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Sedimentation behaviour of flocculant-treated soil slurry

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Abstract

Soil slurry cutting from seabed is becoming more widely used in land reclamation projects. A major problem encountered is that soil slurry is very watery and the dewatering process is difficult and time-consuming. In this paper, the use of chemical flocculant for the dewatering of soil slurry is proposed and experimentally tested. Polyacrylamide (PAM) with different charge types/charge densities was tested in preliminary slurry dewatering tests. The results showed that the most effective flocculant, cationic PAM with +15 charge density, can reduce the volume of soil slurry (500% water content) by around 60% in 10 minutes. In contrast, the volume of pure soil slurry was almost unchanged. Slurry sedimentation tests on slurries with different flocculant contents and water contents were conducted. It is shown that, by adding flocculant into soil slurry, the rate of settlement under self-weight can be considerably increased in the tested range of water contents (100.7-879.5%). But the water content at the final state increases with flocculant additions. Slurry sedimentation curves displayed different characteristics with different flocculant contents as well as water contents. It is evidenced by particle size analysis that the addition of flocculant into soil slurry can attract soil particles and form large flocs (assemblage of particles), which

explains the faster settlement rate in flocculant treated soil slurry as compared with pure soil slurry. Scanning electron microscopic analysis revealed that flocculant treated soil particles are more randomly oriented, while soil particles with no flocculant addition deposit in a more paralleled manner. This could explain the higher water content of flocculant treated soil slurry at the final state.

Keywords: Flocculant; Soil slurry; Land reclamation

1. Introduction

Large-scale land reclamation projects are taking place in coastal regions in rapid developing Asian countries like Singapore, China, Vietnam, and Korea. In Singapore, more than 100 km² new land has been created since the commencement of large-scale land reclamation in 1970s. Several eminent land reclamation projects involve Changi Airport, Jurong Island, Marina Bay, etc. Another about 100 km² land reclamation until 2030 is planned.

Conventionally, sands and rocks are used as fill materials in land reclamation in Singapore. However, sand and rock resources are becoming scarce and expensive. Soft clay is becoming an option to be used as a fill material in land reclamation. Soft clay materials are cheap and more easily obtained, but have very poor engineering properties. According to engineering practice in Changi East reclamation project and a pilot field trial in Jurong Island West Extension reclamation project, the use of soft clay as a fill material faces several technical challenges. A common method to use clay soil as a land reclamation fill is to mix seabed soil with large amount of water to form soil slurry, and transport slurry into land reclamation sites by pumping. In spite of the cheapness and convenience of this method, the subsequent sedimentation process of soil slurry is rather time-consuming. Once the reclaimed land is formed, soil improvement works are

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1 required. Reclaimed land formed by soil slurry is often too weak in bearing capacity to
2 support the load of machine and people carrying out soil improvement works. The
3 formation of a working platform on ultra-soft clay is required and it is another technical
4 challenge. Methods proposed for the formation of a working platform involves sand
5 capping, placement of geotextiles, use of short vertical drains, surface cement mixing,
6 etc. (Broms 2987; Bo et al 2005; Chu et al 2009a; Chu et al 2012). For ground consisting
7 of deep soft soil, vacuum preloading is usually considered as a prior technique as
8 compared with other soil improvement techniques (Bo et al 2007; Chu et al 2009b). But
9 for ultra-soft soil in reclaimed land, prefabricated vertical drains (PVDs) may suffer from
10 pore clogging during vacuum pumping and the drainage capacity can be greatly reduced
11 (Chu et al 2006). These challenges ought to overcome by researchers and practitioners.
12 In this paper, we present an experimental study on the sedimentation behaviour of
13 flocculant treated soil slurry. This research is motivated by a need of fast dewatering of
14 soil slurry in land reclamation projects.

15 Flocculants are a type of organic chemicals that can cause suspended particles to
16 aggregate and form flocs. It is an effective way to remove fine particles in water or to
17 enhance the dewatering process of slurry-type materials. It is widely used in water and
18 wastewater treatment processes for the removal of solid particles. It has also received
19 increasing interests in some geotechnics related applications. Mature fine tailings (MFT)
20 from oil sand mining are generated in large quantities. The proper management of MFT
21 is an ongoing challenge to the oil sand industry in Canada. Flocculants can be used to
22 accelerate the dewatering rate or reduce the water content of MFT (Yao et al 2012;
23 Beier et al 2013). Another application is the management of dredged sedimentation in
24 dredging projects (Hunter et al 2006; Englis and Hunter 2007). Flocculants can also be
25 potentially used for land reclamation projects where dredged soil slurry is used as fill
26 material. However, to the authors' knowledge, this topic has not been studied in the
27 past.

One important step of using flocculants is the selection of proper methods or equipments to carry out the dewatering of materials. For relatively small amount of materials, special machines have been designed to serve this purpose, such as belt filter presses, plate and frame presses, screw presses, and centrifuges, etc (Englis and Hunter 2007). These machines have been adopted in water and wastewater treatment operations. Flocculants can also be used in combination with geotextile tubes for the dewatering of mud (Howard et al 2010). In cases where huge amount of materials need to be treated, small machines may not be practical. In land reclamation and tailing management projects, large-scale containment structures or tailing dams are built to accommodate slurry materials. If flocculants are used in these projects, dewatering by self-weight sedimentation can be a preliminary dewatering treatment before further soil improvement work. In this case, an important problem is the sedimentation behaviour of flocculant-treated soil slurry, which is also the main focus of the paper.

Sedimentation behaviour of soil slurry and ultra-soft soil is of research interests in geotechnical engineering. Some examples of studies are Imai (1980, 1981), Been and Sills (1981), Sills (1998), and Xu et al (2012). The behaviour of soil or soil slurry at this state is very different from that of soil in normal subsurface conditions. Sedimentation of soil slurry subject to its self-weight will undergo three stages, that is, flocculation stage (natural flocculation), settling stage, and consolidation stage (Imai 1981). Details are given in Section 4.2.1. The sedimentation characteristics are affected by initial water content as well as salt concentration (Imai 1980). It is reported by Sills (1998) that soil at ultra-soft state does not strictly follow Terzaghi's consolidation theory, that is, the change in the void ratio is not solely determined by effective overburden stress, but also strongly affected by time-dependent creep. Xu et al (2012) reported that the critical void ratio, at which soil slurry becomes soil, is largely related to the liquid limit of soil.

This research was motivated and directed towards a practical need that soil slurry used in land reclamation requires faster sedimentation rate in order to reduce construction duration. In this paper, an experimental study is given on the sedimentation behavior of

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1 soil slurry treated with flocculant. Soil used in the experiment was marine clay obtained
2 from a land reclamation site in Singapore. Two major testing variables are flocculant
3 contents and water contents. The slurry sedimentation experiments are conducted
4 using cylindrical columns. Particle size analysis and scanning electron microscopy were
5 also used to examine the underlying mechanism of the effect of flocculant.

6 **2. A brief description of flocculants**

7 A flocculant is a long-chain organic compound of repeating monomers (single units
8 whose molecules can join together to form polymers). A flocculant can be characterized
9 by five major parameters, including the types of charge (cationic, anionic, or neutral),
10 the charge density (quantity of positive or negative charge), the molecular weight, the
11 molecular structure, and the type of monomers (Pillai 1997; Brostow et al 2009). A
12 commonly used flocculant is polyacrylamide (PAM). Its monomer unit is acrylamide, as,

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14 (1)

15 This is also the flocculant that is used in this study. The function of flocculants is to
16 absorb fine particles in water and form large aggregates (i.e. flocs), as illustrated in Fig. 1.
17 To select a proper flocculant for a particular application, it is also required to consider
18 the properties of the material to be dewatered, such as the properties of solid particles
19 as well as liquid, the concentration of solid particles, and pH, etc.

20 Flocculants have many industrial uses, such water and wastewater treatment, oil
21 exploitation, paper making, and geotechnical engineering. For geotechnics related
22 applications, flocculants can bring several benefits. First, it can accelerate the
23 settlement rate of fine particles in suspension (Yao et al 2012). Related applications

involves the management of tailings, the proper disposal of dredging materials, and land reclamation uses. Second, it can clean discharge water generated in the construction by removing the suspended solids in the water. Third, it can modify some geotechnical properties of soil, such as permeability and undrained strength (Yao et al 2012; Beier et al 2013). It is also reported that cemented clay soil with the addition of PAM is more flexible and thus more resistant to crack (Deng et al 2012).

3. Materials and methods

3.1 Test plan

Three experiments were conducted in this study. The first experiment was to select the most suitable flocculant and demonstrated effectiveness of flocculant for slurry dewatering. The selected one would be also be used in the subsequent experiments. The second experiment was to study the sedimentation behaviour of flocculated clay slurry as a function of flocculant content and water content. The experiment was conducted using 1 liter glass cylinders (35 cm in height and 6 cm in diameter). The third experiment was also a sedimentation test, but carried out using a larger column (1 m in height and 15 cm in diameter). Soil samples taken from the third experiment were used for particle size analysis and scanning electron microscopic analysis.

3.2 Materials

Soil used in the experiment is marine clay obtained from Jurong Island West Extension land reclamation project in Singapore. In this project, a pilot field trial is carried out to explore the feasibility and effectiveness of using soft clay soil for land reclamation. This soil was dredged from seabed close to the land reclamation site and is used as the fill material in the pilot field trial. The basic soil properties are given in Table 1. The particle size distribution is provided in Fig. 2.

In this study, polyacrylamide (PAM) was used as the flocculant. 9 types of PAM were tested in order to determine which one was the most effective. These 9 types include

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1 cationic PAM (CPAM, charge densities are +15, +20, +30, +40, +50, +60, and +70,
2 respectively, and molecular weight is 15 million), anionic PAM (APAM, molecular weight
3 is 20 million), and non-ionic PAM (NPAM, molecular weight is 15 million). The
4 percentage of active ingredient is larger than 90%. The dissolving time is less than 1
5 hour. These flocculants are commercially available and the producer is Longxin Co. Ltd.
6 These flocculants are widely used in the treatments of wastewater.

7 **3.3 Selection of chemicals**

8 The objectives of this experiment were to demonstrate the effect of PAM for slurry
9 dewatering and to find out the suitable type of PAM used in the subsequent
10 experiments. PAM should be used in the solution form. Dry PAM granules were added
11 into de-ionized water at 0.2% concentration and the mixing was done using a magnetic
12 stirrer for one hour. Soil slurry was prepared by adding and mixing salt water (35 g/L
13 NaCl) with the marine clay. The water content of the slurry was 500%. The test was
14 carried out in glass beakers. The beakers were firstly filled with half liter slurry. Then,
15 PAM solutions were added into the slurry by 5 steps of dosages: 5, 20, 25, 50, and 100
16 mL. After each step of dosage, the amount of flocculant additions are 0.11, 0.54, 1.08,
17 2.16, and 4.32 g/kg dry soil, respectively. In each step of addition, manual stirring was
18 applied with a rod. After 10 minutes, the settlement of soil-water interface was
19 measured. The next step of dosage then follows until the total addition of 200 mL was
20 achieved.

21 **3.4 Slurry sedimentation test using 1-liter cylinders**

22 The slurry sedimentation test was to evaluate the effects of varying PAM content and
23 varying water content on the sedimentation behaviour of soil slurry. The test was
24 conducted using 1-liter glass cylinders. The cylinders were 35 cm in height and 6 cm in
25 diameter. The preparations of pure soil slurry and PAM solution were the same as those
26 described in Section 3.3. Certain amounts of PAM solution and pure soil slurry were
27 mixed together (by one step, not stepwise) to form a slurry sample with designed water

content and PAM content. Manual stirring was applied to the mixture for 30 rounds. After the mixing, the mixture was poured into a cylinder. Observation was made on the settlement (that is, the decrease of the interface of soil slurry and clean water) for 60 days. There are 5 series of tests conducted with water contents from 100.7 – 879.5%. In each series of tests with the same water content, there are 5 test samples with PAM contents of 0, 0.1, 0.5, 1, and 3 g/kg dry soil, respectively.

3.5 Slurry sedimentation test using 1 meter columns

The size of 1-liter cylinder is small and may not be representative of real land reclamation conditions. The amount and rate of slurry settlement was affected by the the cross-section of the containers due to the friction between slurry and the wall. Test results based on containers with larger cross-section are more realistic. Besides, the 1-liter cylinder was only 35 cm deep, which was much smaller than real conditions. For these reasons, experiments using larger columns were conducted. The columns were 1 meter in height and 15 cm in diameter. The flocculant contents were 0-3 g/kg dry soil. The water content was 171.5% for all 4 experiments. The sample preparation method is almost the same as that presented in Section 3.4, expect that the mixing was applied to the mixture until it becomes completely uniform.

The mechanism of chemical flocculants is to form large flocs by attracting small suspended particles in slurry. To examine the existence and size of flocs, particle size analysis was carried out on soil slurry treated with various amounts of PAM. The apparatus used was Mastersizer 2000, Marlven Instrument.

Scanning electron microscopic analysis was also made on soil samples with and without PAM content. The model of the SEM apparatus is JEOL JSM-7600F.

4. Results

4.1 Selection of chemicals

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1 The successful use of flocculants depends on many factors, including the properties of
2 slurry and the parameters of flocculants. Thus, for a specific material that needs to be
3 treated, trial tests should be done to verify the effectiveness of the flocculant used. In
4 this study, 9 types of flocculants, that is, PAM with various types of charges and charge
5 densities, are tested. A picture of tests is given in Fig. 3. The first one was the control
6 test. And the other 9 were soil slurry with different types of PAM. The PAM addition
7 shown in Fig. 3 was 1.08 g/kg dry soil. It can be seen that, in samples with PAM addition
8 soil particles settled greatly, and there was a clear interface between soil slurry and
9 clean water. But in the control test (no chemical added), the soil slurry was almost
10 unchanged. In the following part of the paper, the settlement of slurry is defined as the
11 decrease of slurry-water interface. The test results with various types and amounts of
12 PAM are summarized in Fig. 4. Note that the initial volume of slurry was 500 mL.
13 Compared with the control test, tests with PAM added showed evident settlements. The
14 higher the amount of PAM addition, the larger the settlement was. Among all 9 tests
15 with PAM, CPAM with +15 charge density seems to be the most effective one by
16 showing the largest settlement in 1-4 g/kg range of PAM addition. Within this range of
17 PAM addition, the volume of slurry is reduced by around 60%. In comparison, the
18 volume reduction is less than 10% in the control test. CPAM with +15 charge density
19 was used in the subsequent experiments, because it is the most effective one in terms
20 of volume reduction. The effect of PAM was more pronounced within 1 g/kg addition by
21 showing a steeper decreasing rate. When adding more PAM into the slurry than 1 g/kg,
22 there was still further settlement but was less effective. Therefore, for the economical
23 reason, an addition of around 1 g/kg dry soil may be a suitable dosage. PAM addition of
24 1-2 g/kg of solid particles was also recommended by the flocculant supplier.

25 **4.2 Slurry sedimentation test in 1-liter cylinders**

26 *4.2.1 Background – sedimentation of soil slurry*

27 In previous studies, several researchers have explored the sedimentation behaviour of
28 soil slurry (Imai 1980, 1981; Been and Sills 1981; Sills 1998; Xu et al 2012). According to

Imai (1981), the whole sedimentation process can be divided into three stages, that is, the flocculation stage, the settling stage, and the consolidation stage, as shown in Fig. 5. In each stage, the soil slurry has a unique structure. In the flocculation stage (natural flocculation), there is little settlement in the soil-water interface and the water content throughout the column is basically uniform. In the settling stage, settling zone initially dominates the whole column but it gradually vanishes from the bottom. Meanwhile, the consolidation zone starts to grow from the bottom of the column and dominates at the end of the settling stage. In the consolidation stage, the settlement is purely due to the soil consolidation. The settlement rate in the settling stage is much faster than that in the consolidation stage, and there is an abrupt change in the gradient between the two stages, as shown in Fig. 5. This background knowledge will help to characterize the sedimentation behaviour of flocculant treated slurry in this paper.

4.2.2 Sedimentation curves of soil slurry treated with flocculant

The sedimentation curves for all the tests are presented in Fig. 6. In these tests, two factors, flocculant content and water content, are examined. The flocculant content varies from 0 to 3 g/kg dry soil, and the water content varies from 100.7% to 879.5%. These sedimentation curves can be classified into three types and the classification are given in Table 2. Type I involves all tests with 100.7% and 171.5% water contents, except the one with $w=171.5\%$ and $PAM = 3$ g/kg. As the water content is relatively low, there is only flocculation and consolidation stages, but no settling stage in the curves. Type II involves tests with relatively high water content but low flocculant addition. This type of curves shows all three stages. Type III curves involve tests with relatively high flocculant content. In this type of tests, soil particles and water start to segregate instantaneously during the preparation of the slurry. And thus the settlement curves are rather flat. It should be mentioned that Type III curves are influenced by the slurry preparation conditions. If mixing was applied to the soil slurry for a longer time, Type III soil slurry can become homogeneous, and the sedimentation curves will become Type I or Type II.

4.2.3 Settlement rates

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1 A major objective of using flocculant for soil slurry is to accelerate the settlement rate. It
2 can be clearly seen from Fig. 6 that, the use of flocculant in soil slurry can greatly
3 accelerate the overall settlement rates in the tested range of water contents. These
4 results prove the effectiveness of flocculant. However, it is also of interest to know the
5 exact settlement rates at different stages (settling stage and consolidation stage). As
6 presented in Section 4.2.2, soil slurry at settling stage and consolidation stage shows
7 completely different settlement rate. The settlement rate at settling stage is much
8 faster than that at consolidation stage. The settlement curves manifest a linear shape at
9 settling stage, and manifest a logarithmic shape at consolidation stage. So the
10 settlement rate at settling stage is defined as the slope of sedimentation curve at
11 settling stage:

12
$$v_s = \frac{\Delta h_s}{\Delta t_s} \tag{2}$$

13 The settlement rate at consolidation stage is defined as the slope of sedimentation
14 curve (semi-log scale) in the consolidation stage:

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$$v_c = \frac{\Delta h_c}{\log(t_{cf} / t_{co})} \tag{3}$$

16 The data of v_s and v_c are summarized in Figs. 7 and 8, respectively.

17 It can be seen in Fig. 7, the addition of flocculant into soil slurry can effectively increase
18 the settlement rate at settling stage. For $w=313.1\%$, adding 0.5 g/kg flocculant can
19 double the settlement rate. For $w= 596.3\%$ and 879.5% , adding 0.5 g/kg flocculant
20 shows settlement rates several times higher than those of pure soil slurry. It deserves
21 pointing out that, Type III settlement curves (tests with relatively high flocculant content,
22 see Table (2)) show instantaneous soil-water segregation, implying that the settlement
23 rates are much higher than those in Type II settlement curves by all means. These
24 results clearly indicate that the proper use of flocculants can significantly accelerate the
25 settlement rate of soil slurry at settling stage.

The settlement rates at consolidation stage are presented in Fig. 8. Type III settlement curves show considerably small rates as compared with Types I and II curves. This is ascribed to the initial instantaneous soil-water segregation. For Type I curves, the settlement rates of tests with $w=100.7\%$ are smaller than that with $w=171.5\%$. This could be due to that, soils forming at different initial void ratio may develop different soil structure, which in turn affects the settlement rate in the subsequent consolidation and creep process. However, this explanation requires further investigations. For Type II settlement curves, all the tests show similar settlement rates regardless of water content. This could be because of the soil forming condition for these tests are the same (that is, soil forms from the sedimentation of slurry suspension).

It should be stressed that, the overall settlement rates in all ranges of water contents increase with PAM content by showing a much shorter flocculation stage and much faster settlement rate at settling stage, as can be seen from Fig. 6. In real land reclamation projects, filling of soil slurry and the drainage of clean water need to be carried out in several iterations and this process is time-consuming. The use of flocculants can save time and reduce the number of iterations in such a process.

4.2.4 Water content at final and soil forming states

Average final water contents for all tests are presented in Fig. 9. It can be seen that the average final water content increases with flocculant content, although the trend is not very clear. The reason could be that, adding flocculant into slurry could form larger particle aggregates, alter the arrangement of soil particles when soil forms, and lead to a unique fabric of soil. This explanation will be further examined in Section 4.3.3.

Soil forming state here is defined as the state that soil slurry changes from settling stage to consolidation stage. Average water contents at soil forming state are presented in Fig. 10. The average water contents at soil forming state for all tests are in the range of 200 – 330%. The values increase with initial water content of slurry. But it seems that

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1 flocculant content does not have any considerable effect on the average water content
2 at soil forming state.

3 **4.3 Slurry sedimentation test in 1-meter column**

4 *4.3.1 Settlement curves*

5 The settlement curves in 1-meter column tests are presented in Fig. 11. These curves
6 are similar to those shown in Figs. 6(c) and (d). Both of these two series of curves have
7 the same initial water content of 171.5%. Slurry samples with higher flocculant content
8 exhibit a faster settlement rate at the former section of the curves, but rest at a higher
9 water content at the end of the test. These features are the same as those in 1-liter
10 cylinder tests, as can be seen in Figs. 6(c) and (d).

11 *4.3.2 Particle size distribution*

12 The mechanism of chemical flocculation is to form bigger flocs so that soil particles can
13 settle faster. Fig. 12 displays the particle size distribution curves of four soil samples
14 taken from 1-meter column tests. It is clearly seen that the curves of flocculant treated
15 soils are lower than that of untreated one, indicating that soil flocs are effectively
16 formed. The sizes of flocs are several times to two orders-of-magnitude larger than the
17 sizes of soil particles. For the sample with PAM = 3 g/kg, most the flocs are larger than
18 0.1 mm, which are comparable to the sizes of sand particles. According to Stokes Law,
19 the heavier the solid particle is, the faster it settles in liquid. So, the results of particle
20 size analysis given here clearly demonstrate that it is the formation of flocs are account
21 for the faster settlement rate in the flocculant treated slurry.

22 *4.3.3 Scanning electron microscopy*

23 SEM photos are presented in Fig. 13. Figs. 13 (a) and (b) are soil samples with no PAM
24 addition and with 3 g/kg PAM addition, respectively. In the test with no PAM addition,
25 soil particles tend to deposit in a paralleled manner and more face-to-face contacts are
26 formed between soil particles. In the test with PAM addition, soil particles are more

randomly oriented and there are more edge-to-face contacts. A farther look at the same location shows that soil particles seem to form a floc (Fig. 13(c)). This difference in the particle level fabrics may be explained by the effect of the flocculant. If interactions between soil particles are more repulsive in the soil forming process, soils tend to form a dispersed fabric where more face-to-face contacts can be seen. When flocculant is added, attractive forces dominate in the particle level interactions, and soil particles are apt to form big flocs (assemblage of soil particles), in which the orientation of soil particles are more random. Such a difference in particle-level fabrics could be the reason that flocculant treated slurry settles at a higher water content as compared with pure soil slurry.

5. Practical implications

In land reclamation projects where clay slurry is used as fill materials, slurry is pumped into containment structures and clean water should be pumped out at the same time. According to the engineering practice in the pilot field trial in Jurong Island West Extension reclamation project, slurry pumping ought to be carried out in several iterations in order to accommodate more solid materials. In the meantime, the dewatering of slurry under its self-weight is rather slow. This process is time consuming and this translates to high construction costs. The use of flocculants is intended to solve or alleviate such a problem. The test results presented in this paper clearly show that flocculant can effectively accelerate the settlement rate of soil slurry. This implies that flocculant could be a promising way to reduce the construction period of land reclamation projects.

Equipments have been developed for using flocculant in dredging projects (Hunter et al 2006; Englis and Hunter 2007). Using a dosage control system, the flocculant solution can be directly injected into the pipelines through which slurry is transported. The dosage of flocculant can thus be easily controlled and regulated. The mixing of flocculant and slurry can be made using in-line static mixers. An in-line static mixer has a specially-designed geometry and is replaced in a pipeline. Two fluids can be mixed to a

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1 designed level when flowing through the mixer. These methods can also be adopted in
2 the land reclamation projects.

3 It should be mentioned that the self-weight dewatering of flocculant-treated slurry is a
4 preliminary treatment before further soil improvement work. In addition to the
5 advantages mentioned in this paper, the use of flocculant may have other advantageous
6 features. Flocculant can enhance undrained strength and accelerate consolidation rate
7 (Yao et al 2012; Beier et al 2013). Further soil treatment work, such as the use of
8 vacuum consolidation technique or geotextile tubes, may benefit from these improved
9 soil properties. Related issues will be investigated in future studies.

10 **6. Conclusions**

11 In this paper, the sedimentation behaviour of flocculant treated slurry are examined and
12 the underlying mechanisms are investigated. Major conclusions are given as follows.

13 (i) PAM with different charge types/charge densities can all effectively reduce the
14 volume of soil slurry. Cationic PAM with +15 charge density is of the most effective one,
15 which can reduce the volume of soil slurry (500% water content) by around 60% in 10
16 minutes (PAM addition 1-4 g/kg dry soil). In comparison, the volume reduction of pure
17 soil slurry without any additives is less than 10%.

18 (ii) In 1-liter cylinder tests, sedimentation curves of soil slurry with different PAM
19 contents and water contents display different sedimentation characteristics. The
20 sedimentation curves can be divided into three stages, that is, flocculation stage,
21 settling stage, and consolidation stage. This feature is similar to that of pure soil slurry.
22 The sedimentation curves can be classified into three types. Type II curves have all three
23 stages. When the water content is relatively low, there is no settling stage (Type I
24 curves). When the PAM content is relatively high, the soil slurry manifests instantaneous
25 segregation of water and condensed slurry (Type III curves).

(iii) The addition of PAM into soil slurry can significantly accelerate the overall settlement rate by showing a much shorter flocculation stage and much faster settlement rate at settling stage. The average water content at final state increases with PAM content.

(iv) The particle size analysis on soil samples with various PAM contents shows that, the use of PAM can effectively form flocs. The sizes flocs are several times to around two orders-of-magnitude larger than the sizes of soil particles. This finding is related to the faster settlement rate of flocculant treated soil slurry.

(v) The analysis on the SEM images reveals that soil particles in PAM treated soils are more randomly oriented, while soil particles with no PAM addition deposit in a more paralleled manner. The comparative results can explain why flocculant treated slurry has higher water content at the final state.

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29 with 3g/kg PAM addition.

1 Table 1 Basic properties of marine clay

Specific gravity	Liquid limit	Plastic limit	Organic content	pH
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Table 2. Classification of sedimentation curves

		Water content				
		100.7%	171.5%	313.1%	596.3%	879.5%
Flocculant content (g/kg)	0	I	I	II	II	II
	0.1	I	I	II	II	II
	0.5	I	I	II	II	II
	1	I	I	II	II	III
	3	I	III	III	III	III

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Flocculant

Particles

Floc

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Fig. 1 Illustration of the function of flocculant

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Fig. 2 Particle size distribution of marine clay

Fig. 3 A picture showing the effects of flocculants on the dewatering of soil slurry (types of flocculant are marked in the figure; for all 10 slurry samples, water content of slurry samples is 500% and flocculant addition is 1.08g/kg dry soil; the picture was taken 10 minutes after the slurry-flocculant mixing)

Fig. 4 Effects of different types and dosages of flocculants on the dewatering process of soil slurry (initial volume of slurry is 500 mL for all 10 tests; the volume of slurry was measured 10 mins after the slurry-flocculant mixing)

Fig. 5 General characteristics of sedimentation curve of soil slurry (adapted from Imai 1981)

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Fig. 6 Sedimentation behaviour of PAM treated soil slurry in 1-liter cylinders. (a) and (b): Soil slurry with $w = 100.7\%$; (c) and (d): Soil slurry with $w = 171.5\%$; (e) and (f): Soil slurry with $w = 313.1\%$; (g) and (h): Soil slurry with $w = 596.3\%$; (i) and (j): Soil slurry with $w = 879.5\%$.

Fig. 7 Settlement rate at settling stage (the calculation method of settlement rate at settling stage is based on Eqn. (2); tests on slurry samples that do not have settling stage are not shown in this figure)

Fig. 8 Settlement rate at consolidation stage (the calculation method of settlement rate at consolidation stage is based on Eqn. (3))

Fig. 9 Average final water content

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Fig. 10 Average water content at soil forming state, i.e. the state that soil slurry becomes soil (tests on slurry samples that do not have settling stage are not shown in this figure)

(a)

(b)

Fig. 11 Sedimentation behaviour of PAM treated soil slurry in 1 meter columns. (a) Curves in normal scale; and (b) curves in log scale

Fig. 12 Particle size distribution of flocculant treated soil slurry

(a)

(b)

(c)

Fig. 13 SEM images of flocculant treated soil slurry. (a): Pure soil slurry; (b) and (c) Soil slurry with 3g/kg PAM addition.