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PHYSICAL PROPERTIES OF DEWATERED WASTEWATER SLUDGE FOR LANDFILLING

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ABSTRACT

In the context of landfilling dewatered wastewater sludge in Hong Kong, with landfills up to 140 m high, one of the most significant properties of sludge is its physical nature with regard to moisture characteristics and associated geotechnical stability. Commonly, lower limits are set on total solids content, but no geotechnical stability criteria are applied with the exception of Germany where a minimum requirement for vane shear strength is set at 25 kN/m^2. The purpose of this study was to determine and evaluate dewatered wastewater sludge from three Hong Kong municipal wastewater treatment plants with regard to the following physical and geotechnical properties: (i) vane shear strength; (ii) consolidation characteristics such as compression index, compressibility factor, coefficient of consolidation and compressibility coefficient; and (iii) hydraulic characteristics such as permeability and intrinsic resistance. Although dewatered sludge exhibits quite different characteristics as compared to soils, predictive logarithmic relationships may be established between various properties which are consistent with the critical state model for soils, conventional filtration and consolidation theory. Such representation provides a valuable basis for understanding the sludge characteristics and behaviour to landfill design. Copyright © 1996 IAWQ. Published by Elsevier Science Ltd.

KEYWORDS

Consolidation; filtration; permeability; resistance; shear strength; sludge; total solids content

INTRODUCTION

The estimated total sludge production at wastewater treatment plants in Hong Kong will substantially increase from about 60,000 m^3 in 1992 to about 500,000 m^3 in 1997, based on dry solids content of 30%. This sharp increase in the quantity of sludge over this period is due primarily to the construction of a chemically-assisted primary wastewater treatment plant at Stonecutters Island as part of the Hong Kong Government Strategic Sewage Disposal Scheme. Landfilling provides the major, safe, economical disposal route for dewatered wastewater sludge in the near future. Since Hong Kong landfills are up to 140 m high, the physical characteristics of dewatered wastewater sludge with regard to moisture characteristics and geotechnical stability are of utmost importance. Commonly, lower limits are set on total solids content (Environmental Protection Department, 1990; Degremont, 1991a), but no geotechnical stability criteria are applied with the exception of Germany where a minimum requirement for vane shear strength is set at 25 kN/m^2 (German Federal

Government, 1993). A concise summary in English of the present state-of-the-art of the physical aspects of sludge for landfill is given by van den Berg et al. (1991). The authors have recently shown that the relationship between vane shear strength and total solids content may be reasonably represented by a logarithmic relationship that is consistent with the well established critical state model for soils (Koenig and Kay, 1994; Koenig and Kay, 1995). However, consolidation and hydraulic characteristics of dewatered sludge have not been reported so far. It is evident that they may be of paramount importance with regard to (i) the long-term behaviour of dewatered sludge in landfills, and (ii) performance during the slow filtration phase of mechanical dewatering of sludges.

OBJECTIVES

The purpose of this study is to determine and evaluate dewatered wastewater sludge from three Hong Kong municipal wastewater treatment plants with regard to the following physical and geotechnical properties: (i) vane shear strength; (ii) consolidation characteristics such as compression index, compressibility factor, coefficient of consolidation and compressibility coefficient; and (iii) hydraulic characteristics such as permeability and intrinsic resistance. In addition, an attempt is made to establish a predictive relationship between various sludge characteristics.

METHODS

In a first step, dewatered sludge was collected from three government operated biological wastewater treatment plants at Tai Po, Shek Wu Hui and Yuen Long. Sampling of the sludge and determination of vane shear strength as well as results have been described in detail elsewhere (Koenig and Kay, 1994; Koenig and Kay, 1995). In the second step, dewatered sludge samples underwent standard one-dimensional consolidation tests using a Wykeham Farrance rear loading Oedometer WF 24001 and according to the British Standard Methods BS 1377 (1990). Incremental loads were applied in separate tests at respective intervals of 24, 48 and 168 hours for each case. The consolidation characteristics including the coefficient of permeability were determined according to conventional practice from the consolidation tests (e.g. Das, 1994).

RESULTS AND DISCUSSION

Results of vane shear strength tests

Vane shear strength. The vane shear strength of the dewatered sludge from the different plants varied between 0.69 and 12.96 kN/m^2 for total solids (TS) contents of 13.05 to 22.90%. A summary of the mean values and ranges is given in Table 1. As expected, plate filter presses performed better than the belt filter presses achieving higher values for total solids concentration and vane shear strength. Although the three different sludges which were dewatered by plate filter presses had a very similar total solids content, the mean values for the vane shear strength varied considerably, namely from 3.59 to 7.53 kN/m^2. The critical state theory for the behaviour of clay (Wood, 1990) was found to be applicable to the behaviour of dewatered sludge and the following simplified relationship between vane shear strength and total solids content is proposed for Hong Kong sludges (Koenig and Kay, 1995):

$$s_u = A.e^{-m/TS} \qquad (1)$$

$$\text{or} \quad \ln(s_u) = \ln A - m/TS \qquad (2)$$

where s_u = undrained vane shear strength, in kN/m^2

TS = proportion by weight of total solids in dewatered sludge sample [= 1/(1+water content)]

A = sludge specific constant, in kN/m^2

m = 0.5

Figure 1 shows an example of the best fit of the logarithm of vane shear strength versus the inverse of total solids, using m = 0.5.

Table 1. Vane shear strength and total solids of dewatered sludge from different wastewater treatment plants of Hong Kong

Sample Site	Dewatering method	Vane shear strength (kN/m^2)	Total solids (%)
Shek Wu Hui	plate filter press	3.59 (2.06 - 6.19)	18.67 (15.25 - 22.19)
Yuen Long	plate filter press	7.53 (3.74 -12.96)	17.93 (14.79 - 21.12)
Tai Po	plate filter press	5.51 (3.05 - 9.35)	18.62 (16.38 - 22.90)
Tai Po	belt filter press	1.53 (0.69 - 5.36)	14.14 (13.05 - 17.82)

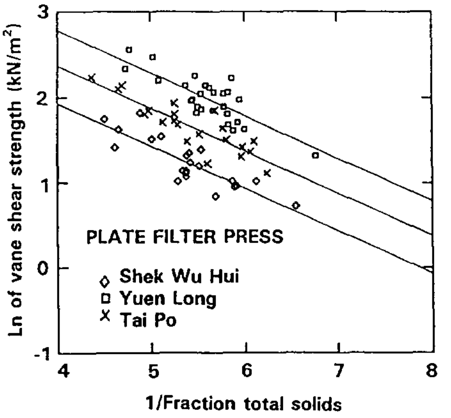

Figure 1. Best fit for log vane shear strength versus 1/Fraction total solids

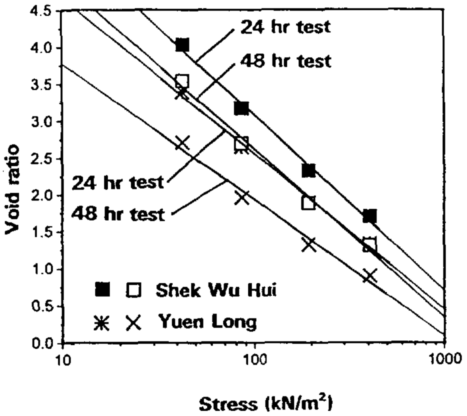

Figure 2. Void ratio e versus log stress for dewatered wastewater sludge of Hong Kong

Results of consolidation tests

Compression index. As a typical result of consolidation tests, in Figure 2 the void ratio e is plotted versus the logarithm of the applied stress. Using linear regression, the compression index C_c, defined as the slope of the e-log p plot, was obtained. The behaviour of sludge is thus seen to conform with standard consolidation theory which may be formulated as (Krizek et al., 1971):

$$e = N_c - C_c \log p \quad (3)$$

where
e = void ratio
N_c = void ratio at $p = 1\ kN/m^2$ on e-log p plot
C_c = compression index
p = applied stress, in kN/m^2

Compressibility factor. Sometimes the compressibility factor, F, is used, where $F = C_c/(e_0 + 1)$ where e_0 is the initial void ratio of the dewatered sludge sample (Krizek et al., 1971). Values obtained for C_c and F are summarised in Table 2.

Coefficient of consolidation, coefficient of permeability, intrinsic permeability, intrinsic resistance. The coefficient of consolidation, c_v, was obtained from the time rate of consolidation plot by means of the square-root-of-time method (Das, 1994). The coefficient of permeability, K, in m/s, could be derived directly. Intrinsic permeability, k, in m^2, was calculated according to Bouwer (1978) while the intrinsic resistance, r, in m^{-2}, was defined as the inverse of the intrinsic permeability. A typical plot of consolidation versus time is shown in Figure 3, while Table 3 summarises some typical data on consolidation and hydraulic characteristics.

Table 2. Compression index C_c and compressibility factor F of different dewatered wastewater sludges of Hong Kong.

Sample Site	Loading intervals	C_c	F
Shek Wu Hui	24 hours	2.38	0.39
	48 hours	2.27	0.38
	168 hours	1.72	0.26
Yuen Long	24 hours	2.10	0.40
	48 hours	1.84	0.35
	168 hours	1.77	0.31
Tai Po	168 hours	2.00	0.21

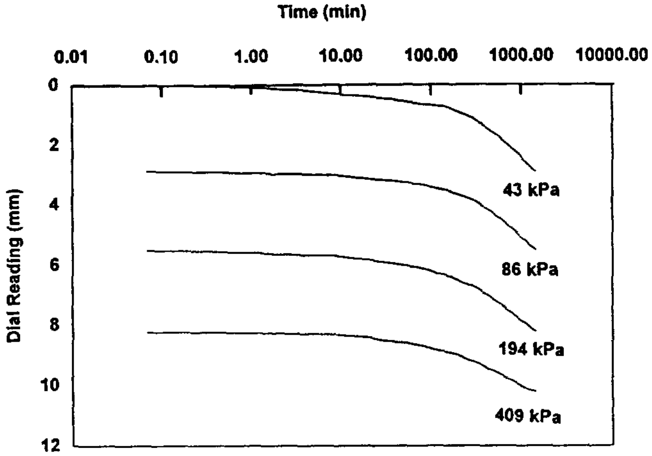

Figure 3. Typical time-deformation curve of consolidation test for Yuen Long sludge

Compressibility coefficient. A plot of log r versus log p in Figure 4 exhibits a linear relationship, similar to the well-known relationship between specific resistance and pressure of the sludge filterability test (Degremont, 1991b). The slope of the log r versus log p plot is defined as the dimensionless compressibility coefficient, s, in this case for dewatered sludge. The relationship can be formulated as:

$$r_1 = r_0 (p_1/p_0)^s \qquad (4)$$

where r_0 = intrinsic resistance at applied stress, p_0, in m^{-2}
r_1 = intrinsic resistance at applied stress, p_1, in m^{-2}
s = compressibility coefficient

Table 3. Consolidation and hydraulic characteristics of different dewatered wastewater sludges of Hong Kong for 48 hours load intervals

Sample site	Applied stress p (kN/m^2)	Coefficient of consolidation $c_v \times 10^{10}$ (m^2.s^{-1})	Coefficient of permeability $K \times 10^{12}$ (m.s^{-1})	Intrinsic permeability $k \times 10^{19}$ (m^2)	Resistance $r \times 10^{-16}$ (m^{-2})
Shek Wu Hui	43	3.40	22.1	22.6	44
	86	2.53	11.8	12.0	83
	194	1.87	4.25	4.34	231
	409	1.51	1.51	1.54	648
Yuen Long	43	3.40	26.6	27.2	37
	86	1.96	10.0	10.3	98
	194	1.39	2.84	2.90	345
	409	1.49	1.36	1.38	726

It was found that the compressibility coefficient varied between 1.2 and 1.35. The intrinsic permeability is related to applied stress in a similar manner as follows:

$$k_1 = k_0 (p_0/p_1)^s \tag{5}$$

where
k_0 = intrinsic permeability at applied stress, p_0, in m^2
k_1 = intrinsic permeability at applied stress, p_1, in m^2
s = compressibility coefficient

Relationship between consolidation theory and filtration theory

It may be of interest to note, that the sample deformation versus square-root-of-time plot for determining the coefficient of consolidation can be modified to a plot of t/V versus V, where V is the volume of water expelled during the consolidation test. Figure 5 illustrates the linear relationship obtained which is analogous to the graphical model used for obtaining specific resistance (Christensen and Dick, 1985). Thus it is evident that the filtration theory and consolidation theory are similar applications of Darcy's law, the former for liquid sludge, the latter for solid or dewatered sludge.

Relationship between vane shear strength and applied stress

Equations (1) and (3) can be combined to derive a relationship between vane shear strength and applied stress. It can be shown that they are related in the following manner:

$$S_{u1} = S_{u0} (p_1/p_0)^{0.434mC_c/G_s} \tag{6}$$

where
S_{u0} = vane shear strength at applied stress, p_0, in kN/m^2
S_{u1} = vane shear strength at applied stress, p_1, in kN/m^2
G_s = specific gravity of sludge solids

Utilizing the previously established approximate values for $m = 0.5$, $C_c = 1.8$ to 2.4 and $G_s = 1.2$ to 1.3, the exponent in Equation (6) is approximately 0.4. For a doubling of applied stress, the vane shear strength would thus increase by about 30%. The relationship derived above could be of special significance in the slow filtration phase (corresponding to a consolidation step) of mechanical dewatering of sludge. At the same time, it could help explain changes of vane shear strength in landfilled sludges where overlying pressure is less than the applied preconsolidation pressure during dewatering.

Relationship between vane shear strength and resistance

In a similar manner to above, Equations (4) and (6) can be combined to derive a relationship between vane shear strength and intrinsic resistance. It can be shown that they are related in the following manner:

$$S_{u1} = S_{u0}\,(r_1/r_0)^{0.434mCc/sGs} \qquad (7)$$

Utilizing the previously established approximate values for m, C_c, and G_s together with s = 1.25, the exponent in Equation (7) is approximately 0.3. A doubling of vane shear strength implies therefore a tenfold increase in intrinsic resistance.

Comparison of results

Vane shear strength of Hong Kong dewatered sludge is quite low and never attains the minimum strength of 25 kN/m^2 now mandated in Germany. This may be largely attributed to the low dewatering efficiency obtained by the available equipment and the absence of metal salts or lime conditioners as recommended elsewhere (ATV, 1995).

Figure 6 shows the values obtained for compressibility factor and initial void ratio together with a wide range of values from different soils. Dewatered sludge is seen to be quite different from natural soils; only some peats and organic soils may have somehow similar consolidation properties. The coefficients of permeability fall within the lower range of clays, while the values of intrinsic resistance appear to be about one to two magnitudes higher than those obtained from filterability tests. Passage of water through landfills may therefore be seriously impeded by improperly placed dewatered sludge.

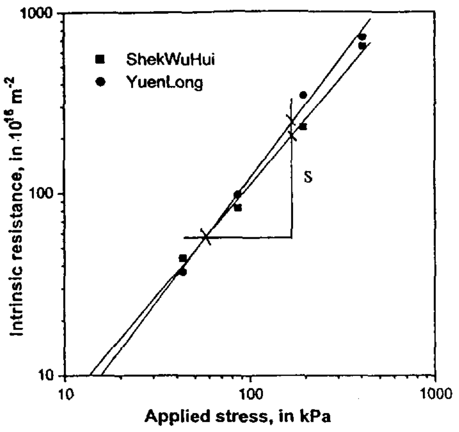

Figure 4. Determination of the compressibility coefficient

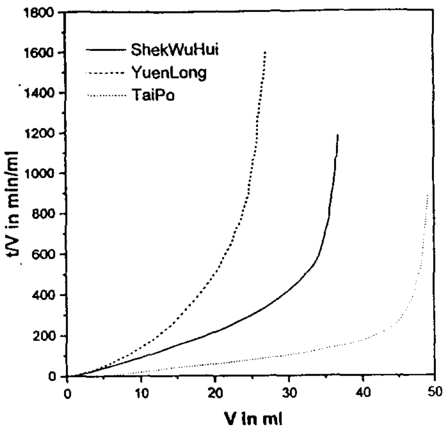

Figure 5. Standard t/V versus V plot for consolidation test at p = 43 kPa

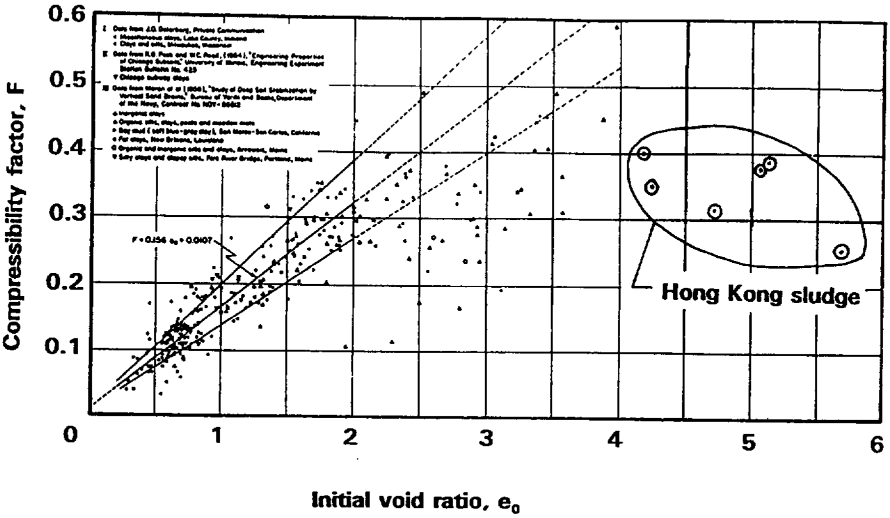

Figure 6. Comparison of compressibility factor and initial void ratio from U.S.A. (Krizek et al., 1971) with results from Hong Kong

CONCLUSIONS

The following conclusions are drawn:

1. The vane shear strength of dewatered sludge is related to the total solids content by a characteristic relationship consistent with critical state theory for soil.
2. Consolidation behavior of dewatered sludge follows conventional consolidation theory, but the values of compression index and compressibility factor are quite high in comparison with those for soils.
3. Permeability and intrinsic resistance are separately related to applied stress by a logarithmic relationship involving the compressibility coefficient.
4. The same graphical evaluation method can be used for filterability tests and consolidation tests.
5. The critical state theory approach can be used to demonstrate the dependency of vane shear strength on applied stress.

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