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Use of sewage sludge and other waste materials for land reclamation

Utilisation de boues d'eaux usées et autres rebuts pour la récupération de terres

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ABSTRACT
A large amount of sewage sludge and other waste materials are produced every year in Singapore. A study was carried out to establish a method to use sewage sludge and other waste materials for land reclamation. Portland cement and/or lime were used as binders. Waste materials, such as copper slag and marine clay, were also added in as fillers. The physical and environmental properties of the sewage sludge used and the properties of the treated sludge were characterized. The consolidation behaviour of the sludge-waste-binder mixtures around vertical drain was investigated using model tests. The study shows that both the geotechnical and environmental properties of the sewage sludge can be improved using the method proposed.

RÉSUMÉ
De grandes quantités de boues d'eaux usées et autres rebuts sont produites chaque année à Singapour. Une étude a été réalisée pour développer une méthode pour l'utilisation de tels matériaux pour la récupération de terres. Du ciment Portland et/ou de la chaux furent utilisés comme liant. Des déchets tels que des scories de cuivre et des argiles marines furent aussi utilisés comme matériau de remplissage. Les propriétés physiques et environnementales des boues d'eaux usées et celles des boues traitées furent caractérisées. Le comportement en consolidation des mélanges boues-rebuts-liants autour de drains verticaux fut aussi investigué en utilisant des modèles. L'étude montre que les propriétés géotechniques et environnementales des boues peuvent être améliorées en utilisant la méthode proposée.

1 INTRODUCTION

The disposal of sewage sludge and other waste materials in Singapore has increasingly become a problem due to a shortage of dumping ground. On the other hand, there is a great demand for fill materials for land reclamation. Therefore, it would be ideal if sewage sludge and other waste materials can be used as fill materials for land reclamation. Toward this purpose, a study on the feasibility of using binder treated sewage sludge and other waste materials for land reclamation was carried out. One of the methods studied is to mix the sludge and other waste materials with a small portion of binders and then consolidate the mixture on site after it is disposed. Depending on the usage of the reclaimed land, the sludge mixture layer can be capped with a layer of granular fill. In this method, the sludge needs not to be converted into a hard granular material before placement. It is only required to be treated into a material comparable to the consolidated seabed marine clay on which the sludge mixture is placed. In this way, the costs involved in treating and disposing sludge can be much lower compared with other disposing methods. The demand for granular fill can also be reduced.

In this study, Portland cement and/or hydrated lime[1] were used as binders. Another waste, copper slag, was used as a filler. As the consolidation behaviour of the binder treated sludge and copper slag mixtures can be quite different from that of soils, some laboratory model tests were conducted using a fully instrumented consolidation tank to study the consolidation process of the binder treated sludge mixture around vertical drains. In this paper, the general geotechnical and geochemical properties of the sewage sludge and the copper slag are characterised. A preliminary study is presented to show that sewage sludge cannot be treated by binders or by consolidation alone. Both chemical and mechanical means need to be used together in order to improve the geotechnical properties of sludge in a cost effective way. Testing arrangement for the model tests is described. Based on the model test results, the consolidation behaviour of the cement treated sludge mixtures around vertical drain is discussed. The geotechnical properties of the consolidated sludge mixtures are evaluated and presented in this paper. The assessment on the leaching of various contaminants from the cement-treated sludge mixtures is presented separately in Lim et al. (2004).

[1] Quicklime was not used as it was not practical to use it on a large scale due to the weather condition and the health regulations in Singapore.

2 MATERIALS TESTED

The anaerobically-digested sewage sludge used in this study was taken from a wastewater treatment plant in Singapore. The sludge had been filter-pressed for dewatering at the plant. Even though, the so-called dewatered sludge was still very soft, very high in water content and had little shear strength. It contained a considerable proportion of organic matters and some heavy metals. The physical and geochemical properties of the sludge are summarized in Tables 1 and 2 respectively. The heavy metal contents in the sludge were determined by microwave-assisted acid digestion of their oven-dried sub-samples followed by analysis of the digestates with the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). The results are presented in Table 3. Calcium and Silicon existed in high concentrations because quartz and calcite or calcium carbonate was the main mineral found in sludge, as revealed by the X-ray diffraction (XRD) tests conducted on the sludge sample (Goi 2004). Concentrations of Zn and Cu were relatively high. Zn could be introduced by factories producing galvanized zinc, whereas Cu might come from copper production plants and corroded copper pipe system. The coefficients of variations (CV) for Zn and Cu concentrations in the sludge were 56% and 36% respectively. These high CV values suggest that there were considerable spatial variations in the heavy metal concentrations in the sludge. Owing to the potential environmental concerns, the sludge needs to be treated to meet both the geotechnical and environmental requirements.

Copper slag is a non-toxic waste product after it has been used as a blast-cleaning agent to remove rust and marine deposits on ships. It is generated in substantial quantity every year in Singapore and its disposal also becomes increasingly a problem. It is well-graded with a mean grain size of 0.5 mm. The geotechnical and geochemical properties of copper slag are summarized in Tables 4 and 5. As copper slag contains heavy metals such as Pb, Zn, Cu, Cr and Ni, it cannot be used directly as a fill material for land reclamation.

Table 1 Physical properties of sewage sludge

Property	Value
Moisture Content (%)	400-514
Total Solids (TS) Content (%)	16.3-20
Bulk Density (Mg/m^3)	1.02
Specific Gravity	1.634
Liquid Limit, LL (%)	397
Plastic Limit, PL (%)	63
Plasticity Index, PI (%)	334
Liquidity Index, LI	1.35

Table 2 Geochemical properties of sewage sludge

Property	Value
pH at 25°C ± 2 (1:6 solid: water)	8.42
Electric Conductivity (EC) at 25°C ± 2 (1:6 solid: water) (mS/cm)	39.4
Redox Potential (Eh) at 25°C ± 2 (1:6 solid: water) (mV)	323
Loss on Ignition: (%)	
VS at 500°C	66
FS at 500°C	34
VS at 950°C	68
FS at 950°C	32
Dissolved Organic Carbon (DOC)* (mg/L)	1581
Phosphates* (mg/L)	66

* Based on the extraction of 1:5 solid: water ratio

Table 3 Total heavy metal concentrations in sewage sludge

Element	Concentration (mg/kg)
Sodium – Na	2,070 [705][a]
Calcium – Ca	32,600 [5,000]
Magnesium – Mg	4,820 [540]
Potassium – K	2,960 [290]
Aluminum – Al	12,700 [2490]
Iron – Fe	22,300 [2,670]
Silicon – Si	66,200 [4,440]
Barium – Ba	427 [76]
Arsenic – As	< 36
Selenium – Se	< 24
Cadmium – Cd	< 1
Chromium – Cr	694 (102)[b]
Copper – Cu	1,491 (533)
Lead – Pb	146 (24)
Nickel – Ni	314 (111)
Zinc – Zn	1,844 (1,032)

[a] Values in [ ] are standard deviations based on 6 determinations
[b] Values in ( ) are standard deviations based on 12 determinations

Ordinary Portland cement or/and hydrated lime were used as binders. Portland cement is an inorganic alkaline binder, which is primarily composed of anhydrous calcium silicate. The hydrated lime is also an inorganic alkaline binder, which consisted of predominantly calcium hydroxide. Negligible heavy metals are present in both types of binders.

Table 4 Physical and geotechnical properties of copper slag

Property	Value
Bulk Density (Mg/m^3)	2.0
Specific Gravity	3.57
Void Ratio	0.264 - 0.651
D_{50} (mm)	0.5
Particle Distribution	Well graded
Particle Shape	Subrounded to angular
Permeability (m/s)	$10^{-4} \sim 10^{-5}$
Friction Angle (°)	29 ~ 47

Table 5 Geochemical properties of copper slag

Property	Value
pH at 25°C ± 2 (1:1 solid: water)	8.4
Redox Potential (Eh) at 25°C ± 2 (1:1 solid: water) (mV)	112
Main Element: (%)	
Fe	37.9
Si	15.5
Acid Neutralizing Capacity	Low
Pozzolanic Characteristics	None
Heavy Metal: (mg/kg)	
Pb	710 (150)[a]
Zn	6,060 (780)
Cu	8,070 (1,200)
Cr	280 (40)
Ni	100 (20)
Cd	< 1

[a] Values in ( ) are standard deviations based on triplicates

3 PRELIMINARY STUDY

The project was carried out by characterizing the properties of the swage sludge first, and then exploring the methods for treating the sludge for land reclamation use.

The study shows that the sludge cannot be treated by using binders alone. Tests were conducted by mixing sludge with cement or lime or and copper slag in various proportions. Some examples are given in Fig. 1. The unconfined compression (UC) test results versus curing time are plotted in Fig. 2. It can be seen that even with a cement ratio of 25%, the UC strengths are still low. Therefore, it is not effective to use chemical treatment along to improvement the geotechnical properties of sewage sludge.

It is not effective either to treat sludge by consolidation or other mechanical means alone. According to Vesilind (2001), there are four distinct types of water that are associated with sludge: free (or bulk) water, interstitial water, vicinal water and water of hydration, and only the free water can be removed with relative ease by mechanical means. Interstitial water can also be removed, but the extra mechanical effort required to do so will not lead to a substantial reduction in the final water content that is efficient and cost-effective. Vicinal and water of hydration cannot be dewatered by any mechanical effort. The UC strength of a sludge sample consolidated under 80 kPa is also shown in Fig. 2. It can be seen that the strength of consolidated sludge was still very low.

Therefore, a combined chemical and mechanical method was adopted in this study. A consolidation tank as shown in Figure

3 was used to conduct model tests. The sewage sludge was first mixed with binders and the mixture was then placed in the consolidate tank for consolidation.

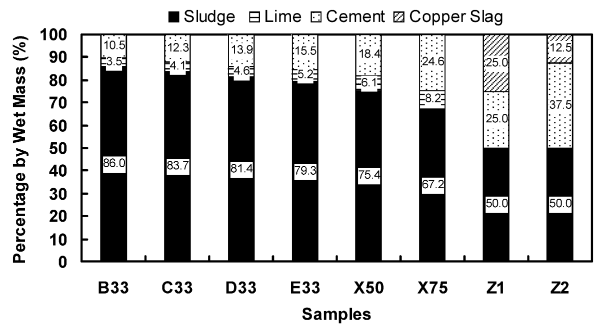

Figure 1 Proportions of constituents in each mix

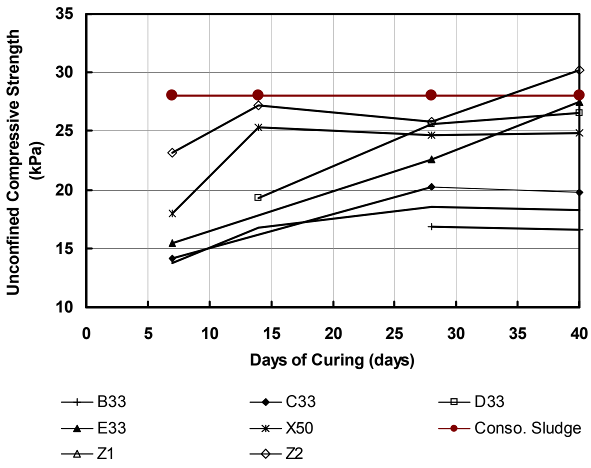

Figure 2 Results of unconfined compression test results

4 RESULTS

A model test was conduced on a mixture of 77% of sludge, 15% of copper slag and 8% of cement. The moisture content of the mixed slurry was 434%. A prefabricated vertical drain was used for this test. The drain was installed before the slurry was placed. Hence there was no smear effect. The consolidation pressure was 80 kPa

The settlement measured during consolidation is shown in Fig. 4. The consolidation test lasted about 550 hours. The settlement reached at the end of the test was 297.6 mm. The initial sample height was 450 mm. Based on the hyperbolic (Sridharan and Sreepada Rao 1981) and Asaoka (1978) methods, the ultimate settlement S_{ult} was estimated to be 330.7 mm and 336.8 mm respectively (Goi 2004). The average degree of consolidation achieved at the end of the test was 89.1%.

The pore pressures measured at depth of 80 mm from the top of the tank are plotted versus time in Fig. 5. Immediately after the opening of the drainage valve, water was discharged and settlement took place (see Fig. 4). However, the pore water pressure did not dissipate immediately, as shown in Fig. 5. Relatively large amount of pore water pressure dissipation only took place half an hour later (see Fig. 5). From 5-hour to about 200-hour, the pore pressure did not dissipate much as shown in Fig. 5, although there were substantial settlement during this period (see Fig. 4). The pore pressures measured by the three miniature pore pressure transducers, PPT2, PPT3 and PPT4, even increased slightly as shown in Fig. 5. The air pressure applied fluctuated within ± 3 kPa. This fluctuation was reflected in the pore pressures measured by the miniature pore pressure transducers (PPT2 to PPT7), but not by the ordinary pore pressure transducers (PPT1 and PPT8), which were mounted on the wall of the tank, as shown in Fig. 3.

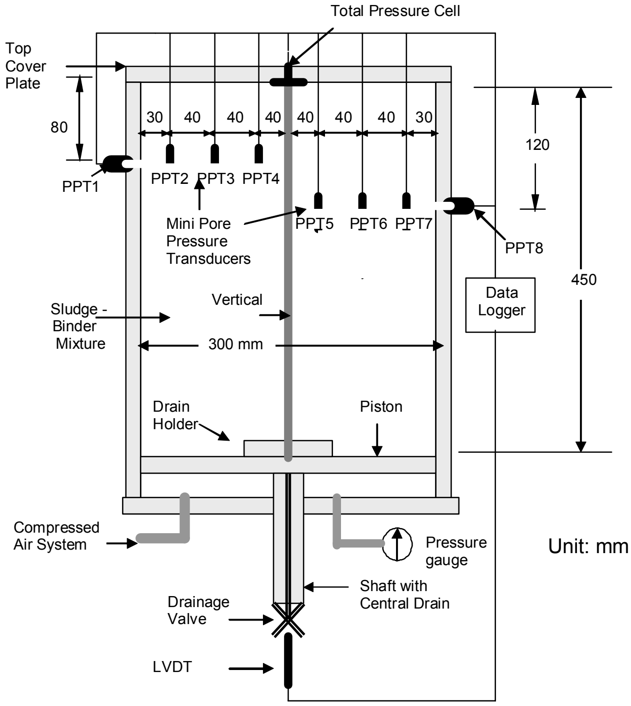

Figure 3 Schematic arrangement of consolidation test

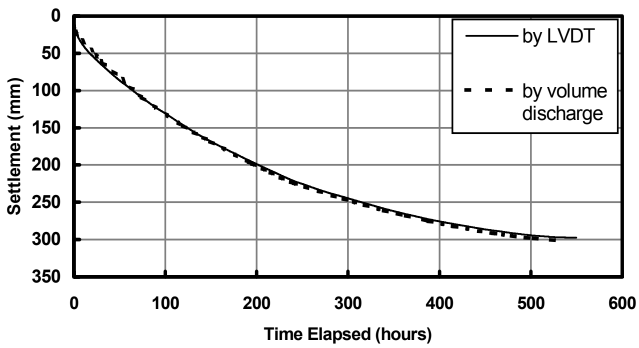

Figure 4 Settlement versus time curve measured during consolidation

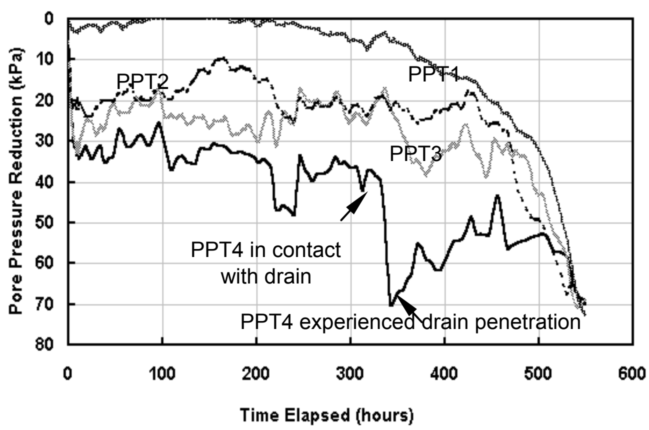

Figure 5 Pore water pressure dissipation versus time curve measured during consolidation

The distributions of excess pore pressures along the radial direction at different time intervals are shown in Fig. 6. The left-hand side was the pore pressure measured at 80 mm depth, while the right-hand side was the pore pressure measured at 120 mm depth. The initial excess pore pressures at the various locations were normalized to 80 kPa. Assuming that the excess pore water pressures at the 2 depths are the same, a family of isochrones are formed. In general, the pore pressure dissipations were generally faster at locations closer to the drain. The difference in the pore pressure dissipations at both sides was largely attributed to the lateral distortion and buckling of the vertical drain during the process of consolidation. Based on the isochrones shown in Fig. 6, the average degree of consolidation, U, can also be calculated (Chu et al. 2005). The U at the end of the test calculated based on pore water pressure is 79%, which is smaller than the U calculated based on settlement.

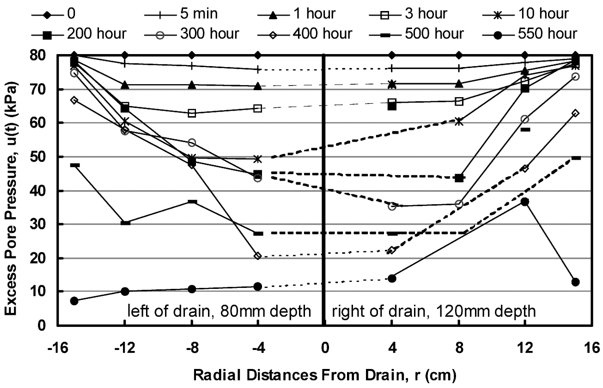

Figure 6 Isochrones of excess pore pressure distribution along the radial distance from the drain at different time intervals.

At the end of the model test, the sample was extruded and cut open along a vertical plane to view the condition of the vertical drain. The vertical drain had buckled to a profile shown in Fig. 7. Samples were taken at the tip position of each PPT for moisture content determination. The moisture content had reduced from the initial 434% to the final 57 to 94%. The moisture content of the soil closer to the vertical drain was lower than that further away from the drain. The variation in moisture content in the sludge mixture is larger than that in natural clay. Therefore, for consolidation of sludge, closer drain spacing or longer duration of consolidation should be used.

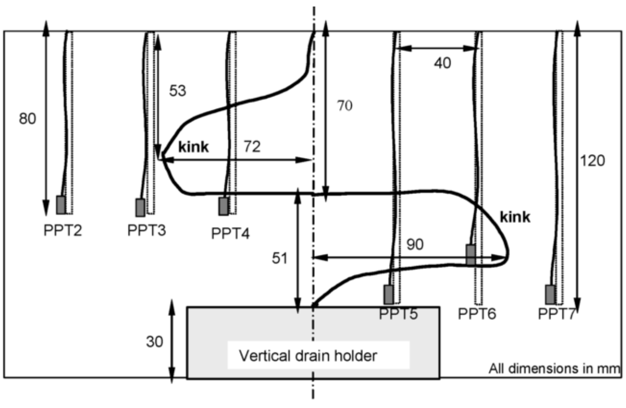

Figure 7 Deformation profile of vertical drain at the end of the test

The SEM images of a pure sludge sample and a treated sludge sample are shown in Fig. 8. It can be seen that there is a considerable change in the microstructure from the pure to stabilized sludge. This change could be the results of hydration of cement and the formation of calcium-silicate-hydrates, which bound the sludge and copper slag particles together. The difference in the microstructures of the pure and stabilized sludge explains why there was a considerable reduction in the compressibility and volume of the sludge after treatment and why the strength of the stabilized sludge was larger. Nevertheless, the basic honeycomb matrix still exists in the treated sludge sample although the pores became smaller as shown in Figure 5. This might have explained why the change in permeability is insignificant.

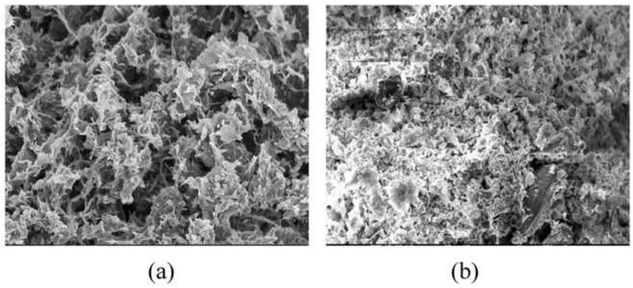

Figure 8 Microstructure of (a) pure sludge and (b) treated sludge

5 CONCLUSIONS

Based on the study, the following conclusions can be drawn:

1. The geotechnical properties of sewage sludge cannot be improved effectively by using either chemical or mechanical method alone.
2. By mixing sludge with binders and copper slag and consolidating the mixture under a pressure of 80 kPa, the physical and geotechnical properties of the sludge can be significantly improved. The moisture content of the sludge can be reduced from more than 500% to a level of 60 to 100%. The cementation effect can be clearly identified. The degree of cementation is affected by the moisture content of the mixture. The greater the moisture content reduction, the higher the cementation effect.
3. The microstructures of the treated sludge mixtures are more densely packed and have much lesser pore spaces as compared to that of the pure sludge. This explains why the treated sludge has a considerable increase in undrained shear strength and a substantial reduction in compressibility.
4. The results of the model test using vertical drain indicate that vertical drains can be used to consolidate the cement treated sludge, provided the PVDs used can sustain large bending and resist corrosion by the chemicals in the sludge.

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