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PERMEABILITY CHARACTERISTICS OF RECONSTITUTED DHAKA CLAY

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ABSTRACT: Coefficients of permeability (k) of reconstituted Dhaka clay have been determined from constant head permeability tests and from one-dimensional incremental loading consolidation tests. Values of coefficient of permeability determined indirectly from consolidation tests have been found to be less than those measured directly from constant head tests. It has also been found that permeability computed from consolidation test using $\sqrt{t}$ fitting method are moderately higher than those determined using log t fitting method. Non-linear e - log k relationships have been found for Dhaka clay. However, apparent linear log [k(1 + e)] - log e relationships have been obtained. This linear relation indicates that permeability - void ratio relation in Dhaka clay may be represented by the relation $k = C\frac{e^n}{1+e}$ as proposed by Samarasinghe, Huang and Drnevich (1982). Approximately linear k versus $e^n/(1 + e)$ relationship has been obtained for Dhaka clay.

KEY WORDS: clays, laboratory tests, permeability, void ratio, consolidation.

INTRODUCTION

One of the important problems geotechnical engineers are often to deal with is the accurate and reliable measurement of permeability. Permeability governs such important engineering problems as the ground water regime in layered deposits, or near natural and excavated slopes, the consolidation of clay foundations under applied loads and the flow of water through or around engineering structures. The permeability is an important parameter in the design of waste disposal facilities involving burial in natural clay deposits or the use of clay liners in underground reservoirs. For coarse grained soils, permeability has been related to grain size distribution. Similar relationship for clays is less successful to predict permeability accurately for engineering purposes. Numerous researchers have suggested functions for the relationship between permeability and void ratio (Taylor, 1948; Raymond, 1966; Lambe and Whitman, 1969; Samarasinghe et al., 1982). The most commonly used approximation for both reconstituted and natural clays has been the linear plot of void ratio versus logarithm of permeability (Tavenas, Jean, Leblond and Leroueil, 1983; Tababa and Wood, 1987; Leroueil, Lerat, Hight and Powell; 1992; Nagaraj, Pandian and Narasimha Raju, 1993). This paper presents the permeability characteristics of reconstituted normally consolidated Dhaka clay in order to evaluate suitable relationship to predict its permeability.

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For clays, Taylor (1948) suggested the following empirical linear relation between the logarithm of permeability (k) and the void ratio (e):

$$\log k = \log k_0 - \frac{e_0 - e}{C_k} \tag{1}$$

where C_k is permeability change index which is being the slope of linear e versus log k relationship and e_0 and k_0 are the in situ void ratio and in situ permeability respectively. This type of relation has become a common way of expressing the variation of permeability of clays with void ratio. The relationship is generally valid for a range of void ratio changes encountered in engineering practice (Meshri and Rokhshar, 1974).

Samarasinghe, Huang and Drnevich (1982) suggested a model to predict permeability of normally consolidated clays. The relationship is as follows:

$$k = C\frac{e^n}{1+e} \tag{2}$$

in which C is a constant in the same unit as k and n is a constant depending on the type of soil. Eq. (2) shows that for a particular value of n, k versus $e^n/(1 + e)$ plot is a straight line passing through the origin. Eq. (2) can be rewritten as follows

$$\log [k(1 + e)] = n \log e + \log C \tag{3}$$

Eq. (3) shows that a plot of log [k(1 + e)] versus log e results in a straight line of which n is the slope and log C is the vertical intercept. Samarasinghe et al. (1982) termed n and C as permeability parameters. Raymond (1966) conducted hydrostatic Consolidation tests and direct permeability tests on the same specimen for three different reconstituted normally consolidated clays of medium to high plasticity. The directly measured permeabilities were compared with those derived indirectly from consolidation tests. Samarasinghe et al. (1982) carried out both direct permeability tests and incremental loading consolidation tests on a artificially sedimented normally consolidated sandy clay to verify the model represented by Eq. (2). Figs. 1(a) and (b) shows permeability plots of the clays tested by Raymond (1966) and Samarasinghe et al. (1982) respectively. The permeability parameters n and C derived from these linear plots shown in Fig. 1. It can be seen from Fig. 1 that, for any method n is about the same for each soil. However, C varies with the method of tests. It has been observed that the reconstituted clays investigated by Raymond (1966) and Samarasinghe et al. (1982) behave exactly in conformity with Eq. (2) as proposed by Samarasinghe et al. (1982).

Tavenas, Leblond and Leroueil (1983) assessed the applicability of Eqs. (1) to (3) for a number of undisturbed natural soft clays. The experimental data obtained in the investigation suggest that any relations, e.g., e - log k, log e - log k and log e - log [k(1 + e)] may be valid for certain clays or certain ranges of void ratio variations and not applicable in other circumstances. Tavenas et al. (1983) report that from a practical point of view, the relation represented by Eq. (1) is excellent for initial void ratios less than 2.5 and for volumetric strains of practical interest in engineering problems. Eq. (3) has also been found to be suitable to represent permeability - void ratio relation in natural clays (Tavenas et al., 1983).

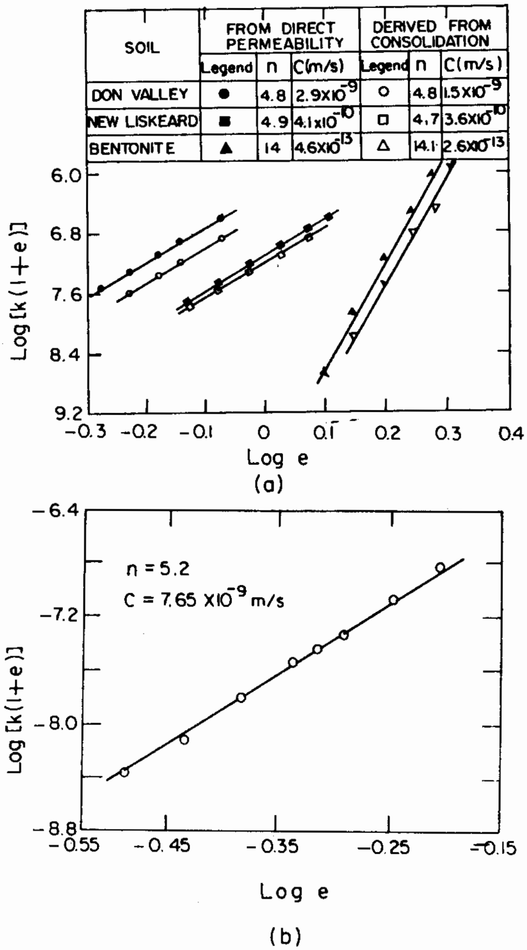

Fig 1. Permeability Plots for Clays (a) Don Valley Clay, New Liskerd Clay and Bentonite; after Reymond (1966), (b) Greyish Sandy Clay; after Samarasinghe et al. (1982)

PREPARATION OF RECONSTITUTED DHAKA CLAY SAMPLE

Reconstituted soils are those which are prepared by breaking down natural soils, mixing them as slurry and reconsolidating them. Reconstituted soil enables to establish a general pattern of behaviour (Jardine, 1985). The major advantages of using data from reconstituted soils are that the ambiguous and substantial effects of sampling of natural soils and inhomogeneity can be eliminated, while the essential history and composition of in-situ soils can be represented. Reconstituted clay has, therefore, been used to investigate the permeability properties of Dhaka clay.

The Dhaka clay was collected from the campus of Bangladesh University of Engineering and Technology, Dhaka from a depth of eight to ten feet. The physical and chemical properties of the clay are shown in Table 1. Reconstituted Dhaka clay was prepared by K_0-consolidation from slurry which had a water content of about twice the liquid limit of the clay. Consolidation of slurry was carried out in a locally fabricated Consolidation - Permeability test equipment. A seating pressure of 24 kPa was used during consolidation. It took about two days for completion of consolidation and sample of 63.5 mm diameter by 38 mm high was produced.

LABORATORY TEST EQUIPMENT AND PROCEDURES

Coefficient of permeability of the samples were determined indirectly from one-dimensional consolidation tests and directly from constant head permeability tests. Standard incremental loading consolidation tests and direct permeability tests were run on the same samples. Consolidation test was carried out using the Consolidation - Permeability test equipment. During consolidation test, a stress increment ratio of 1, (i.e., a load ratio of 2) was used. The vertical stresses applied during consolidation were 47.9 kPa, 95.8 kPa, 191.6 kPa, 383.2 kPa, 766.4 kPa and 1532.8 kPa. Duration of each loading step was twenty four hours. During all these tests drainage was permitted from top and bottom of the sample. These tests were carried out in accordance with the procedure specified in ASTM (1979) Standards.

Time - deformation curves were plotted for each pressure increment and from these plots times corresponding to 50% consolidation i.e., t_{50} and 90% consolidation, i.e., t_{90} were determined using Casagrande's Curve Fitting Method (Das, 1983) and Taylor's Curve Fitting Method (Das, 1983) respectively. Coefficients of consolidation, c_v were calculated for each stress increment using the following equations:

$$c_v = \frac{0.197\,H^2}{t_{50}} \tag{4}$$

$$c_v = \frac{0.848\,H^2}{t_{90}} \tag{5}$$

where, H is the average length of drainage path, i.e., half the height of sample at the end of 100% consolidation for a given stress increment. The coefficient of permeability, k were computed using the following equation (Taylor, 1948):

$$k = c_v\, m_v\, \gamma_w \tag{6}$$

where, m_v = coefficient of volume compressibility; and γ_w = unit weight of water.

Consolidation - Permeability test equipment along with constant pressure apparatus and flow volume measuring unit were used as permeameter for carrying out constant head permeability test. The flow volume measuring unit was also locally fabricated. Fig. 2 shows the general layout schematically to perform constant head permeability tests. Permeability tests were run at the end of stress increment when the primary consolidation was complete. These tests were carried out at end of vertical effective consolidation stresses of 95.7 kPa, 191.4 kPa, 382.8 kPa, 765.6 kPa and 1531.2 kPa. During permeability test, under constant hydrostatic pressure deaired distilled water was permitted to flow through the sample from bottom to top. The volume of flow was monitored from the flow volume measuring unit at increasing time intervals until the steady state of flow was reached. The samples were tested under hydraulic gradients varying from 293 to 857. Fig. 3 shows the plottings of flow volume (Q) versus time for five tests under various hydraulic gradients. The steady state flow rates (Q_α) were determined from the slope of the straight line portion of the curves presented in Fig. 3. Reynonds number, R_e corresponding to each steady flow were calculated using the following equation (Lee, 1983):

$$R_e = \frac{\gamma_w D_{10} v}{\mu_w g} \qquad (7)$$

where, γ_w = unit weight of water;
D_{10} = effective diameter of soil particle
v = flow through unit cross-sectional area or flow velocity
g = acceleration due to gravity;
μ_w = coefficient of absolute viscosity of water

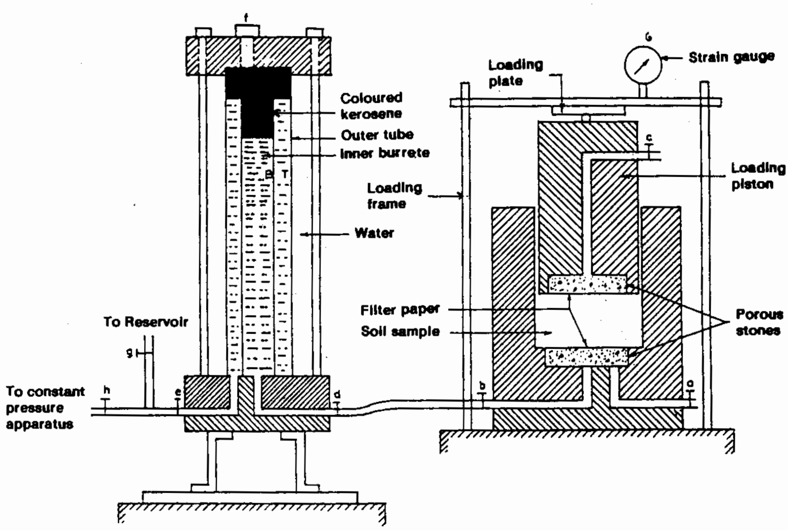

Fig 2. Schematic Layout for Conducting Constant Head Permeability Test

For steady state laminar flow conditions in soils, it can be conservatively assumed that R_e has an upper limit of unity (Lee, 1983). It has been found that R_e-values calculated using Eq. (7) were all less than unity. Hence the samples were tested under laminar flow conditions and consequently Darcy's equation was used to compute coefficient of permeability of the samples.

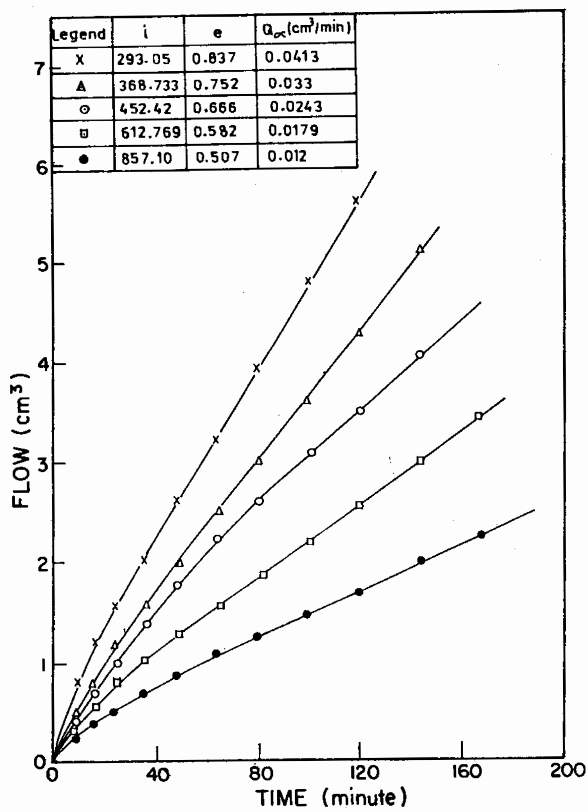

Fig 3. Flow Volume versus Time Plots During Constant Head Permeability Tests

RESULTS AND DISCUSSION

Permeability Test Results Table 2 shows the summary of constant head direct permeability test results of Dhaka clay. It can be seen from Table 2 that for normally consolidated Dhaka clay, coefficient of permeability determined from constant head test varied between 0.74×10^{-10} m/sec and 7.35×10^{-10} m/s for void ratio and dry density of the samples in the range of 0.51 to 0.84 and 14.2 kN/m^3 to 17.4 kN/m^3 respectively. Serajuddin and Ahmed (1967) carried out laboratory permeability test by falling head method on six undisturbed Dhaka clay samples of medium plasticity. Coefficient of permeability of the samples varied between 4.0 x 10^{-8} m/s and 3.6 x 10^{-10} m/s for natural dry density of the samples in the range of about 12.1 kN/m^3 to 15.7 kN/m^3.

Table 1 Physical and Chemical Properties of Dhaka Clay

Specific Gravity	Liquid Limit	Plastic Limit	Plasticity Index	Clay Content (%)	Activity	Organic Content (%)
2.68	40	20	20	22	0.91	0.34

Table 2 Summary of Constant Head Permeability Test Results of Dhaka Clay

Hydraulic Gradient, i	σ_{vc}' (kPa)	Void Ratio	Water Content (%)	Dry Density (kN/m^3)	q_α (cm^3/min)	k (10^{-10} m/s)
293.05	95.8	0.84	31.2	14.2	0.041	7.35
368.73	191.6	0.75	28.1	14.9	0.033	4.71
452.42	383.2	0.67	24.9	15.7	0.024	2.79
621.77	766.4	0.58	21.7	16.5	0.018	1.52
857.1	1532.8	0.51	18.9	17.4	0.012	0.74

Table 3 shows the summary of permeability test results determined from one-dimensional consolidation test. It can be seen from Table 3 that the values of coefficient of permeability determined using $\sqrt{t}$ fitting method are higher than those determined using log t fitting method for all the stress ranges. Similar results have also been found by Siddique (1990) for reconstituted soft London clay (LL = 69, PI = 45). Permeability determined using log t method and $\sqrt{t}$ method varied from 0.62 x 10^{-10} m/s to 8.19 x 10^{-10} m/s and 0.84 x 10^{-10} m/s to 11.25 x 10^{-10} m/s respectively. Comparing the permeability data determined from constant head permeability test (see Table 2) with those computed indirectly from consolidation test (see Table 3), it is evident that the values of coefficient of permeability determined from constant head test are higher than those found from consolidation test.

Table 3 Coefficient of Permeability of Dhaka Clay Determined From One-Dimensional Consolidation Test

Average Void Ratio	Average σ_{vc} (kPa)	k (10^{-10} m/s)	
		log t Fitting Method	$\sqrt{t}$ Fitting Method
0.97	35.90	8.19	11.25
0.88	71.85	6.22	9.03
0.79	143.70	4.04	5.79
0.71	287.4	2.23	3.06
0.63	574.8	1.49	1.99
0.55	1149.6	0.62	0.84

Void Ratio - Permeability Relationships

Fig. 4 shows the plottings of void ratio against logarithm of permeability determined from direct permeability tests and consolidation tests. It can be seen from Fig. 4 that permeability decreases with decreasing void ratio and that e - log k relationships are non-linear. Non-linear e - log k relations have been reported by Samarasinghe et al. (1982) and Raymond (1966) for reconstituted normally consolidated clays. Non-linear e - log k relations have also been reported by Tavenas et al. (1983) and Ahmed (1977) for undisturbed natural Matagami clay of Canada and soft Ranjit clay of Bangkok respectively.

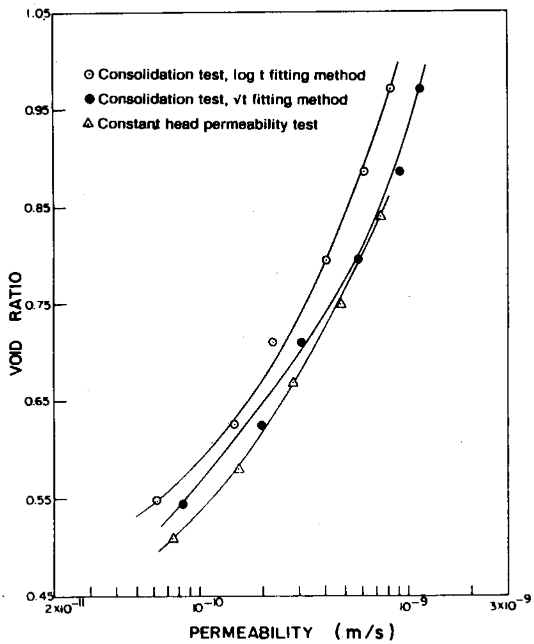

Fig 4. Void Ratio versus Log Permeability Plots for Dhaka Clay

In an attempt to examine the applicability of the theoretical relation [Eq. (2)] as proposed by Samarasinghe et al. (1982), log [k(1 + e)] versus log e have been plotted for Dhaka clay. These plottings are shown in Fig. 5. It can be seen from Fig. 5 that approximately linear log [k(1+e)] -log e relationships have been obtained for the Dhaka clay sample used. It has already been mentioned that in this investigation Dhaka clay collected from the campus of Bangladesh University of Engineering and Technology, Dhaka, has been used. Since, the index properties and clay contents of clay samples collected from different locations of Dhaka do not vary significantly, it, therefore, appears that the permeability - void ratio relationship in Dhaka clay samples can be represented by Eq. (2) as proposed by Samarasinghe et al. (1982). However, further research may be conducted using clay samples obtained from various locations of Dhaka in order to compare and confirm the findings of the present work and also to establish the applicability of the model represented by the Eq. (2) for Dhaka clay samples. The permeability parameters n and C of the Dhaka Clay studied were determined from the plots shown in Fig. 5. The magnitudes of these parameters are presented in Table 4. It can be seen from Table 4 that permeability parameter n varied between 4.5 and 4.8 (average = 4.7), while permeability parameter C varied from 0.85 x 10^{-10} m/s to 1.2 x 10^{-10} m/s (average = 1.1 x 10^{-10} m/s). The values of permeability parameters n and C of Dhaka clay, therefore, indicate that both n and C did not vary significantly depending on test method. Samarasinghe et al. (1982) and Raymond (1966) also found similar values of n for any method of test. Permeability parameter C was, however, found to vary with the test method.

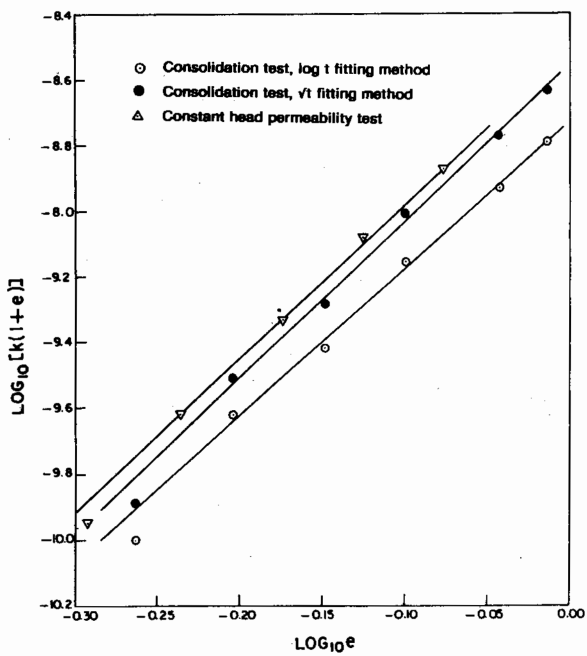

Fig 5. Log [K(1+e) versus Log e Plots for Dhaka Clay

Table 4 Values of Permeability Parameters of Dhaka Clay

Permeability Parameters of Dhaka City					
From Constant Head Permeability Test		From One - Dimensional Consolidation Test			
		Logt Fitting Method		√t Fitting Method	
n	C (10^{-10} m/s)	n	C (10^{-10} m/s)	n	C (10^{-10} m/s)
4.7	1.2	4.5	0.85	4.8	1.0

Fig. 6 shows coefficient of permeability (determined from constant head permeability test) versus $e^n/(1 + e)$ plot for the Dhaka clay. The value of n reported in Fig. 6 has been obtained from the plot of log $[k(1 + e)]$ versus log e for the constant head permeability test as shown in Fig. 5. It can be seen that k versus $e^n/(1 + e)$ relationship is approximately linear. This linear relationship has also been found to be valid for a large number of reconstituted normally consolidated clays (Samarasinghe et al., 1982; Raymond, 1966).

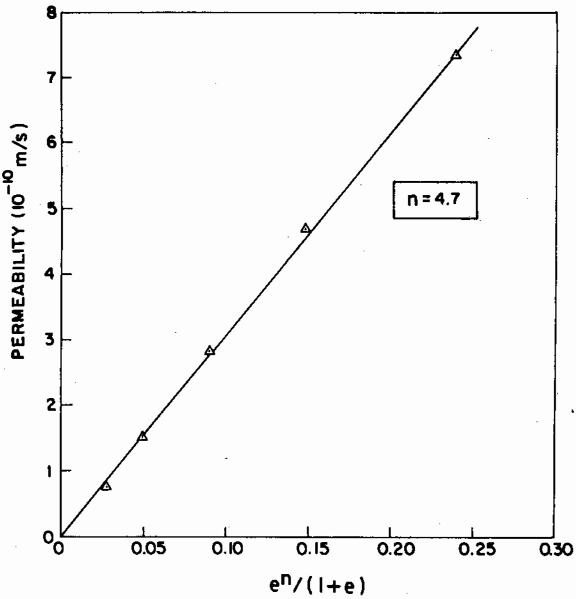

Fig 6. Coefficient of Permeability versus $e^n/(1+e)$ Plot for Dhaka Clay

Permeability - Vertical Effective Stress Relationship

Logarithm of coefficient of permeability versus logarithm of vertical effective stress plots are shown in Fig. 7. It can be seen from Fig. 7 that log k - log σ_{vc}' relationships are non-linear with permeability decreasing with increasing levels of vertical effective stress. Siddique (1990) also found similar results for reconstituted soft London clay.

CONCLUSIONS

Coefficients of permeability of reconstituted Dhaka clay have been determined directly from constant head permeability tests and indirectly from incremental loading one-dimensional consolidation tests.

Coefficient of permeability determined from constant head test varied between 0.74×10^{-10} m/sec and 7.35×10^{-10} m/s for void ratio and dry density of the samples in the range of 0.51 to 0.84 and 14.2 kN/m^3 to

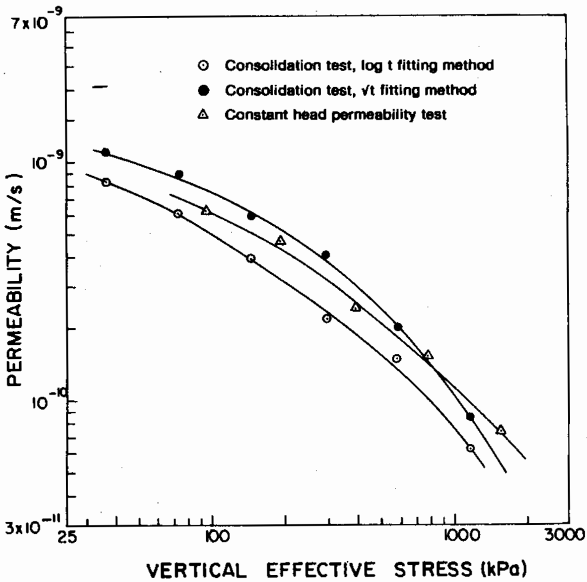

Fig 7. Permeability - Log σ_{vc}' Relationship for Dhaka Clay

17.4 kN/m^3 respectively. Permeability determined using log t method and $\sqrt{t}$ method varied from 0.62 x 10^{-10} m/s to 8.19 x 10^{-10} m/s and 0.84 x 10^{-10} m/s to 11.25 x 10^{-10} m/s respectively for void ratio of the samples in the range of 0.55 to 0.97. Comparing the permeability data determined from constant head permeability test with those computed indirectly from consolidation test. Permeability computed from consolidation test using $\sqrt{t}$ fitting method are 34% to 45% higher than those determined using log t fitting method. Similar findings has also been reported by Siddique (1990) for reconstituted high plastic (PI = 45) London clay. It also appears from the present investigation that coefficient of permeability measured directly from constant head tests compares better with those determined from consolidation tests using $\sqrt{t}$ fitting method than those determined using log t fitting method. For use in practical problems, therefore, coefficient of permeability may be determined indirectly from one-dimensional incremental loading consolidation test using $\sqrt{t}$ fitting method.

The e - log k relationships for Dhaka clay have been found to be non-linear. Non-linear e - log k relations have been also been reported for intact and reconstituted clays (Tavenas et al., 1983; Samarasinghe et al., 1982). However, approximately linear log [k(1 + e)] - log e relationships have been obtained for Dhaka clay. The relation $k = C \frac{e^n}{1+e}$ as proposed by Samarasinghe et al. (1982), therefore, can be used to predict permeability - void ratio relation in Dhaka clay. Although the index properties of clays obtained from different locations of Dhaka do not differ markedly, further research may be carried out using clay samples collected from various sites of Dhaka in order to confirm the findings of the present work and hence to establish the applicability of the above mentioned permeability - void ratio relation for Dhaka clays. The permeability parameter n for Dhaka clay studied has been found to vary between 4.5 and 4.8, average being 4.7, while permeability parameter C varied from 0.85 x 10^{-10} m/s to 1.2 x 10^{-10} m/s, average being, 1.1 x 10^{-10} m/s. It appeared that the values of permeability parameters n and C of Dhaka clay did not vary significantly depending on test from which the parameters n and C have been determined. Approximately linear k versus $e^n/(1 + e)$ relationship and non-linear log k - log σ_{vc}' has been obtained for the reconstituted normally consolidated Dhaka clay

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NOTATION

C	permeability parameter
C_k	permeability change index
c_v	coefficient of consolidation
D_{10}	effective diameter of soil particle
e	void ratio
e_0	in-situ void ratio
g	acceleration due to gravity
H	average length of drainage path
i	hydraulic gradient
k	coefficient of permeability
k_0	in-situ permeability
LL	liquid limit
m_v	coefficient of volume compressibility
n	permeability parameter
PL	plastic limit
PI	plasticity index
Q	flow volume
Q_α	steady state flow rate
t_{50}	time corresponding to 50% consolidation
t_{90}	time corresponding to 90% consolidation
v	flow velocity
γ_w	unit weight of water
μ_w	coefficient of absolute viscosity of water
σ_{vc}'	vertical effective consolidation stress