the coefficient of permeability decreases. From the correlation graphs, it can be seen that the value of R^2 obtained is 0.683.

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The correlation equation obtained can be written as:

$$k = 2\times10^{-5}e^{-0.16\,PI} \qquad (4)$$

where k = coefficient of permeability and PI = Plasticity Index

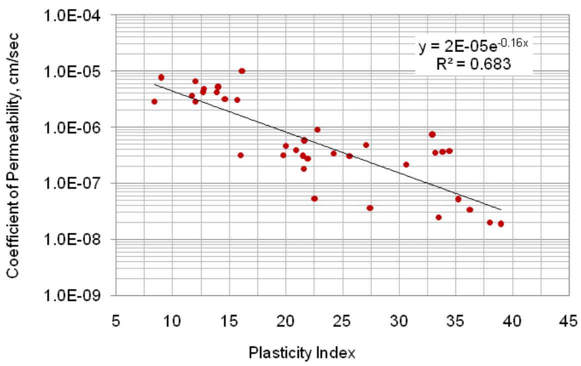

Figure 10- Correlation b/w PI & k

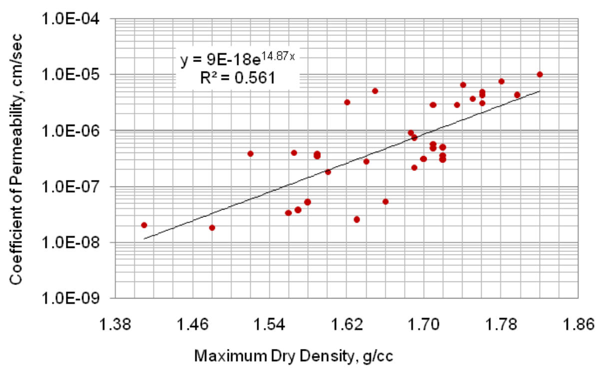

Figure 11- Correlation b/w MDD & k

Figure 11 shows the correlation between the coefficient of permeability and maximum dry density. As the maximum dry density increases, the coefficient of permeability increases. From the correlation graphs, it can be seen that the value of R^2 obtained is 0.561. The correlation equation obtained can be written as:

$$k = 9\times10^{-18}e^{14.87\,MDD} \qquad (5)$$

where k = coefficient of permeability and MDD = Maximum Dry Density

Figure 12 shows the correlation between the coefficient of permeability and OMC. As the % of OMC increases, the coefficient of permeability decreases. From the correlation graphs, it can be seen that the value of R^2 obtained is 0.397. The correlation equation obtained can be written as:

$$k = 0.0002e^{-0.3\,OMC} \qquad (6)$$

where k = coefficient of permeability and OMC = Optimum Moisture Content

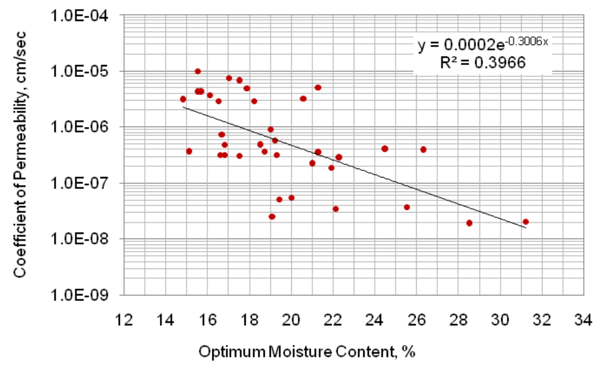

Figure 12- Correlation b/w OMC & k

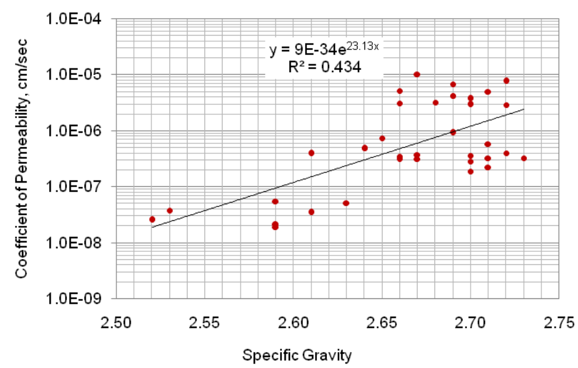

Figure 13- Correlation b/w G & k

Figure 13 shows the correlation between the coefficient of permeability and specific gravity. As the specific gravity increases, the coefficient of permeability increases. From the correlation graphs, it can be seen that the value of R^2 obtained is 0.434. The correlation equation obtained can be written as:

$$k = 9\times10^{-34}e^{23.13\,G} \qquad (7)$$

where k = coefficient of permeability and G = Specific Gravity

Figure 14 shows the correlation between the coefficient of permeability and void ratio. It is expected that the coefficient of permeability should increase with the increase in the voids ration.

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But the present study on the relationship between the voids ratio and the coefficient of permeability for the fine grained soils reveals a very poor correlation, as the void ratio increases, the coefficient of permeability decreases. This may be due to the degree of cementation or fine particles present in the fine grained soils.

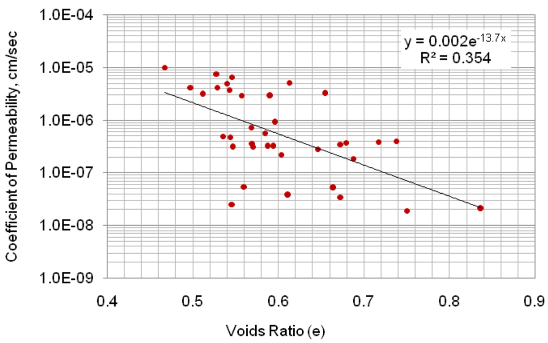
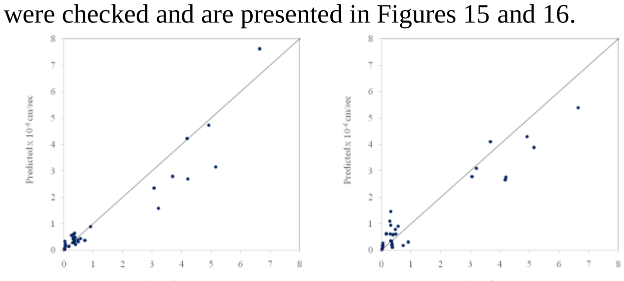


Figure 14- Correlation b/w e & k

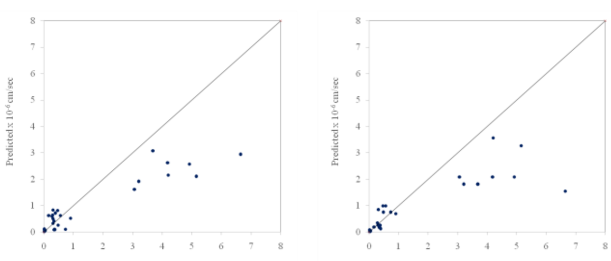
V. VALIDATION

The equations obtained from the present study have been validated using a fresh set of data. Since the R^2 of the correlations from coefficient of permeability and clay sizes, liquid limit, plasticity index and maximum dry density are higher than the other R^2, the validation of these equations were checked and are presented in Figures 15 and 16.



Clay Sizes　　Liquid Limit

Figure 15- Actual k Vs Predicted k



Plasticity Index　　Maximum Dry Density

Figure 16- Actual k Vs Predicted k

It may noted that as the R^2 values decreases the reliability of the correlations developed decreases. The RMSE values obtained for the validation are found generally to be larger. In order to get a perfect correlation, the RMSE values have to be smaller. Better results could be obtained with a smaller data base. However, the present study clearly indicates the effect of clay sizes on the compressibility and plasticity characteristics and further on the maximum dry density and permeability characteristics of the fine grained soils.

VI. CONCLUSIONS

The attempt to study applicability of the prevailing formulas and equations to determine the coefficient of permeability of soils revealed that the equations are not valid for the fine grained soils and they may be valid only for the coarse grained soils as the data set taken for the present study comprise mostly of soil with more than 15 % of 0.002 mm sizes.

The present study on the permeability characteristics of the fine grained soils indicates that the coefficient of permeability of fine grained soils decreases with the increase in clay sizes, liquid limit, plastic limit, and the plasticity index and increases with the increase in maximum dry density and specific gravity.

The correlation equations obtained for determining the coefficient of permeability (k) for the fine grained soils are:

- $k = 2\times10^{-5}e^{-0.14a}$ where a = percentage of clay sizes (R^2 = 0.642)
- $k = 0.0005e^{-0.15\,LL}$ where LL = Liquid Limit (R^2 = 0.793)
- $k = 0.001e^{-0.34\,PL}$ where PL = Plastic Limit (R^2 = 0.407)
- $k = 2\times10^{-5}e^{-0.16\,PI}$ where PI = Plasticity Index (R^2 = 0.683)
- $k = 9\times10^{-18}e^{14.87\,MDD}$ where MDD = Maximum Dry Density (R^2 = 0.561)
- $k = 0.0002e^{-0.3\,OMC}$ where OMC = Optimum Moisture Content (R^2 = 0.397)
- $k = 9\times10^{-34}e^{23.13\,G}$ where G = Specific Gravity (R^2 = 0.434)

The relationship between the voids ratio and the coefficient of permeability for the fine grained soils reveals a very poor correlation, as the void ratio increases, the coefficient of permeability decreases. This may be due to the degree of cementation or fine particles present in the fine grained soils.

Permeability is a complex property that depends on the sizes and shapes of the particles in a soil mass that control the rate of the flow of the soils. The factors which influence the nature of interconnections include grain size distribution, particle shape, and density (degree of compaction). Because of the complex nature of permeability and a number of factors influencing it, it is not possible to develop a predictive equation that can explain 100% variability of permeability of fine grained soils.

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