

# Vane shear strength of dewatered sludge from Hong Kong

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**Abstract** The vane shear strength and total solids content of dewatered sludge from Hong Kong were determined in order to evaluate their geotechnical suitability for disposal in landfills. The results obtained indicate that (i) the total solids and vane shear strength of dewatered sludge from different treatment plants varied considerably depending on the type of sludge and dewatering method; and, (ii) percent total solids alone is not sufficient to guarantee geotechnical stability in terms of vane shear strength. The critical state model for soils provided a good fit for the characteristic relationship between vane shear strength and total solids, which can be used to estimate vane shear strength from total solids only. No relationship between volatile solids and vane shear strength was found. The results of the laboratory vane shear test correlated well with those obtained by a pocket shearmeter indicating the usefulness of this method for rapid determination of vane shear strength on site. Some factors that influence vane shear strength were briefly evaluated. Implications of the results for sludge management with special emphasis on dewatering and landfilling were discussed.

**Keywords** Dewatering; landfill disposal; vane shear strength; sludge characteristics; Hong Kong

## Introduction

The estimated total sludge production at sewage treatment works (STW) in Hong Kong will substantially increase from approximately 190,000 m<sup>3</sup> (64,000 tonnes dry matter) in 1997 to approximately 770,000 m<sup>3</sup> per year (260,000 tonnes dry matter) by 2021, based on a dry solids content of 30% (EPD, 1999). This sharp increase in the quantity of sludge is due primarily to the attainment of full operation of the chemically enhanced primary STW at Stonecutters Island as part of the Hong Kong Government Strategic Sewage Disposal Scheme. Landfilling will provide the major, safe, economical disposal route for sewage sludge in the near future. In addition, after the phasing out of dumping at sea, dewatered water treatment sludge also requires landfill disposal. In 1997, approximately 18,000 tonnes dry matter of such sludge was generated, which is expected to rise to 34,000 tonnes dry matter by 2021 (EPD, 1999). In the context of municipal waste landfill operations in Hong Kong, with landfills up to 120 m high, concern has been expressed about the effect of dewatered sludge on the geotechnical stability of landfills. One of the most significant properties influencing landfill stability is the physical nature of dewatered sludge with regard to moisture characteristics and mechanical strength (van den Berg *et al.*, 1991). Commonly, upper limits are set on moisture content, or conversely lower limits on total solids (TS) content of dewatered sludge prior to landfilling (Environmental Protection Department, 1990; Degremont, 1991). In the USA, the only criterion about physical condition requires that the dewatered sludge should not be in a liquid state (Federal Register, 1991). Geotechnical stability criteria are rarely applied. The first application of soil testing methods for the physical evaluation of dewatered sewage sludge for landfilling was reported in Germany (Moeller *et al.*, 1984). This work was followed by more systematic research efforts for the Commission of the European Communities and resulted in the recommendation of vane shear strength as the most suitable geotechnical stability parameter (Loll, 1991). This recommendation was incorporated in sludge disposal guidelines in Germany (ATV, 1989, 1991, 1992). Since 1993, the criterion of vane shear strength is

applied for the landfilling of all solid wastes, with a mandated minimum value for vane shear strength of 25 kN/m<sup>2</sup> (German Federal Government, 1993). Accordingly, reference is no longer made to moisture content or solids content criteria when landfilling waste or sludge. The objectives of this study were (i) the experimental determination of the vane shear strength of dewatered sludge of Hong Kong; (ii) comparison of obtained results with regard to recommended criteria for disposal of sludge in landfills; and, (iii) evaluation of the pocket vane shear tester for rapid testing.

### Materials and methods

Dewatered sludges from six government operated STWs and one government operated water treatment works (WTW) were studied. The STWs at Sha Tin, Tai Po, Shek Wu Hui, Yuen Long and Stanley apply conventional secondary treatment, but the Sha Tin and Tai Po plants have recently been modified for biological nutrient removal with required removal efficiencies for N and P of 80% and 70%, respectively. With the introduction of sea water for flushing purposes in 1998, the influent sewage to the plants in Tai Po and Sha Tin became highly saline with a chloride concentration of 4,000 to 6,000 mg/L. The recently constructed Stonecutters Island STW employs chemically enhanced (FeCl<sub>3</sub>) primary treatment only, for a similarly high saline wastewater. In the WTW at Pak Kong the raw water undergoes a conventional two-stage treatment process, which consists of the addition of a coagulant (alum), rapid mixing, flocculation, sedimentation, and filtration. Polyelectrolyte is added for sludge thickening and conditioning prior to dewatering. Since 1999, ferric chloride (FeCl<sub>3</sub>) is employed as an additional conditioner. The treatment plants were sampled over different periods of time, using a different researcher for each sampling period. Table 1 summarizes the sludge types, dewatering method, type of conditioner used, sampling periods, and number of samples taken during each sampling period for each treatment plant.

**Table 1** Types of dewatered sludge and sampling information from different treatment works in Hong Kong

Sludge source and design DWF m <sup>3</sup> /d	Type of sludge	Dewatering equipment	Type of conditioner used	Sampling period	No. of samples taken
Stonecutters Island STW 1,725,000	undigested primary sludge (+FeCl <sub>3</sub> )	Centrifuge	FeCl <sub>3</sub>	1999	26
Sha Tin STW 150,000	Anaerobically digested combined sludge	Centrifuge	FeCl <sub>3</sub>	1999	20
Tai Po STW 84,000	Anaerobically digested combined sludge	Belt filter press	Polymer	1993/94	27
		Belt filter press	Polymer	1994/95	10
		Plate filter press	Polymer	1993/94	21
		Plate filter press	Polymer	1994/95	10
		Plate filter press	Polymer + FeCl <sub>3</sub>	1999	21
Yuen Long STW 70,000	Anaerobically digested combined sludge	Plate filter press	Polymer	1993/94	27
			Polymer	1994/95	12
			Polymer + FeCl <sub>3</sub>	1999	18
Shek Wu Hui STW 60,000	Anaerobically digested combined sludge	Plate filter press	Polymer	1993/94	22
			Polymer	1994/95	14
Stanley STW 11,600	Aerobically stabilised combined sludge	Belt filter press	Polymer + FeCl <sub>3</sub>	1999	20
Pak Kong WTW 800,000	Alum sludge	Plate filter press	Polymer	1997	24

SWT = Sewage treatment works; WTW = water treatment works.

Grab samples of dewatered sludge were collected from fresh sludge cake during dewatering operations. After collection, the samples were transported to the laboratory of the Department of Civil Engineering and immediately analysed for the determination of total solids, volatile solids, and vane shear strength. The vane shear strength was determined using a Wykeham Farrance laboratory vane apparatus WF 23500 with motorised operation and according to the British Standard Methods BS 1377 (1990) for the determination of shear strength by the laboratory vane method. For the 1999 sampling period, a Torvane pocket shearmeter was additionally employed. The analyses for TS and volatile solids (VS) were carried out according to Part 2540 G of Standard Methods (1989). More details on the methodology and the early results from 1993/94 have already been presented elsewhere (Koenig *et al.*, 1996).

## Results and discussion

The mean vane shear strength of the dewatered sludge from the different plants varied considerably between 1.53 and 36.06 kN/m<sup>2</sup>, while the mean TS content ranged from 11.42% to 36.10%. A summary of the mean values and ranges is given in Table 2. As expected, the dewatering efficiency of the belt filter press was lower than that of the plate filter presses. However, the results for belt filter press are directly comparable only in the case of Tai Po STW, but not for Stanley STW where a different type of sludge was dewatered (aerobically stabilised versus anaerobically digested). The same applies to the results of dewatering by centrifuge. In general, the dewatering efficiencies compare well with commonly expected values of 18% to 30% TS for belt filter presses and 28% to 38% TS for plate filter presses (ATV, 1995) considering that no lime was used for conditioning. The Hong Kong values of vane shear strength also show good agreement with typical German values (ATV, 1995), even though the strength levels of the German sludges are generally higher because of the use of lime as additional conditioner. The VS content of the sludge was unexpectedly high for all the sewage sludge samples, varying from 60.60% in Sha Tin STW to 78.00% in Stanley STW. It should be noted, however, that in Sha Tin STW the anaerobically digested sludge was mixed with alum sludge from the 1.300,000 m<sup>3</sup>/d Sha Tin WTW prior to

**Table 2** Sludge characteristics of dewatered sludge from different treatment works in Hong Kong

Sludge source	Sampling period	Vane shear strength kN/m <sup>2</sup>	TS %	VS % TS	Ln A kN/m <sup>2</sup>	m	r <sup>2</sup>
Stonecutters STW	1999	16.37* (10.22–24.55)	36.10 (23.63–40.77)	73.14	3.71	-0.35	0.28
Sha Tin STW	1999	9.71 (6.16–26.92)	23.68 (20.97–27.52)	60.60	4.79	-0.62	0.58
Tai Po STW	1993/94	1.53 (0.69–5.36)	14.14 (13.05–17.82)	76.09	3.54	-0.45	0.61
	1994/95	6.63 (5.01–8.04)	14.47 (13.05–15.15)	76.83	4.32	-0.35	0.39
	1993/94	5.51 (3.05–9.35)	18.62 (16.38–22.90)	78.00	4.42	-0.51	0.88
	1994/95	10.50 (8.79–12.56)	18.98 (16.05–21.23)	77.59	3.49	-0.22	0.58
	1999	29.02 (13.93–49.19)	27.56 (20.71–32.69)	70.19	5.87	-0.70	0.87
Yuen Long STW	1993/94	7.53 (3.7–12.96)	17.94 (14.79–21.12)	75.48	5.04	-0.55	0.81
	1994/95	12.40 (7.56–17.02)	20.09 (18.22–23.56)	75.41	0.21	+0.45	0.41
	1999	36.06 (11.96–74.28)	30.02 (21.73–36.47)	65.90	6.59	-0.91	0.92
Shek Wu Hui STW	1993/94	5.80 (2.03–14.23)	18.67 (15.25–22.19)	72.09	3.94	-0.50	0.85
	1994/95	9.30 (4.81–14.23)	19.91 (16.78–23.32)	72.15	2.33	-0.03	0.00
Stanley STW	1999	4.44 (2.77–6.03)	11.42 (9.95–13.00)	76.97	2.98	-0.17	0.14
Pak Kong WTW	1997	11.50 (8.51–17.86)	29.70 (24.66–33.27)	10.21	4.56	-0.63	0.72
Tai Po STW	All periods				6.23	-0.83	0.95
Yuen Long STW	All periods				5.65	-0.65	0.86
Shek Wu Hui STW	All periods				4.76	-0.30	0.30
Anaerobic sludge	All periods				5.57	-0.69	0.74
PF dewatered sludge	All periods				5.94	-0.75	0.74

SWT = Sewage treatment works, WTW = water treatment works, PF = plate filter press, \*mean value, () range.

dewatering, hence resulting in a relatively low VS concentration. The dewatered sludges from Stonecutters Island, Tai Po, Yuen Long and Pak Kong exhibited a very similar TS content of around 30% for the 1999 sampling period, but the mean values for the vane shear strength varied considerably from 11.50 to 36.06 kN/m<sup>2</sup>, pointing to different sludge characteristics. Compared to earlier results of 1993/94 and 1994/95, the TS content and vane shear strength of Tai Po and Yuen Long STW sludge showed significant increases from about 18% TS to 30% TS and 6 kN/m<sup>2</sup> to 30 kN/m<sup>2</sup>, respectively. This improved performance reflects the application of FeCl<sub>3</sub> as additional sludge conditioner since 1999, following the introduction of stricter sludge disposal requirements to landfills of at least 30% TS content.

#### Relationship between vane shear strength and solids content

In Figure 1, vane shear strength is plotted versus TS content for all dewatered sewage sludges from Hong Kong STWs. Apart from the undigested primary sludge, all other sludges appeared to follow the same characteristic trend. A similar, non-linear trend of vane shear strength versus TS content was reported for German sludge (Moeller *et al.*, 1984).

It was suggested in an earlier paper (Koenig *et al.*, 1996) that the critical state theory for the behaviour of soil (Wood, 1990) could provide a satisfactory explanation for the relationship between vane shear strength and total solids in dewatered sludge. This theory states, on the basis of conventional triaxial compression tests of clay, that both the critical state line and normal compression lines could be assumed to be reasonably straight and parallel in a semi-logarithmic compression plane of specific volume (*v*) versus the logarithm of mean effective stress over a reasonable range of mean effective stress. The theory can be used to link undrained shear strength with the consolidation history of clay and/or the compression history of sludge during dewatering. In order to apply the critical state model in terms of the commonly used sludge parameter TS, instead of the soil mechanics parameter *v*, the formulation presented by Wood (1990) was rearranged as follows:

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

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

where  $s_u$  = undrained vane shear strength, in kN/m<sup>2</sup>  
 TS = fraction of TS by wet weight  
 A, m = sludge specific constants

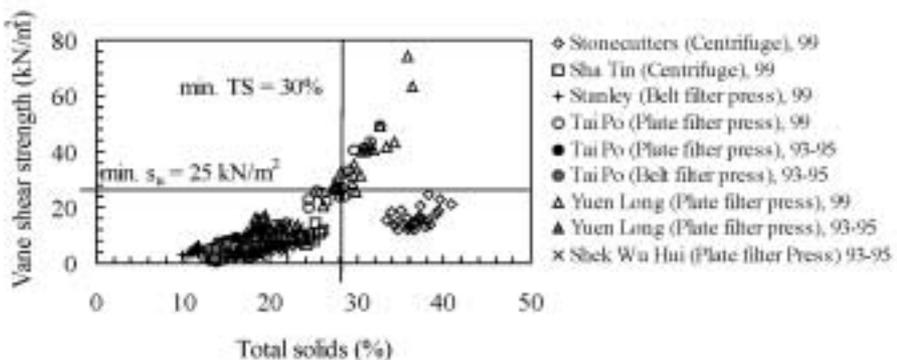
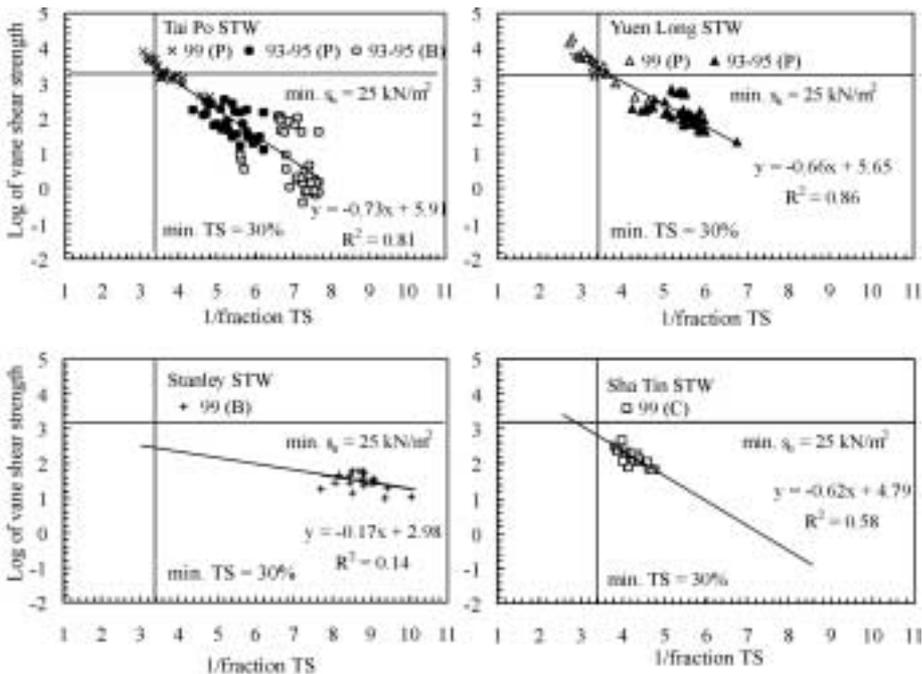


Figure 1 Vane shear strength versus TS for all dewatered sewage sludges of Hong Kong

A plot of the natural logarithm of the vane shear strength versus the inverse of the TS fraction should therefore give a straight line with slope  $m$ . This is supported by Figure 2. When all data for the plate filter press dewatered sludges from Tai Po and Yuen Long STW were plotted according to Equation (2), the slope parameter  $m$  was found to be  $-0.83$  and  $-0.65$ , respectively, with the corresponding correlation coefficient  $r^2$  between  $\ln(s_u)$  and  $1/\text{TS}$  equal to  $0.95$  and  $0.86$ . For all other sludges, the sludge specific constants  $m$  and  $\ln A$  were determined in a similar manner. They are summarized in Table 2 for each sampling period individually and combined, as well as grouped according to the most common sludge type (anaerobically digested) and dewatering method (plate filter press). For the sludges dewatered by plate filter press, the individual slope parameters  $m$  varied between  $-0.50$  and  $-0.91$  with correlation coefficients  $r^2$  ranging from  $0.72$  to  $0.92$ ; however, for the sampling period 1994/95 the values for  $m$  ( $-0.22$  to  $+0.45$ ) and  $r^2$  ( $0.00$  to  $0.58$ ) were much more irregular, most likely attributable to a different laboratory technician operating the vane shear apparatus. The evidence would appear to be sufficient to indicate that critical state theory can be applied to estimate the vane shear strength of dewatered sewage sludge on the basis of the more easily measured TS content, especially for anaerobic sludges dewatered by plate filter press. On the other hand, the  $m$  values for the sludges dewatered by centrifuges ( $-0.35$  and  $-0.62$ ) or belt filter presses ( $-0.45$ ,  $-0.35$ , and  $-0.17$ ) varied more widely than those for plate filter presses, with relatively low correlation coefficients  $r^2$  between  $0.14$  and  $0.61$  (see also Figure 2 for Shatin and Stanley STW). Possible reasons are the different dewatering methods applying lower compression pressure, but also narrower TS range, different sludge type (in the case of Stonecutters and Stanley STWs), or vane shear strength and TS values lying outside the reasonable range. It is thought that differences in the values of  $m$  and  $A$  are mainly due to the intrinsic properties of each sludge. The influence of different dewatering methods or conditioners on  $A$  and  $m$  could not be ascertained.



**Figure 2** Log vane shear strength versus inverse of TS fraction for dewatered sewage sludges from different sewage treatment works of Hong Kong (B = belt filter press, C = centrifuge, P = plate filter press)

**Relationship between minimum vane shear strength and minimum solids content for landfilling**

From Table 2 and Figure 1 it is clearly seen that few dewatered sludges in Hong Kong attain the minimum vane shear strength of 25 kN/m<sup>2</sup> mandated in Germany or the minimum TS content of 30% mandated in Hong Kong. This is in part related to the low dewatering efficiency obtained by the available equipment such as belt filter press or centrifuge, but also to the conditioning method. In fact, in Germany it has been suggested that only plate filter presses be used for dewatering because belt filter presses are not considered suitable to produce sludge of sufficient geotechnical stability (Moeller, 1991). For plate filter press dewatering, a high dewatering efficiency with a mean value of vane shear strength above 25 kN/m<sup>2</sup> is obtained when the sludge is conditioned with metal salts and lime. However, sludge conditioning by polymer addition alone generally results in a lower dewatering efficiency and an expected mean value for vane shear strength of 15 kN/m<sup>2</sup>. Hence conditioning sludge with polymers alone is not recommended (ATV, 1995). Figure 2 demonstrates for Tai Po and Yuen Long STW the effect of the introduction of FeCl<sub>3</sub> as an additional conditioner in 1999 when compared to the use of polyelectrolyte alone in earlier periods. It is remarkable that despite the new conditioning method and higher dewatering efficiency the sludge specific constants A and m apparently did not change. An examination of the results presented in Figure 1 shows that the often mandated requirement of minimum TS, e.g. 30%, may not be sufficient to guarantee geotechnical stability for sludge. For example, the dewatered primary sludge from Stonecutters Island STW easily meets the required total solids content of 30%, but does not attain the geotechnical stability criterion of 25 kN/m<sup>2</sup>. Conversely, a close inspection of Figure 2 indicates that the dewatered sludge from Yuen Long STW could meet the geotechnical stability criterion of 25 kN/m<sup>2</sup> for a TS content of only 26%. The same holds for Tai Po STW sludge. For a particular sludge, therefore, meeting the criterion of geotechnical stability may not always guarantee an adequate TS content for landfill operation, especially for municipal solid waste landfills with co-disposal of dewatered wastewater sludge. It is therefore considered prudent to retain requirements on minimum TS content of sludge (e.g. Degremont, 1991).

In some instances the characteristic relationship may predict an unrealistically high TS content in order to meet the minimum vane shear strength, e.g. for undigested primary sludge of Stonecutters Island STW. If the best available mechanical dewatering equipment can not achieve the required TS, then the existing dewatering operation would have to be improved or modified. This is commonly achieved by more effective stabilisation of sludge or by addition of more chemical conditioners and lime, but lime conditioning will increase the total mass of dry solids for further processing and disposal. Where mechanical dewatering is incapable of meeting geotechnical stability criteria, sludge solidification has been proposed, e.g. by mixing the dewatered sludge with a blend of pulverised fuel ash (PFA) and other hydraulic binding agents. However, the large increase in the mass of TS tends to preclude the application sludge solidification processes in most STWs.

**Factors that influence vane shear strength**

The effect of TS content on vane shear strength was formulated above in terms of the critical state model. However, at present not enough is known to elucidate with a sufficient experimental and theoretical basis the factors influencing the magnitude of the sludge specific constants A and m. It seems reasonable to assume that the same sludge characteristics which favour or hinder effective dewatering are of most importance. Such frequently cited factors are source and origin of sludge; degree of stabilisation; VS content (both in absolute terms and as a fraction of TS); oil and grease content; particle size distribution; conditioning method; type and dosage of chemical conditioners; temperature and salinity. In the

absence of any specific investigations, the following observations can be made, on the basis of experimental results over the past five years:

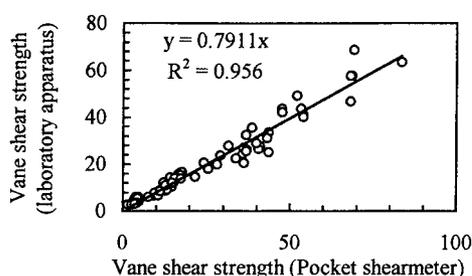
- (i) Undigested primary sludge from Stonecutters Island and the water works sludge from Pak Kong appeared to exhibit a different pattern in the characteristic relationship of vane shear strength and TS than the digested sludges. Hence, type of sludge and stabilisation method applied may influence the sludge specific constants.
- (ii) Vane shear strength appeared to be independent of VS as no meaningful correlation could be found, either for sludges from individual plants or for all plants combined.
- (iii) In Yuen Long and Tai Po STW, the introduction of  $\text{FeCl}_3$  conditioning and improved membrane filter presses did lead to higher dewatering efficiency and higher TS contents, but no obvious change in the sludge specific constants A and m was observed.
- (iv) In Tai Po STW, the introduction of salt water flushing (20% of the wastewater) did not lead to a change in sludge specific constants A and m, i.e. the characteristic relationship between vane shear strength and TS remained unchanged.

#### Rapid method to estimate vane shear strength

The standard determination of vane shear strength by the laboratory vane method requires a laboratory vane apparatus and an experienced operator. For rapid *in situ* testing of undisturbed dewatered sludge samples, a pocket shearmeter was evaluated. Figure 3 demonstrates an excellent correlation between the results obtained by pocket shearmeter with those obtained by the standard method, though the results of the pocket shearmeter tended to be higher by about 27%. The pocket shearmeter proved also useful in measuring vane shear strength of dewatered sludge samples laterally or perpendicularly to the applied dewatering pressure. The vane shear strength thus measured was about 40% to 50% higher than the value determined by laboratory vane apparatus for the disturbed, remoulded sludge cake.

#### Conclusions

The findings of this study show that the vane shear strength and total solids content of dewatered sludge from different treatment plants vary considerably, depending on type of sludge and dewatering method, but appear to exhibit a defined, non-linear relationship. It was found that the critical state model for soils provides a good fit for this characteristic relationship and can be used to estimate vane shear strength on the basis of total solids only. No relationship between vane shear strength and volatile solids could be demonstrated. For rapid vane shear testing on-site, the pocket shearmeter proved to be very useful and reliable. Generally, Hong Kong dewatered wastewater sludge does not meet proposed criteria of minimum vane shear strength for disposal in landfills.



**Figure 3** Relationship between vane shear strength measured by pocket shearmeter and by laboratory apparatus ( $n = 81$ )

While much effort has been made to elucidate filtration/consolidation in the formation of sludge cake and its implication to sludge dewatering (Lee and Wang, 2000), much remains to be done to elucidate the strength properties of dewatered sludge and its implication to landfill design and operation. Little is known about the relationships between the intrinsic properties of constituent sludge particles, the bulk strength properties of dewatered sludge, and the sludge stability analysis and design of mono-fills or of landfills where sludge is co-disposed with municipal solid waste. Moreover, long-term storage and biodegradation of dewatered sludge, together with the associated gas formation may cause a decrease in its mechanical strength properties over the years (ATV, 1991).

Although high total solids content and high vane shear strength are desirable with regard to geotechnical stability of dewatered sludge, high values of these parameters also imply low hydraulic conductivity which in turn could lead to perched water tables and hence to potential stability problems within landfills. For example, the hydraulic conductivity of anaerobically digested sewage sludges in Hong Kong was found to vary between  $1.28 \times 10^{-8}$  to  $5.34 \times 10^{-8}$  cm/s under compaction, far lower than the permeability requirement of compacted clay for liner use in the USA (Wan *et al.*, 1996). Care has to be taken, therefore, in the placement of dewatered sludge in landfills to prevent localised impermeability. So far, sludge disposal has not been taken into account for stability analysis of the three existing strategic landfills in Hong Kong (Holley *et al.*, 1997). However, the expected increase of the co-disposal ratio of dewatered sludge and solid waste could have a significant effect on landfill stability, especially when considering the 150 m maximum thickness of waste within the landfills at a slope gradient of 1:3. Unfortunately, reliable information on sludge properties for landfill stability analyses is still limited, in Hong Kong as elsewhere. A better understanding of the strength properties of dewatered sludge should therefore be urgently developed.

### Acknowledgement

This research was supported in part by a grant from the Hong Kong Research Grants Council. The authors also wish to thank the Drainage Services Department of Hong Kong for providing the samples for this study. In addition, the efforts of many students in the experimental phase of the study are greatly appreciated.

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