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Experimental study on treatment of waste slurry by vacuum preloading with different conditioning agents

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Abstract. In China, serious environmental problems are induced by the extremely soft construction waste slurries in many urban areas, and there is no appropriate method to treat it presently. In this paper, four model tests were conducted to investigate the efficiency of waste slurry treatment by combining three conditioning agents which can change characteristics of the slurries with a traditional vacuum preloading method. The tests of size analysis of particle aggregate were conducted to investigate the influence of different conditioning agents on the size distributions of particle aggregate. During the model test, the discharged water volumes were monitored. The pore-size distribution and void ratio of the waste slurries after the vacuum preloading were measured by mercury intrusion porosimetry (MIP). It is found that 1) During the natural precipitation, volume of water out of the organic agent is higher than that of the mixed agent, but it is smaller than that of the mixed agent in the vacuum preloading stage; 2) the mixed agent has a higher total volume of water out than the organic agent and the inorganic agent after test, while the organic agent and the inorganic agent have little difference with respect to the drainage effect. The results demonstrate that the combination of mixed conditioning agent and vacuum preloading for the solid-liquid separation in waste slurry has a satisfactory effect and can be applied in engineering practice.

Keywords: conditioning agent; flocculation; skeleton effect; vacuum preloading; waste slurry

1. Introduction

Engineering waste slurry, a kind of liquid waste caused by underground engineering construction, is a dispersion system with high water content, high porosity and many suspended particles. The suspended particles in the waste slurry are subjected to both electrostatic repulsion and electrostatic attraction. The electrostatic attraction prompts the suspended particles to form aggregates, and the electrostatic repulsion prompts the concentration of the suspended particles to be more uniform. When the electrostatic repulsion equals the electrostatic attraction, the slurry dispersion system reaches an equilibrium state. The smaller the soil particles sizes are, the longer the time required to precipitate them. Normally the engineering waste slurry remains in the initial dispersed orientation state for a long time, at least 1~2 years. Even if the solid-liquid separation occurs in the slurry, the bottom part of the supernatant is still a high concentration suspension system with water contents ranging from 120% to 200%. If these waste slurries, which have colloidal properties, are abandoned on the beach, river or ocean without treatment, the environment will be seriously polluted over time. Waste slurry disposal is a serious problem (Zhang *et al.* 2011).

The treatment of the waste slurry changes the slurry dispersion system from the initial dispersed orientation state to a solid-liquid separation state; normally appropriate agents are added to the slurry to promote this process (Bolto and Gregory 2007, Lee *et al.* 2015, Zhu *et al.* 2012, Zumsteg *et al.* 2013, Lentz 2015). The agents can destabilize the slurry dispersion system by changing the charging characteristics of the suspended particles and the contact relationships between the particles (Li and Zong 2010), which is called a conditioning function. The solid-liquid separation of slurry is not only related to the particle composition, the water content and the mineral component but also to the type and amount of the added agent. However, the slurry after agent-conditioning (Adding conditioning agent and making some changes on characteristics of slurry such as permeability call agent-conditioning in this paper) still has high water content and cannot reach the bearing capacity required for actual projects. Thus, further solid-liquid separations are needed, and the added agent is a vital factor in determining the final treatment effect.

The vacuum preloading with flocculation for the solid-liquid separation of waste slurry is a method where agents are first added to the slurry, and then the vacuum preloading is implemented to further reduce the water content. The treated slurry can be utilized as foundation soil (Zhao *et al.* 2016). The vacuum preloading method, which is one of the most efficient and cost-effective ground improvement and land reclamation method, is very mature in theory and practice and is suitable for the improvement of large area foundations (Chu *et al.* 2000, Mohamedelhassan and Shang

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2002, Chai *et al.* 2005, Li *et al.* 2007, Indraratna *et al.* 2009, Saowapakpiboon *et al.* 2010, Mesri and Khan 2012, Ong *et al.* 2012). For waste slurries with high water content, it is necessary to add agents to reduce the water content of waste slurries to target values before the vacuum preloading is implemented. In the previous research (Wu *et al.* 2017), the effect of APAM as the agents for the treatment of slurry was investigated. But the added agents have different conditioning functions, thus leading to different treatment effects. Study on the conditioning functions of agents is insufficient; therefore, vacuum preloading tests are implemented on the inorganic agent-conditioned, organic agent-conditioned, mixed agent-conditioned and non-conditioned slurries in this investigation. Agent-conditionings are investigated by comparing the discharged water volumes, water contents, particle aggregate size distributions, characteristics of slurry flocs, pore-size distributions and unconfined compression strengths of the waste slurries.

2. Materials and methods

2.1 Waste slurry and agents

The used waste slurry in tests was selected from a drilled shaft construction site located in Shanghai. Before the tests, the properties and mineral composition of the slurry were investigated; the investigation results are shown in Table 1. The slurry is a liquid with a water content of 146.74% and a unit weight of 12.85kN/m3. In the slurry, the primary minerals (mostly quartz, feldspar, calcite, hornblende and dolomite) account for 61%, and the secondary minerals (mostly clay minerals such as illite and kaolinite) account for approximately 39%, excluding montmorillonite. The sand content, silt content, clay content and colloidal particle content are 7.49%, 63.8%, 14.05% and 14.66%, respectively, for the slurry in this paper; the slurry particles are mostly fine particles.

The organic agent used in this test is anionic polyacrylamide (referred to as APAM), produced in Henan, China which has a molecular weight of 20 million and a solid content of 88%. The inorganic agent used in this test is calcium oxide (CaO), produced in Shanghai, China. CaO is finely ground, with purity of 96% and fineness of 200 mesh.

APAM is a kind of organic polymer flocculants. After the hydrolysis, there are polar amide groups (-$CHNH_2$) on the long chains of the polymer. These polar amide groups coalesce the small soil particles into larger particle aggregates and precipitate, thus promoting the solid-liquid separation of the slurry. In addition, there is also cationic polyacrylamide (referred to as CPAM). CPAM has a bridging function and has roles in neutralization due to its positive electric charges. The electrostatic repulsion between soil particles is decreased by the charge neutralization. The soil particles are easier to aggregate and flocculate with CPAM-conditioning compared to APAM-conditioning. CPAM was not used in this investigation mainly due to its relatively high cost.

CaO is generally used as a curing agent. The reaction between CaO and water in the slurry generates Ca(OH)2; the cementitious compounds produced by the Ca(OH)2-slurry reactions are calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). The water stabilities of CSH and CAH are good. When the concentrations of CSH and CAH are in moderate, they attach to the soil particles and form connected network structures. The connected network structures are not easy to compress due to their strength and have good permeability due to their relatively large pores. When the concentrations of CSH and CAH reach certain values, the flow channels of the network structures are further blocked and the permeability of the network structures decreased.

2.2 Analysis for the effects of agents on drainage analysis

The effects of the different agents on the drainage were checked by the model test and the sketch of model is shown in Fig. 1. The model boxes made of organic glass are an open cylindrical shape; the dimensions are 50 cm×50 cm (diameter × height). The sealing covers used in the tests are discs with dimensions of 48 cm×2 cm (diameter × height) and are also made of organic glass. Two rubber sealing rings were set between each model box and sealing cover to prevent leakage. The filter pipe is composed of a geotextile with an equivalent pore-size of 180 μm and a wire spring with a diameter of 2 mm. Due to slurry consolidation, the spring would be compressed longitudinally, and the geotextile between adjacent spring coils would shrink along the radial inwards to a diameter of 1.5 cm. Therefore, the distance between the nearest sampling monitoring points and the centre line is 1.5 cm. During vacuum preloading, the top surfaces and the bottom surfaces of the model boxes are impermeable, and thus the slurries can be considered under a radial drainage condition.

The cases done in this paper are shown in Table 2. During the test, CaO was added into the slurry directly. APAM was first hydrolyzed to a 0.2% concentration and then added to the slurry. The slurries in case B, C and D are conditioned with CaO, APAM and the mixed agent of CaO and APAM, respectively. Case A utilized non-conditioned slurry as a reference test. And the test producers were as following: slurry samples of equal volume (62.4 L) were poured into the four model boxes. The slurries were stirred evenly first, and the agents were then added at a uniform speed during stirring to ensure complete reaction between the slurries and the agents. The amounts of the agents added are shown in Table 2. The addition amounts of CaO and APAM were determined from a series of settling column tests. The results show that the best flocculation efficiency could be achieved if only the APAM was added and that CaO has infiltration and skeleton effect (CaO can strongly bond several particles and formed the aggregate which has strong strength like skeleton). After being mixed evenly with the agents, the slurries stood for 48 hours. Slurry surface settlements and supernatant volumes versus standing time were monitored. After completion of the standing precipitation, the supernatant was discharged. Then, the vacuum preloading tests were implemented on the slurries; the degree of vacuum in the suction bottles, the water volumes in the suction bottles and the settlement

Table 1 Physical parameter of the waste slurry

Physical index	Initial water content (%)	Unit weight (kN/m^3)	Liquid limit (%)	Plastic limit (%)	>0.075mm (%)	0.075~0.005mm (%)	0.005~0.002mm (%)	<0.002mm (%)
Value	146.74	12.85	36.57	22.95	7.49	63.8	14.05	14.66

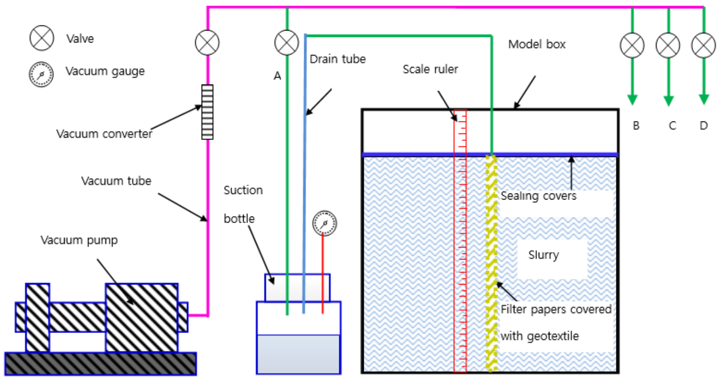


Fig. 1 Sketch of model test

Table 2 Cases done in the test

Case	A	B	C	D
Slurry volume (L)	62.4	62.4	62.4	62.4
CaO (g)	0	163.64	0	163.64
APAM (L)	0	0	9.36	9.36

values of the top surfaces were recorded in the process of vacuum preloading.

2.3 Determination of size distribution of particle aggregate

In order to investigate the effect of agent-conditioning on the variation of particle aggregate size, the particle aggregate size distributions of agent-conditioned slurries were tested. Considering that the flocculation was easy to destroy, the particle aggregate sizes were checked by the wet sieving and hydrometer method. The samples were standing for 24 hours after adding the agents. And then the wet sieving was used for checking the particle aggregate sizes which are bigger than 0.075mm and the hydrometer method was used in the particle aggregate analysis for the sizes which are smaller than 0.075mm.

The original pH value of slurry was 7.9. After adding the CaO, the pH value changed and affected the flocculation effect of APAM. For investigating the effect of pH, the flocculation effect of APAM were checked under different pH values (7.9, 8.4. 10.8 and 11.8) by particle aggregate size analysis. The pH value in the soil was measured using a pH meter (AZ8685)

2.4 Microscopic characteristics of slurry flocs

To show the influence of the structural characteristics of slurry flocs on the vacuum preloading effect, the agent-conditioned and non-conditioned slurries were observed by SEM tests, to investigate the microstructures of the slurries qualitatively. The test samples were got before vacuum preloading.

2.5 Pore-size distribution analysis

Soil is a three-phase body with solid, liquid and gas, and it has a certain degree of compressibility due to the large number of pores in it. The pores in the soil have different sizes and shapes. To facilitate the quantitative study, the soil pores are defined at five levels (Yuan 2012): ultra-large pores (d > 40 μm), macropores (4 μm < d < 40 μm), medium pores (0.4 μm < d < 4 μm), small pores (0.04 μm < d < 0.4 μm) and micropores (d < 0.04 μm).

After the vacuum preloading, the agent-conditioned slurries show different pore-size distribution characteristics. To investigate the pore-size distribution characteristics of the slurries, the void ratios of the slurries after the vacuum preloading were obtained by MIP. The MIP test instrument used in this test is Mike AutoPore IV 9500 mercury porosimetry, which is made in the USA. The surface tension and electrical conductivity of liquid mercury are the main factors that affect the veracity of the MIP test result. Due to the quantitative relationship between the mercury injection pressure and the corresponding soil pore diameter, the MIP test can be used to quantitatively analyze the soil pores.

"The mercury injection pressure is balanced by the surface tension", based on the theory, Washbum determined the relationship between the pore radius and the mercury injection pressure

$$P \cdot r = 2\sigma \cdot \cos\theta \tag{1}$$

where P is the mercury injection pressure, r is the pore radius corresponding to the mercury injection pressure, σ is the surface tension of mercury, generally 0.485N/m, and θ is the wetting angle between mercury and porous material, generally 130°~142°. σ and θ are constant; thus, P is inversely proportional to r, which means small pores need high mercury injection pressures and large pores need low mercury injection pressures. Based on the measured mercury injection pressures, the pore-sizes can be calculated.

2.6 Unconfined compression strength analysis

Shear strength of slurry is of a vital concern in subsequent load of manual operation after vacuum preloading. After vacuum preloading, the unconfined compression strength tests were implemented on the slurry samples that were sampled from different points (9 cm and 18 cm from the centre) in the model boxes. And the unconfined compression test device (YYW-II) was used for checking.

3. Test result and discussion

3.1 Effects of agents on drainage

The variations in the discharged water volumes with time during the standing precipitation and vacuum preloading are shown in Fig.2. It is obvious that 1) in the standing precipitation stage, the non-conditioned slurry has the slowest solid-liquid separation speed, the longest solid-liquid separation time and the least supernatant volume (3.85 L); 2) the CaO-conditioned slurry has faster solid-liquid separation than the non-conditioned slurry and discharged more supernatant (approximately 10 L); 3) the mixed agent-conditioned slurry has faster solid-liquid separation compared to the CaO-conditioned slurry and tends to stabilize after 30 hours of standing. The supernatant volume of the mixed agent-conditioned slurry is approximately 20 L including the additional 9.36L water from 0.2% APAM which was added into the slurry; 4) the APAM-conditioned slurry has the fastest solid-liquid separation and tends to stabilize after 30 hours of standing. The supernatant volume of the APAM-conditioned slurry is the largest, which is approximately 30 L (including additional 9.36L water from APAM).

The possible reason is that the particle aggregate size of slurries changed after the agent-conditioning. The particle aggregate size of case C was the biggest, and thus the particle aggregate sedimentation rate for case C was the biggest during the standing stage. Hence, the solid-liquid separation rate and discharged water volume for case C was the biggest during the standing stage.

In the vacuum preloading stage, the water discharge rate of the mixed agent-conditioned slurry is the fastest, followed by the CaO-conditioned slurry. The water discharge rate of the non-conditioned slurry is slightly faster than that of the APAM-conditioned slurry.

The possible reasons are: For case D, the network structures of the CAH and CSH, acting as frameworks, have

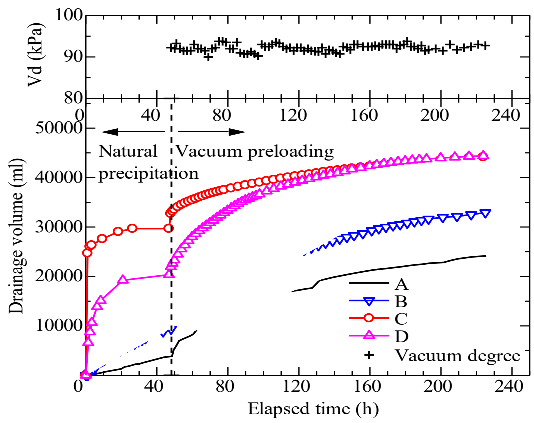


Fig. 2 Discharged water volume versus time (Vd: Vacuum degree)

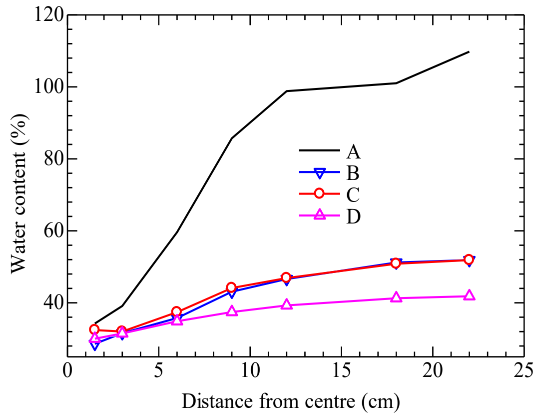


Fig. 3 Variations in water content of the slurries with distance from centre

high compression strengths and enhance the permeability of the waste slurry. Second, the lubrication function of the APAM facilitates the water flow in the slurry. The superposition of these two effects leads to an extremely fast water discharge rate in the early stage of the vacuum preloading. In the wake of the slurry consolidation, the pores between the flocs are gradually compressed, and thus the permeability coefficient and the water discharge rate of the slurry are decreased. For case B the CaO-conditioned slurry also has the connected network structures of CSH and CAH, but the void ratios of the structures are small. The permeability coefficient is small and the water flow resistance is relatively large for the CaO-conditioned slurry. In the early stage of the vacuum preloading, the water discharge rate of the CaO-conditioned slurry is smaller than that of the mixed agent-conditioned slurry, but the water discharge rates of the slurries become similar with the decreasing permeability coefficient of the mixed agent-conditioned slurry. For case C, most of the water has been discharged in the standing precipitation stage. The discharged water volume is the least, the water discharge rate is the slowest and the pore-water is difficult to discharge for the APAM-conditioned slurry during the vacuum preloading. This is due to the following two reasons: First, the lubrication function of the APAM reduces the flow resistance of the water in the slurry, which enhances the water discharge in the standing precipitation stage. Second, the APAM polymer chains are relatively soft and the fluffy flocculent structures composed of the APAM polymer chains and soil particle aggregates are easy to compress; thus, the permeability coefficient of the APAM-conditioned slurry decreases rapidly during the vacuum preloading.

Fig. 3 shows the variations in the water contents along the radial direction. For the non-conditioned slurry, the water content increases with an increasing radial distance from the centre, i.e., the water content increases from 34.2% (1.5 cm from the centre) to 101% (18 cm from the centre). The water content has a relatively large variation along the radial direction, which means that the non-conditioned slurry has a low permeability coefficient. The mixed agent-conditioned slurry has the lowest water content and the mildest variation in water content along the radial direction. The water content changes from 30% (1.5 cm from the centre) to 41.3% (18 cm from the centre), which demonstrates that the permeability coefficient of the slurry along the radial direction is relatively large and there is no clogging near the filter pipe. The water contents of the CaO-conditioned and APAM-conditioned slurries are similar and stand between those of the non-conditioned and mixed agent-conditioned slurries.

3.2 The size distributions of particle aggregate of original and agent-conditioned slurries

Fig. 4 shows the particle aggregate size distribution curves of the original and the agent-conditioned slurries (by the wet sieve and hydrometer method). For the APAM-conditioned slurry, the soil particle aggregates in the size range of 0.6mm to 3mm have the biggest increment.

The CaO-conditioned slurry has no obvious variation in the soil particle aggregate size, and only the sizes of the original small particle aggregate increased slightly. The soil particle aggregate size of the CaO-conditioned slurry tends to be more uniform. The soil particle aggregate size curve of the mixed agent-conditioned slurry is located between those of the APAM-conditioned and CaO-conditioned slurries. According to the Stokes formula, the settling velocity of a particle is proportional to the square of the particle size. Hence, the settling velocity of soil particle aggregates is the fastest in the APAM-conditioned slurry, which caused the fastest solid-liquid separation rate of APAM-conditioned slurry during standing as shown in the Fig. 2.

In addition, the particle aggregate size of mixed agent conditioned slurry is smaller than that of the APAM-conditioned slurry. The possible reason is that CaO wasadded at first and the pH value increased which made the pH condition in the slurry become alkali. To determine the influence of pH value on the flocculation effect of APAM, the particle aggregate size distributions of APAM-conditioned slurries with different pH values were checked and shown in Fig.5. It can be found that the particle aggregate size increased with the decrease of the pH value. And the same trend was reported by Li (2016). The reason is that if the pH value is bigger than 7, OH- in the slurry will be attracted by the particle and form protective layer

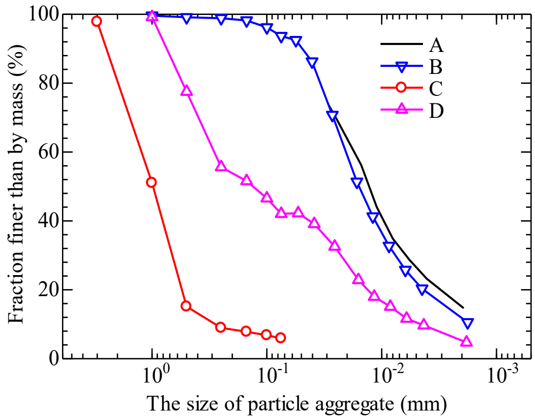


Fig. 4 The size distributions of particle aggregate

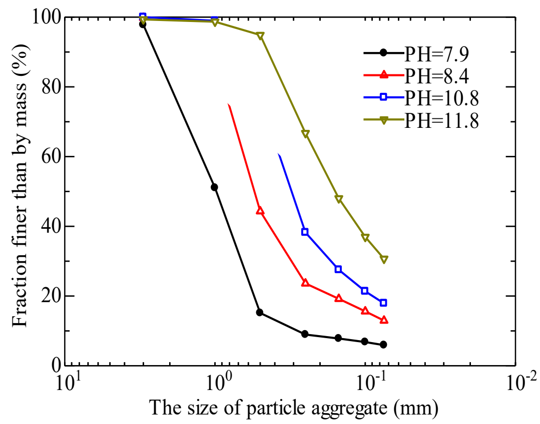


Fig. 5 The size distributions of particle aggregate with different pH values

which make the combination between flocculants and particles difficult.

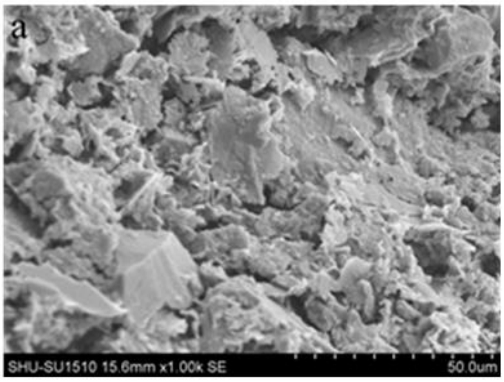
3.3 Microscopic characteristics of slurry flocs

Fig. 6 shows the SEM images of the original, CaO-conditioned, APAM-conditioned and mixed agent-conditioned slurries before vacuum preloading.

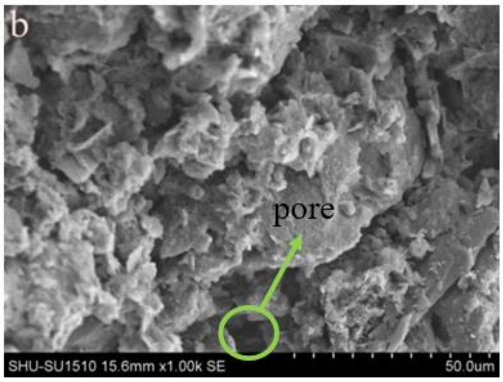
As can be observed from Fig. 6(a), most of the soil particles are small, isolated and angular, some of the small particles adhere to large particles, and a number of the soil particles pile together. There are different contact types between the particle aggregates: edge-edge, angular-angular and edge- angular. The original slurry has loose structures with a large amount of large pores linking together.

Fig. 6(b) is the SEM image of the CaO-conditioned slurry. The number of small and angular particle aggregates in the slurry decreases and the particle aggregates tend to be passive and uniform, which is due to the particle aggregation caused by the cation exchange and the compressed double electric layer effect. This result is coincident with that of the particle aggregate size analysis from Fig. 4. There are a large number of large pores linking together in the CaO-conditioned slurry.

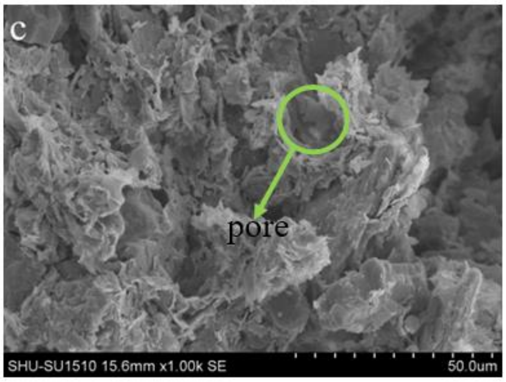
Fig. 6(c) is the SEM image of the APAM-conditioned slurry. There are many intertwined flocs, angular flocs, large particle aggregates with close structures and pores of



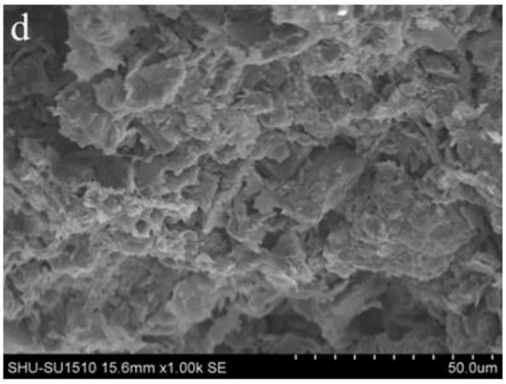
(a) Original slurry



(b) CaO-conditioned slurry

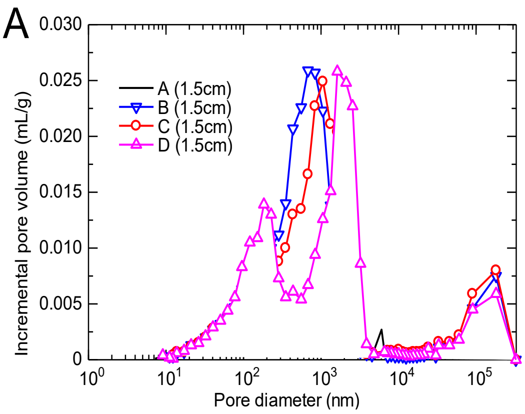


(c) APAM-conditioned slurry

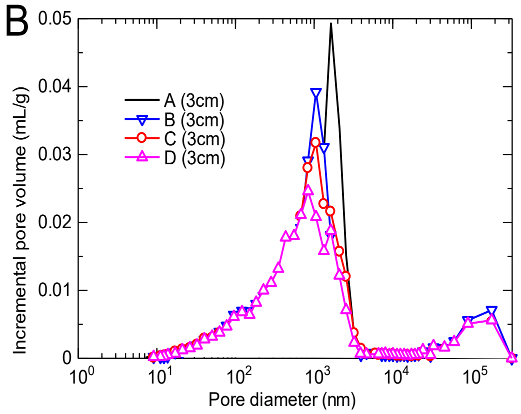


(d) Mixed agent-conditioned slurry

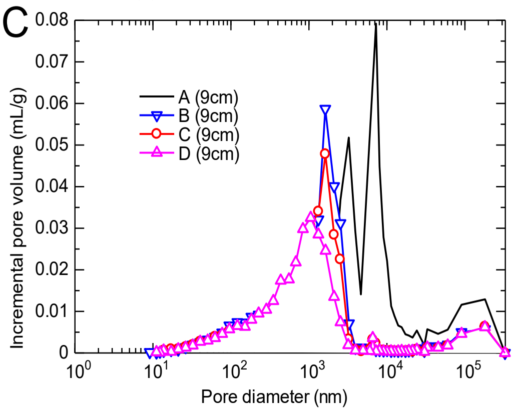
Fig. 6 Picture of SEM before vacuum preloading



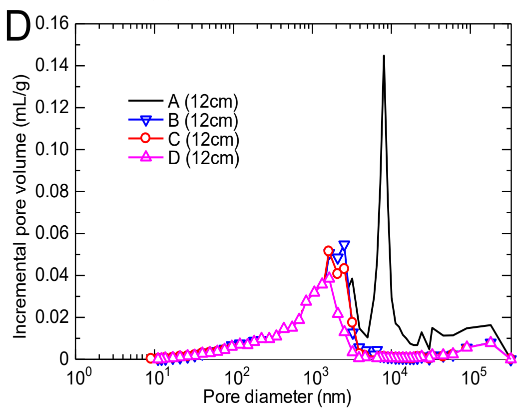
(a) 1.5 cm from centre



(b) 3 cm from centre



(c) 9 cm from centre



(d) 12 cm from centre

Fig. 7 Pore-size distributions after vacuum preloading at different monitoring points different sizes in the slurry. Many soil particles are absorbed by the polar amide groups (-$CHNH_2$) on the floc long-chains of the APAM. During the stirring and sinking of the slurry, the floc long chains were twined to each other and formed group flocs. The pores inside the group flocs are small, and thus the structures of the group flocs are relatively compacted, but the pores between the floc groups are relatively large.

Fig.6(d) is the SEM image of the mixed agent-conditioned slurry. The slurry has imperceptible flocculent structures but obvious lamellar structures. Due to the passivating effect of the CaO, the particles in the slurry have relatively close connections and unobvious edges. During the standing precipitation, some of the soil particles precipitated without being adsorbed on the APAM long chains; thus, there are both group flocs and small particles in the slurry. The flocculation effect of the mixed agent is worse than that of APAM.

3.4 Pore-size distribution of original and agent-conditioned slurries after vacuum preloading

Fig. 7 shows the pore-size distributions of the slurries at each monitoring point in the model boxes. Fig. 6(a) shows the pore-size distributions of the slurry samples at 1.5 cm from the center. It can be seen from the curves that 1) curve D has three peaks and the other three curves have two peaks, which are near 1 μm and 100 μm. The peaks near 100 μm are caused by the pores on the surfaces of soil particle aggregates, which cannot reflect the pores inside the soil particle aggregates. 2) The majority of pore-sizes of the non-conditioned, CaO-conditioned and APAM-conditioned slurries range between 0.4 μm and 1 μm and are mainly medium pores. The majority of pore-sizes of the mixed agent-conditioned slurry range from 0.1 to 0.3 μm and 0.8 to 3 μm, which are medium pores and small pores. The pore size difference within the mixed agent-conditioned slurry is caused by the soil particle aggregates with great size differences. The small soil particles near the filter pipe flow away through the pores between the group flocs, which increase the pore sizes between the group flocs. During the flowing, part of the small particles is detained somewhere in the slurry; thus, the pore-sizes of the slurry at these positions are decreased, which is similar to the piping phenomenon. 3) These four curves illustrate that most of the pores in the slurry samples are medium and small pores. The void contents of the slurry samples at 1.5 cm from the center are all less than 0.025 mL/g. The pore-sizes corresponding to the peaks of pore-size distribution curves are all less than 1 μm (except test D), which means the slurries are very dense.

Fig. 7(b) shows the pore-size distributions of the slurry samples at 3 cm from the centre. It can be seen from the curves that the non-conditioned slurry has the largest pore-sizes and the highest macropores content, followed by the CaO-conditioned, APAM-conditioned and mixed agent-conditioned slurries; the pore-sizes of these three slurries are medium pores. The maximum void content of the samples ranges between 0.25 mL/g and 0.05 mL/g and are approximately double those of the samples at 1.5 cm from the centre, which means the samples at 3 cm from the centre are looser than the samples at 1.5 cm from the centre.

Fig. 7(c) shows the pore-size distributions curves of the slurry samples at 9 cm from the centre. The pore-size distribution regularities of the samples at 9 cm and 3 cm from the centre are identical, but the non-conditioned slurry has a larger difference with the agent-conditioned slurries for the slurry samples at 9 cm from the centre. For the non-conditioned slurry at 9 cm from the centre, the pore-size corresponding to the peak of the pore-size distribution curve is 6 μm (belonging to the macropores group). The pore-size distribution regularities of the samples at 12 cm and 9 cm from the centre are identical, but the slurry samples at 12 cm from the centre have larger pore-sizes and more macropores. The maximum void contents of the samples at 12 cm from the centre range between 0.04 mL/g and 0.15 mL/g.

Fig. 8 shows the distributions of the void ratios along the radial direction for these four slurries. The void ratios are obtained by the MIP test. It can be seen from the curves that (1) the void ratios increase with increasing radial distances from the centre inside 12 cm. Curve A has two segments, and the void ratio of the non-conditioned slurry increases sharply beyond 9 cm from the centre. For the other three curves, the void ratios and the radial distances from the centres show linear relationships; (2) the void ratio of the non-conditioned slurry has a sharp variation along the radial direction and the curve has an inflection point at 9 cm from the centre, which means that the drain channels may be clogged at this position. The void ratios of the agent-conditioned slurries are changed gently, which means that the influence scope of the vacuum degree is relatively large for the agent-conditioned slurries; (3) at 1.5 cm from the

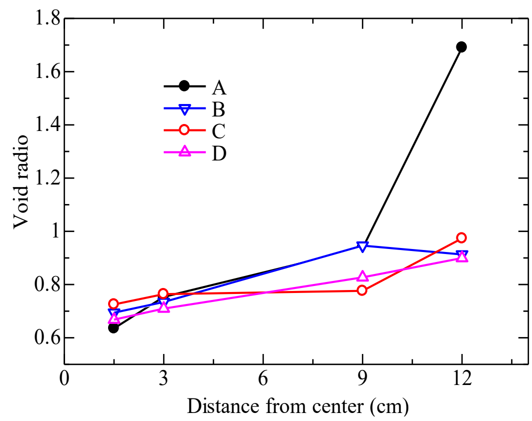


Fig. 8 Void ratio distribution for four different cases

Table 3 Unconfined compression strength and corresponding water content

Model box	A		B		C		D	
Centre distance (cm)	9	18	9	18	9	18	9	18
Unconfined compression strength q_u (kPa)	/	/	/	/	22.81	12.67	67.65	51.56
Water content w (%)	85.7	101	43.1	51.2	44.1	50.8	37.4	41.3

"/" denotes that the slurry is in flow state and cannot be used for the unconfined compression test centre, the non-conditioned slurry has the smallest void ratio (0.64), while the void ratio of the mixed agent-conditioned slurry is 0.67. At 9 cm from the centre, the void ratio of the non-conditioned slurry is 0.94, while the void ratio of the mixed agent-conditioned slurry is 0.83. At 12 cm from the centre, the non-conditioned slurry is the largest (1.69), while the void ratio of the mixed agent-conditioned slurry is the smallest (0.90). The slope of curve D is thesmallest compared to the other three curves, which means that the void ratio of the mixed agent-conditioned slurry has no evident variation along the radial direction.

The MIP tests verify the conclusion of water discharge from the perspective of the pore-size variation and explain the reason why the mixed agent-conditioned slurry has a better drainage effect. The hydration products of the CaO-water reaction serve as skeletons between the soil particles. Thus the mixed agent-conditioned slurry can maintain a void ratio with little variation along the radio direction and a good permeability during the vacuum reloading.

3.5 Unconfined compression strength

The unconfined compression strength was listed in Table 3. It can be found that the non-conditioned slurry is in a flow state, with q_u being 0. The CaO-conditioned slurry has a certain strength but it is still in a relatively loose and soft plastic state, with q_u being 0. The APAM-conditioned slurry has a certain strength; the q_u at 9 cm and 18 cm from the centre are 22.81 kPa and 12.67 kPa. The mixed agent-conditioned slurry has the highest strength; the q_u at 9 cm and 18 cm from the centre are 67.65 kPa and 51.56 kPa, which means that the mixed agent can significantly improve the cohesion of the slurry.

Table 3 also lists the water contents of the slurry samples, the CaO-conditioned and APAM-conditioned slurries have similar water content at the corresponding positions. The APAM-conditioned slurry has slightly higher water content than the CaO-conditioned slurry at 9 cm from the centre, but the q_u of the CaO-conditioned slurry is 0 at this position, which is caused by the conditioning functions of the agents. The aggregates consisted of CaO and soil particles have high compression strength thus aggregates can retain its shape and make a good permeability during the vacuum preloading. However, there is no strong aggregates. Hence, the undrained shear strength of soil sample is low. The APAM has the opposite effect, the APAM long chains can bind soil particles together and improve the cohesion of the slurry.

The combination of CaO and APAM enhance both cohesion and permeability of the slurry.

4. Conclusions

In this paper, the effect of different agents added to slurry on the ground improvement by the vacuum preloading was investigated. The model test results show that:

• The solid-liquid separation rate of slurry was biggest with the treatment of APAM (Case C) during the standing stage and with the treatment of APAM and CaO (Case D) during the vacuum preloading stage.

• The size of particle aggregate of APAM-conditioned slurry is biggest among the four slurries that can explain why the solid-liquid separation of APAM-conditioned slurry was fastest during the standing stage.

• The void ratio distributions observed after vacuum show Case D can keep best drainage, which can thus explain why the solid-liquid separation rate of the slurry was biggest during the vacuum preloading stage.

• The unconfined compression strength after the treatment of Case D was the biggest (67.65 and 51.56kPa at 9cm and 18cm from the centre respectively) which means the mixed agent can significantly increase the cohesion of the slurry.

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