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Model test on dewatering of high-water-content dredged slurry by flocculation-horizontal vacuum two-staged method

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Abstract: A two-stage method for dewatering high-water-content dredged slurry by flocculation and vacuum-assisted prefabricated horizontal drain (PHD) was proposed to increase the dewatering efficiency by addressing the issues of serious bending and clogging that are typically encountered when using the prefabricated vertical drain (PVD). Firstly, comparison of model tests using PVD and PHD, respectively, under vacuum preloading indicates that the PHD has advantages of uniform settlement of soil, negligible bending of the drain board, uniform dewatering rate and better dewatering efficacy. For the cases considered in this study, the mass of water drained out by PVD was only 77.4% of that by PHD. Effect of flocculation on the dewatering efficacy was investigated and the results indicated that impact of the flocculant (APAM) dosage on the dewatering rate was significant. With moderate addition of APAM (e.g., 0.45% of dry soil mass), the time required for dewatering was shortened by 35%. Lastly, the influence of sedimentation time (i.e., waiting time before applying vacuum pressure) on dewatering rate was studied. The results showed that if the sedimentation time is insufficient, the effect of flocculation cannot be mobilized fully , and as a result, will lead to significant non-uniform consolidation and reduced dewatering efficacy. The best time to start the vacuum pressure is 24 hours after the beginning of sedimentation.

Keywords: prefabricated horizontal drains; vacuum preloading; flocculation; model test

1 Introduction

In recent years, a huge volume of dredged slurry is produced in China by the water environment remediation. Relevant data show that the annual average volume of dredged slurry in China exceeds 500 million cubic meters. How to quickly and effectively dispose of these dredged slurry with high water content is of great significance for reducing space occupation, saving land resources and engineering costs. Vacuum preloading technology assisted by prefabricated vertical drain (PVD) is an effective method commonly used to improve soft soils[1]. This method is further applied to the treatment of high water content dredged slurry because it’s easy to use and of low cost[2–3]. Despite various improvements have been made, PVD method still has two main drawbacks: (a) serious bending deformation of the PVD board occurs when large deformation develops in the slurry, which leads to reduction of the dewatering efficiency of the PVD; (b) serious clogging of the PVD filter by the surrounding soil occurs after a period of vacuum preloading, which leads to great loss of vacuum pressure and results in reduction of vacuum preloading efficiency.

In order to address the problem of PVD bending, Chiba et al.[4] proposed a method for prefabricated horizontal drain (PHD) which is laid horizontally. The advantages and feasibility of this new method is proven by field tests. Later, Luo et al.[5] and Wang et al.[6] conducted experiments and field studies on the PHD assisted with vacuum preloading to treat the dredged slurry and found that the horizontal drain board can settle together with the slurry and thus avoided board bending. Further, Shinsha et al.[7] pointed out that using PHD can achieve concurrent consolidation and filling (see Fig.1), i.e., vacuum consolidation can be carried out while the dredged slurry is being filled into the disposal facility, so that the storage capacity of the disposal facility is maximized. Shinsha's field test results show that the total amount of dredged slurry (under water) treated is 1.1 times the total volume of the disposal facility.

In recent years, organic flocculants commonly used in sewage treatment have been widely introduced into the dewatering treatment of dredged slurry[8]. The flocculant mainly has the following two functions: (a) it accelerates the formation of large flocs from the fine suspended particles in the slurry, and thus accelerates the sedimentation of soil; (b) the presence of large flocs increases the pores between the soil particles and the coefficient of permeability of the soil, which helps

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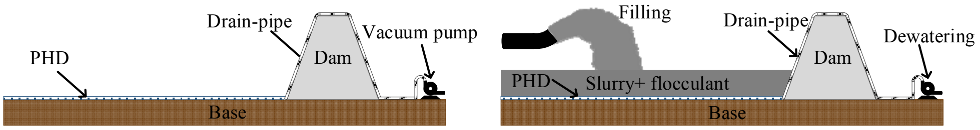
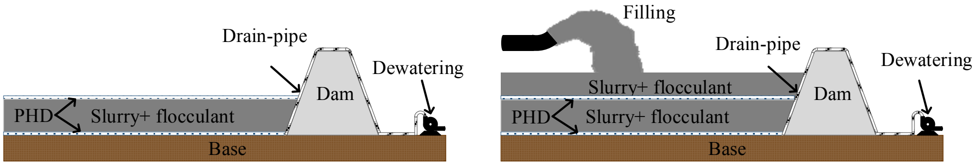
alleviate the "soil pillar" phenomenon around the drain board. If the combination of prefabricated horizontal drain assisted with vacuum preloading and flocculant (i.e., flocculation-horizontal vacuum two-staged dewatering) is used to treat the high water content dredged slurry, it can avoid bending of the board and resolve the clogging issue, so as to greatly improve the efficiency of slurry dewatering.



(a) Installing PHD (b) Filling and dewatering



(c) Installing and dewatering (d) Filling and dewatering

Fig.1 Schematics of concurrent filling and vacuum dewatering with PHD

However, the existing research on prefabricated horizontal drain assisted with vacuum preloading is still in the exploratory stage, and there are few researches focused on flocculation and vacuumassisted PHD. The treatment performance of high water content dredged slurry with this new method is worthy studying. The combined treatment method can maximize the dewatering effect of the flocculant, reduce the soil water content before vacuum preloading begins and therefore can shorten the construction period, reduce vacuum preloading time and energy consumption. In this method, there are two dewatering processes happening simultaneously: (a) flocculation- induced sedimentation and (b) vacuum consolidation. Since this is a new method, the mutual influence of the two dewatering processes, the characteristics of the dewatering and the optimal flocculant content are yet to be studied.

In this paper, the advantages of prefabricated horizontal drain in treating dredged slurry are demonstrated by comparing the vacuum dewatering performance of PVD and PHD. Anionic polyacrylamide (APAM) is used as flocculant in the model tests. The water content, soil settlement and floc particle size are measured to analyze the performance of this new method with different flocculant dosages and different sedimentation time.

2 Model test

2.1 Test materials

The slurry used in the model test was taken from a dredging project in the eastern China. The basic physical properties of the soil were tested according to the national standard "*Standard for Geotechnical Testing Method*" (GB/T50123-2019)[9], and the main physical properties of dredged slurry are listed in Table 1. The soil has a liquid limit of 61.26% and therefore is a high liquid limit clay. The particle size analysis of dredged slurry was carried out using Bettersize 2000E laser particle size analyzer and the results showed that the proportion of particles smaller than 10 μm in the soil sample is 59%. The high content of fine particles may be an important reason for the clogging of drain board. The flocculant APAM provided by Guangdong Foshan Quanyong Company, and it is white and granular with a relative molecular weight of 12 million. The test uses the so-called "anti-clogging drain board"[10] and the basic parameters provided by the manufacturer are shown in Table 2.

Table 1 Basic physical parameters of dredged soil

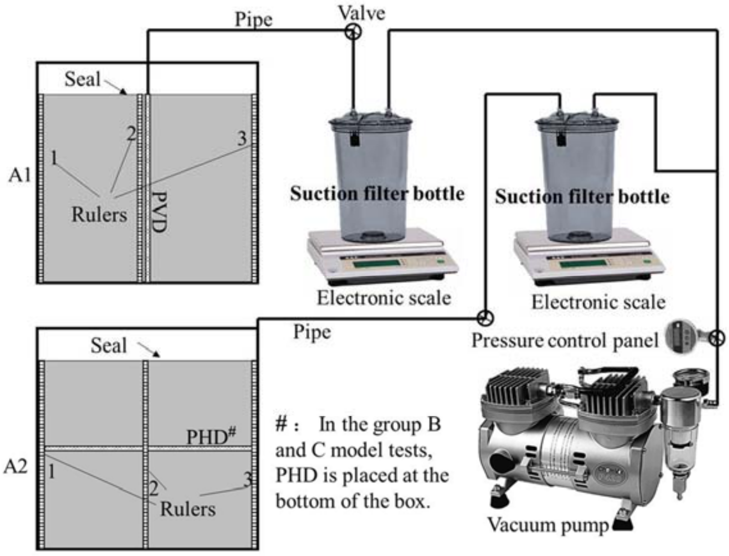
Specific gravity of soil solids, d_s	Liquid limit, w_L /%	Plastic limit, w_P /%	Plasticity index, I_P /%	Natural water content, w/%
2.66	61.26	26.34	34.92	90

Table 2 Parameters related to prefabricated drain

Core		Filter	
Width/mm	100	Opening size, O_{95} /μm	120
Thickness/mm	4	Permeability(cm · s^{-1})	⩾5.0×10^{-3}
Tensile strength/kN	⩾2	Tensile strength/(N · cm^{-1})	⩾20
Discharge capacity/(cm^3 · s^{-1})	⩾40		

2.2 Model test device

The model test system is composed of vacuum pump, suction filter bottle, electronic scale, drain board and model box (Fig. 2). The model box is made of plexiglass material with a thickness of 1 cm, and the size is 40 (60) cm×11.5 cm×40 cm (length×width×height). The drain board was placed at the bottom of the model box, with one end being connected to the suction filter bottle through a conduit joint that was connected to the vacuum pump through a pressure control panel. The other end of the drain board was sealed with glue. The pressure control panel can adjust the vacuum pressure as needed in the test. Electronic scale placed under the suction filter bottle can monitor the mass of water drained from the model box during vacuum dewatering. In addition, three observational rulers were pasted on the outer wall of the model box to observe the soil settlement at three locations.



#: In the group B and C model tests, PHD is placed at the bottom of the box.

Fig.2 Schematic of model tests

2.3 Model test program

In this study, three different groups of model test (A/B/C) were carried out. Group A had two model tests (A1 and A2), which used PVD and PHD, respectively assisted with flocculants to treat the dredged slurry. Group B (i.e., B1–B6) contained 6 cases of model tests with different amount of APAM. Group C contained 4 cases of model tests (i.e., C1–C4), and each test used a different sedimentation time before starting the vacuum. The detailed test plan is shown in Table 3.

Table 3 Design parameters of model tests

Group No.	Test No.	Drain type	Initial water content / %	APAM content / %	Sedimentation time / h	Preloading pressure / kPa
A	A1	PVD	270	0.30	0	80
A	A2	PHD	270	0.30	0	80
B	B1	PHD	400	0.00	48	80
B	B2	PHD	400	0.05	48	80
B	B3	PHD	400	0.15	48	80
B	B4	PHD	400	0.30	48	80
B	B5	PHD	400	0.45	48	80
B	B6	PHD	400	0.60	48	80
C	C1	PHD	400	0.30	1	80
C	C2	PHD	400	0.30	12	80
C	C3	PHD	400	0.30	24	80
C	C4	PHD	400	0.30	48	80

Note: The APAM content (%) is the mass ratio of flocculant powder to dry soil.

For the group A model tests, 40 cm long model box was used and a drain board with the same length was placed in model box for different cases (Fig. 2). For all model tests, vacuum pressure was applied at the same time and the mass of drained water and soil settlement at different time were recorded. The deformation of the drain board was examined at the end of vacuum preloading. In order to reduce the influence of drain board size effect, the model tests of groups B and C adopted a 60 cm long model box, and were carried out according to the following steps:

(a) Prepare the APAM solution at concentration of 10 g/L, and add the APAM solution to the slurry sample according to the design proportion in Table 3 (applicable to group A); add water content of 400% and then mix the slurry uniformly.

(b) Place the drain board horizontally at the bottom of the model box, pour the mixed slurry into the model box and allow the slurry to settle freely. During this process, we recorded the change of soil-water interface. The sedimentation time of the tests is 48 hours in test group B, and 1, 12, 24 and 48 hours in test group C for different cases.

(c) After the sedimentation, empty the water above the soil surface, seal the model box, and apply 80 kPa vacuum pressure. When the dewatering rate of the slurry is < 10 g/day, the vacuum pressure can be stopped and samples can be taken for subsequent geotechnical property tests.

3 Results and discussion

3.1 Dewatering characteristics of using PHD

The mass of drained water versus time for A1 (PVD) and A2 (PHD) model tests is shown in Fig. 3.

In the beginning 50 hours of the test, the dewatering trends of the two groups were basically the same. However, after 50 hours, the dewatering rate for PHD was significantly higher than for PVD. When using PVD, the dewatering rate slowed down at 50 hours, and the dewatering almost stopped after 150 hours. PHD's dewatering rate was maintained at a relatively high level before 80 hours (a mechanical malfunction caused the vacuum pump to quit working for 15 hours). Even after 150 hours, the dewatering rate of PHD was still high. The final mass of drained water for using PHD was 15011 g, while that for the PVD case was 11 622 g, which was approximately equal to 77.4% of PHD. Compared with the study of Zhou et al[11], it can be seen that initial water content and flocculant may cause a relative change of the dewatering rate of PVD and PHD during the consolidation process. However, both tests verified that treatment of dredged slurry with PHD has higher dewatering efficiency and higher final mass of drained water.

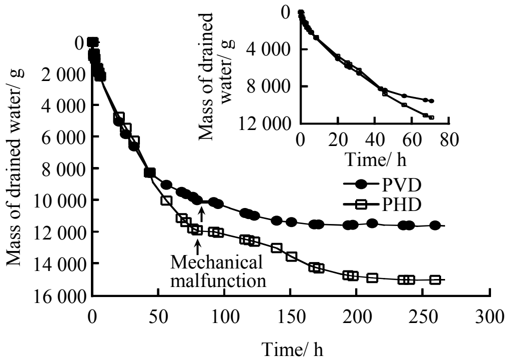
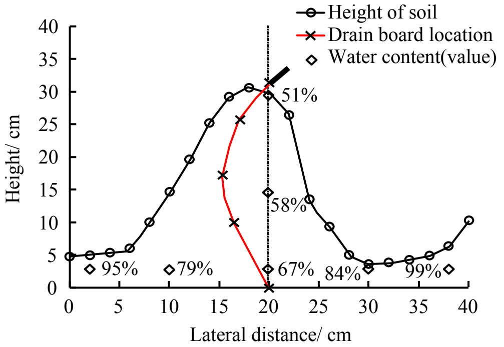


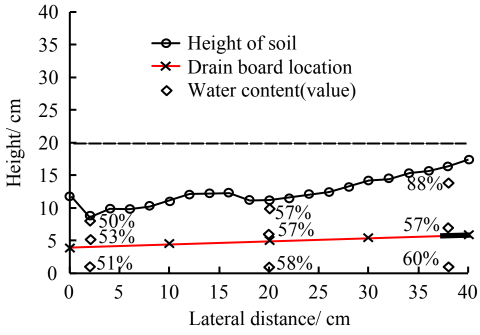
Fig.3 Curves of drained water with time in model tests A1 and A2

After the model test, the deformation and displacement of the drain board (especially PVD) were measured, checked and recorded in detail, and the shape and position of the drain board were described as shown in Fig.4(a) according to the measured data. Due to the bending of the PVD, the drain board shifted to one side with respect to the central axis with a maximum offset of about 5 cm. In contrast, it was found that although PHD was slightly inclined, there was almost no visible bending deformation. The tilt of PHD was mainly due to the small settlement at the joint area caused by weak vacuum transmission and poor dewatering of the soil.

In addition, the height and water content of the soil were measured every two centimeters in the horizontal direction. The results are presented in Fig.4. In the PVD model test, the deformation of the soil was extremely uneven, and the settlement of the soil near the drain board was much smaller than that far away from the board. The maximum differential settlement in PVD model box was about 25 cm. The soil deformations at different sides of the drain board were also different due to PVD bending and deviation, and the soil settlement on one side was greater than on the other side. The soil water content was about 60% near the drain board and was as high as 95–99% away from the drain board. In the PHD model test, the soil settlement and the thickness of the soil on both sides of the drain board (5–7 cm) were evenly distributed in the lateral direction, and the soil water content at almost every location was below 60% (except for one point in the upper right corner). The maximum differential settlement on the surface was about 7 cm, which mainly stemmed from the adverse effect of the joint on the nearby vacuum transmission. In general, the overall settlement of the soil was uniform when using PHD to treat dredged slurry. Moreover, the PHD can settle together with soil, therefore, the drainage distance becomes shorter as the vacuum consolidation progresses.



(a) PVD



(b) PHD

Fig.4 Deformations of soil and drains with water content after tests

3.2 Dewatering characteristics under different flocculant contents

Figure 5 shows the variation curves of soil dewatering volume versus time under different contents of APAM. In the sedimentation stage, the dewatering mass and dewatering rate increased with the increase of APAM content. Through flocculation-horizontal vacuum two-staged dewatering method, more than 22 kg of water was discharged from the slurry in each test, and the water content of the slurry was reduced from 400% to 51%–55%. In addition, we also conducted two sets of free sedimentation model tests (without applying vacuum pressure) as comparison cases. In these two cases, the APAM content was 0% and 0.45%, respectively. The experimental results are also plotted in Fig.5 using dotted lines. It can be seen that the dewatering rate induced by sedimentation is very low, and the final mass of drained water is 13 kg, which is only 59% of that in the flocculation-vacuum combined model test. The test results show that the proposed two-staged method can significantly increase the dewatering efficiency of the slurry. Under the effect of flocculants, fine soil particles coagulate into large particle flocs[12], which can improve the sedimentation rate. However, as reported in previous studies, sedimentation dewatering does not increase indefinitely with the increase of flocculation content, and there exists an optimal content[13]. In this study, for APAM content of 0.45% and 0.6%, the sedimentation dewatering rates of the slurry are almost the same. Therefore, 0.45% can be regarded as the optimal dosage. Excessive addition of flocculant cannot further increase the floc size, because the soil particles cannot provide more adsorption surface for excess APAM molecular chain[12] to form larger floc.

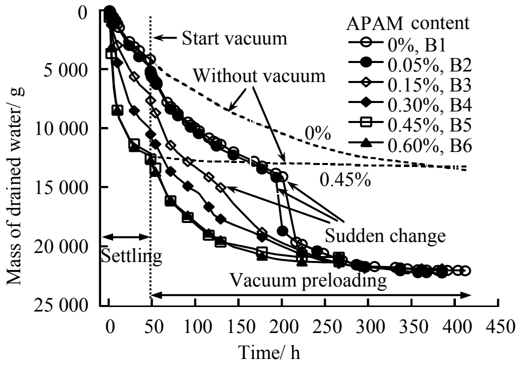


Fig.5 Curves of drained water with time in model tests B1–B6

After applying a vacuum pressure (t > 48 hours), the dewatering rate of each test was significantly accelerated, and the final mass of drained water for tests B1–B6 was similar. However, for the model test with higher content of APAM (tests B5 and B6), the final total settlement was slightly smaller. After the model test, the particle size of the soil near the PHD was analyzed and the results are illustrated in Fig. 6. As the content of APAM increased, the particle diameter also increased, with the average particle diameter D_{50} increasing from 1.8 μm to 25.9 μm for APAM content increasing from 0% to 0.6%. When APAM content is high, the formation of large-size floc will enclose a small amount of pore water in the pores between flocs[14]. Even under a high vacuum pressure (such as 80 kPa), this part of the encapsulated pore water is not easy to be completely discharged. Therefore, the particle size is larger with higher APAM content, which is the reason for the minimum mass of drained water in tests B5 and B6. In general, the time required for the termination criteria of the test (i.e., dewatering rate < 10 g/day) varies with the content of APAM used. The higher the APAM content, the earlier the dewatering ends. For tests B5 and B6, the test termination time is 260 hours, which is 35% shorter than the other tests (approximately 400 hours).

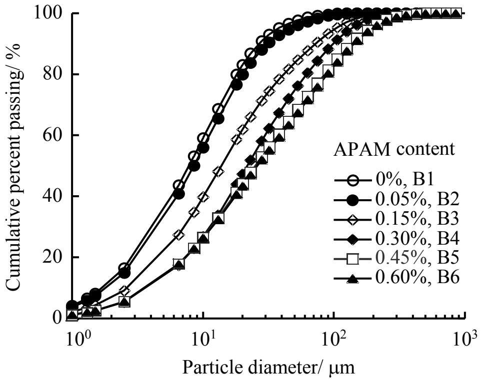


Fig.6 Particle size distributions after vacuum consolidation for B1–B6 model tests

Figure 7 shows the proportion of the mass of drained water in the two dewatering stages, i.e., sedimentation stage versus vacuum consolidation stage. For the case of 400% initial water content and 48 hours sedimentation time, when the content of APAM is higher than 0.45%, about 60% of the water can be drained during sedimentation stage and, as a result, the subsequent vacuum dewatering time and energy consumption are decreased significantly.

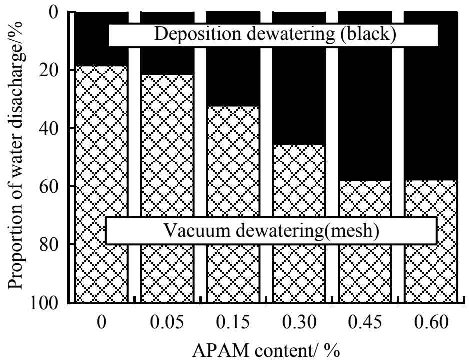


Fig.7 Histogram of dewatering ratio between settling and vacuum consolidation

Figure 8 shows the mass of drained water with time under different contents of APAM in the vacuum consolidation stage. Since the supernatant above the soil surface was removed after 48 hours of sedimentation, the slurry in each test had different water contents before applying vacuum pressure. Taylor[15] reported that the permeability of the soil is mainly determined by the water content, but in the initial stage of consolidation in our tests (before $t = 80$ hours), there is no significant difference in the dewatering rate of the soil with different water contents. Therefore, it can be considered that the soil in each model box has similar permeability. It can be seen that when the APAM content is high (e.g., B5 and B6), even if the soil water content is low, the permeability of the soil can be increased by the flocculation effect. After 140 hours of vacuum preloading, the dewatering rates of tests B5 and B6 gradually decreased and became stable. In addition, as shown in Figs.5 and 8, for tests B1–B3 (0–0.15% APAM), sudden changes in the mass of drained water were observed, and the times of the sudden changes were about 155, 145, and 80 hours, respectively, after the start of model test (Fig.5). In a short period of time (between two monitoring times, about 10 hours), the sudden change in the mass of drained water is 5559 g, 4623 g and 3770 g, respectively. However, there was no sudden change observed in tests B4, B5 and B6, and the dewatering curves decreased steadily and became stable gradually. The reasons for the sudden change of the dewatering rate in tests B1~B3 are as follows.

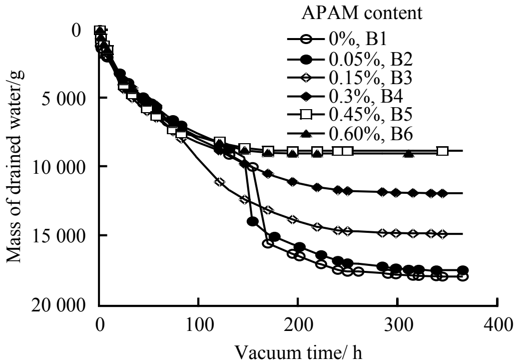


Fig.8 Curves of drained water with time during vacuum consolidation stage

Several studies[16] have shown that the distribution of stress in the soil during the consolidation process is non-uniform, especially in the early stage of consolidation, the vacuum pressure can fully act on the soil near the drain board for a short time, but not on the soil far away from the drain board and the densified soil near the drain board will further delay the drainage of distant pore water which is not conducive to consolidation of faraway soil. The research of Zhou and Chai[17] suggested that the higher the soil water content, the more obvious the phenomenon of non-uniform consolidation, and the greater the impact on the consolidation dewatering. In PVD consolidation, the problem of non-uniform consolidation is manifested by the phenomenon of 'soil pillars'. In this study, after the vacuum was applied, the soil would be 'stratified', i.e., the 'lower layer' was the vacuum consolidation zone, the 'upper layer' was the self-weight consolidation zone, and the boundary between the upper and lower layers was called seepage frontline [17]. Zhou et al.[18] and Liu et al.[19] further pointed out that the seepage frontline will extend into the soil body further away from the drain board. For tests B1–B3, due to the low content of flocculant, the sedimentation of the slurry was not finished after 48 hours of sedimentation. After the vacuum pressure was applied, the slurry above the seepage frontline was significantly deposited and a water layer was formed above the soil surface, whereas the soil below the seepage frontline was mainly consolidated under vacuum and produced large lateral deformation, resulting in cracks between the soil and the box wall. When the seepage frontline extended to the upper soil layer with high water content or the supernatant layer, the side cracks were connected, resulting in a large amount of supernatant to be drained out in a short period of time. The movement of the seepage frontline is directly affected by the soil permeability parameters (e.g., coefficient of permeability, and initial hydraulic gradient)[20]. In tests B1–B3, the slurry in the initial stage of the vacuum consolidation had high water content and the nonuniform consolidation was obvious. A dense soil layer was formed near the PHD, which affected the movement of the seepage frontline. The soil property can be improved with increasing the APAM content. Higher flocculation effect yielded faster movement of the seepage frontline and shorter time required for the connection of the 'upper layer' and 'lower layer'. For tests B4, B5, and B6, firstly, the water content in the initial stage of vacuum consolidation was lower than that of B1–B3, and non-uniform consolidation was not obvious; secondly, due to the addition of a higher content of APAM, the permeability of soil was improved markedly, the seepage frontline can be transmitted to the upper edge of the soil in a very short period of time, and the soil was quickly consolidated. Even if the supernatant (if any) was generated, it can be drained in time by the vacuum pressure.

3.3 Dewatering characteristics under different sedimentation time

In the group C model test, the relationship between sedimentation time and mass of drained water is manifested in Fig.9. Generally, the effect of sedimentation time on the final mass of drained water is not significant (the difference between the final mass of drained water of tests is within 0.5%), but the sedimentation time has significant effect on the dewatering rate. In simple words, the longer the sedimentation time is, the faster the soil dewatering in the vacuum stage. The total time required to complete the dewatering of the slurry with a sedimentation time of 1, 12, 24, and 48 hours under vacuum pressure is 400, 390, 222, and 216 hours, respectively. Since the total dewatering time corresponding to the sedimentation time of 24 hours and 48 hours is very close, after the static sedimentation time exceeds 24 hours, increasing the sedimentation time cannot further increase the dewatering rate. When the sedimentation time is 1 hour and 12 hours, APAM has no sufficient time to fully mobilize the effect of flocculation and, in this case, the total dewatering time is much longer than the other two tests (C3 and C4), and the delamination phenomenon occurs in the C1 test. Since sedimentation only lasts 1 hour, the water content of the slurry is still very high in test C1, the slurry with high water content will cause significant non-uniform consolidation, and consolidation dewatering and sedimentation dewatering will occur at the upper and lower parts of the slurry, respectively, forming obvious 'stratified' until the side cracks are connected and the water above the soil is drained. The above facts indicate that the starting time of the vacuum application has a great impact on the consolidation performance. On the one hand, if the vacuum preloading is applied too early, APAM cannot fully mobilize the role of flocculation, and the non-uniform consolidation and the delamination (such as the test C1) caused by the high water content of the slurry before the vacuum application will reduce the consolidation rate. On the other hand, if the vacuum preloading is applied too late, the total construction time would be extended. The results of model test show that the optimum sedimentation time is about 24 hours.

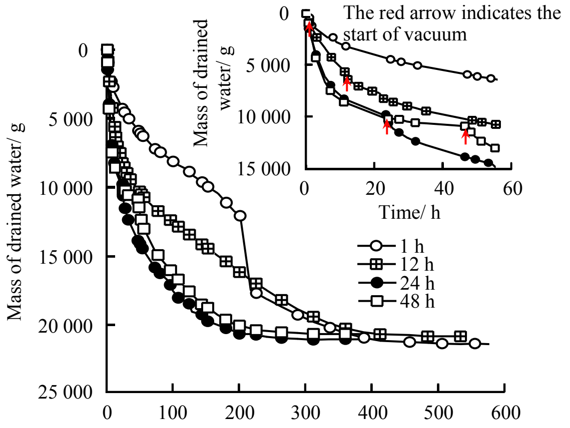


Fig.9 Curves of drained water with time in model tests C1–C4

4 Conclusions

The performance of two-staged dewatering method that combines flocculation and vacuum-assisted prefabricated horizontal drain (PHD) was proposed and verified through a series of model tests on the treatment of high-water-content dredged slurry. The following conclusions can be drawn:

(1) The comparative test on the PHD and PVD shows that the PHD has better dewatering efficiency than the PVD when vacuum preloading is used to dewater the high water content dredged slurry. The test results show that the total mass of drained water for using PVD is only about 77.4% of that using PHD.

(2) The proposed flocculation and vacuum-assisted PHD method can greatly improve the dewatering efficiency. The test results show that, compared with the vacuum preloading method without flocculation, the flocculant can reduce the dewatering time by up to 35%. Compared with the test with only sedimentation (no vacuum), the amount of dewatering caused by vacuum pressure is 1.67 times that caused by sedimentation. In other words, sedimentation-induced amount of dewatering is 60% of that by vacuum preloading. The proposed method can improve the treatment performance in terms of dewatering efficiency and the total magnitude of dewatering.

(3) There is an optimal content of flocculant. Too little or excessive amount of flocculant cannot yield the best sedimentation rate of slurry. With the optimal content of flocculant, not only the sedimentation-induced dewatering is significantly improved, but also the negative effect of non-uniform consolidation during vacuum preloading stage is alleviated.

(4) The duration of sedimentation with flocculant has a significant effect on the subsequent vacuum preloading behavior. The test results show that when the sedimentation duration is less than 24 hours, the dewatering efficiency is not good. While when the sedimentation duration is more than 24 hours, the final dewatering rate is not further increased. Therefore, for the tests conducted in this study, 24 hours appears to be the optimal sedimentation duration.

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