
Proceedings Paper:

Al-Moadhen, M orcid.org/0000-0003-2404-5724, Clarke, BG orcid.org/0000-0001-9493-9200 and Chen, X orcid.org/0000-0002-2053-2448 (2017) Hydraulic conductivity of composite soils. In: Proceedings of the 2nd Symposium on Coupled Phenomena in Environmental Geotechnics (CPEG2). 2nd Symposium on Coupled Phenomena in Environmental Geotechnics (CPEG2), 06-07 Sep 2017, Leeds, UK. .

Hydraulic conductivity of composite soils

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ABSTRACT: Many natural soils (e.g. glacial tills, residual soils, and alluvial soils) and artificial soils (e.g. engineered fill, environmental barriers) are formed of a range of particle sizes and types. These soils are often difficult to sample and test when using standard site investigations thus it is necessary to resort to empirical correlations; most of which were developed for coarse-grained (e.g. clean sands) or fine-grained (e.g. pure clays) soils. The hydraulic conductivity is dependent on the void ratio, clay type and particle size distribution and, in the case of composite soils it is also dependent on the clay content. Composite soils formed of four clay minerals and two sands were consolidated from slurry to determine the variation of hydraulic conductivity with clay content, clay type and void ratio. The matrix dominated soils, the flow is a function of the matrix void ratio and clay type; and, in clast dominated soils, the intergranular void ratio and particle size distribution. The transition from a matrix dominated soil to a clast dominated soil occurs at a fines content between 20% and 35%

KEYWORDS: composite soils, hydraulic conductivity, matrix void ratio, intergranular void ratio

1. INTRODUCTION

The classical approach to geotechnical engineering is to separate soils into two major groups; fine-grained soils are those soils that are formed of particles less than 0.063mm diameter and coarse-grained soils are formed of particles greater than 0.063 mm. In situ, most soils are formed of a range of particle sizes such that they are classed as composite or intermediate soils. BS6031:2009 suggests that composite soils are those that contain at least 10% of the secondary fraction. BS14688-1:2013 defines a composite fine soil as one in which the fines content determines the engineering behaviour. A composite coarse soil is one which contains fines but behaves as a coarse grained soil. In terms of engineered fills (BS6031:2009), soils that contain at least 15% fines are classed as cohesive soils and for the geotechnical design of cuttings and embankments, cohesive soils are defined as those containing at least 35% fines. Environmental barriers are often formed of bentonite sand mixtures, a composite soil.

The essential difference between them is the hydraulic conductivity which ranges from (1 x 10^{-13} to 1 x 10^{-7} cm/sec) for fine grained soils to (1 x 10^{-8} to 0.01 cm/sec) for coarse grained soils. Stephenson et al (1988) suggests that there is a correlation between particle size distribution and hydraulic conductivity; most significantly a reduction of three orders of magnitude if the clay content exceeds 15% to 20%. This is consistent with the observations of Skempton (1985), Georgiannou et al (1990), Salgado et al (2000), and Vallejo and Mawby (2000) who suggested that a composite soil more than 20% to 25% clay content behaves as a fine grained soil. Monkul and Ozden (2005) proposed a transition fines content of 20% to 34% when the intergranular void ratio of the composite soil is equal to the maximum void ratio of the host granular soil. The intergranular void ratio is the volume of voids and fine grains expressed as a percentage of the volume of coarse grains.

Given the difficulty of obtaining representative samples of composite soils, empirical correlations are often used to determine the characteristics of a composite soil. The hydraulic conductivity, k_h, of clean sands was defined by Hazen (1892) as a function of the particle size distribution. Kozeny (1927), modified by Carman (1939), suggested that k_h depends on soil porosity, particle shape and size, and surface area. Estimates of flow in fine grained soils are usually based on empirical correlations with Atterberg limits, particle size and void ratio. Chapius (2012) undertook a review of the characteristics of predictive methods to reach the conclusions that many methods are flawed because of errors in the experimental procedures but the methods attributed to Hazen (1892), Taylor (1948), Terzaghi (1925), and Shahabi et al. (1984) provided reliable predictions for coarse grained soils based on:-

$$k_h = A\,\frac{e_g^3}{1+e_g} \qquad (1)$$

Where A is a constant based on the particle size distribution and e_g the global void ratio.

Chapius (2012) concluded that regional correlations gave reasonable predictions for fine grained soils:-

$$log_{10}\,k_h = a + b\,log_{10}\left[\frac{e_g^3}{1+e_g}\frac{1}{I_L^2}\right] \qquad (2)$$

Where a and b are constants, and I_L the liquid limit.

These predictive methods suggest that flow through composite soils will be a function of the void ratio, particle size and Atterberg limits. Flow in in coarse grained composite soils will depend on the intergranular void ratio; flow in fine grained composite soils will depend on the matrix void ratio.

It is possible to estimate k_h indirectly from oedometer tests using:-

$$k_h = c_v m_v \rho_w \qquad (3)$$

Where c_v is the coefficient of consolidation and m_v the coefficient of volume compressibility. Tavernas et al (1983) suggest that indirect assessments are unreliable because of the assumptions made in the analysis. Chapius (2012) and Dafalla et al (2015) suggested that Equ (3) under predicts the hydraulic conductivity by two to three orders of magnitude. Given the difficulty of determining k_h directly in composite soils, an indirect assessment can be used to study the impact the characteristics of composite soils have upon k_h. This is the aim of this paper.

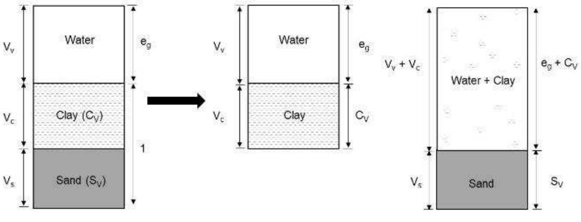


Figure 1. Phase-diagrams of: (a) saturated composite soil; (b) fine-grained dominated soil; and (c) coarse-grained dominated soil

2. GENERAL BEHAVIOUR OF COMPOSITE SOILS

A key to understanding the behaviour of saturated composite soils is the phase diagram formed of water, sands, and clays (Figure 1a). The global void ratio, e_g, is used to estimate consolidation characteristics of single uniform grained soils. It may not be appropriate for composite soils as it does not take into account the influence of the matrix upon the permeability of sandy clays or the intergranular structure of clayey sands.

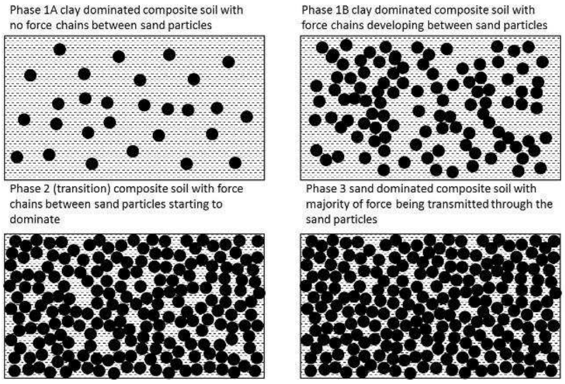


Figure 2. The effect of sand content on composite soils

Mitchell (1976) introduced the concept of the matrix void ratio, e_m, which is function of the fine grained soil content within a composite soil. If the sand content in a soil is small (Figure 2a) the global behaviour of the soil will be controlled by the electrical chemical inter-particle forces existing along clay grains as the coarse grained particles may not be in contact with each other; that is the coarse grained particles are inactive.

As the coarse grained content increases, force chains start to develop between the coarse grained particles until the soil behaviours becomes dominated by the coarse grained particles (Figure 2d). Thus there is a transition zone, Figure 2c, when the soil has characteristics of both a fine grained and coarse grained soil.

Therefore, for a fine grain dominated composite soil, it is the properties of the fine grains that govern the behaviour of the composite soil. The matrix void ratio is:

$$e_m = \frac{V_v}{V_c} \tag{4}$$

Where V_v is the volume of voids and V_c the volume of clays. If e_g is known then:

$$e_m = \frac{e_g}{C_v} \tag{5}$$

Where C_v is the volumetric fraction of dry solids occupied by the clay in the mixture. The mass of clay C_w can be measured directly. The particle density can be used to convert C_w to C_v:

$$e_m = \frac{e_g}{\frac{G_T}{G_c} * C_w} \tag{6}$$

Where G_T is the particle density of the composite soil; G_c is the particle density of the fine grained particles.

When the fine grained content is less than the transition fines content (typically 20% to 35%) (Figure 2d), the coarse grained fraction controls the behaviour of the soil with water and fine grained particles filling the voids between coarse grained particles and having a limited effect on the process of consolidation. The composite soil may behave in a way somewhat similar to that of clean sand. In such case, the intergranular void ratio, e_i, (Thevanayagam, 1998) is:

$$e_i = \frac{V_v}{V_s} = \frac{V_w + V_c}{1 - V_c} \tag{7}$$

This can be expressed in terms of e_g and clay content C_v:

$$e_i = \frac{e_g + C_v}{1 - C_v} \quad or \quad = \frac{e_g + \frac{G_T}{G_c} * (C_w)}{\frac{G_T}{G_s} * (1 - C_w)} \tag{8}$$

3. EXPERIMENTAL PROGRAMME

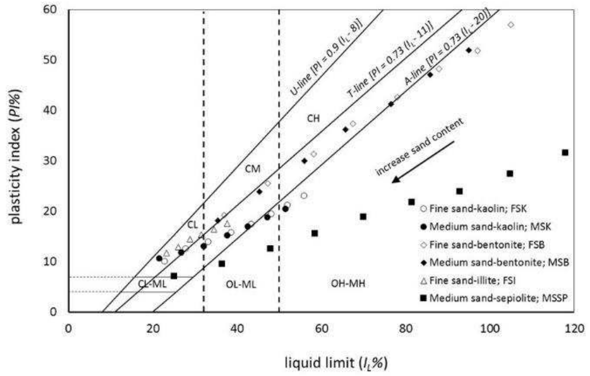


Figure 3. The plasticity chart for the composite soils showing the rela tionship of the limits to the T-line

3 .1 *Materials*

Investigation of the contribution a soil's composition makes to its consolidation properties is often based on artificial soils because the variability and fabric of natural soils will mask the intrinsic behaviour. Therefore, soils of known composition were prepared by mixing commercially produced clays with sands. The materials used in the study included four types of clays; kaolinite, bentonite, illite and sepiolite; and two uniform sands; medium and fine sands. Commercially available kaolin,

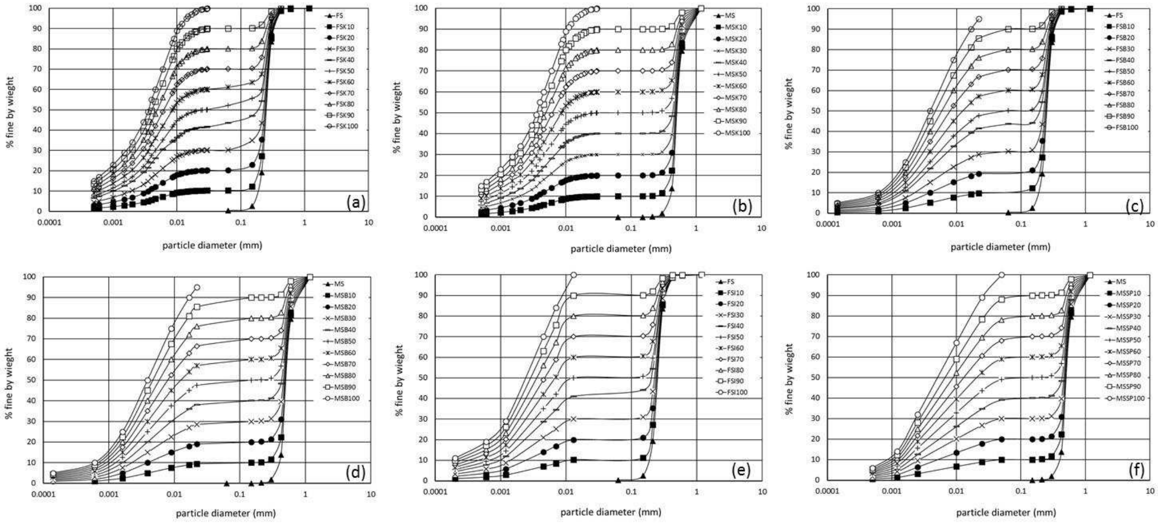


Figure 4. Particle size distribution of; (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; and (f) medium sand-sepiolite mixtures

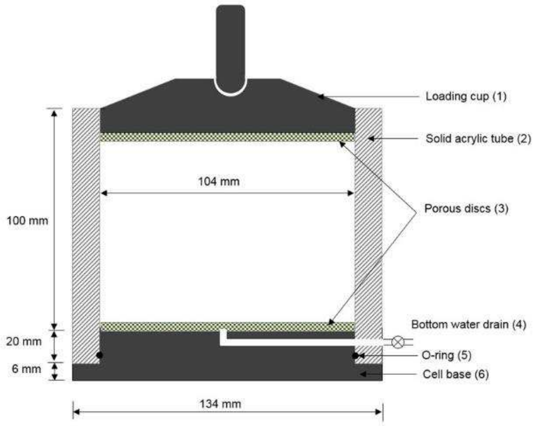


Figure 5. The consolidation cell

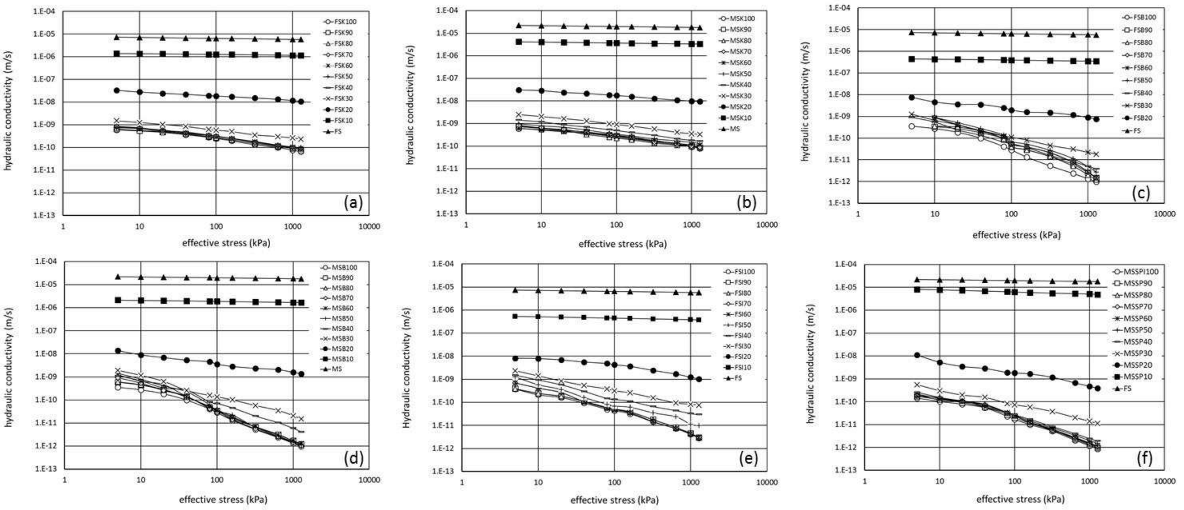
Figure 6. The test equipment showing the loading frame and consolidation cell

polywhite E grade is one of the most common minerals found in natural clays (Grim, 1959) and has a consistent and uniform mineralogy with low organic content (Yukselen-Aksoy and Reddy, 2012). Bentonite CB (calcium type) was used because of its importance in civil engineering as it is a thixotropic, support and lubricant agent used in diaphragm walls and foundations, tunnelling, horizontal directional drilling and pipe jacking. Commercial illite clay with low plasticity and sepiolite, a highly porous clay mineral with low bulk density were also used. The plasticity chart and the particle size distribution of the materials used are illustrated in Figure 3 and 4, respectively. The plasticity chart includes the T-line (Boulton and Paul, 1976), a line around which the limits of composite glacial soils tend to cluster. The composite soils in this study tended to migrate towards the T-line as the sand content increased. Note that in this study the limits were based on the whole sample rather than particles smaller than 425μm.

3 .2 *Test equipment and procedures*

A rigid-wall consolidation cell was used to investigate the consolidation characteristics and to indirectly determine the coefficient of hydraulic conductivity of the composite soils. The standard consolidation cell was designed for testing natural homogeneous clays. It is recommended that the maximum particle size is 10% of the height of the sample but given the amount of sand present in the samples, a 20mm sample height was considered inappropriate. Further, to ensure saturated conditions, a slurry-like mixture was used to form the reconstituted samples, which meant a sample would undergo large volume changes under the initial loading. For these reasons, a new consolidation cell was designed.

The principles behind the design of the new consolidometer cell are similar to those prescribed in BS 1377-5:1990 and ASTM D2435 standards. The cell, shown in Figure 5, consists of a solid acrylic cylindrical cell (2) to contain and laterally restrain a soil specimen; a stainless steel base (6); bottom drainage systems (4); and a loading cap (1). The cell body is made of clear solid acrylic with 15mm wall thickness which could withstand soil pressures up to 1280kPa. An O-ring (5) sits between the cell base and the acrylic tube to ensure a complete seal during the operation. The cell was designed to sit in a standard oedometer test rig which restricted the outer diameter to 134mm and height 126mm. Drainage was allowed from top and bottom of a sample. The British standard recommends using a screen of filter papers between the specimen and the porous stones. Head (1982) stated that, when using such screen, fine soil grains can be enmeshed in the fibre pores of the filter screen, leading to clogging the pores and impeding the drainage of water, and thereby this can adversely affect the measurements. Thus, porous discs were used to transfer the applied stress to the sample and to provide a drainage path for the water.



Figures 7. The variation of hydraulic conductivity with log effective stress for (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; (f) medium sand-sepiolite mixtures

The composite soils were prepared as slurry to ensure that they were fully saturated but prevent segregation. A soil with varying coarse (sands) and fine (clays) grained fractions was mixed together dry for about half hour using a motorised rotary mixer. After that the dry soil mixture was blended to a slurry with tap water using an initial moisture content of up to 1.5 time of the liquid limit to prevent segregation and be sufficiently viscous time to allow air bubbles to be removed

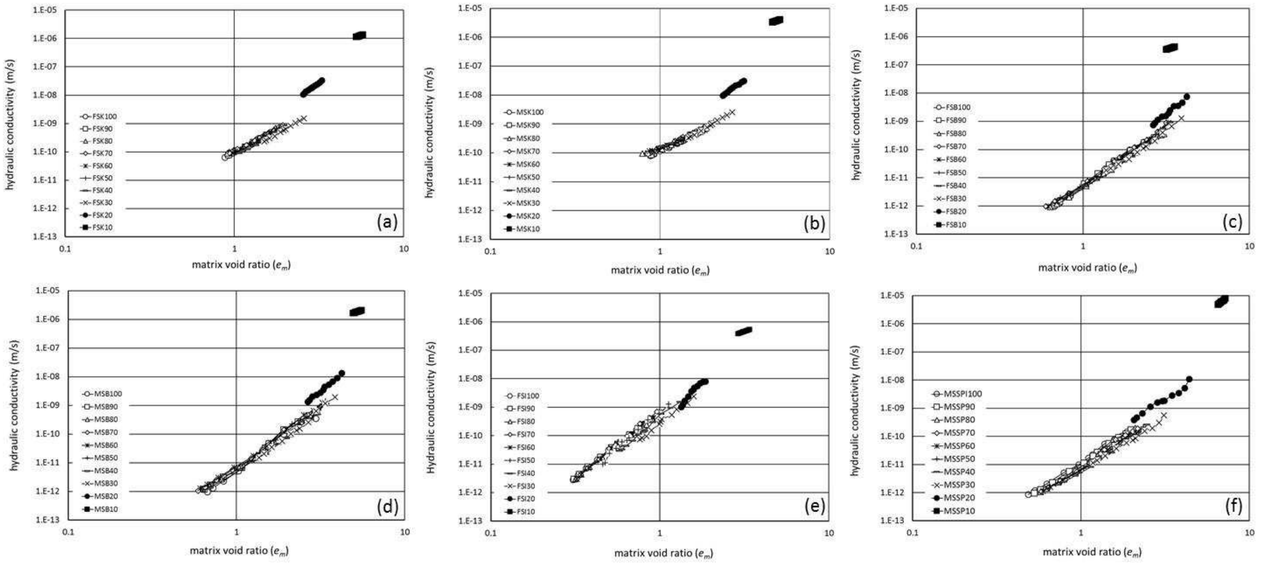


Figure 8. The variation of hydraulic conductivity with matrix void ratio for: (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; (f) medium sand-sepiolite mixtures

when the sample was vibrated during preparation. The internal surfaces of the cell were lubricated with a grease to reduce the side friction that may develop during the consolidation process. The slurry-like mixture was poured into the cell in layers with up to the desired height. The cell was vibrated using a shaking table to eliminate any entrapped air and the sample sealed and stored overnight to ensure a homogenous sample. A loading cap with a porous disc was placed on top of the soil sample slurry. The assembled cell was centrally placed on the platform of the loading frame (Figure 6).

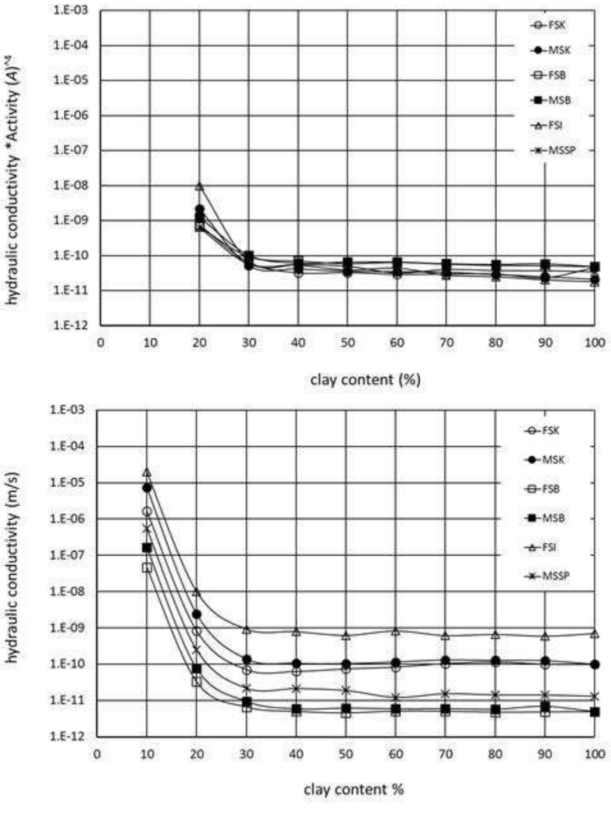


Figure 9. The variation of hydraulic conductivity for a matrix void ratio of one for the sand clay composites with (a) clay and (b) sand contents

An initial stress of 2.5kPa used to consolidate the slurry to achieve a firm consistency. Thereafter, the applied stress was doubled at each increment. Each stress increment was maintained for a time periods ranging from 1 to 4 days based on the rate of consolidation, a function of the soil mix.

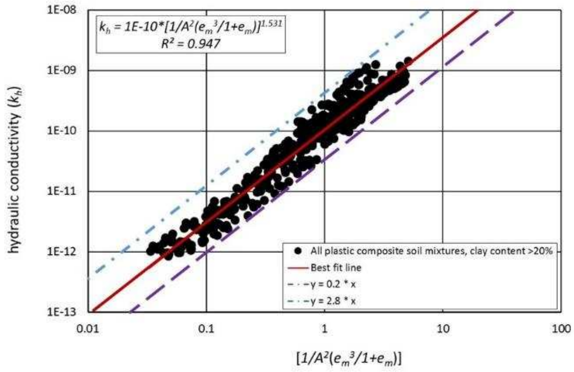


Figure 10. The variation of hydraulic conductivity of fine dominated composite soils as a function of matrix void ratio and activity

4. RESULTS AND DISCUSSION

The variation of k_h with effective stress, shown in Figure 7, confirms that, for composite soils, it is stress dependent and decreases with clay content. Figure 7 also suggests that a composite soil can exist in one of three states:- clay dominated with clay content in excess of 30% to 40%; sand dominated with clay content less than 20%; and a transition zone with clay content between 20% and 30% or 40%. This is also consistent with those composite soils that exhibit plastic behaviour and those soils which are non-plastic. The data, replotted in Figure 8 using the matrix void ratio, show that, for a clay content in excess of 30% the variation in hydraulic conductivity with effective stress, for a specific type of clay mineral, falls within a narrow band; that is, it is the clay matrix that dominates the permeability. This is consistent with the concept (Figures 2a and 2b) that flow is governed by the fine grained matrix with the coarse grained particles having little effect provided the coarse grained content is less than 30%. Figure 9 shows the transition fines content more clearly. k_h at a matrix void ratio of one is very nearly constant for all composite soils provided the clay content is greater than 30%.

k_h of fine grained soils is also dependent on the liquid limit according to Equ 2. In the case of composite soils, k_h must depend on the amount of clay and the clay type which can be expressed as the activity of the clay (A). Figure 10 shows that the results all fall within a band defined by:

$$k_h = 1e^{-10}\left[\frac{1}{A^2}\frac{e_m^3}{1+e_m}\right]^{1.53} \tag{9}$$

Interestingly Equ 2 does not give such close fit. This could be due to the fact that Equ 2 was developed from tests on clays soils as opposed to composite soils and the results were obtained from direct measurements.

Figure 8 shows that there is no correlation between hydraulic conductivity and matrix void ratio for non-plastic soils. Thevanayagam (1998) and others have suggested that the shear behaviour of coarse grained composite soils is a function of the intergranular void ratio. This also applies to hydraulic conductivity even though the intergranular void ratio includes the clay volume. The hydraulic conductivity of coarse grained soils is also a function of d_{10} (Hazen, 1892). Figure 11 shows all data for non-plastic soils lie about the line:-

$$k_h = 2e^{-4}\left[d_{10}^2\left(\frac{e_i^3}{1+e_i}\right)\right]^{0.885} \tag{10}$$

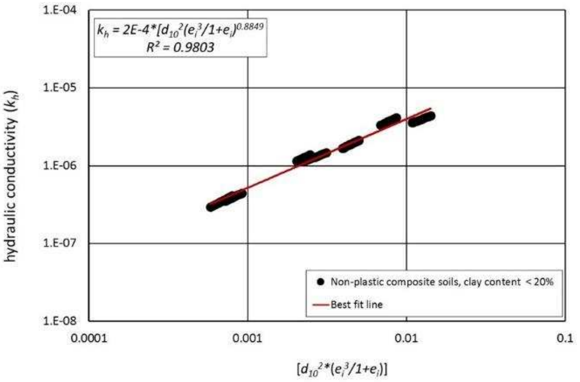


Figure 11. The variation of hydraulic conductivity of coarse dominated composite soils with intergranular void ratio and effective particle diameter.

5. CONCLUSIONS

This study of composite soils shows that they can be matrix dominated soils in which the fine grained component dictates the engineering behaviour or clast dominated soils in which the coarse grained component dictates the engineering behaviour. The transition fines content is between 20% and 35% depending on clay type. Therefore, there is transitional behaviour between matrix dominated and clast dominated behaviour. In matrix dominated soils, the permeability is controlled by the impermeable characteristic of the clay. The sand has little effect on the conductivity as the sand particles are randomly distributed through the clay matrix. As the clay content reduces, the number of active contacts between the sand particles increases, leading to an increase in the size of pores contained within the soil matrix increasing the permeability. This is the transition zone where the hydraulic conductivity starts to increase. With a further reduction in clay content, the hydraulic conductivity of the soil continues to increase until the flow is dominated by the sand characteristics as the influence of the clay on the flow of water is small and can be ignored. The soil in this zone is non plastic.

These results show that there is a relationship between hydraulic conductivity and void ratio. In matrix dominated soils, the relationship is a function of clay type and matrix void ratio; in clast dominated soils, it is a function of particle size and intergranular void ratio.

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