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Case Study of Solid Waste Based Soft Soil Solidifying Materials Applied in Deep Mixing Pile

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Highlights:

The solidifying agent deep mixing pile showed excellent early strength and late strength.
The mechanism of solidifying agent to solidify organic clay was analyzed.
The integrity of the solidifying agent mixing pile was significantly improved by a meniscus blade.
Mixing a total of four times is suitable for the construction of the solidifying agent deep mixing pile.

Abstract: The research on solid waste based soft soil solidifying materials has received extensive attention in recent years. However, the properties of deep mixing piles are significantly affected by the construction technology. In view of this, this work carried out the systematic study on the influence of materials, the mixing tool and process optimization on the integrity and mechanical properties of deep mixing piles. Factors considered include the shape of the blade (strip and meniscus), the types of solidifying materials (PO 42.5 cement, self-developed soft soil solidifying agent), the content (50 kg/m, 65 kg/m, 80 kg/m and 100 kg/m) and how many times the materials needed to be mixed (two, four and six times). The solidification mechanism was analyzed. The results showed that the utilization of a meniscus blade contributed to the excellent integrity of the deep mixing pile, as well as solved the problems of oozing slurry and wrapped blade during construction. Mixing the materials four times is the most suitable for the construction of deep mixing piles in organic clay. The solidifying agent deep mixing pile showed satisfactory early and late strength. Microscopic analysis showed that more calcium silicate hydrate and ettringite formed in the solidifying agent solidified soil. Organic clay particles were better cemented and pores were fully filled, so that the solidified soil showed an integral and dense structure. The microscopically integral and dense structure contributed to the excellent integrity and mechanical properties of the solidifying agent deep mixing pile.

Keywords: solidifying materials; engineering application; cement deep mixing pile; unconfined compressive strength; construction technology

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1. Introduction

The cement deep mixing pile is widely conducted in soft foundation reinforcement because of its favorable economics and easy handling. Cement is suitable for cementation in dinas medium, but controversial in soil medium [1,2]. Many factors could significantly affect the cementation between cement and soil, such as high water content, high void ratio and high organic matter content [3–5].

In recent years, the research on alkali-activated solidifying materials has received extensive attention [6–8]. Solid wastes including silicon–alumina glass phases are widely utilized to design soil solidifying materials, such as ground granulated blast furnace slag, steel slag and fly ash. Alkaline components are used to activate the silicon–alumina glass phases, such as sodium hydroxide, sodium carbonate and sodium silicate [9–13]. The alkali activation reactions include dissolution of the vitreous body, formation of polymer gel and gel hardening [14,15]. Alkali-activated cementitious material is considered a new type of green and low-carbon material because of its low energy consumption and low carbon emission [16–18]. At present, the geotechnical solidification materials are classified into inorganic, organic polymer, ionic and biological enzymes [19,20]. Deng et al., [21,22] studied the effect of the solidifying materials, which is composed of steel slag powder, calcium oxide and metakaolin, on the properties of solidified soft soil. The study found that the reasonable addition of metakaolin could effectively improve the unconfined compressive strength of steel slag solidified soil. Shu et al., [23] studied the effect of different types of activators on the solidification effect of slag powder solidified organic clay. The results showed that the composite incorporation of sodium carbonate and sodium hydroxide significantly improved the solidification effect on organic clay. The unconfined compressive strength (UCS) of the steel slag based solidified organic clay mixed with 10% sodium hydroxide and 10% sodium carbonate was 2.37 MPa after a 28 d curing period. The microstructure showed that more C-S-H formed in the solidifying agent solidified organic clay than cement and the structural compactness was significantly improved. Latifi et al., [24] studied the effect of different contents of xanthan gum on the solidifying effect of bentonite. The SEM results showed that the bentonite particles were more tightly packed after the addition of xanthan gum and the large pores were filled with gel. The solidifying mechanism is the gelation and intermolecular interactions, which include electrostatic interactions and hydrogen bonds. Gautam et al., [25] found that the ionic solidifying materials changed the microstructure of bentonite from flake to bead, which significantly reduced the volume expansion rate of the solidified soil. Kushwaha et al., [26] studied the effect of eco-biological enzymes on the solidification effect of expansive soil. SEM showed that the incorporation of biological enzymes significantly reduced the internal porosity of soil and soil particles were thus agglomerated.

It can be seen that there has been in-depth research on the development of soft soil solidifying materials, but a small amount of research relates to the application technology of the new solidifying agent in deep mixing piles [27–29]. Zhou et al., [30] studied the effect of gypsum and lime on the unconfined compressive strength of deep mixing piles. The study showed that after the addition of lime and cement with the ratio 1:1, the unconfined compressive strength of the deep mixing pile at the curing period of 28 d is 6.6 MPa, which is 46% higher than that of the cement–fly ash deep mixing pile. Lu et al., [31] studied the effect of different components, which include fly ash, lime, triethanolamine, sodium chloride and sand, on the property of silty soil deep mixing piles. The results showed that the components could improve the solidification of solidified soil. Triethanolamine could significantly improve the early strength of a deep mixing pile. The skeleton structure of sand contributed satisfactory mechanical properties to the deep mixing pile. Hong et al., [32] studied the effect of basalt fiber on the mechanical properties of cement deep mixing piles. The study found that the strength of basalt fiber deep mixing piles was about 71.2–77.8% of laboratory testing. The uneven dispersion of basalt fiber seriously affected the strength of the deep mixing pile.

In summary, most of the current research focus on the influence of different types of solidifying materials on the property of the deep mixing pile. However, there is very little work related to systematic research on the construction technology of deep mixing piles.

Therefore, the influence of construction technology, which includes materials (PO 42.5 cement and a self-developed solidifying agent), the mixing tool (strip blade and meniscus blade), and mixing times (two, four and six times) on the properties of deep mixing piles was systematically studied in this work. A complete set of construction technology for the new solidifying agent deep mixing pile suitable for organic clay is proposed, which provides guidance for the subsequent large-scale application.

2. Materials and Methods

2.1. Materials

(1) Green soft soil solidifying agent

The solidifying agent used in this work was self-developed based on the previous research [23]. The solidifying agent was composed of steel slag powder (SS) and ground granulated blast furnace slag powder (GGBS). Alkali-activated material was also incorporated. A certain amount of composite alkaline activator was used to activate the solid waste. The properties of the soft soil solidifying agent are shown in Table 1. The solidifying agent meets the requirements of "Stabilizer for soft soil" (CJ/T 526-2018, Beijing, China). In addition, it also reveals that the solidifying agent showed excellent fluidity and early strength.

Table 1. Properties of soft soil solidifying agent.

Performance Index	Moisture Content/%	Fineness (>80 μm)	Initial Setting Time/min	Fluidity of Solidifying Agent Paste (25 °C)/s			Mortar Strength/MPa	
				Initial	30 min	60 min	7 d	28 d
Specification requirements	≤1	≤10	≥45	≥100	≥90	≥80	/	/
Experimental result	0.7	5	130	240	210	170	35.6	41.8

(2) Geotechnical parameters of experiment field

This research work was carried out in the Robot Valley No. 3 project in Shunde District, Foshan. Geological data showed that there is massive alluvial organic clay and the average distribution thickness is 11.3 m. Organic clay at the depth of 7 m was drilled and tested; the result is shown in Table 2. The organic clay has the characteristic of a high content of moisture and organic matter.

Table 2. Basic properties of engineering soil.

Geotechnical Parameters	Natural Moisture Content/%	Organic Matter Content/%	Specific Gravity, g/cm^3	Liquid Limit/%	Plastic Limit/%	<0.075 mm,%	USCS Soil Classification
Test result	103.2	12.1	1.69	51.5	40.56	54.5	OH

2.2. Field Experiment

(1) Deep mixing pile machine

A deep mixing pile machine (SJB-II) with forward and reverse mixing functions is shown in Figure 1. The crankshaft slurry pump with the pressure of 0.6 MPa was used. The inner and outer rods were rotated by the two motors with the power of 45 KW.

Figure 1. Deep mixing pile machine used in this study.

(2) Construction technology

The construction technology of the deep mixing pile is shown in Table 3. According to the design requirements, the length and diameter of the deep mixing pile are 11.5 m and 0.5 m, respectively. This work fully studied the influence of the change in the solidifying materials, the mixing tool and the construction process on the properties of the deep mixing pile.

Table 3. Construction technology of the mixing pile in this study.

Diameter of Mixing Pile/mm	Length of Mixing Pile/m	Shape of Mixing Blade	Type of Solidifying Materials	Mixing Content of Solidifying Agent (kg/m)	Number of Mixing Times
0.5	11.5	Strip, Meniscus	Solidifying agent, PO 42.5 Cement	50, 65, 80, 100	Two, Four, Six

Mixing tool: The effect of different shaped blades on the integrity of the deep mixing pile are studied (shown in Figure 2). The conventional blade is shown in Figure 2a, which is composed of four groups of long strip blades. The meniscus blade is shown in Figure 2b, which is composed of 4 groups of blades with a 30° inclination angle.

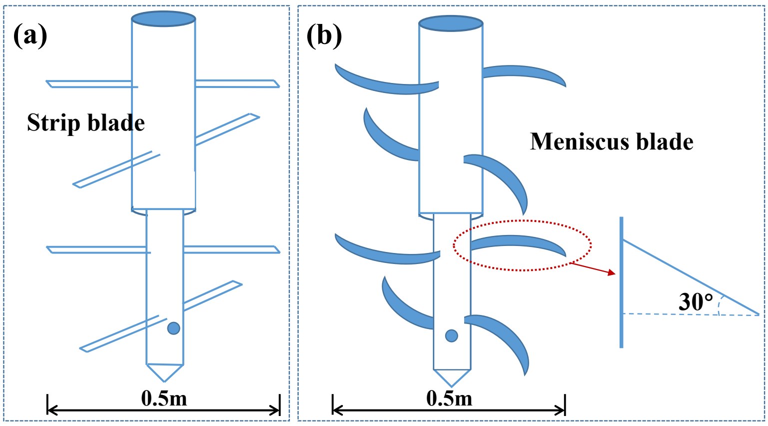

Figure 2. Different shapes of mixing blades: (**a**) strip blade and (**b**) meniscus blade.

Materials: Two types of solidifying materials are studied, including the self-developed solidifying agent and PO 42.5 cement; the content of 50 kg/m, 65 kg/m, 80 kg/m and 100 kg/m are considered. The W/B ratio and specific gravity of the solidifying agent were 0.6 and 1.71 g/cm^3, respectively. Geological data are shown in Table 2. The soil from ground to 11.5 m depth is organic clay.

Construction process: The number of mixing times of twice, four times and six times are studied. The drill bit is drilled from ground to the depth of 11.5 m with the stirring speed of 42 r/min, and then raised to ground, which is defined as mixing twice. One round-trip repetition is defined as mixing four times, and two round-trip repetitions are defined as mixing six times. The penetration speed and retrieval speed are 0.83 m/min and 1.24 m/min, respectively. Solidified material slurry should be grouted at the first two times of mixing.

2.3. Unconfined Compressive Strength Test

The deep mixing piles at the curing ages of 14 d and 28 d were drilled out. The piles at the depth of 2 m, 6 m and 10 m were fully cut into nine cylinders with the diameter and height of 50 mm and 100 mm, respectively. The loading rate of the force was set at 80 N/s during the unconfined compressive strength test. The minimum of three cylinder strengths at each depth was selected as the unconfined compressive strength of one deep mixing pile. The average value of the three minimum strengths at three different depths (2 m, 6 m and 10 m) was determined as the strength of one deep mixing pile.

2.4. Microscopic Analysis

In this work, the SEM test of the core sample of the deep mixing pile was carried out on the TESCAN MIRA4 machine. The samples were sprayed with gold before testing. Magnifications were 2000, 5000 and 10,000 times, respectively.

3. Result and Discussion

3.1. Effect of the Shape of Blade

For the construction of the traditional cement deep mixing pile in organic clay, the wrapped blade (Figure 3a) and oozing slurry (Figure 3b) frequently occurred. The strip blade cannot play the mixing function when the wrapped blade occurred, which could seriously reduce the properties of the deep mixing pile. The effective cement amount decreased when oozing slurry occurred, which could significantly weaken the strength of the deep mixing pile, as well as cause a lot of waste of resources.

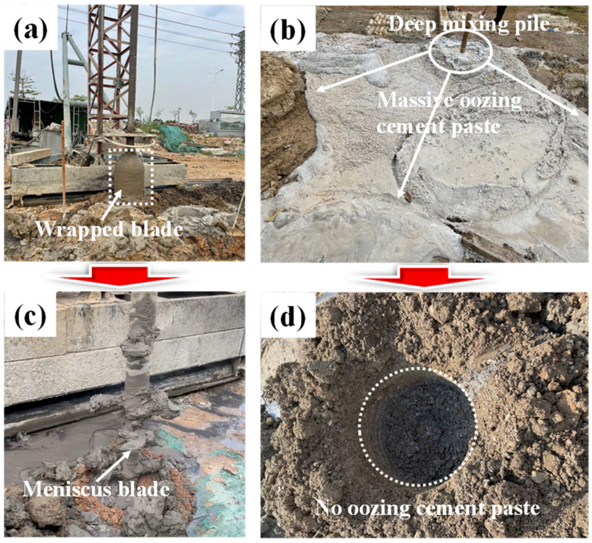

Figure 3. Influence of different types of blades on the construction process: (**a**,**b**) strip blade and (**c**,**d**) meniscus blade.

After the utilization of the meniscus blade, it can be found that the blade was not wrapped by soft soil (as shown in Figure 3c); therefore, the meniscus blade can always play the role of mixing during construction. Figure 3d shows that there no oozing slurry occurred, which means that the utilization of the meniscus blade can solve the construction problems of oozing slurry and the wrapped blade. There is a good adaptability for the meniscus blade with an inclination angle in organic clay.

The integrity of a conventional cement deep mixing pile and a solidifying agent deep mixing pile are shown in Figure 4. It can be seen from Figure 4a that there is no mixing pile formed in organic clay. The pile was in the soft state and there is no strength formed. The main reason is that the high organic matter, high water content and high void ratio make it difficult for the cement to hydrate and develop strength in the organic clay. Figure 4b shows that the solidifying agent deep mixing pile exhibited excellent integrity. It means that the meniscus blade should be used in the construction of deep mixing piles in organic clay, which can give the deep mixing pile excellent integrity.

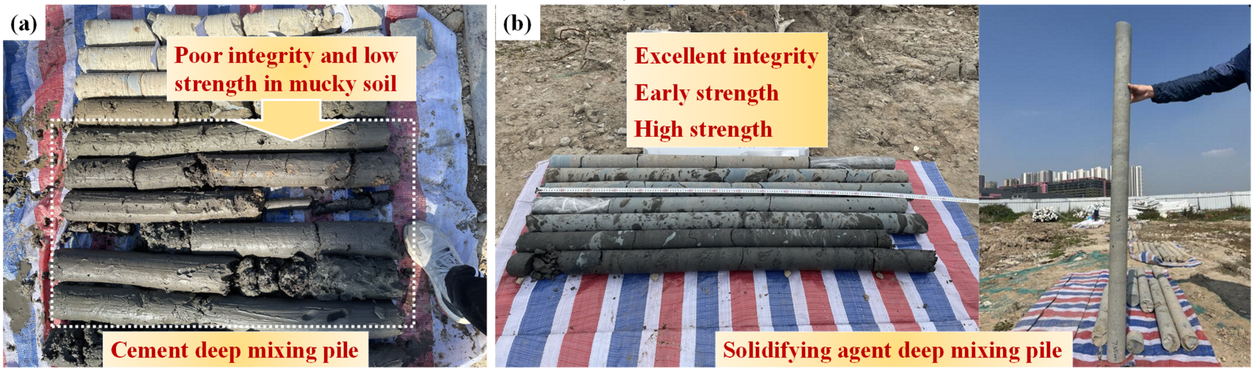

Figure 4. Integrity of different types of solidifying materials in deep mixing piles: (**a**) cement and (**b**) solidifying agent.

The homogeneity of a deep mixing pile is shown in Figure 5. It can be seen from Figure 5a that there are obvious boundaries between soft soil and cement hydration products in the cross section of the conventional cement mixing pile, which indicates that the cement slurry and the soft soil were not mixed evenly. The deep mixing pile showed poor homogeneity. Figure 5b shows that the solidifying agent deep mixing pile exhibited good homogeneity. No obvious boundary between the soft soil particle and the solidifying agent hydration product could be found, which indicates that the utilization of the meniscus blade could improve the uniformity of the deep mixing pile. To sum up, it can be seen that the deep mixing pile showed excellent uniformity and integrity after the utilization of the self-developed solidifying agent and the meniscus blade.

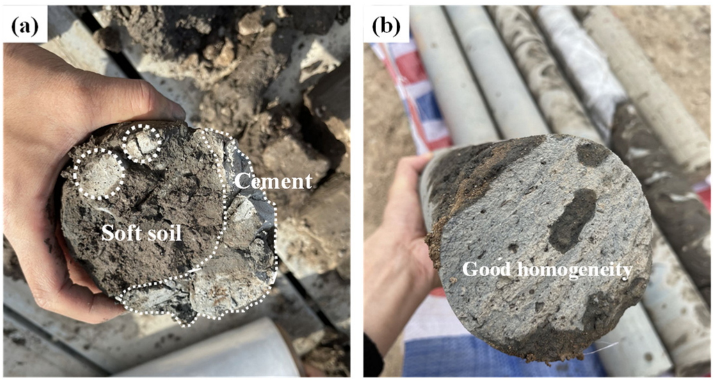

Figure 5. Homogeneity of different types of solidifying materials in a deep mixing pile: (**a**) cement and (**b**) solidifying agent.

3.2. Effect of Mixing Times

The effect of mixing times is shown in Figures 6 and 7 and Table 4. Oozing slurry occurred when mixed twice (as shown in Figure 6a), yet did not occur when mixed four or six times (as shown in Figure 6b,c). The reason is that the grouting hole was located under the blades. When mixing twice, the blade does not play the role of mixing the slurry and soft soil particles during the retrieval of blade. Due to the density difference, the original solidifying agent slurry will slowly ooze to the ground. When mixing four or six times, due to the repeated mixing, the slurry can be fully and evenly mixed with the soil particles, so oozing is avoided.

Figure 6. Influence of mixing times on oozing slurry of a mixing pile: (**a**) two, (**b**) four and (**c**) six.

Figure 7. Influence of mixing times on the integrity of the mixing pile: (**a**) two times, (**b**) four times and (**c**) six times.

Table 4. Influence of construction efficiency on oozing and integrity of the paste of a deep mixing pile.

Mixing Times	Efficiency	Oozing Cement Paste	Integrity
two	23.1 min	yes	excellent
four	46.3 min	no	excellent
six	69.3 min	no	excellent

The effect of mixing times on the integrity of a solidifying agent deep mixing pile is shown in Figure 7. It can be seen that the solidifying agent mixing piles showed excellent integrity regardless of whether mixed twice, four times or six times, which indicates that the number of mixing times is not the key factor affecting the integrity of the deep mixing pile. A reasonable improvement in the mixing tool (a meniscus blade with a 30° inclination angle) can ensure the integrity of the deep mixing pile.

The construction efficiency of a different number of mixing times is shown in Table 4. Although all the deep mixing piles showed excellent integrity, the effective solidifying agent content for solidification was decreased when mixed twice, which would weaken the mechanical properties of the deep mixing pile. Therefore, mixing twice is not recommended. The construction efficiency of mixing six times is 69.3 min/pile, which is 50% slower than that of mixing four times, so it is not recommended. For the construction of a deep mixing pile in organic clay, mixing four times is satisfactory; no oozing slurry occurred and the construction efficiency was also acceptable.

3.3. Effect of Types of Solidifying Materials

The effect of different types of solidifying materials (cement and self-developed solidifying agent) with the content of 65 kg/m on the unconfined compressive strength of a deep mixing pile was contrastively studied and the result is shown in Figure 8. The strength of the solidifying agent deep mixing pile is higher than that of the cement mixing pile at both curing periods of 14 d and 28 d. The strengths of the solidifying agent deep mixing pile at the curing periods of 14 d and 28 d are 1.4 MPa and 2.35 MPa, respectively. The early strength and late strength are about nearly triple that of the cement deep mixing pile. The result means that the solidifying agent is more suitable for solidifying organic clay than cement. Therefore, suitable solidifying materials should be developed and utilization when solidifying organic clay.

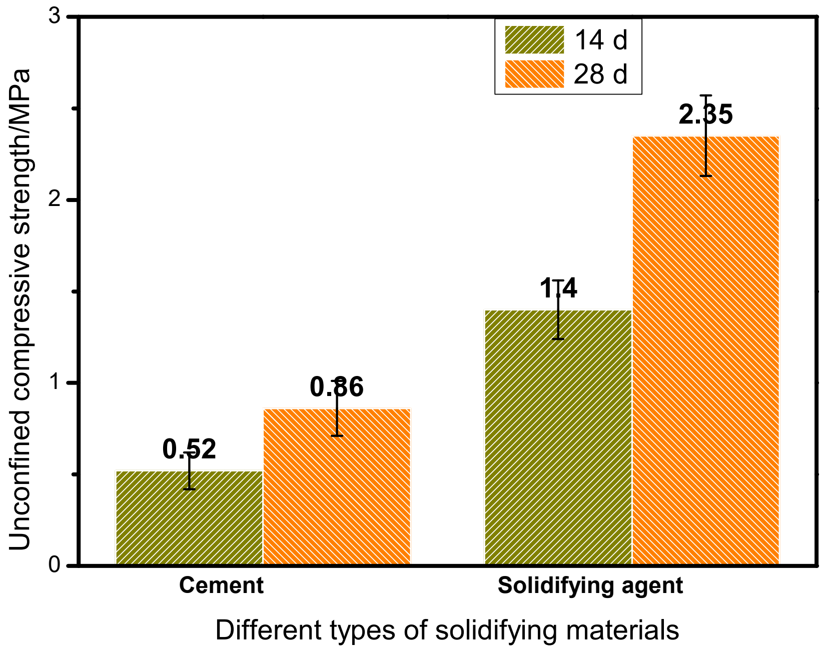

Figure 8. Effect of different types of solidifying materials on the unconfined compressive strength of a deep mixing pile.

3.4. Effect of Content of Solidifying Agent

The effect of the content of the solidifying agent on the unconfined compressive strength of a deep mixing pile is shown in Figure 9. It can be seen that the early and later intensity of solidified soil gradually increased with the content of the solidifying agent. At the curing period of 14 d, the strength of the deep mixing pile with the dosage of 50 kg/m is 1.13 MPa. With the dosage increased to 100 kg/m, the strength of the deep mixing pile at the 14 d curing period increased to 2.15 MPa. It means that the solidifying agent showed excellent early strength. The 28 d strength of the deep mixing piles with a dosage of 50 kg/m of solidifying agent is 1.54 MPa. When the dosage of the solidifying agent increased to 100 kg/m, the 28 d strength increased to 2.97 MPa. As mentioned in the literature [3,28,29], different types of soil have different effects on the properties of a cement deep mixing pile after a longer curing period. For example, the strength of cement deep mixing piles in cohesive soils continued to increase, while in organic clay, the strength of cement deep mixing piles decreased significantly after curing for three months. Therefore, a future study will be carried out for the performance study of the solidifying agent deep mixing pile in cohesive soils and organic clay after a longer than 6 months' curing period.

3.5. Microcosmic Analysis

The microscopic morphologies of the cement deep mixing pile and the solidifying agent deep mixing pile are shown in Figure 10. Figure 10a shows that small amounts of hydrated calcium silicate gel and ettringite were generated in the cement solidified soil. A large number of soft soil particles were loosely distributed, which were not cemented into a whole. A large number of pores were found in the cement solidified soil. Figure 10b shows that the soft soil particles were fully covered with calcium silicate hydrate and a large amount of ettringite was generated. It is worth noting that the boundary of the soft soil particles was filled with calcium silicate hydrate and ettringite. No pores were observed. The solidifying agent solidified soft soil exhibited a monolithic and dense structure.

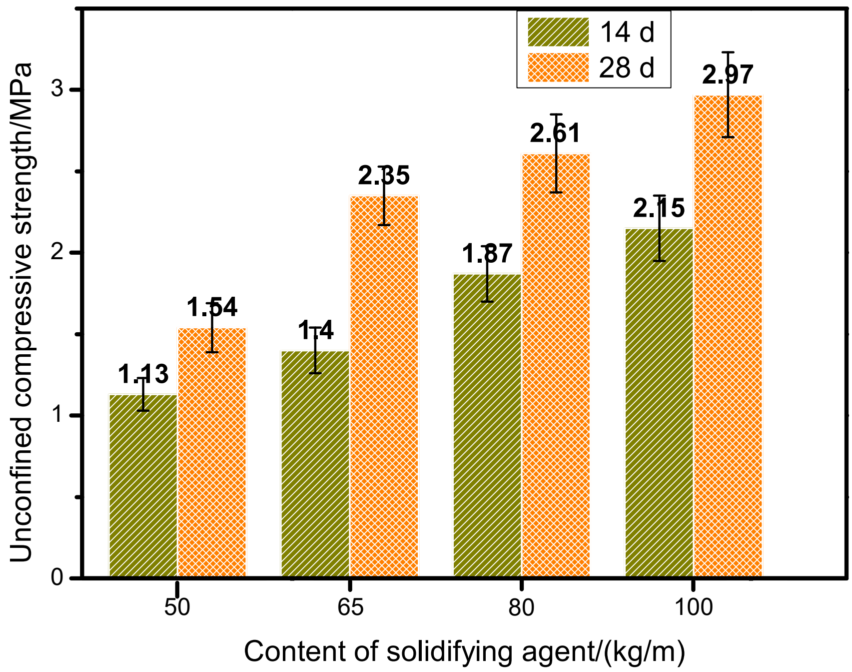

Figure 9. Effect of the content of the solidifying agent on the unconfined compressive strength of the mixing pile.

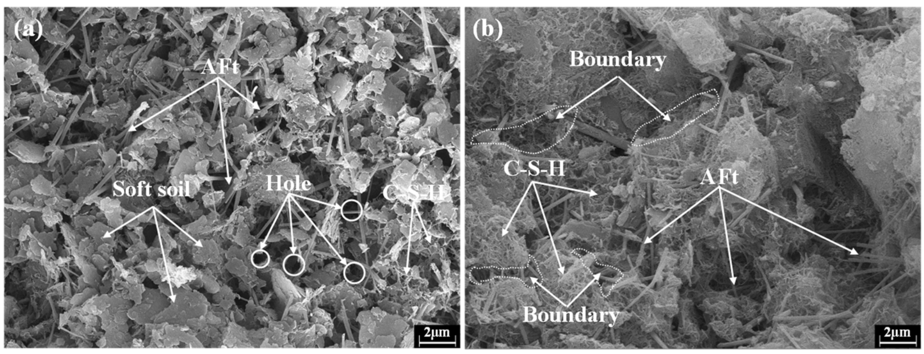

Figure 10. Micro-morphology of core samples of different types of solidifying materials in deep mixing piles: (**a**) cement and (**b**) solidifying agent.

3.6. Mechanism Analysis

The loose structure of the cement deep mixing pile and the cement solidified soil (as shown in Figures 4a and 10a) was mainly caused by three reasons: firstly, the high content of moisture and organic matter weakened the cementation of cement in organic clay [33,34]; secondly, massive oozing slurry decreased the effective content of the cement for solidifying soft soils; thirdly, the pore diameter of the cement solidified soil was concentrated in 300–1000 nm, which is dozens of times larger than that of cement concrete [35]. However, the quality of expansive materials, such as AFt in cement hydration products, was strictly limited; thus, the cement stabilized soil showed a loose structure and a large number of pores still existed. The above three reasons led to the poor integrity and low strength for the cement deep mixing pile in organic clay.

The reasons for the excellent integrity and strength of the solidifying agent mixing pile are mainly due to the following two aspects: firstly, the meniscus blade with 30° inclination angle solved the problem of slurry oozing and a wrapped blade, thus the effective content of the solidifying agent solidifying soil particles was increased. In addition, the meniscus blade with a 30° inclination angle improved the homogeneity of the solidifying agent solidified soil. More hydration products such as calcium silicate were generated, thus more soil particles were cemented. The integrity and the strength of the solidifying agent deep mixing pile were thus improved. Secondly, the component of SO_4^{2-} and OH^- in the solidifying agent promoted the formation of AFt. AFt increased the volume of solid phase by 120% [36], which could effectively fill the massive pores (300–1000 nm) in the solidified soil, as well as improve the compactness of the solidified soil. Therefore, the solidifying agent deep mixing pile showed satisfactory integrity and strength (as shown in Figure 4b). The solidification mechanism diagrammatic sketch of the conventional cement deep mixing pile and the solidifying agent deep mixing pile (including the new type of mixing tool and solidifying materials) is shown in Figure 11.

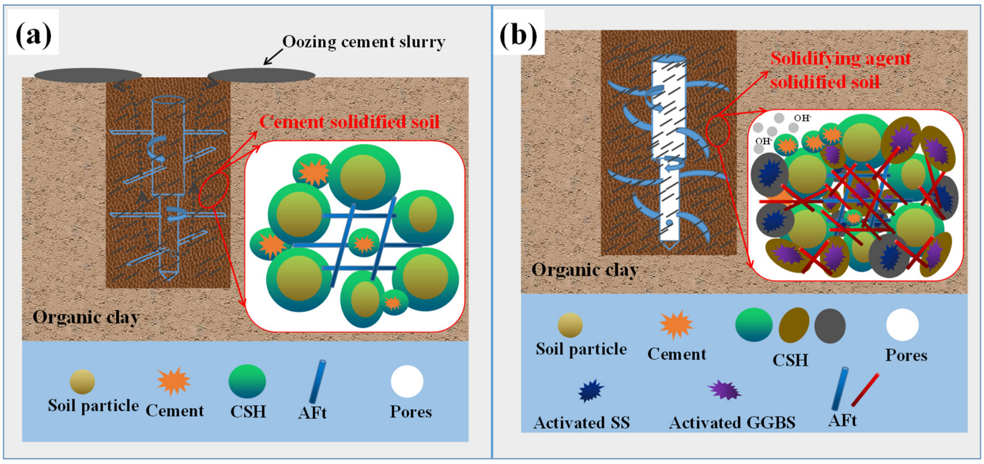

Figure 11. The solidification mechanism diagrammatic sketch of (**a**) the conventional cement deep mixing pile and (**b**) the solidifying agent deep mixing pile.

4. Conclusions

In this paper, a systematic study on the influence of materials, the mixing tool and the construction process on the properties of deep mixing piles is carried out and the solidification mechanism is analyzed. The main conclusions are as follows:

(1) The utilization of meniscus blades contributed to the excellent integrity of the deep mixing pile. Meanwhile, the homogeneity of the deep mixing pile was significantly improved. Mixing times and the type of solidifying material are not the key factors affecting the integrity. For the construction of deep mixing piles in organic clay, mixing a total of four times is the most suitable.

(2) The strength of the solidifying agent deep mixing pile was nearly three times that of the cement deep mixing pile (65 kg/m). The solidifying agent deep mixing pile showed satisfactory early and late mechanical properties. With the content of the solidifying agent, the early strength (14 d) and late strength (28 d) of the deep mixing pile both gradually increased. Under the content of 50 kg/m of the solidifying agent, the unconfined compressive strength of the deep mixing pile at the curing periods of 14 d and 28 d are 1.13 MPa and 1.54 MPa, respectively. When the content of the solidifying agent is increased to 100 kg/m, the unconfined compressive strength of the deep mixing pile at the curing periods of 14 d and 28 d are 2.15 MPa and 2.97 MPa, respectively.

(3) Compared with the cement solidified soil, more calcium silicate hydrate and AFt were generated in the solidifying agent solidified soil. Soil particles were better cemented by C-S-H and AFt, meanwhile the pores were fully filled. The integral and dense structure was formed under the solidification of the solidifying agent. Therefore, the solidifying agent deep mixing pile showed the characteristics of excellent integrity, early strength and late strength.

Future study will be carried out for the performance study of the solidifying agent deep mixing pile in cohesive soils and organic clay after a longer 6 months' curing period.

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