

**Environmental and Landfill Operational Aspects of Co-disposal of  
Dewatered Sewage Sludge and Municipal Solid Waste**

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## **Environmental and Landfill Operational Aspects of Co-disposal of Dewatered Sewage Sludge and Municipal Solid Waste**

**Abstract:** The co-disposal of dewatered sewage sludge and municipal solid waste may cause significant impacts (such as total and differential settlement, slope stability of the waste, and leachability) on landfill operations and the subsurface environment. The objectives of this study were to investigate the co-disposal of dewatered sewage sludge and municipal solid waste with respect to their consolidation characteristics, vane shear strength, and leachability. The results of the consolidation tests show that, for a given stress increment, the deformation (the change in the void ratio) of the dewatered sewage sludge is larger than the deformation of its sludge mixtures. When the sludge ratio in the mixture increases, the compressibility of the mixture increases. The total consolidation settlement taking place in landfilling of dewatered sewage sludge alone would be much greater than that for co-disposal of sludge with solid waste. The results of the shear stress strength tests of the sludge and its mixtures imply that side slopes of 20° can probably be constructed in a landfill site without causing a sliding problem. Based on the results of the column leachability tests, Fe, Cu and nitrogen leached out from the sludge and its mixture might cause groundwater pollution.

## **INTRODUCTION**

At present, most sewage sludge generated in Hong Kong is dewatered and disposed in landfills together with municipal solid waste (HKEPD 2000). The estimated total dewatered sludge (with 70% moisture content) generated from wastewater treatment plants in Hong Kong is projected to increase substantially from 1220 tonnes/day in 2001 to about 2120 tonnes/day in 2015. This 40- 50% increase in the quantity of sludge is due primarily to the construction of a Chemically Enhanced Primary Treatment (CEPT) Plant at Stonecutters Island as part of the Hong Kong Government's Strategic Sewage Disposal Scheme. However, the disposal of such a large amount of sewage sludge to landfills would inevitably create many concerns about the landfill sites, such as compression, differential settlement, local instability and global instability of the landfill slopes, and potential subsurface pollution.

Currently, lower limits are set on total solids content, which has been reported to be a major factor affecting the shear strength of wastes in landfills (Koenig and Kay 1996), but no geotechnical stability criteria have been applied, with the exception of Germany where a minimum requirement for undrained shear strength is set at 25 kPa. It has also been reported that consolidation and hydraulic characteristics of dewatered sewage sludge are of paramount importance with regard to the long-term behavior of dewatered sludge in landfills (Koenig et al. 1996). Once placed in landfills, sludge can be viewed as a geotechnical material, and it should be compared to non-consolidated cohesive soils with high organic content (Klein and Sarsby 2000). It has been reported that the consolidation behavior of dewatered biologically digested sludge in Hong Kong follows the conventional consolidation theory, with a higher compression index than that of soil (Koenig et al. 1996). A similar study on waterworks sludge also showed that sludge has extreme plasticity and high compressibility (Wang et al. 1992).

The practice of co-disposal in landfills shows that the composition of the waste affects the gas and leachate characterizations. Co-disposal of municipal solid waste (MSW) and sewage sludge has a significant effect on the generation and quality of leachate. Sludge may increase the moisture input, thereby enhancing leachate generation. Microbiological seeding and nutrient enrichment of MSW with sludge has been found to increase the rate of biological stabilization (Pohland 1992). Results from a laboratory-scale study show that sewage sludge addition could initially increase concentrations in leachate and total amount of gas product, if the amount of organic matter added as sewage sludge was substantial. It has also been found that ammoniacal nitrogen and total phosphorus levels in leachate were significantly increased (Pohland 1992).

The ultimate objectives of this study were to investigate the potential settlement, slope stability, and leachability of CEPT sludge co-disposed with MSW in landfills. Consolidation characteristics and undrained shear strength of CEPT sludge alone and of its mixtures with MSW were analyzed and used for assessing their differential settlement, hydraulic characteristics, and slope stability. Bench-scale column leaching tests were conducted to determine the types of contaminant leakage from the co-disposal of CEPT sludge with solid waste.

## **EXPERIMENTAL METHODS**

### **Sample Preparations and Compositions**

In Hong Kong, an average of 15,500 tonnes of solid waste is disposed daily in landfills (HKEPD 1999). Of these, the intakes of dewatered sludge and municipal and construction waste to landfills are 307 tonnes/day and 14,890 tonnes/day, respectively. Thus, the ratio of dewatered sludge to municipal and construction waste is about 1:49. In Hong Kong, the maximum allowable

sludge to waste co-disposal ratio at a landfill is 1:10. For this reason, three different sludge compositions as listed below were tested in this study:

Sample A: Sludge mixture (dewatered sludge: solid waste =1:10)

Sample B: Sludge mixture (dewatered sludge: solid waste =1:49)

Sample C: Solid waste alone

The municipal solid waste was collected from the South East New Territories (SENT) landfill, while the dewatered sewage sludge was from the chemically enhanced primary treatment (CEPT) plant at Stonecutters Island in Hong Kong.

### **Physical and Chemical Properties**

The physical properties of dewatered CEPT sludge and the sludge mixtures were characterized. In geotechnical engineering, water content is defined as the amount of water present in a sample in terms of its dry mass. Water content was determined by drying the sludge samples in an oven at a temperature of 110°C for a period of 12 to 18 hours according to ASTM D 2216. Total solids (TS) were determined by drying a measured mass of the sludge to a constant weight at 103–105°C, whereas total volatile solids (TVS) were determined by igniting the dry solids at 550°C in a furnace. Both TS and TVS are widely used in sludge treatment and management practices as measures of dry matter and organic matter in sludge. The specific gravity  $G_s$  of the samples was determined according to ASTM D 854. The metal contents of dewatered CEPT sludge were also characterized. The sludge was first digested by a CEM MDS 2000 microwave digestion system following Standard Method 3030 (APHA 1998). The metal

contents were then analyzed using a Hitachi Z8200 Zeeman-Effect Atomic Absorption Spectrophotometer. The measurement of total Kjeldahl-N and the specific conductance of the sludge were conducted according to the Standard Methods (APHA 1998).

### **Conventional (Odometer) Consolidation Test**

Conventional one-dimensional odometer tests were conducted on all samples according to ASTM procedure D 2435 to determine the consolidation behaviors of the sludge-containing waste materials. Each test comprised five increments of loading, and each loading increment was held constant for 24 hours. The load duration of 24 hours provided good estimates of strain to evaluate the long-term compressibility of the sludge (Koenig et al. 1996; Zimmie and Moo-Young 1995). At the end of each load stage in the odometer tests, about 98% of primary consolidation was achieved. With an initial pressure of 12 kPa, each applied stress doubled the stress used in the previous stage. The compressibility factor,  $F$ , used to analyze the compressibility of the sludge was computed using:

$$F = C_c / (e_0 - 1) \quad [1]$$

where  $e_0$  is the initial void ratio and  $C_c$  is the compression index obtained from a plot of the void ratio ( $e$ ) versus the logarithm of consolidation pressure ( $\log p$ ).

### **Hydraulic Consolidation Test**

In order to determine the consolidation behavior of dewatered CEPT sludge under a high strain magnitude, a modified consolidation-cell was developed in this study. A schematic

diagram of the consolidation-cell permeameter is shown in Fig. 1. The design of the testing apparatus differed from the conventional odometer in that the test sample was loaded hydraulically by water pressure acting on the loading piston instead of by a mechanical lever system. Compared with a conventional odometer, this arrangement enabled larger samples to be tested and allowed for larger consolidation settlement. Other important features in this design are the ability to control drainage and to measure pore water pressure during the course of the consolidation tests.

A sludge sample was compacted in the consolidation permeameter cell following the standard laboratory compaction method as described above. After compaction, the sample was trimmed to fit the sample chamber, which was 10 cm in diameter and 10 cm in height. The loading piston was then put on the sample and the permeameter cell was assembled. Deionized water was used as the permeant, which filled the upper chamber of the cell. The bladder accumulators were used as outflow containers during both the consolidation and permeability tests to protect the control panel from contamination.

#### *Consolidation with Vertical One-Way Drainage*

The A1, A2 and B2 valves along the drainage line were initially closed and hydraulic pressure was then applied through the pressure control panel into the water chamber acting on the loading piston as shown in Fig. 1. After loading, the consolidation process was started by opening the A1 drainage valve and, at the same time, timing the process. The settlement of the sludge sample was determined by measuring the quantity of the change of outflow volume. Drainage took place vertically upwards while the pore water pressure of the sludge sample was measured at the base of the sample through a pore pressure transducer attached to valve B1. Loading

increments similar to those used in conventional odometer tests were applied to the sludge sample.

### *Vertical Permeability*

After each 24-hour-loading consolidation stage, the three-way valves were switched to A2 and B2. The inlet pressure was kept at 5 psi (34.5 kPa) and the outlet pressure was set to zero. The hydraulic head caused the upward flow through the sample. The rate of outflow discharge and the hydraulic gradient were monitored on a daily basis until a constant and stable condition was reached, which was usually achieved after about 20 days of permeability testing. The hydraulic conductivity,  $k$ , of the sludge sample at a given consolidation pressure is obtained using Darcy's law:

$$q = kiA \quad [2]$$

where  $q$  is the rate of outflow discharge under steady-state conditions;  $i$  is the hydraulic gradient determined under steady-state conditions; and  $A$  is the cross-sectional area of the sample.

### **Direct-shear test**

Undrained direct shear tests conducted according to ASTM D 3080-90 were used to determine the friction angle of the CEPT sludge and the sludge mixtures. Three specimens of the same mass obtained from the same sample source were carefully weighed and compacted in a shear box to the same density. The relationships between undrained shear stresses at failure and at normal applied stresses at 31 kPa, 62 kPa and 124 kPa were obtained. The strength parameters



of the sludge wastes are useful in establishing the possible placement slope angle of the sludge during landfilling. For each sludge sample, four parallel tests were carried out to obtain the possible ranges of friction angles and interparticle adhesion.

### **Bench-scale Column Tests**

To study the leaching properties of a landfill receiving dewatered CEPT sludge with solid wastes and waste alone, three bench-scale columns called columns A, B, and C containing samples A, B, and C, respectively, were set up. As shown in Fig. 2, the columns were made of PVC sheets and stainless steel screws, and the joints were sealed with a silicon sealant to avoid leakage. Each column was 58 mm in diameter and 500 mm in height.

Since the average rainfall rate in Hong Kong is about 2000 mm/year and in order to simulate the worst situation (i.e., presuming that all precipitation infiltrates into the landfill), the daily water addition required to achieve an equivalent infiltration of 2000 mm/year was calculated as:

$$\left\{ \left[ \frac{5.8}{2} \right]^2 \cdot 200 \right\} / 365 = 15 \text{ cm}^3/\text{day}.$$

Deionized water was adjusted to pH 5.0 before infiltration. This simulated the slight acidity of rainfall in Hong Kong. Four flow meters were used for electronic flow control. Therefore, a constant volume of 15 cm<sup>3</sup> of the acid de-aired water each day was used as the inflow rate to the column. The leachate was drained through the water-outlet at the bottom of the column and collected for chemical analysis when a volume of about 100 ml was reached.

## **EXPERIMENTAL RESULTS AND DISCUSSION**

### **Physical and Chemical Properties**

The physical properties of CEPT sludge and the sludge mixtures are summarized in Table 1. Based on the geotechnical definition of water contents that is on dry basis, CEPT sludge and sludge mixtures with mix ratios of 1:10 and 1:49 have water contents of 180%, 51% and 40%, respectively. If the weight of sludge samples on wet basis instead of dry basis is considered, their moisture contents are 64% for CEPT sludge, 33.8% for sludge mixtures of 1:10, and 28.7% for sludge mixture of 1:40 (referring to Table 1). In this paper, the geotechnical definition of water content is used for easy comparison with experimental data for geotechnical testing obtained from literature. The volatile fraction in the dewatered CEPT sludge is 58%, while it is around 50% in the sludge mixtures. The specific gravities of CEPT sludge and the sludge mixtures with mix ratios of 1:10 and 1:49 are 1.55, 2.86, and 3.85, respectively. These are different from the specific gravity of organic clay, which is typically in the range of 1.0 to 2.6 (Bowles 1992).

The chemical composition of CEPT sludge was characterized. It contains high concentrations of calcium, iron, zinc, nickel, chromium, and total nitrogen. The mass concentrations of these elements on wet basis are 16,400 ppm, 24,000 ppm, 504 ppm, 576 ppm, 595 ppm, 40,202 ppm, respectively. In addition, the specific conductance of pore water of CEPT sludge is about 450  $\mu$ mhos/cm, which can be considered low compared with the specific conductance of leachate (i.e., 1400  $\mu$ mhos/cm) generated from a typical landfill that is 20 years old.

### **Conventional (Odometer) Consolidation**

Fig. 3 illustrates the results of consolidation tests on three sludge samples and their comparison with other materials. It is found that the consolidation behavior of sludge materials, such as dewatered CEPT sludge, sludge mixtures and papermill sludge, follow the conventional consolidation path of soils, but sludge experiences much larger deformation than does organic clay and silty clay. The dewatered CEPT sludge at a water content of 180% has a similar compressibility to papermill sludge. Compared with pure CEPT sludge at its natural water content of 180%, sludge mixtures undergo smaller deformation during consolidation. Since the compressibility of CEPT sludge and its sludge mixtures is quite different and affected by its water content and composition, differential settlement might occur if a landfill cell receives CEPT sludge and other wastes separately rather than as sludge mixtures. A severe differential settlement can lead to serious damage to the leachate and gas collection systems.

Table 2 summarizes the consolidation parameters of sludge-containing waste samples determined from conventional consolidation tests. Among the three tested samples, the CEPT sludge with a water content of 180% has the highest compression index (i.e., 1.59) and compressibility factor (i.e., 0.37), while the sludge mixture with a mix ratio of 1:49 has the lowest compression index (i.e., 0.43) and compressibility factor (i.e., 0.12). These results mean that the total consolidation settlement taking place in a landfill of dewatered CEPT sludge from its natural water content alone would be much higher than that from the co-disposal of sludge with other solid wastes under the same overburden pressure given in a landfill site. Careful planning of daily disposal of CEPT sludge is therefore an essential means to prevent differential settlement in a landfill site. The dumping of a large amount of sludge into a particular area should

be avoided as uneven settlement may occur. This differential settlement could cause damage to drainage pipes and top liners and destabilize the landfill site.

Table 2 also shows that when the sludge ratio in the mixture increases, the compressibility of the mixture increases as well. Since the sludge alone is quite compressible in nature, more sludge dumped into the landfill may cause the sludge to become more compressible. However, at the same time, the void ratio decreases with the increasing the sludge amount. The wastes and the highly compressible sludge should be placed and compacted closely together, so that the void ratio in the waste mixture can be reduced.

### **Hydraulic Consolidation**

The consolidation results for CEPT sludge and MSW at a ratio of 1:10 obtained from the hydraulic consolidation test are presented in Figs. 4 and 5. Fig. 4 illustrates the consolidation behaviors of the CEPT sludge mixture at five different consolidation pressures. The void ratio reduction behavior is similar to that obtained from conventional odometer tests. Similar compression indices (i.e., 0.55-0.62) are obtained from the hydraulic consolidation tests. However, the pore water pressure dissipation was extremely slow during the consolidation process for the CEPT sludge as shown in Fig. 5. According to Terzaghi's theory, the excess pore water pressure dissipates during consolidation and reaches zero or dissipates completely at the end of the primary consolidation. However, results from the hydraulic consolidation test indicate that the dewatered sludge does not follow this theory. Since the difference between the sludge and soil is in the microstructure of the sludge, this consolidation feature not following Terzaghi's theory might be due the fibrous flocs in the microstructure. There is some liquid called the "interstitial pore water" within the fibrous flocs in the sludge. During consolidation, this

interstitial water may cross the floc boundary and become either free water or surface water (Klein and Sarsby 2000). The pore water pressure inside is nearly the same after changing the water pressure of the interstitial water to the water pressure of either free water or surface water. The rate of primary consolidation of the sludge mixture will be reduced from this continuous regeneration of the pore water.

Results of tests on the hydraulic conductivity versus the consolidation pressure and the hydraulic conductivity versus the void ratio are presented in Figs. 6a and 6b, for the case of the 1:10 sludge mixture. Fig. 6a shows that an increase in the effective stress might increase the consolidation of the sludge mixture and thereby cause the reduction of void ratio, which will decrease the hydraulic conductivity. The relationship between the hydraulic conductivity and the effective pressure for the 1:10 sludge mixture can be expressed by the following equation:

$$\log k = -0.313 \log p - 4.7 \quad [3]$$

In addition, the relationship between the hydraulic conductivity and the void ratio for the 1:10 sludge mixture is determined as follows:

$$\log k = 0.504 e - 6.23 \quad [4]$$

For most soils, the relationship between the logarithm-of-hydraulic conductivity ( $\log k$ ) and the void ratio ( $e$ ) is linear (Lambe and Whitman 1969). The linear relationship determined here is additional proof that the sludge mixtures behave like soils.

Fig 6b also shows that the change in hydraulic conductivity is quite insignificant because there is only about a half order of magnitude decrease when the void ratio decreases by 36%. In other words, consolidation may not have a great influence on the hydraulic conductivity of the sludge mixture. Due to the heterogeneous nature of the waste in landfills, the sludge mixture may experience a slight reduction in its hydraulic conductivity resulting in lower resistance in leachate flow.

### **Shear Strength and Landfill Stability**

Table 3 summarizes the experimental results obtained from the direct shear tests. The angles of internal friction  $\phi$  of the CEPT sludge and its mixtures vary from 26.1° to 45.8°, while the cohesion or interparticle adhesion,  $C$ , ranges from 8.3 to 15.3 kPa. The friction angle in the sludge sample with a mixture ratio 1:10 (i.e., 39.9-45.8°) is more or less the same as that with a mixture ratio of 1:49 (i.e., 40.1-44.9°). Compared with the sludge mixtures, the cohesion of CEPT sludge alone is relatively higher but its friction angle is relatively lower.

The shear strength properties ( $\phi$  and  $C$ ) of the sludge samples can be obtained from standard laboratory tests. However, these parameters may not be reliable because of the heterogeneous nature of the waste materials and the varying degrees of degradation of the sludge. Thus, a combination of theoretical analysis and field study should be utilized to investigate the shear strength of the waste and the stability of the landfill slopes. Since a lower shear strength in the field may result from a weak zone or internal erosion by seepage, which will eventually lead to progressive failure of the landfill slope, the shear strength properties ( $\phi$  and  $C$ ) obtained from laboratory tests should be reduced by 15-25% or a higher safety factor (1.5-2) should be used as

suggested by Bagchi (1990). As shown in Table 4, all the friction angles of the sludge samples are larger than  $20^\circ$  for the case when their shear strength properties are reduced by 25%. Therefore, theoretically, when CEPT sludge or sludge with other solid waste is disposed in landfills with slopes less than  $20^\circ$ , they should be stable.

Another concern is based on the operation principle of landfills. When waste is deposited on a working face, it is spread and compacted to form a portion of the active cell. The side slope of this active cell is as steep as practical operation will permit. In general, the best compaction occurs at about 10% slope ( $\sim 6^\circ$  or 1V: 10H), but slopes up to 30% ( $\sim 20^\circ$  or 1V: 3H) may be allowed, which is the common practice in landfills (Krizek et al. 1987). Based on the above practical concerns and the data obtained from the direct shear tests of CEPT sludge and its mixtures in this study, the maximum allowable value of side slopes of  $20^\circ$  can be constructed for CEPT sludge and sludge mixture during landfill operations.

### **Bench-scale Column Tests**

The chemical characteristics of the three columns are shown in Table 5. The contaminant concentrations leaching from the columns after 20 weeks of leaching tests are summarized in Table 6. Since there are no strict standards to determine the contamination level of the groundwater in Hong Kong, the groundwater criteria used in the Netherlands for contaminated land are used for comparison with the metal and nitrogen concentration in the leachates obtained from the column tests. It should be emphasized that those values shown in the last column of Table 6 are not ‘standards’ but rather guidelines for use in assessing the significance of contaminated land.

As shown in Table 6, only in the 1:10 sludge mixture do the Fe and Cu concentrations after 20 weeks of leaching tests exceed the Netherlands' groundwater guidelines; while in the 1:49 sludge mixture, only the Fe concentration exceeds the guidelines. After 20 weeks of the column tests, the Fe concentration in column C (waste only) is one-eighth of that in column B (1:49 sludge mixture). Other metals in the leachate after 20 weeks of leaching are all below the guidelines. These results indicate that for the case of the co-disposal of sewage sludge with other solid wastes, the groundwater might be potentially polluted by the high Fe and Cu concentrations.

After the 20-week leaching tests, the nitrogen content, ammonia-N and Kjeldahl-N found in the leachate from all three columns does not exceed the guidelines. However, when the sludge mixture ratio increases, the ammonia-nitrogen content in the leachate also increases. The ammonia-nitrogen content in column A (sludge mixture of 1:10) is nearly five times higher than in column C (waste only). This might be due to the fact that the CEPT sludge contains a high N content, and the soluble nitrogen content in the sludge might dissolve into the liquid phase when water flows through the landfill, thereby resulting in high concentrations of ammonia-N in the leachate. This indicates that ammonia-N is also one of the most critical components among all the contaminants with regard to the impact of the leachate on the subsurface environment.

## **CONCLUSIONS**

From the experimental results obtained in this study, it can be concluded that dewatered sewage sludge collected from the Stonecutters treatment plant in Hong Kong is characterized by high water content, high organic content, and high compressibility. The void ratio reduces significantly during consolidation, which results in high compressibility. Based on the results of



the direct shear tests, side slopes of 20° can probably be constructed without causing sliding problems with CEPT sludge and sludge mixtures during landfill operations. In addition, compared with the disposal of sludge alone in landfills, the co-disposal of sludge with other solid wastes commonly found in Hong Kong shows higher shear strength and lower compressibility. According to the contaminant concentrations in the leachate obtained from the bench-scale columns, Fe, Cu and nitrogen exceed the Netherlands' groundwater guidelines. These contaminants may cause subsurface pollution.

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**TABLE 1. The Physical Properties of CEPT Sludge and its Mixtures**

Physical index	Units	CEPT sludge	Sludge mixture (1:10)	Sludge mixture (1:49)
Water Content <sup>1</sup>	$w$ (%)	180	51.1	40.3
Moisture Content <sup>2</sup>	$mc$ (%)	64	33.8	28.7
Total Solids	$TS$ (ppm)	357,000	634,600	712,000
Total Volatile Solids/Total Solids	$TVS/TS$ (%)	58.5	52.7	47.2
Specific Gravity	$G_s$	1.55	2.86	3.85
Unit Weight	$\gamma$ (kN/m <sup>3</sup> )	10.68	15.7	15.97
Bulk Density	$\gamma_t$ (Mg/m <sup>3</sup> )	1.09	1.6	1.63
Void Ratio	$e$	3.0	1.7	2.33
Porosity	$n$	0.75	0.63	0.7
Degree of Saturation	$S_r$ <sup>5</sup>	0.94	0.84	0.7
Air Content	$A$ <sup>6</sup>	0.05	0.1	0.21

<sup>1</sup>water content = (weight of water/weight of dry sample) x 100%

<sup>2</sup>moisture content = (weight of water/total weight of wet sample) x 100%

<sup>3</sup> $e = G_s (1 + w\%) \gamma_w / \gamma - 1$

<sup>4</sup> $n = e / (1 + e)$

<sup>5</sup> $S_r = w\% * G_s / e$

<sup>6</sup> $A = n (1 - S_r)$

**TABLE 2. The Consolidation Parameters of Sludge Containing Waste Samples  
Determined from Odometer Tests**

Waste Samples	Initial Void Ratio, $e_o$	Compression Index, $C_c$	Compressibility Factor, F
CEPT Sludge	3.3	1.59	0.37
Sludge Mixture (1: 10)	2.2	0.56	0.17
Sludge Mixture (1:49)	2.7	0.43	0.12

**TABLE 3. Cohesion and Friction Angles Determined from Direct Shear Tests**

Waste Samples	Cohesion, $C$ (kPa)	Friction Angle, $\phi$ (deg)
CEPT Sludge	8.3-14.4	26.1-31.9
Sludge Mixture (1: 10)	5.6-12.3	39.9-45.8
Sludge Mixture (1:49)	6.1-15.3	40.1-44.9

**TABLE 4. Shear Strength Estimation from Experimental Tests**

Waste Samples	Shear Strength Estimation from Laboratory Tests	Reduced by 25 %
CEPT Sludge	$S = 11.35 + \sigma_n \tan 29.0^\circ$	$C = 8.51 \text{ kPa}; \phi = 21.75^\circ$
Sludge Mixture (1:10)	$S = 8.95 + \sigma_n \tan 42.85^\circ$	$C = 6.71 \text{ kPa}; \phi = 32.14^\circ$
Sludge Mixture (1:49)	$S = 10.7 + \sigma_n \tan 42.5^\circ$	$C = 8.02 \text{ kPa}; \phi = 31.88^\circ$

Note:

$S$  = shear strength of the waste sample, in kPa

$\sigma_n$  = normal stress or intergranular pressure, in kPa

$C$  = cohesion or interparticle adhesion, in kPa

$\phi$  = friction angle of the waste sample, in deg

**TABLE 5. Chemical Characterizations of Three Columns**

Parameters	Column A (Sludge mixture 1:10)	Column B (Sludge mixture 1:49)	Column C (Waste Only)
Weight of Waste Sample (g)	976	992	985
Bulk Density (Mg/m <sup>3</sup> )	1.6	1.63	1.52
NH <sub>4</sub> -N (mg)	515.13	131.82	126.25
TKN (mg)	4679.21	1172.33	953.57
Cr (mg)	170.89	155.24	143.64
Cu (mg)	1073.26	887.46	714.52
Fe (mg)	3679.68	2235.62	1018.33
Ni (mg)	424.77	346.13	329.59
Zn (mg)	450.23	363.69	348.47



**TABLE 6. Evaluation of Pollutant Concentrations Relative to the Netherlands' Guidelines**

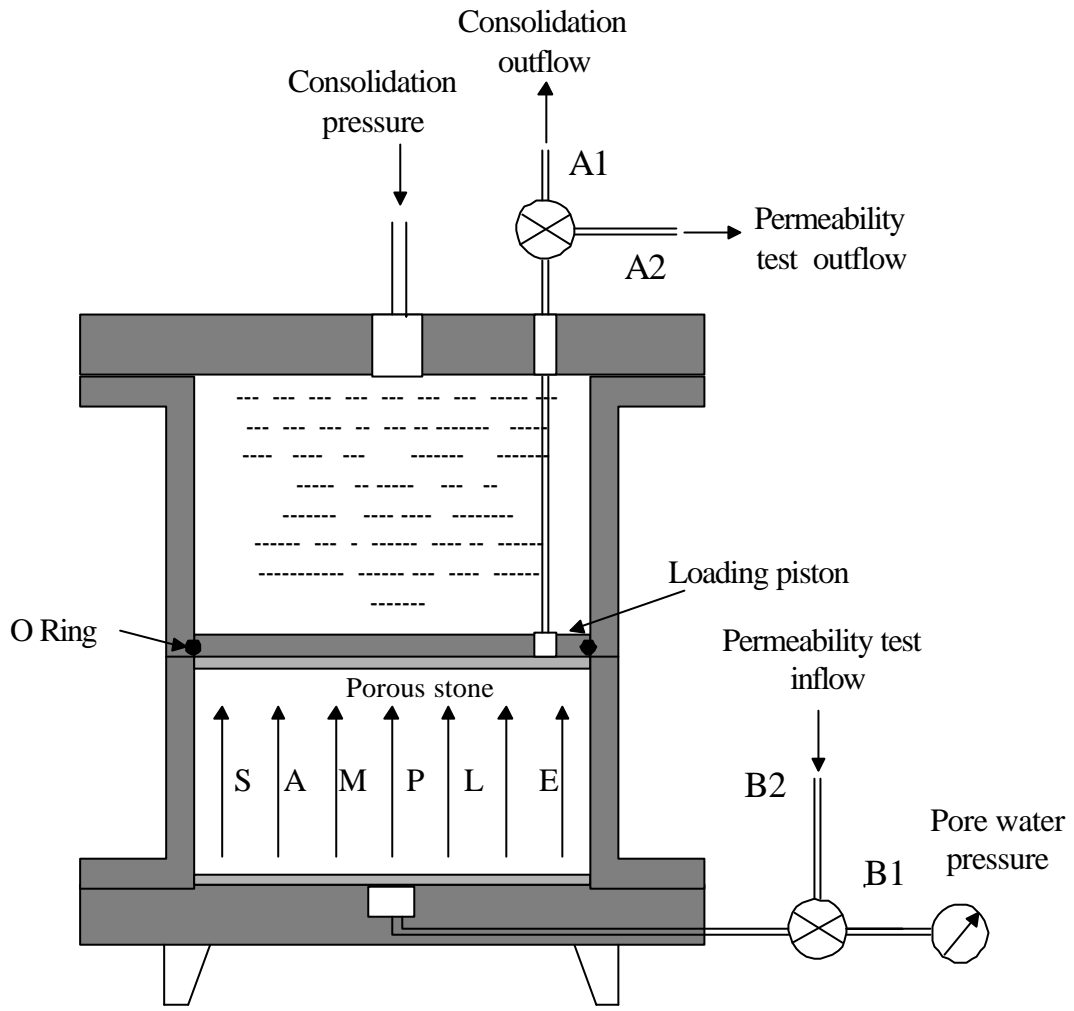
Contaminants	Column A		Column B		Column C		Contamination levels in guidelines <sup>c</sup>
	Max <sup>a</sup>	End <sup>b</sup>	Max <sup>a</sup>	End <sup>b</sup>	Max <sup>a</sup>	End <sup>b</sup>	
Ammonia-N	7.48	0.57	0.37	0.14	0.26	0.11	3
Kjeldahl-N	11.6	5.19	10.9	1.56	8.2	0.47	6
Copper	5.82	0.23	5.48	0.21	5.45	0.093	0.2
Iron	14.69	4.33	11.52	1.43	7.91	0.57	0.2
Nickel	0.12	0.021	0.34	0.024	0.38	0.023	0.2
Zinc	0.22	0.027	0.45	0.043	0.52	0.041	0.8
Chromium	0.17	0.067	0.3	0.053	0.36	0.048	0.2

Note: All data are expressed in units of mg/l unless indicated.

<sup>a</sup>Maximum concentration of contaminant in the leachate during column tests.

<sup>b</sup>The contaminant concentration after 20-week leaching tests.

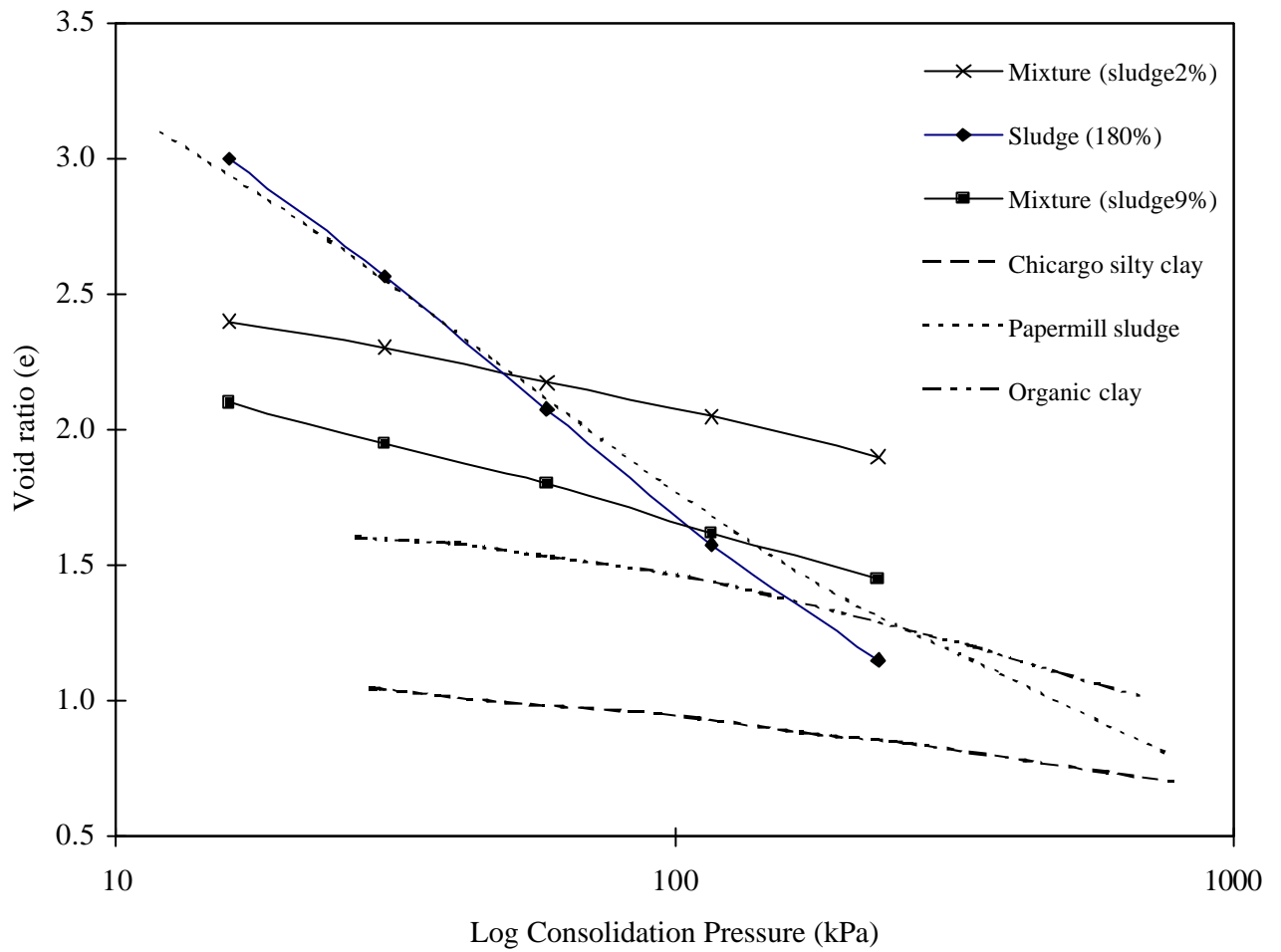
<sup>c</sup>The concentrations which imply significant pollution present and cleanup required.



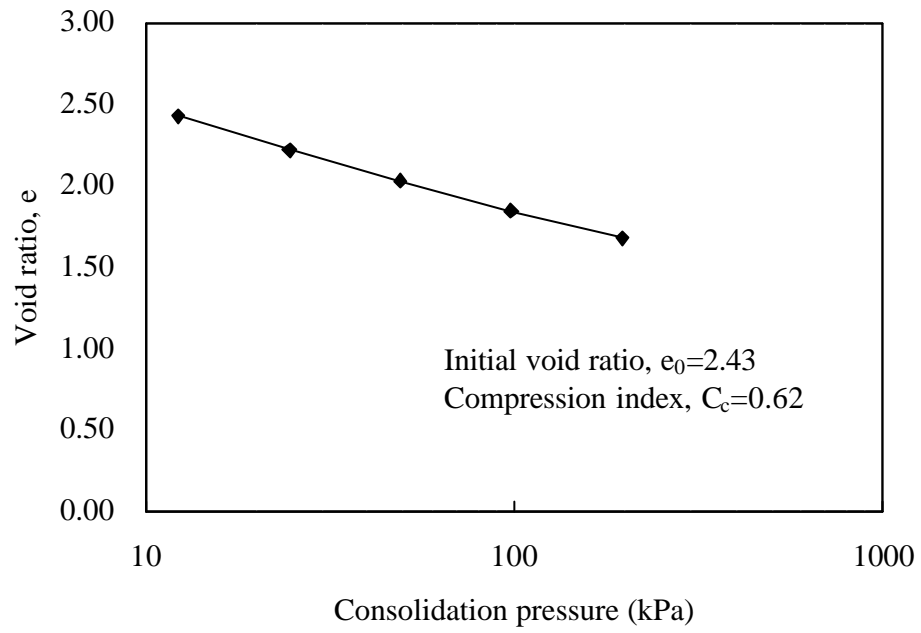
**FIG. 1. Experimental Setup of the Hydraulic Consolidation Test**



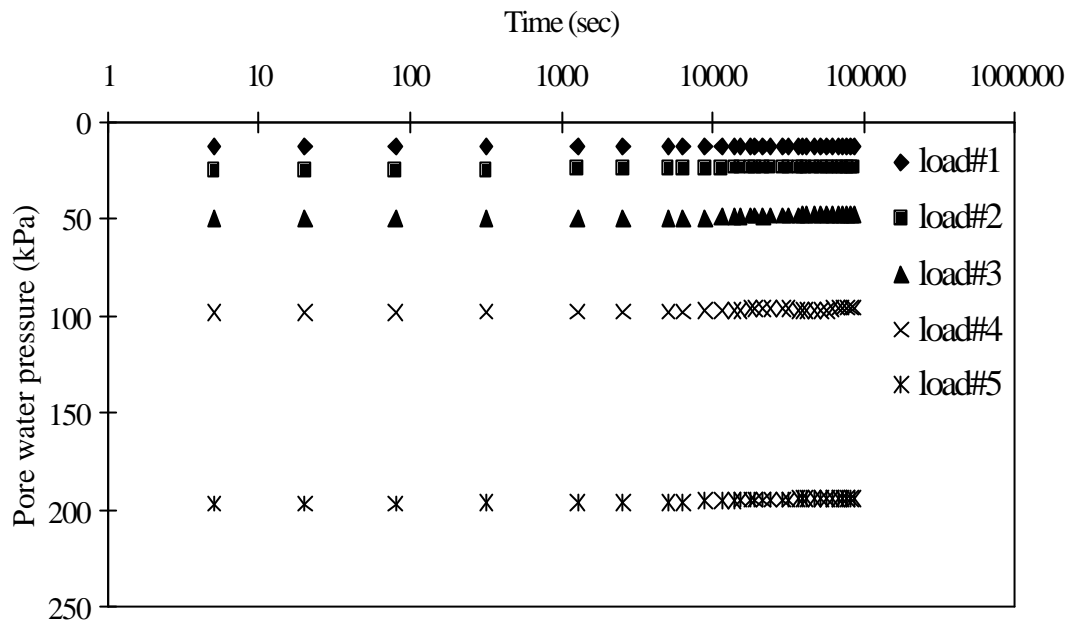
**FIG. 2. Bench-scale Column Tests for 1:10 Sludge Mixture,  
1:49 Sludge Mixture and Solid Waste Alone**



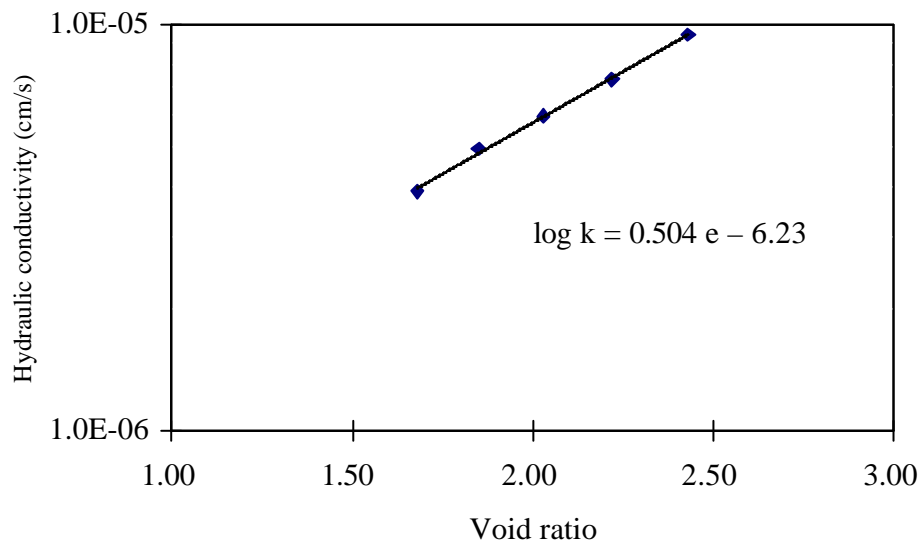
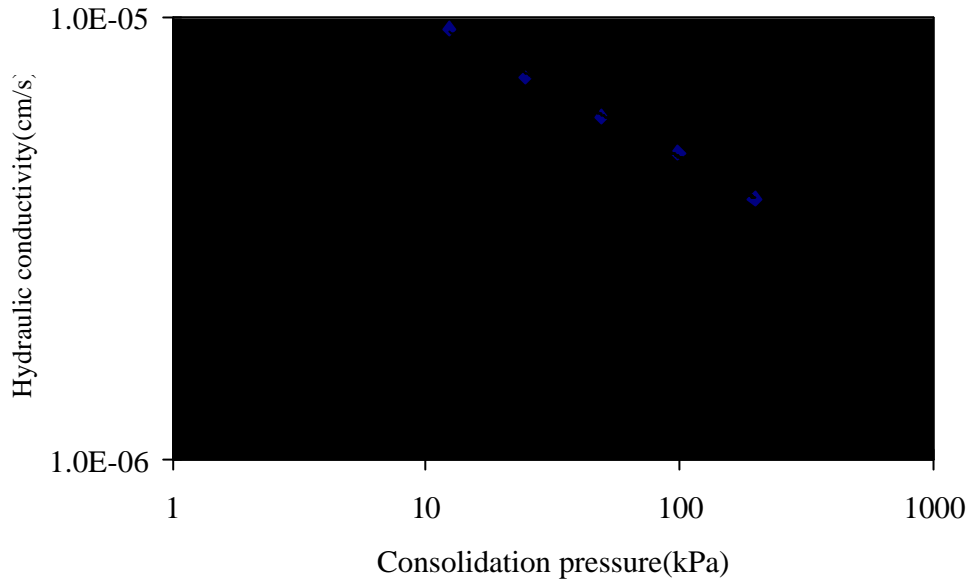
**FIG. 3. Consolidation Curves of CEPT Sludge Samples, Papermill Sludge (Moo-Young and Zimmie 1996), Organic Clay and Chicago Silty Clay (Krizek et al. 1987)**



**FIG. 4. Consolidation Behavior of the 1:10 Sludge Mixture**



**FIG. 5. Pore Water Pressure Dissipations of the 1:10 Sludge Mixture**



**FIG. 6. Hydraulic Behaviors of the 1:10 Sludge Mixture:**

**(a) log k vs. log p and (b) log k vs. e**