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Consolidation property of a highly compressible construction waste sludge

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ABSTRACT: The slurry produced as a by-product of construction works has a high water content and contains a large amount of fine clay particles, thus necessitating its flocculation and dehydration for the sake of volume and water content reduction. The purpose of this study is to investigate the consolidation properties of flocs of different sizes, made by the application of flocculant to sludge, under lower consolidation pressures. Three types of experimental studies were carried out using clay flocs of different sizes. Based on the results of dewatering and consolidation tests, it can be concluded that the flocs' compressibility decreases with the increase in their size under consolidation pressures below 10 kPa, and that the hydraulic consolidation test could reliably predict initial deformation under lower consolidation pressures.

1 INTRODUCTION

In construction works such as shield tunnels or diaphragm walls, a great deal of slurry, called "construction waste sludge", is produced. It has a high water content and contains a large amount of fine clay particles, thus necessitating its flocculation and dehydration for the sake of volume and water content reduction. For the dehydration of construction waste sludge, dehydrators such as filter-presses or belt-presses are commonly used. At the intermediate treatment plant selected for this study (Ichikawa-city, Chiba), a special dehydrator called a "Dehydrum"(Figure 1) is used. The Dehydrum is a large size cylindrical rotor (ϕ=3,340 mm and L=10,230 mm), which rotates in a single direction at a slow speed. The consolidation pressure of the Dehydrum is assumed to be much lower than that of other dehydrators, which are estimated to be approximately 500 kPa to 700kPa. It has been observed at the present plant that the consolidation properties of flocs, made by the application of flocculant to sludge, change according to their sizes. The purpose of this study is to investigate the consolidation properties of flocs of different sizes under lower consolidation pressure. Three types of experimental study were carried out using clay flocs: 1)a gravity dewatering experiment to confirm the changes in the dewatering property of the flocs, 2)a constant rate of strain consolidation (CRS) test to investigate consolidation properties under a wide pressure range, and 3)a hydralic consolidation test to investigate consolidation properties under a lower pressure range.

2 SAMPLES, FLOCCULANT AND SPECIMENS

In the plant, the quality of dehydrated sludge varies greatly due to the flocs' size. It has been known that the size of the flocs varies in terms of additive volume, additive order and the combination of flocculants (J.H.Liu et al. (1996), Kawaguchi et al. (1998)). Therefore, additive volumes of flocculants have provided the key method of managing dewatering treatments. The authors tried to control the size of flocs by additive volumes of flocculant using bentonite slurry. The physical properties of the bentonite used are shown in Table 1. Distilled water was added to powdered bentonite to prepare sample slurry, and the slurry was settled for 24 hours to allow for sufficient swelling. Flocculants were then added to slurry, and the flocs obtained are used for experiments. In this study, we changed additive volumes and orders of organic flocculant (polyacrylamide solutions, 0.1% by weight) and inorganic floculants (LAC, a kind of polyaluminium chloride) in order to prepare three sizes of flocs: large, medium, and small(Table 2, Figure. 2).

3 GRAVITY DEWATERING EXPERIMENT

3.1 *Introduction*

The gravity dewatering experiment was performed on three types of flocs of different sizes in order to confirm the changes in the dewatering property of each floc.

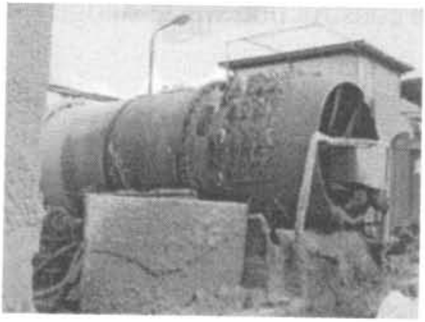

Figure 1. Dehydrum installed at plant.

3.2 *Experimental Procedure*

Three types of floc, the mass of which had been known, was poured into a 75μm sieve and the mass of discharged water passing through the sieve was measured. The water content at the beginning of the experiment was determined 3600 % for each sample. From these measurements, estimates was made regarding the relationships between water content and elapsed time.

3.3 *Results and Discussion*

Figure 3 shows the relationships between water content and elapsed time. This figure demonstrates that the time required to reach a steady state in volume change becomes short and the void ratio reduction of flocs becomes large as the flocs increase in size. Thus, this experiment demonstrates the influence of the flocs' size on their dewatering properties, a characteristic that has been previously observed in the treatment plant.

Table 1. Physical properties of Bentonite.

Water content w (%)	3578
Density ρs (Mg/m^3)	2.58
Liquid limit w_L (%)	406.7
Plastic limit w_p (%)	28.3
Plasticity index Ip	378.4
pH	10.1
Sand (2mm-75mm)	0
Silt (75mm-5 μ m)	12
Clay (5 μ m-)	88

Table 2. Additive volume of flocculant and grain size of flocs.

Floc size	LAC	Polyacrylamide	Grain Size
large	0.09%	65ppm	ϕ 10mm-
medium	0.19%	65ppm	ϕ 3-7mm
small	0.28%	65ppm	ϕ 1-2mm

(a) small size floc

(b) medium size floc

(c) large size floc

(d) without additive

Figure 2. Several type of flocs to floccurants (a) small size, (b) medium size, (c) large size, and (d) without additive.

4 CONSTANT RATE OF STRAIN CONSOLIDATION TEST

4.1 *Introduction*

Using gravity dewatering experiments, the changes in consolidation properties due to size of flocs was confirmed, which had been observed previously at the treatment plant. The constant rate of strain consolidation test (CRS) was then performed on the three flocs of different sizes to investigate each consolidation property under a wide pressure range.

4.2 *CRS Test Procedure*

The CRS test apparatus consisted of the loading apparatus, the consolidation cell, and loading piston. A guide ring of 3.5 cm was fixed on the O-ring in order to obtain a specimen of sufficient height, since the flocs were highly compressible. The inside surface of the consolidation ring was greased to minimize friction during loading.

Each of three types of flocs prepared in Chapter 2 was poured into a consolidation ring up to a depth of 30 to 40mm and settled. The axial load was monitored using the pressure transducers, the pore pressure at the impervious base was measured using a pore water transducer and the deformation of the specimen was monitored using dial gauge. These data were monitored and recorded using a data logging system. The strain rate was set at a rate of about 0.5(%/min), which was larger relative to the 0.01-0.1(%/min) recommended, because the excess pore pressure could not be measured until the deformation had proceeded considerably at the recommended strain rate. The applied back pressure was 10kPa. The CRS test conditions are listed in Table 3.

4.3 *Test Results and Discussion*

The CRS test results are summarized in the form of e-log σ_v' in Figure 4. Figure 4 shows that compressibility under a consolidation pressure of lower than 10 kPa varies greatly due to the size of the floc. The Compression Index of each floc's Cc under such consolidation pressures are about 39.6 for the small size, about 21.8 for the medium size, and about 10.2 for the large size. However, the remarkable differences in compressibility among the three flocs were not observed under a consolidation pressure of higher than 10 kPa. As a result, the flocs in the Dehydrum would be dewatered under consolidation pressures of lower than 10 kPa, where the remarkable differences in compressibility due to size of floc could be observed during a series of CRS tests. From the e-log σ_v' curves in Figure 4, it was found that the compressibility of large size flocs maintains an approximately constant value under a wide consolidation pressure range and firm flocs have already been formed during the flocculation for large flocs.

It is clear that the large deformation of the floc aggregates occurred with a decrease in floc size. For example, the void ratio of small flocs decreased to approximately one-fourth from that at the beginning of the test to a consolidation pressure up to 100 kPa.

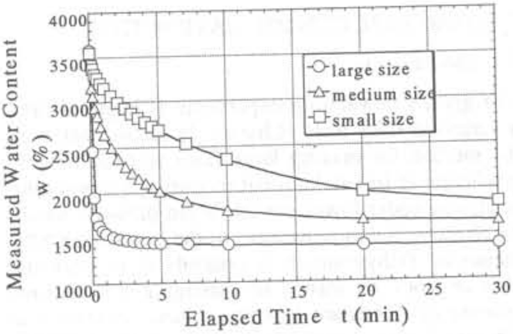

Figure 3. Measured water content versus elapsed time.

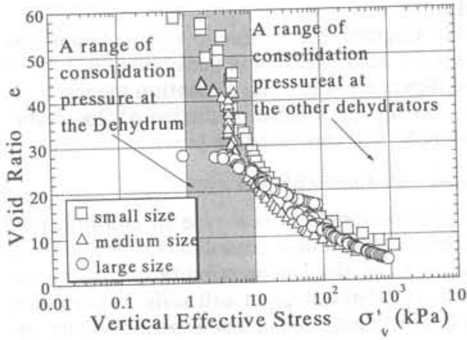

Figure 4. e versus log σ_v' for CRS tests.

This large deformation at the initial state of the dewatering process would cause a loss in consolidation energy. Furthermore, the amount of flocs fed into a dehydrator at the beginning of the dewatering process would determine the amount of dewatered sludge obtained (George Tchobanoglous. & Franklin L. Burton. (1993)). Therefore, either the method for making large size flocs or the reliable prediction of this initial deformation under lower consolidation pressure would be indispensable technology for the successful operation of the Dehydrum.

Table 3. CRS test conditions.

Flock size	large	medium	small
Rate of strain ε (%/min)	0.50	0.57	0.50
Initial height H_0 (cm)	1.99	1.75	1.96
Final height H_n (cm)	0.25	0.29	0.17
Initial water content w_n(%)	105.2	80.0	36.7

5 HYDRAULIC CONSOLIDATION TEST

5.1 *Introduction*

The gravity dewatering experiment (Chapter 3) and a series of CRS tests (Chapter 4) shows that both the method for making large flocs and the reliable prediction of initial deformation during a dewatering treatment under lower consolidation pressure would be effective for improvement of the dewatering efficiency of Dehydrum. It is possible to manage the size of flocs by means of managing the additive volume of flocculant to some extent, as shown in Chapter 2. However, since construction waste sludge generally contains some chemicals, the flocculation of the sludge at the plant site would become much complicated.

In this Chapter, the hydraulic consolidation test proposed by Imai (1979) was performed on flocs of three different sizes in order to confirm the test's effectiveness for the reliable prediction of floc deformation under low consolidation pressure.

5.2 *Hydraulic Consolidation Test*

Imai (1979) proposed a new type of consolidation test called the "hydraulic consolidation test" for the measurement of the compressibility and hydraulic conductivity relationships of soft soils. In principle, the hydraulic consolidation test is performed by applying a downward hydraulic gradient across a soil specimen in a rigid-wall consolidometer. Seepage forces consolidate the soil and produce a non-uniform effective stress distribution within the specimen. Once steady flow conditions are reached, local pore pressures are measured using needles that are inserted into the specimen from underneath. The distribution of the void ratio at a steady state is determined based on local water content measurements that are obtained by slicing the specimen after it has been removed from the cell. From these measurements, relationships for void ratio, vertical hydraulic conductivity, coefficient of volume change, and coefficient of consolidation can be obtained as a function of vertical effective stress.

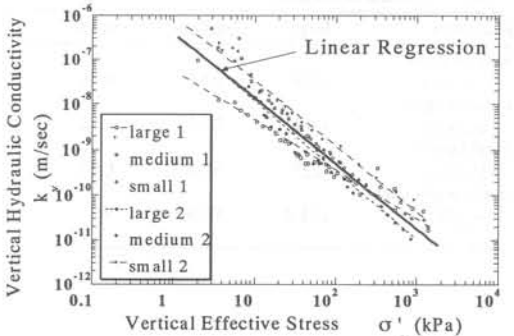

Figure 5. Measured hydraulic conductivity versus vertical effective stress for 6 types of bentonite flocs.

On the other hand, Fox and Baxter (1997) assumed that the logarithms of vertical hydraulic conductivity (k_v) varies linearly with the logarithms of vertical effective stress (σ'_v). They proposed an analytical method that eliminated the need for measurements of local pore pressure using needles, which had been problematic in the original hydraulic consolidation test proposed by Imai (1979).

Assuming the logarithms of vertical hydraulic conductivity (k_v) varies linearly with the logarithms of vertical effective stress (σ'_v) following equation can be written:

$$k_v = k_{v0}\left(\frac{\sigma'_v}{\sigma'_{v0}}\right)^{-A} \qquad (1)$$

where $A = -d \log k_v / d \log \sigma'_v$, and k_{v0}= vertical hydraulic conductivity corresponds to an arbitrary reference stress σ'_{v0}. For this assumption, the results of constant rate strain of consolidation test for bentonite flocs in Chapter 4 indicate that a linear log k_v versus log σ'_v is a good approximation (Fig. 5). Therefore, the author adopted the method of data analysis proposed by Fox and Baxter (1997), thus the measurement of local pore pressure was eliminated in this study.

5.3 *Hydraulic Consolidation Test Procedure*

The hydraulic consolidation test was performed on flocs of three different sizes, in accordance with the method proposed by Imai (1979). The hydraulic consolidation test apparatus consists of a consolidometer, air compressor, air regulators, pressure gauge, head tanks, and double-tube flow meters. The consolidometer used in this study has dimensions of 10 cm in diameter and 15 cm height.

In this study, the compressibility and hydraulic conductivity of a bentonite floc specimen were measured using a two-stage flow procedure (Fox and Baxter (1997)). To begin with, the flocculants were added to bentonite slurry to prepare a bentonite floc specimen and then poured into the consolidomter, paying careful attention to avoid entrapping air bubbles or rupturing the flocs.

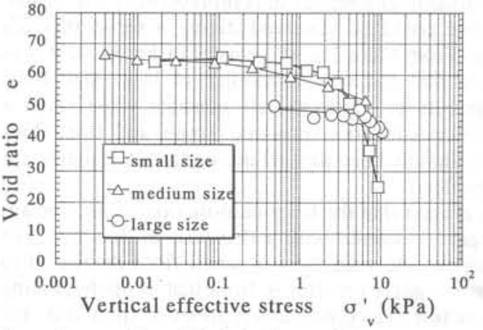

Figure 6. e versus log σ_v' for hydraulic consolidation tests.

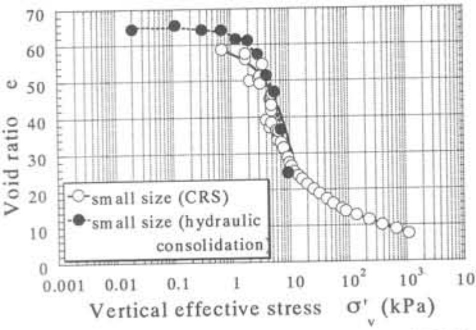

Figure 7. Comparison of hydraulic consolidation test with CRS test in terms of e versus log σ_v' form.

Same back pressure (10 kPa) was applied to the two head tanks. For the first flow stage of the test, a downward hydraulic gradient was applied across the specimen only due to local water head to make (u_t - u_b) (kPa) approximately 5.0 kPa, where u_t, u_b = the pore pressures at the top and bottom of the specimen. Once the steady flow was reached for flow stage 1, the specimen height H(m), discharge velocity v (m/sec), and (u_t - u_b) (kPa) value were recorded. The hydraulic gradient was then increased up to twice for the second flow stage of the test by adjusting the air regulator. Specimen height, discharge velocity and (u_t - u_b) value were again recorded at a steady state for flow stage 2. Then, sampling was performed by inserting a sampling tube vertically into the specimen (a tube of 35 mm in inside diameter, 120 mm length and 1 mm thick). After the tube was removed from the specimen, a piston was inserted into the tube from its bottom to push the specimen out of the tube gradually. Then, water content distribution was obtained by measurement of water content of sliced sample column.

5.4 *Test Results and Discussion*

The test measurements at steady flow state for each flow stage are given in Table 4 to Table 6. The hydraulic consolidation test results are summarized in the form of *e-log* σ_v', in Figure 6. From the *e-log* σ_v' curves in Figure 4, the tendency for the compressibility of flocs to decrease with increases in size of flocs was recognized under a consolidation pressure of lower than 10 kPa, which was the same tendency as observed during CRS tests. The results of CRS tests and hydraulic consolidation tests were demonstrated in Figure 7 which indicates that the hydraulic consolidation test is a suitable method for estimation of the consolidation characteristics of flocs under much lower consolidation pressures. Therefore, the hydraulic consolidation test could reliably predict initial deformation under lower consolidation pressures, thus improving the dewatering efficiency in the plant.

6 CONCLUSIONS

The above types of the dewatering experiment and the consolidation tests for bentonite flocs demonstrate the following conclusions:

(1) The gravity dewatering experiment shows the influence of flocs size on their dewatering properties, which had been observed previously in the treatment plant.

(2)The CRS test results revealed that the flocs' compressibility differs greatly according their size under a consolidation pressure of 10kPa and the smaller the size of flocs become, the greater the flocs' initial deformation.

(3)The hydraulic consolidation test shows that the flocs' compressibility tends to decrease with the increase in floc size under consolidation pressures lower than 10 kPa, and the same tendency was observed in CRS tests.

(4) A reliable prediction of initial deformation under lower consolidation pressure would be accomplished using the hydraulic consolidation test.

Table 4. Summary of test results for two stage hydraulic consolidation test of small floc.

Test measurement	Flow stage 1	Flow stage 2
u_t - u_b (kPa)	4.9	9.8
σ'_{vt} (kPa)	0.001	0.001
σ'_{vb} (kPa)	5.50	10.4
H (m)	0.0607	0.0575
v (m/sec)	8.1×10^{-6}	1.1×10^{-5}

Table 5. Summary of test result for two stage hydraulic consolidation test of medium floc.

Test measurement	Flow stage 1	Flow stage 2
u_t - u_b (kPa)	4.9	9.8
σ'_{vt} (kPa)	0.001	0.001
σ'_{vb} (kPa)	5.46	10.3
H (m)	0.0568	0.0578
v (m/sec)	1.5×10^{-5}	1.6×10^{-5}

Table 6. Summary of test result for two stage hydraulic consolidation test of large floc.

Test measurement	Flow stage 1	Flow stage 2
u_t - u_b (kPa)	4.9	9.8
σ'_{vt} (kPa)	0.001	0.001
σ'_{vb} (kPa)	5.46	10.3
H (m)	0.0568	0.0558
v (m/sec)	1.5×10^{-5}	1.6×10^{-5}

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