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Research on closed-loop utilization of engineering waste mud in engineering sites

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The large amount of waste mud generated during construction projects makes it difficult to implement closed-loop on-site treatment, resulting in the inability to achieve zero emissions, which not only wastes land resources but also pollutes the environment. This article first studied the flocculation effect and mechanism of two flocculants. Then, the treated sediment was used to prepare fluidized solidified soil, and the effect of flocculants in the sediment on the performance of fluidized solidified soil was studied. Finally, this technology of flocculation and re-solidification was applied in engineering. The results showed that the composite effect of adding PAC flocculant first and then APAM flocculant in the mud had the best mud-water separation effect. The soil was combined with the flocculants to prepare fluidized solidified soil that can effectively improve the strength and water stability of the solidified soil. Through engineering applications, it has been proven that closed-loop utilization of engineering waste mud can be achieved on-site. Therefore, this work provides a new method for achieving zero emissions through closed-loop utilization of engineering waste mud on-site and innovative experience for the construction of "waste-free cities".

Keywords: *engineering waste mud, flocculation, solidification, engineering applications, zero emissions*

1. Introduction

With the accelerating urbanization construction, various engineering projects, such as highways, large bridges, super high-rise buildings, and high-rise buildings, have entered a peak period of rapid development. However, due to inadequate construction techniques or negligence in construction management, a large amount of abandoned mud is often generated. According to statistics, the annual production of engineering waste mud in China is as high as 300 million cubic meters, accounting for over 60% of the nation's total construction waste [1, 2]. This waste mud not only occupies land resources and pollutes the environment but can also easily lead to safety accidents due to the large volume of outward transportation and treatment [3, 4]. Therefore, it is urgent to carry out the reduction and resource utilization treatment of engineering waste mud.

At present, the main effective reduction treatment method for engineering waste mud uses dehydration to reduce water content and external displacement [5–7]. The main dehydration methods include mechanical pressure filtration dehydration [8, 9], direct solidification dehydration [10, 11], and flocculant precipitation dehydration [12, 13], but mechanical pressure filtration has high mechanical requirements and low treatment efficiency. Direct solidification dehydration is achieved by adding a curing agent to seal and transform a large amount of water into semi-solid or solid, increasing the transportation volume. Flocculant precipitation dehydration is a widely used method in engineering projects. It mainly involves adding flocculants to waste mud to separate the solid and water phases, which can greatly reduce the amount of mud transported and reduce the discharge of construction waste from the source. However, due to the lack of resource utilization of dehydrated sediment, there is still a certain amount of waste soil that needs to be discharged.

There are many methods for the resource utilization of waste soil, for example using the calcination method to prepare building materials

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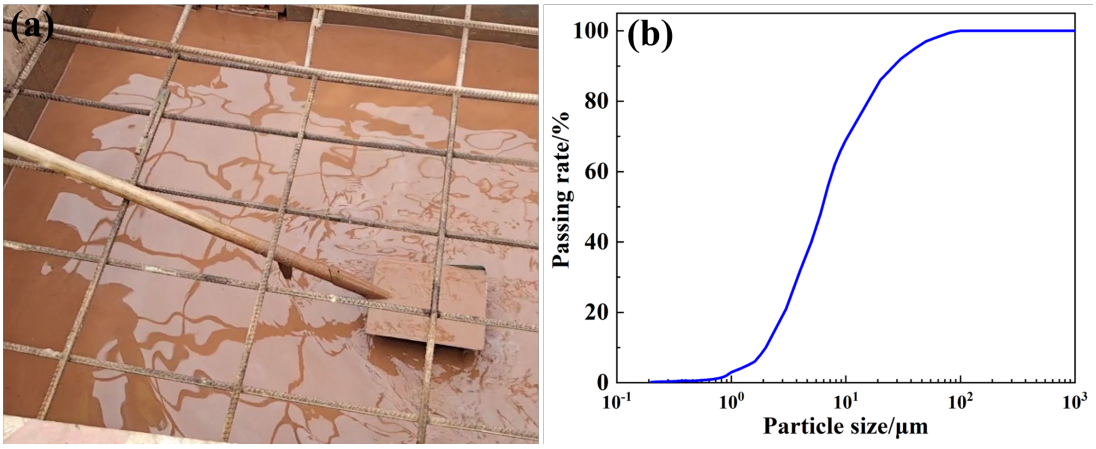


Fig. 1. (a) Waste engineering slurry; (b) Particle size distribution of solid clay particles in waste engineering slurry

[14–16] and pozzolanic materials [17–19]. Some methods add stabilizers, solidification agents, and organic matter to the waste soil to prepare fine aggregates [20, 21], controllable low-strength materials [22, 23], and planting soil [24, 25], respectively. For engineering waste mud, the main method is to directly add curing agents to the original mud to solidify it into a certain strength curing material for easy transportation or resource utilization treatment [26, 27]. However, there is limited research on the solidification and utilization of low water content sediment after flocculation and sedimentation, and there is a lack of research on the impact of flocculants in sediment on the performance of sediment solidification materials, which makes it difficult for engineering waste mud to be closed-loop utilized on the project site.

This article first examines the optimal dosage of two types of flocculants in the mud and studies the impact of the flocculants on the mud-water separation effect and related mechanisms through the combination of the two flocculants. Secondly, cement was added to the sediment to prepare fluidized solidified soil, and the effect of retained flocculants in the bottom mud on the performance of fluidized solidified soil was studied. Finally, this flocculation and solidification technology was applied to practical engineering to achieve on-site closed-loop utilization of engineering waste mud. The research of this work will be of great significance in improving the resource utilization rate of waste soil and promoting the low-carbon and green development of buildings.

2. Materials and methods

2.1. Materials

The engineering waste mud used in this article comes from the construction site, with a moisture content of about 87.5% (the proportion of water to the entire mud mixture) and a pH value of 6. The appearance and particle size distribution of the original mud are shown in Figure 1, and the solid particles are mainly mudstone soil. Polyaluminum chloride (PAC), with a content of 28%, produced by Sichuan Wanjiajing Environmental Protection Technology Co., Ltd and Anionic polyacrylamide (APAM) with a molecular weight of 12 million, produced by Xinqi Polymer Co., Ltd. The cement is ordinary Portland cement (P.O 42.5) produced by Sichuan Jinding (group) Emei Cement Plant Co., Ltd.

2.2. Sample preparation

(1) The optimal concentration of flocculant: First, PAC was configured into aqueous solutions with mass ratios of 0.5%, 1.0%, 1.5%, 2.0%, 2.5%, and 3.0%, while APAM was configured into aqueous solutions with mass ratios of 0.05%, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5%. Then, 10ml of PAC and APAM solutions were measured separately

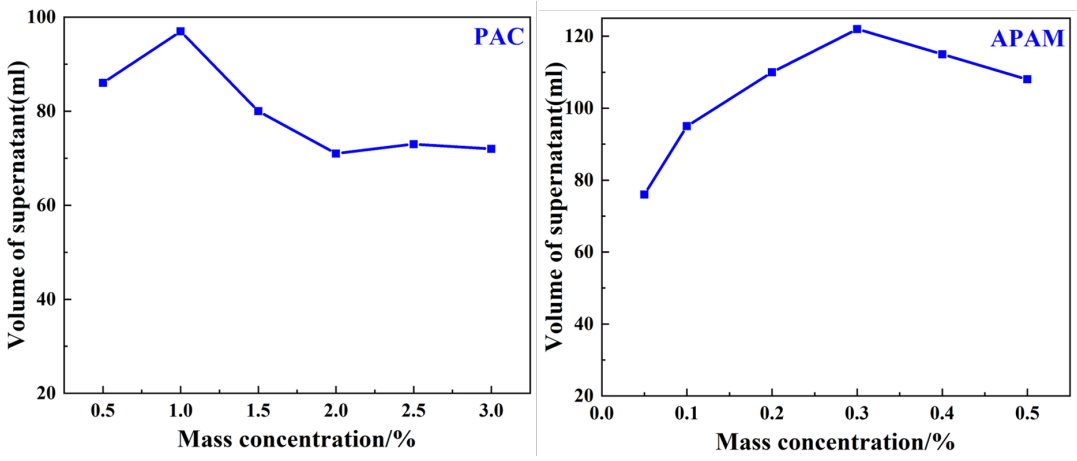


Fig. 2. Changes in the volume of supernatant after mud-water separation with the mass concentration of different flocculants

and poured into a measuring cylinder containing 170ml of original mud while stirring. We stirred for 10s and let it stand. The volume change of the supernatant (the water after flocculation) in the measuring cylinder, as shown in Figure 2, was observed. The results indicate that the optimal concentrations of flocculants used for the waste mud in this experiment are 1.0% PAC and 0.3% APAM, respectively.

(2) Preparation of comparative samples for mud-water separation test: Based on the optimal concentrations of the two flocculants determined above, we added the optimal concentration of flocculants to the measuring cylinder containing 170ml of original mud and observed and tested the volume change and turbidity of the supernatant to determine which method has the best mud-water separation effect. The detailed addition methods are shown in Table 1.

Table 1. Samples with different flocculants added

Samples	**1.0% PAC**	**0.3% APAM**
Original mud	Water 10ml	
A	10ml	/
B	/	10ml
C	First add 10ml of PAC, stir for 10s, and then add 10ml of APAM	
D	10mlPAC+10ml APAM	
E	First add 10ml of APAM, stir for 10s, and then add 10ml of PAC	

(3) Preparation of fluidized solidified soil sample: This article studies the influence of flocculants on the performance of fluidized solidified soil by fixing cement and total water content and changing the types of flocculants in soil and water. Before the experiment, the sediment after flocculation and sedimentation with different flocculants was dried to a semi-dry soil with a moisture content of 20%. Then, we weighed 10kg of semi-dry soil and placed it in a mortar mixer, adding 5% cement and 30% water by weight to the soil, mixing for 5 minutes, obtaining pre-mixed fluidized solidified soil, and testing its slump expansion. To test the strength and water stability coefficient of solidified soil, pre-mixed fluidized solidified soil was poured into a 100mm × 100mm × 100mm cubic mold and covered with plastic film. After being placed in the cubic mold in an environment with a temperature of 20°C for 24 hours, the cube test block was placed in a standard curing room (temperature 20 ± 2°C, relative humidity 95%) for 7 and 28 days. The detailed mix proportion of fluidized solidified soil is shown in Table 2.

2.3. Characterization

Laser particle size analyzer (Mastersizer 2000): tests the particle size of solid particles in mud. Turbidimeter (Hach 2100 N): tests the turbidity of the supernatant after mud-water separation. Slump cone (100mm × 200mm × 300mm): tests the

Table 2. Mix-ratio of fluidized solidified soil

Samples	Soil type	Soil (kg)	Cement (kg)	Water (kg)	Water type	Flocculant as a percentage of cement (%)
1	No flocculant	10	0.5	3	Tap-water	0
2	No flocculant	10	0.5	3	Supernatant with PAC+APAM	<0.1%
3	Add PAC	10	0.5	3	Supernatant with PAC	~8.0%
4	Add APAM	10	0.5	3	Supernatant with APAM	~2.4%
5	Add PAC+APAM	10	0.5	3	Supernatant with PAC+APAM	~10.4%

slump flow of pre-mixed fluidized solidified soil, the value is the average diameter of the self-flowing spreading surface of pre-mixed fluidized solidified soil after extracting the slump cone. Electro-hydraulic pressure testing machine (DYE-2000): tests the unconfined compression strength of the fluidized solidified soil, and the loading rate is 5 kN/min. The softening coefficient related to the test is the ratio of the strength of the soaked and nonsoaked test blocks, with a soaking time of 48 hours (starting after 26 days of curing the test blocks). Field emission electron scanning microscope (SEM, JSM-5900LV JEOL): tests the internal microstructure of fluidized solidified soil specimens. X-ray diffraction (XRD, Ultima IV, Rigaku Corporation, Japan): tests the components related to fluidized solidified soil, with a testing range of 5° to 40° and a testing speed of 10°/min.

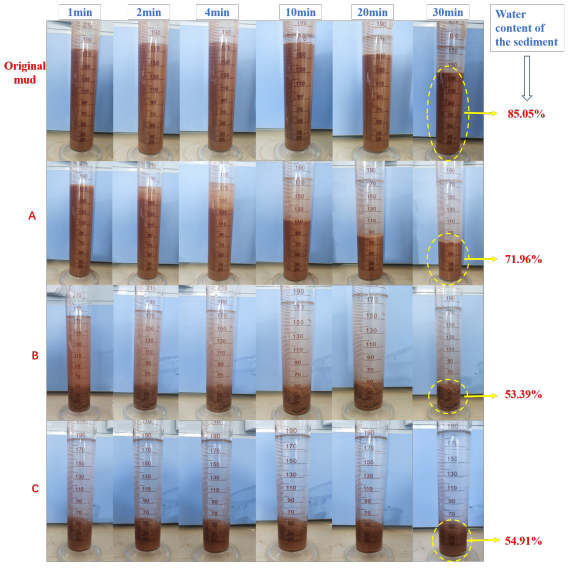


Fig. 3. Plot of settling time of samples after adding different flocculants

3. Results and discussions

3.1. The effect of flocculants on the separation of mud and water

The efficiency of mud-water separation is not only related to the content of flocculants but also closely related to the types of flocculants. To study the effect of the types of flocculants on the speed of mud-water separation, the change in volume of the supernatant with settling time after the addition of flocculants was observed, as shown in Figure 3. Although the original mud still has a certain settling rate, it is much slower than the sample added with flocculant. The sample containing the original mud only showed a small volume of supernatant at 10 minutes, but the sample with added flocculant showed a large amount of supernatant at 1 minute. By analyzing the influence of the types of flocculants on the speed of mud-water separation, it was found that after adding PAC flocculants, the mud-water separation speed was slower, and there were no obvious flocs produced in the bottom mud. However, when APAM and composite PAC+APAM flocculants were added, there was a rapid separation of mud and water, and obvious flocs appeared in the bottom mud. In addition, after removing the supernatant, the water content of the sediment in groups B and C was measured by the drying method and found to be similar, and it decreased to about 54% with a flocculation dehydration efficiency of about 78%. This indicates that the flocculant containing APAM has an effective separation effect on mud and water.

To study more clearly and accurately the effect of different flocculants on the separation efficiency of mud and water, the volume and turbidity of

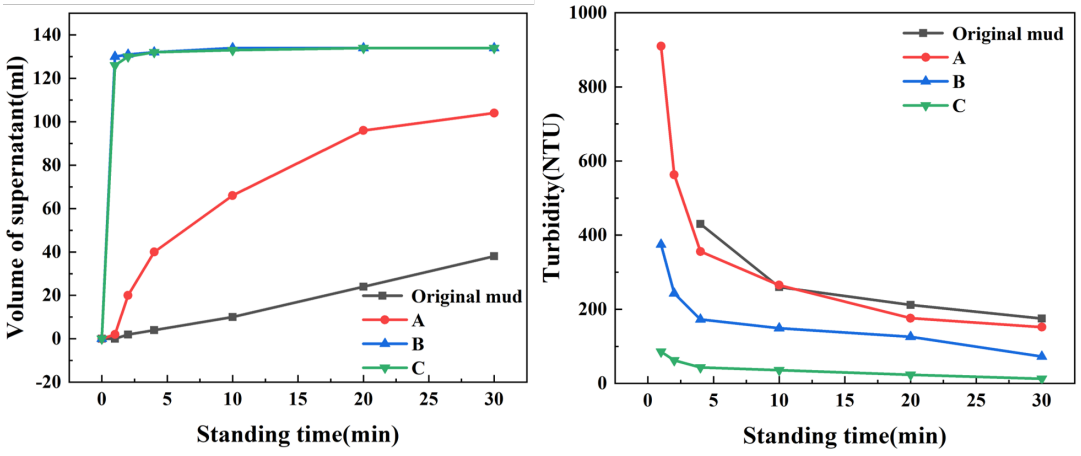


Fig. 4. Changes in volume and turbidity of supernatant over time

the supernatant after mud-water separation were tested, and the results are shown in Figure 4. By comparing the volume of the supernatant of the original mud in groups A, B, and C, it was found that the volume of the original mud's supernatant showed a linear curve over time after being left standing for 10 minutes with an average sedimentation rate of about 1.23ml/min, so it reached 37ml after 30 minutes. After adding PAC to the mud and letting it stand for 30 minutes, the volume of the supernatant reached 104ml. After adding APAM or PAC+APAM to the mud, the volume of the supernatant can reach nearly 130ml after standing for 1 minute, indicating once again that APAM has a better mud-water separation effect than PAC. In addition, the turbidity analysis of the supernatant found that the turbidity of the supernatant in the samples added with PAC, APAM, and PAC+APAM decreased sequentially, and in the C group samples added with PAC+APAM, the turbidity of the supernatant was as low as 12.8 NTU. Explanation: In this experiment, the combination of PAC and APAM has the best mud-water separation effect. The separated supernatant can be recycled on the project site due to its low turbidity, which reduces sewage discharge.

To study the effect of the addition order of PAC and APAM in the PAC+APAM composite flocculant on the mud-water separation effect, PAC and APAM were added to the mud in different orders, and the mud-water separation situation was observed after standing for 4 minutes, as shown in Figure 5(a). Sample (D), with an even mixture of PAC and APAM before adding mud, had the worst mud-water separation effect with high turbidity in the supernatant. This was mainly due to the reaction between PAC and APAM during mixing, forming a complex or colloid that cannot perform normal flocculation function. The mud-water separation effect of sample (E), which had APAM added first and then PAC, was also poor, indicating that PAC flocculant had no synergistic effect on the APAM flocculant and even had an antagonistic effect, significantly weakening the effectiveness of APAM flocculant and resulting in a poor mud-water separation effect. For sample (C), with PAC added first and then APAM, the mud-water separation effect was best with low turbidity of the supernatant and larger floc particles in the sediment. The main reason was that the clay particles in the mud preferentially complex with PAC to form small particles, which are then entangled by the large molecular chains of APAM to form larger particles, thereby improving the settling speed and achieving an excellent mud-water separation effect.

To investigate whether the PAC+APAM composite flocculant with the optimal mixing order mentioned above is suitable for other types of muds, mudstone soil muds, clay soil muds, and silt soil muds with similar solid content and particle distribution were selected. The results after adding

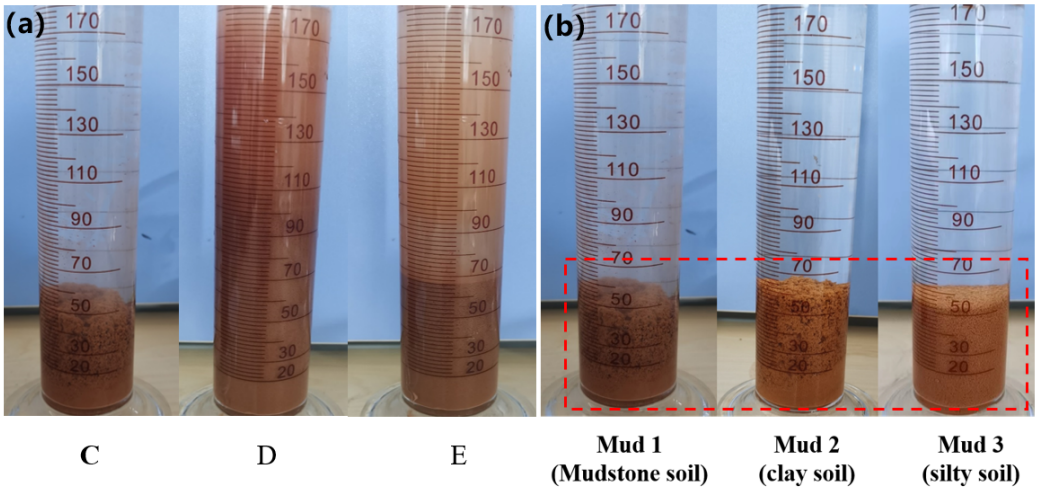


Fig. 5. (a) Separation effect of the combined flocculants with different addition sequences; (b) Separation effect of different slurries mixed with the same composite flocculant

the composite flocculant are shown in Figure 5(b). The composite flocculant had a good mud-water separation effect on all three types of mud, and it was found that the turbidity of the supernatant of mud 2 (clay soil) could reach 8.9 NTU, and the flocculent particles in the sediment were the largest. The main reason was that the cohesion of clay was higher than that of mudstone and silt, making it easier for particles to aggregate and form larger particles. The gaps formed by the overlapping of large particles were larger, and the particle stacking was looser, resulting in a larger volume after flocculation settlement.

In summary, to achieve efficient mud-water separation of engineering waste mud within 10 minutes or even less, save mud storage space, and accelerate construction progress, the method of adding PAC flocculant first and then APAM flocculant should be chosen to treat the mud.

3.2. Mechanism of flocculant action

The surface of clay particles in mud usually carries electric charges, causing charge repulsion between particles and making it difficult for particles to aggregate and form agglomerate settlement. This results in a poor natural settlement effect. After adding the flocculant, the mechanism of action of the flocculant can be seen in Figure 6. When dissolved in water, the inorganic PAC flocculants will produce complexes and various polynuclear hydroxyl complex ions. After the clay particles in the mud adsorb the flocculant, the flocculant will promote the aggregation of small particles into clusters through potential neutralization, compression of the double layer, and reduction of Zeta potential. However, the formed particles are very small due to the short molecular chain of inorganic flocculants, resulting in slow sedimentation and weak flocculation.

For organic APAM flocculants, the flocculation effect is mainly achieved through the bridging effect of long molecular chains. Due to the longer molecular chain of APAM compared to PAC, it is easier for APAM to form a flocculent molecular network structure in solution mud that can capture small particles and colloidal substances in the mud to form larger particles and accelerate flocculation settlement. In addition, there are many active groups (such as hydrogen bonds, carboxyl groups, amino groups, etc.) on the long chain of APAM molecules that can attach to the surface of soil particles and further accelerate the settlement of flocs. However, as the concentration of the flocculant increases to a certain value, the flocculation effect will decrease since the long chains of its molecules intertwine and cannot be stretched to form flocs. The active groups on the long chains cannot continue to adsorb particles, resulting in a

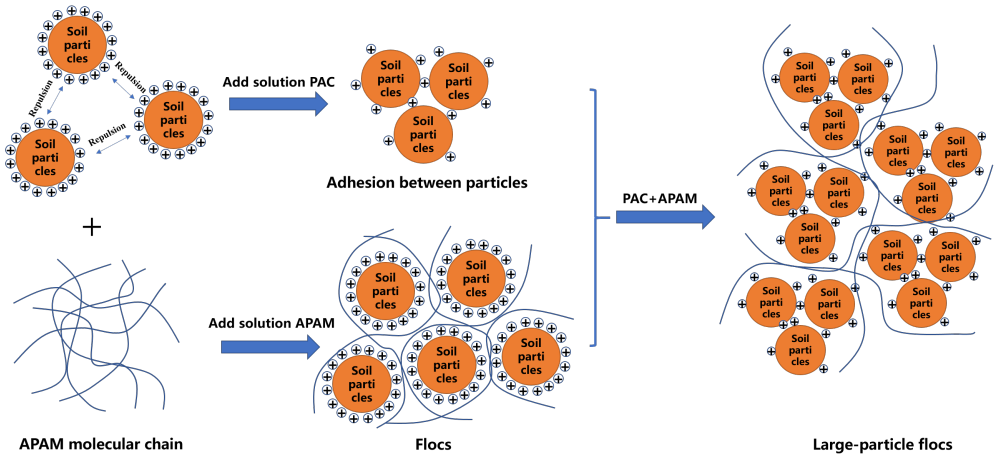


Fig. 6. Simulation diagram of flocculation mechanism of flocculants

significant decrease in the bridging effect of the links.

For the PAC+APAM composite flocculant, adding the PAC flocculant first can neutralize the surface charge of solid particles in the mud and reduce the repulsion forces between particles. At the same time, it exerts compression on the double electron layer structure on the surface of mud solid particles, allowing them to bond to form small flocculent particles. Then, the APAM flocculant, whose long chain molecular network structure can bridge, wrap, and sweep the small flocculent particles formed by PAC flocculation, causes the small particles to condense and form large particle flocs. These large particle flocs can quickly settle after destabilization, significantly improving the mud-water separation effect on waste mud.

3.3. The effect of flocculants on the performance of fluidized solidified soil based on sediment

The water content of the engineering waste mud can be significantly reduced after being flocculated, reducing the transportation volume of the waste mud, but the outward transportation of sediment still causes environmental pollution and waste of land resources. If it is reused as a resource on the construction site, it will contribute to the green construction development of the project. Therefore, this article recommends adding cement to the sediment treated with flocculants to prepare fluidized solidified soil and achieve resource utilization of the mud. Although there have been many studies on fluidized solidified soil [28–30], almost no reports have been made on fluidized solidified soil containing flocculants in the original soil, and the impact of the presence of flocculants on the performance of fluidized solidified soil is still unclear. It is urgent to carry out such research to promote the resource utilization of engineering waste mud.

First, the most important aspect of the application process of fluidized solidified soil is its construction performance. Therefore, this article studied the effect of flocculants on the slump flow of pre-mixed fluidized solidified soil, as shown in Figure 7. When the raw material (water or soil)

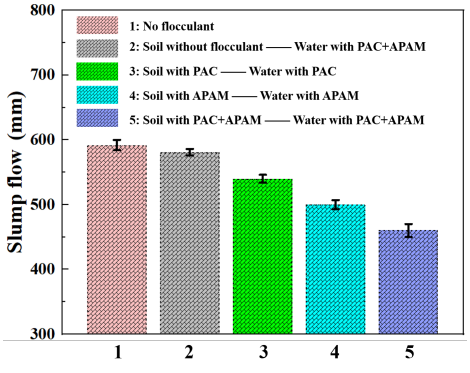


Fig. 7. Slump flow of different pre-mixed fluidized solidified soil

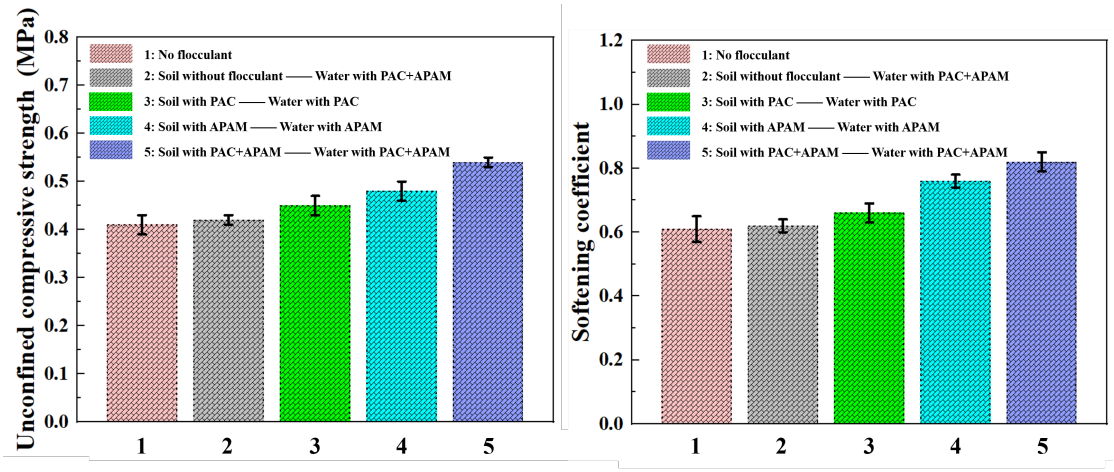


Fig. 8. (a) unconfined compressive strength and (b) water softening coefficient of the fluidized solidified soil

used for preparing fluidized solidified soil contains flocculants, the slump flow of pre-mixed fluidized solidified soil will decrease, and the degree of reduction in slump flow of solidified soil by APAM flocculants (4) is higher than that of PAC flocculants (3). If both PAC and APAM are present in the soil (5), the slump flow is the smallest. For PAC, its molecular chain is short, the particles formed by flocculation are small, and the frictional resistance between particles is small, which has a small impact on the flow performance. For APAM, its long molecular chain will form a network structure, adsorbing and entwining more soil particles to form larger flocs, increasing the resistance to sliding between flocs, which has a significant impact on the slump flow of pre-mixed fluidized solidified soil. When PAC and APAM coexist, the long-chain network of APAM will trap and entangle small particles that have already been flocculated by PAC, forming larger particle flocs. The resistance between the flocs will further increase, resulting in lower flow performance of pre-mixed fluidized solidified soil.

In addition, the strength and water stability of fluidized solidified soil are important performance indicators, so it is crucial to study the influence of the presence of flocculants in the soil on its strength and softening coefficient, as shown in Figure 8. For sample 2 as only the added water contains trace amounts of flocculants, the impact on strength and softening coefficient was relatively small. For samples 3, 4, and 5, flocculants had an enhancing effect on the strength and water stability of the fluidized solidified soil (the enhancing effect of flocculants in descending order is PAC+APAM $>$ APAM $>$ PAC) due to the high content of flocculants in the soil. The main reasons are that PAC can neutralize the surface charge of soil particles, promote the aggregation of clay particles, improve engineering plasticity, and improve the stability of soil. The formed flocs can improve the strength of soil by filling the pores in the soil and bonding the soil particles. In addition, APAM has long polymer chains and adsorption bridging ability. Its molecular chains are intertwined with the soil particle skeleton, and the molecular chains are cross-linked to form a network structure that runs through the soil skeleton, improving the integrity of the skeleton and greatly improving the strength of the soil. Furthermore, the molecular structure of APAM contains amide groups, which hydrolyze to produce hydroxyl groups and react with cement hydration products (Ca^{2+}, Al^{3+}, etc.) to form stable complexes, which are tightly connected to the cement through chemical bonds, further enhancing the strength and water stability of the soil. If PAC and APAM are used together, they will have a positive superposition effect on the performance of solidified soil. For example, the unconfined compressive strength and softening coefficient of the fluidized solidified soil in sample 5 can be increased by 25% and 34%, respectively,

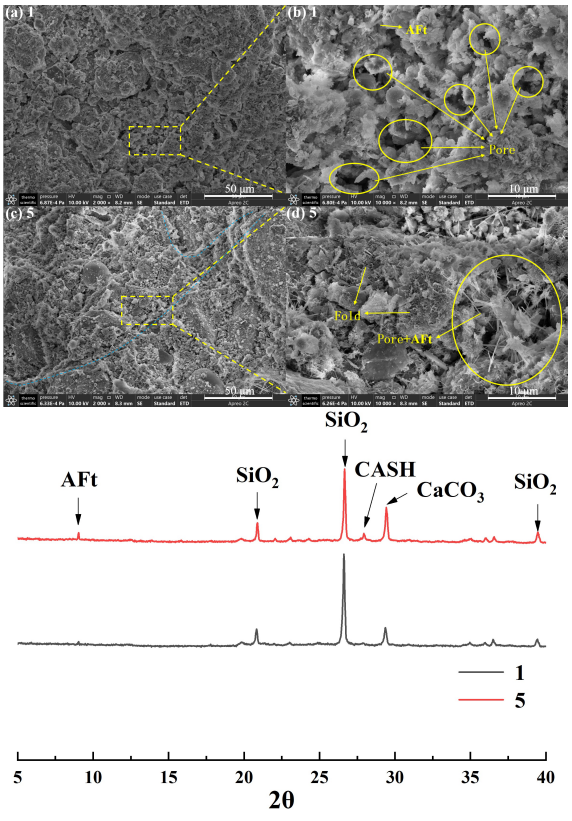


Fig. 9. Microscopic morphology and XRD spectra of 1 fluidized solidified soil with no flocculants (a, b) and 5 fluidized solidified soil with flocculants (c, d)

compared to sample 1. The corresponding data indicators meet the requirements of most foundation pit backfilling indicators, so they can be applied to backfilling projects on the project site.

To further demonstrate the strengthening effect of the combined flocculants on fluidized solidified soil from the microstructure, SEM and XRD were used to observe the fluidized solidified soil without flocculants (1) and the fluidized solidified soil containing the combined flocculants (5). The results are shown in Figure 9. From Figure 9(a, b), it could be seen that the clay particles in sample 1 were dispersed, with many pores between the particles, and there was very little needle-like ettringite (AFt). In Figure 9(c, d), sample 5 showed dense and large flocs, with wrinkles on the surface of the flocs, indicating that organic APAM flocculants adhere to the surface of the particles, and there were many needle-like ettringite filled between the interface gaps of the large flocs. In addition, it could be observed in the XRD pattern that the diffraction peak of ettringite in sample 5 was significantly stronger than that in sample 1. The main reason for the occurrence of a large amount of ettringite in sample 5 is that PAC reacts with the hydration product $Ca(OH)^2$ of cement, rapidly generating $Al(OH)_3$ precipitates. Then, the colloidal particles take $Al(OH)_3$ as the reaction core in water and adsorb $SO4^{2-}$ and Ca^{2+} into the floc to form ettringite. At the same time, APAM has a synergistic effect, which can further promote the formation of a large amount of ettringite [31]. Therefore, flocculants can promote the formation of ettringite, facilitate the integrity of soil structure, and improve the strength and stability of solidified soil.

4. Engineering application

To form a closed-loop self-digestion system for waste mud in the construction site and achieve zero discharge. This article focuses on the engineering demonstration application of the fluidized solidified soil containing the combined flocculants studied above, and the process is shown in Figure 10. First, a sedimentation mud tank was excavated at the engineering site, and the waste mud was placed in it. Then, a corresponding volume of the combined flocculants (PAC solution with a concentration of 1%, followed by APAM solution with a concentration of 0.3%) was added, mixed evenly, and left to stand for 1 minute. Then, the supernatant was pumped out into the reservoir, and the sediment was transported to the drying site for drying to reduce moisture content. When the project started backfilling the foundation pit, a temporary mixing station was established in the drying

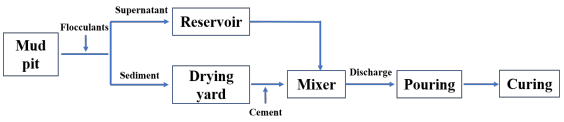


Fig. 10. Engineering demonstration application flowchart



Fig. 11. Engineering Demonstration Application of Fluidized Solidified Soil on Project Sites; (a) The site for drying the sediment; (b) Measurement and transportation of sediment; (c) Mixer; (d) Fluidized solidified soil discharge; (e) Pumping pouring; (f) Self-leveling of fluidized solidified soil; (g) Curing and shaping

site. Finally, the dried soil, cement, and supernatant that needed to be added after calculation were sent to the mixer for uniform mixing and pumped into the foundation pit for curing and shaping. The actual construction process on site is shown in Figure 11. The pouring process and relevant performance indicators of the fluidized solidified soil material had been inspected and accepted by the project's quality control, and all comply with the Chinese "Technical standard for the backfilling project by using premixed fluid solidifying soil" T/CECS 1037-2022 [32].

The detailed engineering application data: (1) Backfilled foundation pit data: total length 703m, depth 6.3m∼15.4m, average width 2.5m (narrowest point only 0.8m); (2) The technical requirements for fluidized solidified soil: slump flow greater than 400mm, 28-day unconfined compressive strength greater than 0.4MPa; (3) Actual application detection value: The slump flow is 460mm, and the 28-day unconfined compressive strength is 0.52MPa.

Through the demonstration application of this project, the engineering waste mud was regenerated into high-value-added green building materials, achieving zero discharge of waste mud from the project and reducing environmental pollution and safety issues caused by transportation and disposal. At the same time, the transportation cost of engineering slurry is saved. The recycled liquid solidified soil can replace the originally designed high-fluidity foam concrete or ordinary concrete, improving construction efficiency and saving material costs. In summary, the demonstration application of this project has achieved on-site closed-loop treatment of engineering waste mud, which could lead to reduced construction waste emissions and the development of a "waste-free city".

5. Conclusion

In this work, the influence of flocculants and related mechanisms on the mud-water separation effect and the performance of fluidized solidified soil were studied, and the feasibility of closed-loop utilization of waste mud in the field was verified through engineering demonstration applications. The relevant results are as follows:

(1) APAM flocculant had a better mud-water separation effect than PAC flocculant, and when the two were combined, the mud-water separation effect had a superposition effect, which could quickly and effectively separate the mud and water. However, there was an optimal addition sequence (that is, adding PAC first and then APAM).

(2) The combined flocculants in the sediment could promote the mutual bonding between clay particles and the reaction with the hydration products of cement to form reinforced ettringite, which filled the gaps between large flocculent particles, improving the compactness of the soil and the strength and water stability of the fluidized solidified soil.

(3) The engineering demonstration application showed that constructing a temporary production line on the construction site, flocculating and regenerating green building materials from the engineering waste mud, and reusing them on the construction site can improve construction efficiency, save costs, and reduce environmental pollution.

The research facilitated the industrial closed-loop resource utilization of waste mud, providing a reference for the engineering application of our method to achieve zero discharge of mud.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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