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Experimental study on vacuum preloading with flocculation for solid-liquid separation in waste slurry

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Abstract. This vacuum preloading combined with polyacrylamide (PAM) flocculation was proposed to separating solid-liquid in waste slurry and to improving bearing capacity of soft soil ground. By using waste slurry taken from drilled shaft construction site in Shanghai, China, a series of settling column tests with four typical flocculants and one normal for waste slurry were carried out for comparative analysis. The optimal amounts for each flocculant were obtained from the column tests. Then, model tests on vacuum preloading with anionic polyacrylamide (APAM) flocculation and without flocculants were carried out. The out of water and the settlement of slurry surface ground were monitored during the model tests, and the changes in water content, particle-size and pore-size distributions in different positions after the model tests were measured and discussed. It is found that water content of the waste slurry without APAM flocculation changed from 204 to 195% by 24 hours standing and 15 hours vacuum preloading, while the water content of the waste slurry with APAM flocculation was declined from 163 to 96% by 24 hours standing, and was further reduced into 37% by 136 hours vacuum preloading, which shows that the combined method is feasible and effective.

Keywords: vacuum preloading; flocculants; waste slurry; settling column tests; model test

1. Introduction

Vacuum preloading method, which is one of the most efficient and cost-effective ground improvement and land reclamation methods, was widely used for soft clayey deposits during last twenty years (Hansbo 1981, Tang and Shang 2000, Chu *et al*. 2000, Imai 2005, Kelly and Wong 2009, Chai *et al*. 2005, 2013, Saowapakpiboon *et al*. 2010, Ong *et al*. 2012, Mesri and Khan 2012, Wu *et al*. 2015). Prefabricated vertical drains (PVDs) are normally used together with the vacuum preloading technique, water was extracted through PVDs and solid particles were blocked at the surface of PVDs. However, when the particle size of solid particles (such as, slurry, etc.) is less than 5 μm, the surface filters of PVDs were easily clogged by solid particles. In some cases, undrained shear strengths on site are less than 30 kPa because of high water content, the construction machineries for PVDs and sand cushion can't be approached.

Waste slurry, caused by shield and drilled shaft constructions, are increased with the increasing of engineering construction in China. If these waste slurries are abandoned without treatment, the

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environment will be polluted seriously. Previous researches show that polymer flocculants can accelerating solid particles sedimentation from the slurry (Bartholomew 2003, Moran 2004, Bolto and Gregory 2007, Zhu *et al*. 2012, Zumsteg *et al*. 2013, Lee *et al*. 2015, Lentz 2015, Guezennec *et al*. 2015, Li and Wang 2016). The strength of waste slurry can be improved quickly, although it can't reach the bearing capacity of the actual project need.

Here, by using typical waste slurry selected from drilled shaft construction site in Shanghai, China, the settling column tests were performed with one inorganic and three organic polymer flocculants. The most suitable flocculants and its optimal amount were obtained. Model tests on the waste slurries with anionic polyacrylamide (APAM) flocculation and without flocculantswere carried out by vacuum preloading. The strengthening effect was inspected by using water content, particle-size distributions, pore-size distribution by mercury intrusion porosimetry (MIP), and micro-structure by scanning electronic microscopy (SEM). Finally, the applicability of the combined waste slurry treatment method was discussed.

2. Experimental description

2.1 Slurry and flocculants materials numerical simulation procedure

2.1.1 Slurry materials

The waste slurry material (with approximate 163% water content, 7.8 PH values, and 2.65 specific gravity) used in this study was selected from drilled shaft construction site located at Zhabei district of Shanghai, China. Fig. 1 plots the particle size distribution curve. The particle size distributions of ASTM Ottawa sand and London clay are also plotted together in Fig. 1 for comparison.

The soil was classified as inorganic silt (ML) according to the Unified Soil Classification System (USCS). The contents for sand (which particle sizes are between 0.075 and 2 mm), silt

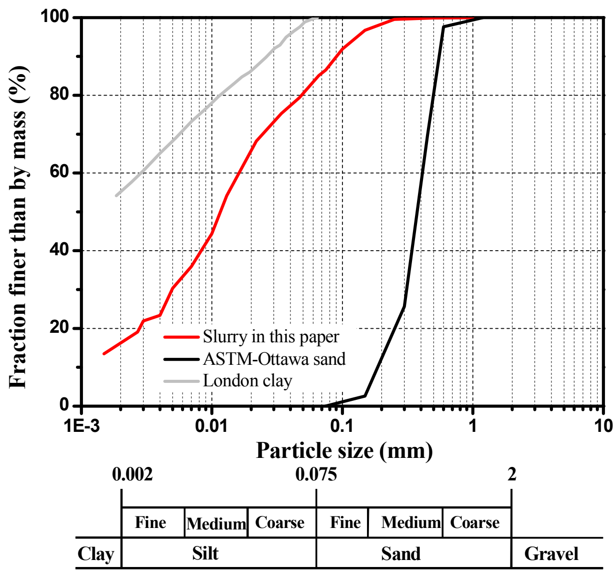


Fig. 1 Particle size distributions of construction waste slurry before treatment

(which particle sizes are between 0.002 and 0.075 mm), and clay (which particle sizes are less than 0.002 mm) equal 14%, 70%, and 16%, respectively.

2.1.2 Flocculants materials

One inorganic and three organic polymer flocculants were used for comparative analysis in settling column tests. The inorganic polymer flocculants was Poly Aluminium-ferric Chloride (referred to as PAFC) with 27% alumina content and 3% iron content, and the three organic polymer flocculants were Anionic Polyacrylamide (referred to as APAM), Cationic Polyacrylamide (referred to as CPAM), and Non-ionic Polyacrylamide (referred to as NPAM), respectively. The molecular weights for PAFC, APAM, CPAM, and NPAM were approximate 1.7, 20, 15, and 8 Mg/mol, respectively. APAM flocculants was used as the material for the vacuum preloading model test.

2.2 Settling column test procedures

The settling column test procedures used in this study follows EPA/600/R-02/090 (O'Connor *et al*. 2002). First, the weight waste slurry, which is transported from site, was poured into a container, and manufacturing flocculants with designed concentration was added. Second, the waste slurry was mixed with flocculants by mechanical agitation in the test columns. Third, stopping mechanical agitation and immediately draw off samples at each sample port and determining their suspended solids concentration, recording the beginning time, solutions height, etc. Previous research showed that the nephelometric will become steady after one hour (Moran 2004); hence, the Nephelometric Turbidity Units (NTU) values were recorded after three hours. The experimental equipment includes cylinder, beaker, pipette, burette, electronic scales, SGZ-200AS turbidimeter, etc. The photos of turbidimeter and cylinder with solutions are shown in Fig. 2.

2.3 Model test procedures

The model test apparatus consists of a model tank, vacuum system and data measurement system. As shown in Fig. 3(a), the dimensions of the model tank were 500 × 500 mm (diameter × height). Fig. 3(a) shows the vacuuming system (including a vacuum pump, a vacuum tube, a vacuum table, a seal membrane, a drain tube, and a suction bottle, etc.), model tank with scale

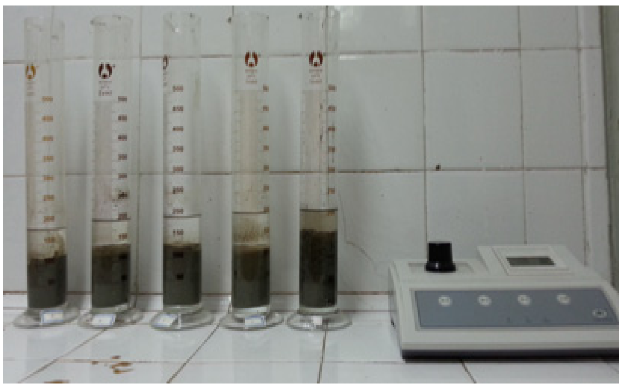
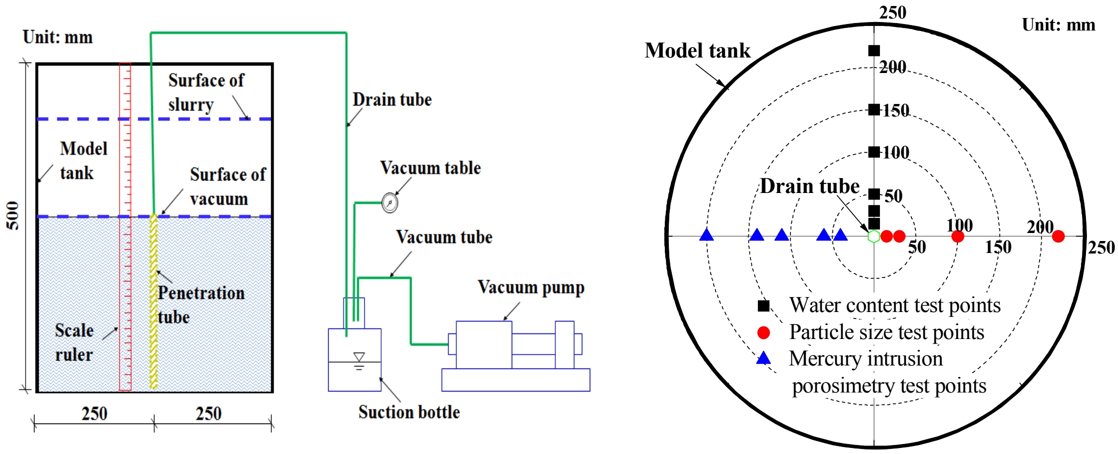


Fig. 2 Photos of settling column with solutions and turbidimeter



(a) Equipment arrangement (b) Testing point arrangement

Fig. 3 Layout of model test

ruler, and penetration tube. Fig. 3(b) shows the testing points arrangement of water content, particle size, and MIP. TM85 soil density meter, AutoPore IV 9500, and SU-1500 SEM were used for void ratio measurement, MIP test, and microscopic observation test, respectively. Penetration tube was flexible water permeable with 180 μm equivalent aperture, 45 mm out-diameter, and geotextile wrapped around.

Firstly, 71.76 L waste slurry with 1.92 mg/L APAM flocculants were poured into model tank; Secondly, mechanical agitation the solution, and then standing for 24 hours. Thirdly, discharge the water on the top of model tank, and record the discharge water volumes, the water content and height of left remained slurry. The MIP test and SEM test for slurry before vacuum preloading were also carried out in the same time. Fourthly, set seal membrane and open vacuum pump, keeping the degree of vacuum at 85 kPa for 136 hours. Finally, stop the vacuum preloading, and measure the water content, particle size, and void ratio at designed positions (see Fig. 3(b)) through different methods.

3. Test results and analysis

3.1 Settling column test results

The curves on NTU versus concentration for one inorganic and three organic polymer flocculants are shown in Fig. 4. The optimal amount of inorganic and organic polymer flocculants for slurry in this paper is shown in Table 1. Fig. 4 shows that the NTU values of all four flocculants are changed from decrease to increase with the increasing of concentration, which means that each flocculant has its own optimal amount. When the amount of PAFC is less than 1.92 mg/L, the negative charge around soil particles were neutralized by cationic (such as, Fe^{3+}, Al^{3+}, etc.); the coagulated precipitate and flocculation effect are increased with the increasing of gravitational among particles because of the reducing of electrostatic repulsion. When the amount of PAFC is larger than 1.92 mg/L, excess cationic attached around the soil particles leads the increase of electrostatic repulsion among soil particles (Patrick and Amirtharajah 1983). When the

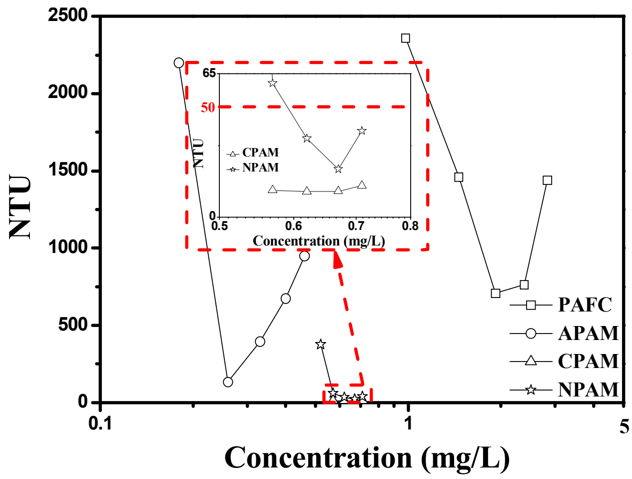


Fig. 4 Curves on NTU versus concentration for all the polymer flocculants

Table 1 Optimal amount of inorganic and organic polymer flocculants for slurry in this study

Name	Solute mass (g)	Concentration (mg/L)	NTU
PAFC	0.4	1.92	707.0
APAM	0.06	0.26	132.8
CPAM	0.18	0.62	11.6
NPAM	0.2	0.67	21.8

concentration of organic polymer flocculants is less than one value, the small particle are bridging flocculation in combination with other small particles into larger particles after flocculants addition, which cause precipitate increasing. When reaches a certain value, the blank portion of soil particle surface will be occupied by the excess organic polymer flocculants, which causing precipitate stabling or reducing. Therefore, the optimal amount should be considered to achieve the best flocculation effect for the all flocculants.

Fig. 4 and Table 1 show that the flocculants of CPAM and NPAM can reduce the NTU of water (which is from slurry) under 50 value, and those values obtained by APAM and PAFC equal 132.8 and 707, respectively. It also shows that the amount of CPAM and NPAM should be 3 times and 3.3 times of that of APAM to reach themselves optimal amount; and the amount of PAFC even need 7 times of that of APAM. In developed country (such as USA), North Carolina regulations require that the turbidity of discharged waters from construction sites to non-trout streams not exceed 50 NTU in trout waters. However, in many developing country (such as China), this value is about 150 NTU, even non standard. The settlement of slurry surface versus time with different flocculants and without flocculants are plotted in Fig. 5.

Fig. 5 shows that the waste slurry with NPAM flocculants has the quickest settling ratio in the all conditions; the settling ratio of waste slurry with APAM flocculants was quicker than that of waste slurry with CPAM flocculants in the first 22 hours, and slower after 22 hours. After 90 hours flocculation, the settlement values of waste slurry surface with PAFC, APAM, CPAM, and NPAM flocculants was approximate 1.8, 3.5, 4.1, and 5.2 times of that of waste slurry surface without

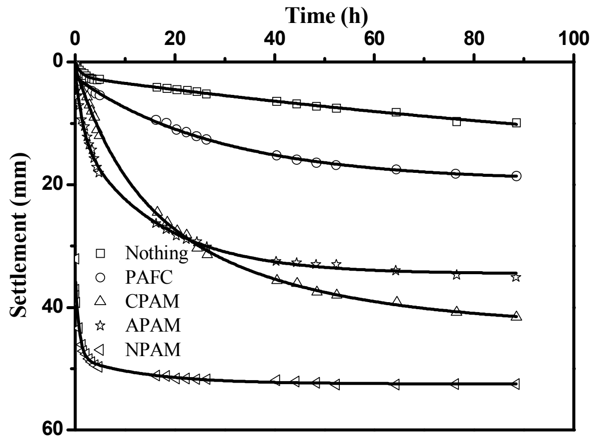


Fig. 5 Muddy surface settlement versus time with different flocculants

flocculants. Hence, the organic polymer flocculants have better flocculation effect than inorganic polymer flocculants used in this paper; With considering both efficiency and economy, APAM flocculants used for waste slurry treatment and soil strength improvement is the best choose in China.

3.2 Model test results

3.2.1 Out of water during vacuum preloading

The total and each two hours drainage volumes versus vacuum preloading time under 85 kPa vacuum degree for both combined with APAM and without flocculants are shown in Fig. 6. It shows that the total drainage volumes are increased with vacuum preloading time and tend stable at last; and drainage volumes per unit time are reduced with vacuum preloading time.

For vacuum preloading without flocculants, nearly 275 ml/h average ratio of out of water in the first four hours, then rapid declined into nearly 70 ml/h after 11 hours. For vacuum preloading with APAM flocculants, nearly 600 ml/h average ratio of out of water in the first four hours, then slowly declined into 150 ml/h after 24 hours, 70 ml/h after 89 hours. It means that nearly 8 times the high out of water time can be extended through using APAM flocculants. Approximately 50% of the total drainage volumes are happened in the first 24 hours; some unstable per unit out of water are happened during this time because of film tightness. During the whole time, some fluctuations are happened because of intermittent (interval 12 hours per 12 hours evacuated drainage) vacuum preloading method. Set the 70 ml/h value as the stopping standard, the total out of water volumes for vacuum preloading without flocculants, and with APAM flocculants equal 2080 ml, and 17960 ml, respectively. It means that nearly 7.6 times total out of water volumes were improved through using APAM flocculants.

3.2.2 Settlement of surface

The waste slurry surface will settlement after flocculation and vacuum preloading because of pore water drawn and void ratio compression; the bearing capacity of slurry will be improved in this process. Fig. 7 shows the waste slurry surface reduction after 24 hours solid-liquid separation by APAM flocculants, and settlement versus vacuum preloading time under 85 kPa intermittent

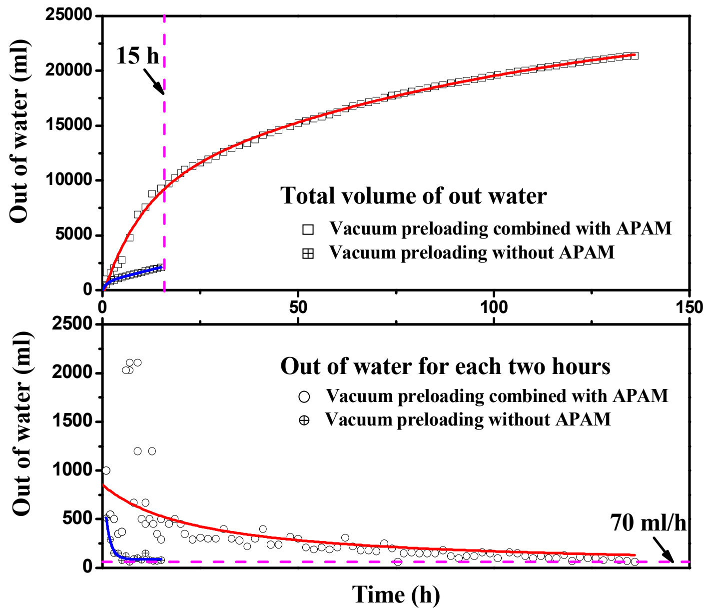


Fig. 6 Out of water versus vacuum preloading time

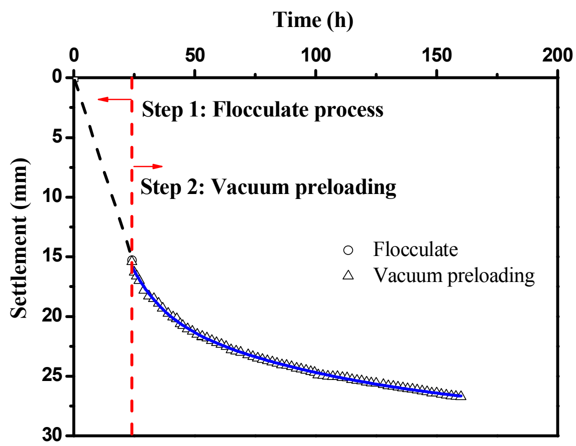
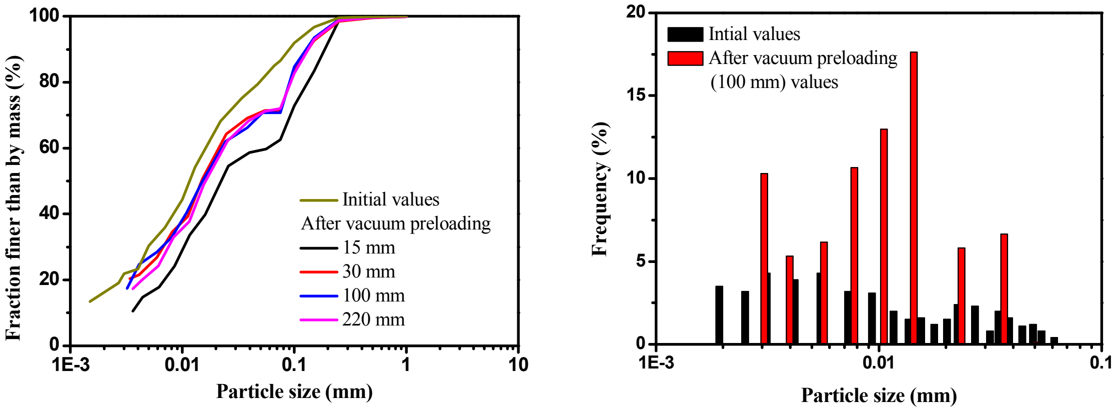


Fig. 7 Slurry surface settlement versus treatment time and methods

vacuum preloading. The total settlement increased with vacuuming time, and tends to a stable value at last.

3.2.3 Particle size distribution

The particle size distributions of waste slurry after combined treatment with four different positions (see Fig. 3(b)) are plotted in Fig. 8(a). Fig. 8(a) also plots the initial particle size distributions of waste slurry before combined treatment for comparative analysis. Set granule distributions at 100 mm distance from centre as an example, the granule distributions before and after combined treatment are comparative shown in Fig. 8(b). It shows that the proportion of large particles are increased after combined treatment at each position comparative with its own initial



(a) Grain size (b) Granule

Fig. 8 Particle size distributions of slurry after combined treatment

values, which means that the soil particle size will be increased by flocculation effect of APAM flocculants. It also shows that the proportion of large particles at 15 mm distance from centre position is relative larger than those at 30 mm, 100 mm, and 220 mm positions. The reason may be that a small part of solid particles is discharged together with out of water through large porosity during the beginning of vacuum preloading.

3.2.4 Water content

The water content of waste slurry at the beginning, after solid-fluid separation by APAM flocculates, and after vacuum preloading are shown in Fig. 9. Both the measured values and the calculated values through out of water for water content after vacuum preloading are comparative plotted in Fig. 9. It shows that the water content of waste slurry was reduced from 163% into 96% value after flocculate process, and was further reduced into average 37% value after vacuum preloading process. The measured values of water content are increased with the increasing of distances from the centre because of the low permeability of waste slurry.

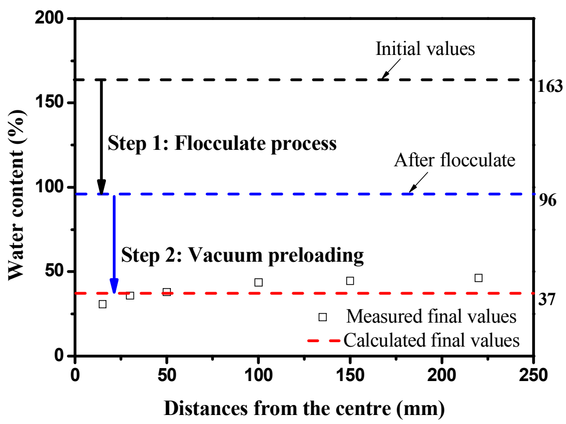


Fig. 9 Water content changing with each process at different positions

3.2.5 Void ratio

In order to reveal the mechanism of settlement by combined treatment method, the void ratios of waste slurry were measured through MIP and SEM tests. The cumulative mercury values and the aperture distribution density of waste slurry after combined treatment with five different positions (see Fig. 3(b)) are plotted in Figs. 10 and 11, respectively. Figs. 10 and 11 also plot the values before combined treatment. It shows that the cumulative mercury values of waste slurry are increased with the increasing of distances from the centre, which means that the void ratios are increased with the increasing of the distances from the centre. It also means that the consolidation degree of soil beside of the penetration tube was relative more than those far from the penetration tube. Fig. 11 also shows that the majority of aperture is distribution between 1000 and 3000 nm after vacuum preloading, while those values are distribution between 8000 and 15000 nm before vacuum preloading. In general, nearly 55-65% void ratio of waste slurry was reduced after vacuum preloading process.

As shown in Figs. 12(a) to (e), the photos of soil surface with 1500 magnification through SEM experiment at difference positions (see Fig. 3(b), at 40, 60, 90,120, and 180 mm) are plotted. It can be found that the sizes of pore are increased with the increasing of the distances from the centre,

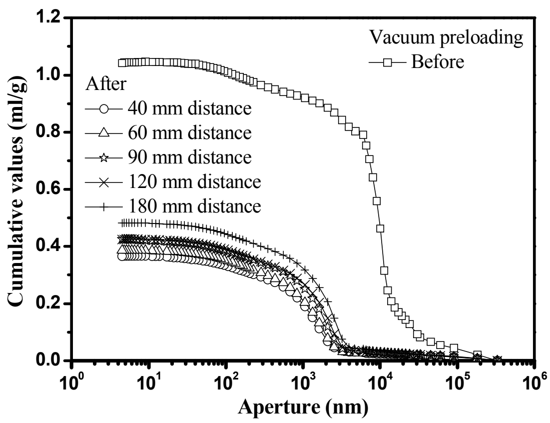


Fig. 10 Cumulative mercury values versus aperture by MIP tests

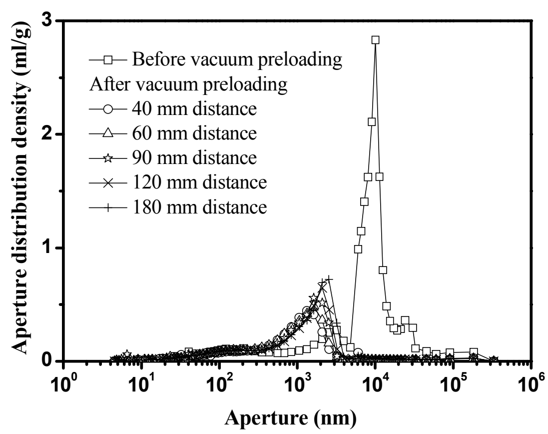


Fig. 11 Aperture distribution density versus aperture by MIP tests

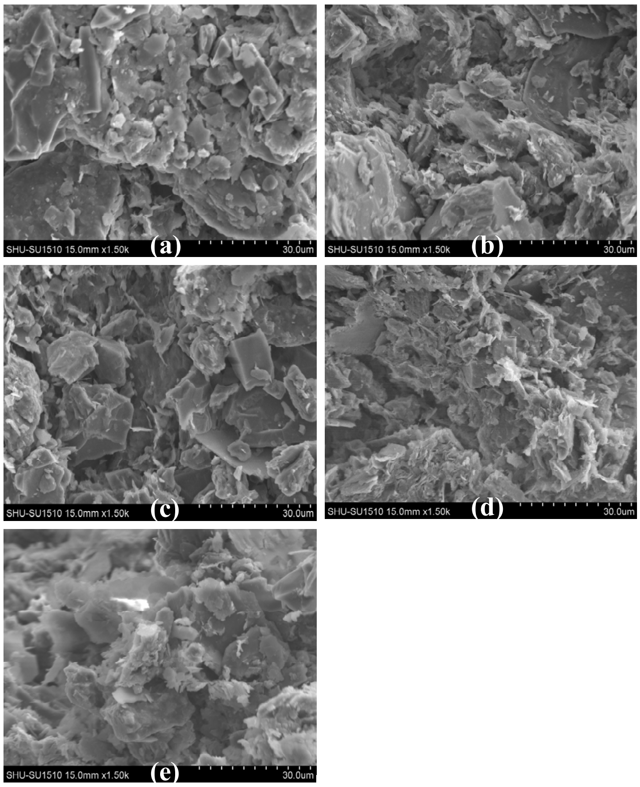


Fig. 12 SEM Photos of soil surface at different distances: (a) 40; (b) 60; (c) 90; (d) 120; and (e) 180 mm

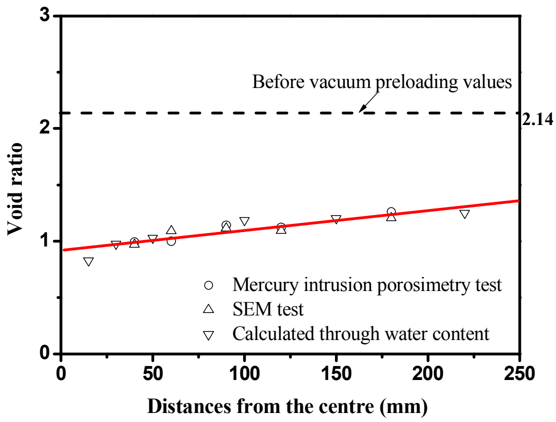


Fig. 13 Void ratios versus distances obtained through different methods

the solid skeleton are becoming looser and more 3D shapes with the increasing of the distances from the centre. It means that the soil compactness is reduced with the increasing of the distances from the centre.

The void ratios of waste slurry after solid-fluid separation by APAM flocculates (before vacuum preloading), and after vacuum preloading are measured through MIP and SEM tests, the detail values are shown in Fig. 13. Fig. 13 also plots the void ratio values obtained by calculation with water content (average 37% from Fig. 9). Before the vacuum preloading process, the measured (through MIP test) and calculated (through water content) values of void ratios of waste slurry equal 2.12 and 2.59, respectively. After the vacuum preloading process, the values of void ratios of waste slurry equal 0.98-1.26, and are increased with the increasing of the distance from the center.

4. Conclusions

Based on results of the settling column tests and the vacuum preloading model tests on the waste slurry with flocculants for solid-liquid separation, some conclusions can be obtained as follow:

- Each flocculant has its own optimal amount for waste slurry treatment. The flocculants of CPAM and NPAM can reduce the NTU of water (which is from slurry) under 50 value (the standard for some developed country), and those values obtained by APAM and PAFC equal 132.8 and 707, respectively. The organic polymer flocculants have better flocculation effect than inorganic polymer flocculants used in this study. With considering both efficiency and economy, APAM flocculants is the best choose for the waste slurry treatment and soil strength improvement in China.
- The water content of waste slurry was reduced from 163% into 96% after flocculate process, and was further reduced into about 37% after vacuum preloading process. Set the 70 ml/h value as the vacuum preloading stopping standard, the nearly 8 times high out of water time can be extended through using APAM flocculants; the total out of water volumes can be nearly 7.6 times improved.
- The proportion of large particles are increased after combined treatment at each position comparative with its own initial values, which means that the soil particle size will be increased by flocculation effect of APAM flocculants. Before the vacuum preloading process, the void ratio of waste slurry ranged from 2.12 to 2.59. After the vacuum preloading process, the void ratio of waste slurry ranged from 0.98 to 1.26, and was increased with increasing the distance from the center.
- The MIP test shows that the majority of aperture ranges between 1000 and 3000 nm after vacuum preloading, while the value ranged between 8000 and 15000 nm before vacuum preloading. In general, nearly 55-65% void ratio of waste slurry was reduced after vacuum preloading process.

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