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Mechanical properties of saline soil solidified with lime, fly ash and modified polyvinyl alcohol under freeze-thaw cycles

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Abstract: The repeated freeze-thaw cycles with seasonal alternations have an obvious effect on soil structure. To reduce the temperature sensitivity of saline soil and then use it in engineering, a combined treatment method is proposed, where lime, fly ash and modified polyvinyl alcohol (MPA) are used as solidified materials. Unconfined compressive strength (UCS) tests and microstructure characterization are firstly used to evaluate the solidified effect and obtain the parameters range of solidified materials. Then, the shear strength tests for determining cohesion and internal friction angle are conducted. Experiments are conducted by considering separate and combined treatments of materials mentioned above. The results indicate that the combined treatment with lime, fly ash and MPA can improve the strength of saline soil. After combined treatment, the UCS is 1130.25 kPa, which is 5.18 times than that of saline soil (218 kPa). The strength of combined solidified saline soil meets the requirements of engineering specification (JTG 3430-2020). The stable value of UCS of combined solidified saline soil is 700 kPa under freeze-thaw cycles. The fluctuation is about 5% after three freeze-thaw cycles. The cohesion and the internal friction angle of combined solidified saline under the optimal proportion can be 208.2 kPa and 38.56° , respectively after three freeze-thaw cycles. The sensitivity of the factors is in an order of decreasing importance: curing time, lime content, MPA content, dry density, salt content, and freeze-thaw cycles. With an increase of lime, fly ash and MPA content, the strength of combined solidified saline soil increases and then tends to become stable. The optimization of solidification parameters can effectively weaken the influence of freeze-thaw on coastal saline soil. Based on tests results of compressive strength and shear strength, it can be concluded that the optimal combination of solidified parameters is 14% of lime, 30% of fly ash, 1% of MPA, 28 days of curing time, and a dry density of 1.65 g/cm^3.

Keywords: mechanical property; freeze-thaw performance; combined treatment method; compressive strength; shear strength; microstructure; Saline soil

1 Introduction

Seasonal frozen soils is widely distributed in the coastal areas[1]. As high moisture content and salinity exist in soil, the soil structure is serious destructed in the repeated freeze-thaw environment. Soil pore structure varies in the process of ice formation, along with the increasing of the average pore diameter[2–3]. Besides, the macroscopic crystal pressure, generated by water and salt crystallization, is the main cause of deformation and failure of saline soil[4–5]. In addition, all of the liquid plastic limit, specific surface area, and permeability coefficient of saline soil change under freeze-thaw cycles, and the soil strength decreases obviously[6]. Therefore, it is of great significance to reduce the temperature sensitivity before engineering application.

Solidification is one of methods to improve the strength and stability of soil. Lime treatment can improve the physical and mechanical properties of saline soil[7]. Fly ash has a smooth surface and microspores, its hydration products can reduce the soil porosity and form a dense structure[8]. Cement treatment is only effective in non-cohesive or medium cohesive soil[9]. Better results can be found in combined treatment with lime and fly ash[10], which is helpful for improving the comprehensive properties[11–12]. However, specific environment often has special requirement for solidified parameters, which is the key problems before application.

In this paper, a combined treatment method is proposed to solve the freeze-thaw damage problem, where lime, fly ash and MPA are chosen as solidified materials. Unconfined compressive strength and microstructure characterization tests are firstly used to evaluate the solidified effect and obtain the parameters range of solidified materials. Then the shear strength test (cohesion and internal friction angle) and the orthogonal experiment are used to analyze the influence of each factor and the optimal combination of solidified parameters. The results can not only enrich the theory of treatment of soil, but also provide technical guidance for infrastructure construction in coastal areas.

2 Materials and methods

2.1 Materials

2.1.1 Saline soil

Saline soil was collected from Binhai New Area, Tianjin, China. It is classified as silty clay and chlorine

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saline soil. The particle size distribution and the basic physical properties are presented in Fig. 1 and Table 1, respectively.

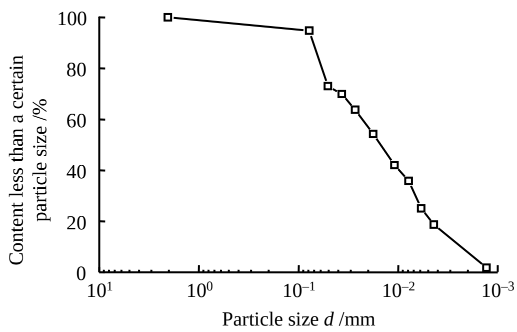

Fig. 1 Particle size distribution of saline soil

2.1.2 Solidified materials

The lime used in the experiment was from Jixian County, Tianjin, China. The fly ash was taken from the Yangliuqing Power Plant, Tianjin, China, and the mass ratio of fly ash and slag is 7:3. The basic physicochemical parameters of the lime and fly ash are shown in Tables 2–3.

MPA is a kind of water-soluble polymer material with low viscosit[13]. Acute toxicological tests in animals and plants have confirmed that MPA is environmental friendly[14]. The basic physicochemical properties are presented in Table 4. A network system will be formed under the bonding, chelation, adsorption, and bridging interaction once it contacts with the soil (Fig. 2). Therefore, MPA can strengthen the integrity and the wind and rain erosion-resistance of soil [15].

Table 1 Basic physical properties of saline soil

Salt content /%	Air dried moisture content /%	Optimum moisture content /%	Maximum dry density /(g • cm^{-3})	G_s	Consistency index		
					Liquid limit /%	Plastic limit /%	Plastic index
3	2.4	18	1.71	2.7	30.6	18.8	11.8

Table 2 Basic physicochemical parameters of the fly ash

Major components	Specific surface area /(m^2 • g^{-1})	Average pore size /nm	Total pore volume /(mL • g^{-1})	Main chemical composition /%						
				SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	P_2O_5
Slag	0.135	1.10	4.50×10^{-4}	52.58	30.32	8.73	2.33	0.37	1.52	0.84

Table 3 Main chemical composition of the lime

Composition	SiO_2	CaO	MgO	SO_3
Content /%	1.08	95.32	0.68	0.01

Table 4 Physicochemical properties of MPA

Properties	Parameters
Solid content	6%
Density	1.09 g/cm^3
Molecular weight	>20 000 g/mol

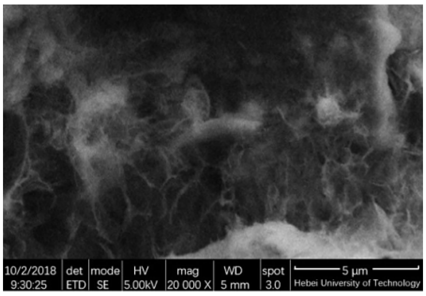

Fig. 2 SEM of soil solidified by MPA

Table 5 Parameter setting of materials from references

References	Solidified material	Content /%	Soil type
Han [16]	Lime	0, 7, 8, 9, 10, 11	Saline soil
Li et al.[17]	Lime	12	Saline soil
Wei et al.[12]	Lime MPA	8, 10, 12 0.5, 1, 1.5	Saline soil
Li et al.[18]	Fly ash	5, 10, 15, 20, 25, 30	Saline soil
Zhao et al.[19]	Lime Fly ash	6, 9, 12, 15, 18 6, 12, 18, 24, 36	Saline soil

Note: the content of solidified material refers to the weight ratio of dry soil.

2.2 Test methods

2.2.1 Material parameters and sample types

In line with previous experimental studies and group researched results (Table 5), the preliminarily content range of lime, fly ash and MPA is 6%–14%, 5%–30%, and 0.6%–1.2% (by weight), respectively. The same content intervals are selected in this study. Sample types included saline soil, lime treated soil, lime + MPA treated soil and lime + fly ash + MPA treated soil.

2.2.2 Sample preparation

According to the "*Standard for geotechnical testing method*" (GB/T50123-2019) [20], the saline soil was air-dried, sieved with 2mm filter and then stored in plastic bags. Before sample preparation, 2/3 water mass of the optimum moisture content was mixed with the dry soil and then sealed in a plastic bag for 24 h to ensure the uniform mixture distribution. Later, the lime and fly ash were mixed and sealed for 24 h again to eliminate the swelling problem caused by the initial reaction between them. At the same time, MPA was dissolved in 1/3 water mass of the optimum moisture content. According to ASTM D2850-15[21], soil samples with and without solidified material were prepared by the standard static compaction method (H×D=125 mm× 61.8 mm). Then they were cured for 7, 14, 21, and 28 days in the standard condition. Three parallel samples were used in the experiment, and the initial dry densities were 1.50, 1.55, 1.60, 1.65, 1.70 g/cm^3, respectively.

2.2.3 Simulation of freeze-thaw environment

According to previous meteorological data, the minimum temperature in Beijing-Tianjin-Hebei region of China at night is around –19 ℃, and the average temperature is around 18 ℃[22]. Sun et al.[23] proved that the initial 5 freeze-thaw cycles were the main descent stages. LÜ et al.[10] showed that the physical and mechanical properties of soil tend to be stable after 7 freeze-thaw cycles. Therefore, the DR-2A freeze-thaw chamber (Nanhua Instruments Co Ltd., Wuxi, China) was used to control the test temperature. The soil samples first froze at –20 ℃ for 24 h, and then thawed at 20 ℃ for 24 h in one freeze-thaw cycle, and 10 cycles are designed in the experiment. In order to prevent moisture loss during experiment, the sample surface was wrapped with a double-layer of cling film.

2.2.4 Mechanical properties and micro-mechanism study

According to ASTM D2166/D2166M-13[24], an improved California Bearing Ratio (CBR) apparatus was used in UCS test with the strain rate of 0.10 mm/min and a load cell of 10 kN. SJ-1A.G desktop triaxial shear apparatus was used in unconsolidated undrained (UU) shear strength test, the strain rate was 0.828 mm/min and confining pressures were 100, 200, 300 and 400 kPa, respectively.

A scanning electron microscope with energy dispersive X-ray analysis (FEI, Nova Nano 450) was employed to investigate the microstructural characteristics of the samples. Pieces of dry soil samples after the test were put on the specimen holder, and coated with a thin layer of gold palladium to ensure surface conductivity. The coated specimens were then placed in a SEM, and the photomicrographs were recorded.

2.2.5 Orthogonal experimental design

With the help of orthogonal experiment analysis, the curing time, lime content, MPA content, freeze-thaw cycles, salt content, and dry density were taken as the influence factors. Considering the inhomogeneity of salt distribution and the general applicability of research technology, the salt content in the test is determined as 1%, 3%, 5%, 7% and 9% based on the existing references [25–27].

Five levels are set for all factors. Cohesion and internal friction angle were taken as the evaluation index. The orthogonal experimental scheme is shown in Table 6.

Table 6 Orthogonal experimental scheme

Levels	Influence factors					
	Curing time /d	Freeze-thaw cycles	Lime content /%	MPA content /%	Salt content /%	Dry density /(g • cm^{-3})
1	7	1	6	0.7	1	1.50
2	14	3	8	0.8	3	1.55
3	21	5	10	0.9	5	1.60
4	28	7	12	1.0	7	1.65
5	35	9	14	1.2	9	1.70

3 Analysis of test results

3.1 Distribution of unconfined compressive strength in freeze-thaw environment

Figure 3 shows the stress–strain curves of saline soil with and without solidification after 28 days under 0–10 freeze-thaw cycles. The initial UCS of saline soil is 218 kPa. However, the UCS decreases by 50.36% after 1 freeze-thaw cycle, and only 50 kPa is remained after 5 freeze-thaw cycles, which is 77.06% less than the initial value (Fig. 3(a)). The axial stress of saline soil shows a parabolic distribution with the increase of axial strain before the freeze-thaw cycle. The peak axial stress occurs when the strain is 1.6%. The failure of saline soil presents strain softening brittle type. However, the peak of axial stress does not appear obviously with the increase of axial strain in the freeze-thaw environment, its failure is strain hardening type. These results are consistent with those from Ma et al.[7]

Figures 3(b) and 3(c) illustrate that the strength of lime solidified saline soil and lime + MPA solidified saline soil is significantly higher than that of saline soil. The initial UCS of them is around 400 kPa, then the UCS of lime solidified saline soil decreases by 27.11% after one freeze-thaw cycle, and 43% after five freeze-thaw cycles, which is 228 kPa. As to the lime + MPA solidified saline soil, the UCS decreases by 26.15% after one freeze-thaw cycle, and is stable at 240 kPa at five freeze-thaw cycles. With the increase of axial strain, the stress-strain curves of solidified saline soil all appear obvious peaks, and the curves are all strain softening type. It can be seen that solidification can weaken the effect of freeze-thaw cycles and has little impact on the stress–strain curve form, which is consistent with the results of LÜ et al.[28]

Figure 3(d) shows that the mechanical property of lime + fly ash + MPA solidified saline soil is further improved. Its initial UCS can reach to 1130.25 kPa, which is 5.18 times that of saline soil, and is much higher than 680 kPa of cement treated saline soil[29], and 584 kPa of lime treated saline soil[7]. The strength of lime + fly ash +MPA solidified saline decreases by 25.13% after one freeze-thaw cycle, and it is stable at 700 kPa after five freeze-thaw cycles, which meets the requirements of "*Test methods of soil for highway engineering*" (JTG 3430-2020)[30].

Comparing Figs.3(a)–3(d) shows that, in the freeze-thaw environment, the UCS of lime solidified saline soil, lime + MPA solidified saline soil and lime + fly ash + MPA solidified saline soil is 4.56–14 times that of saline soil, and all of the strength fluctuations range are about 5% after three freeze-thaw cycles. The failure strain of both saline soil and lime solidified saline soil is 1.6%, and those of lime +MPA solidified soil and lime + fly ash +MPA solidified soil is 2% and

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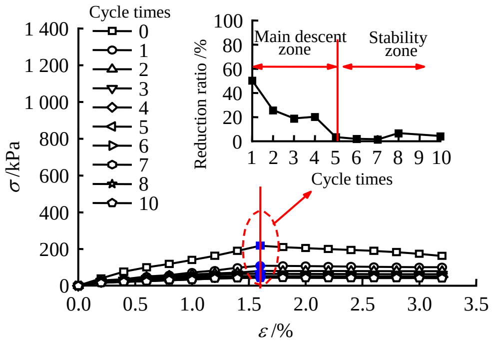
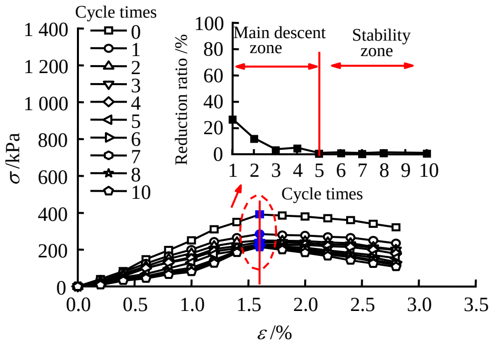
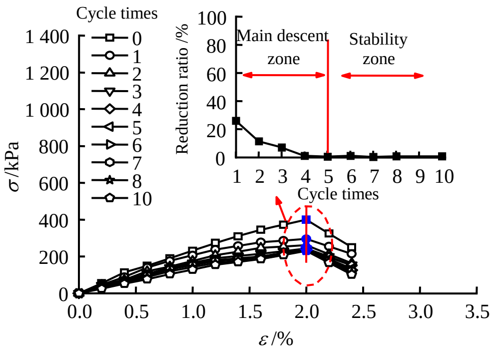
2.2%, respectively. The lime and fly ash are mainly to improve the strength, and MPA is to enhance the deformation resistance. The combined solidification with MPA, lime and fly ash can achieve synchronous improvement of stress and strain.



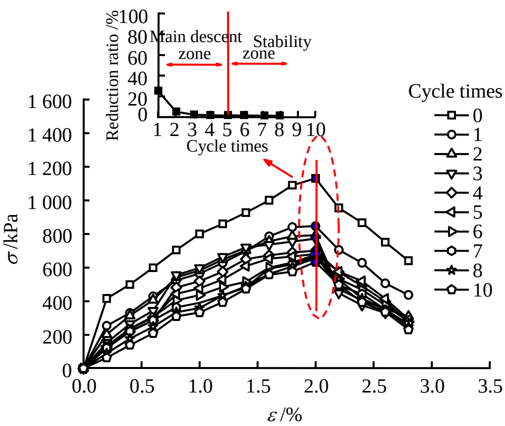
(a) Saline soil



(b) 6% lime solidified saline soil



(c) 6% lime + 0.6% MPA solidified saline soil



(d) 6% lime + 25% fly ash + 0.6% MPA solidified saline soil

Fig. 3 Stress–strain curve and strength reduction curve of soil under different freeze-thaw cycles

The deformation modulus E_0 (the ratio of stress to strain) variations of four soils with freeze-thaw cycles are shown in Fig. 4. The deformation moduli of saline soil, lime solidified saline soil, lime+MPA solidified saline soil and lime+fly ash+MPA solidified saline soil gradually decrease and tend to be stable after four freeze-thaw cycles. Thus, the initial four freeze-thaw cycles are the main descent stages. This is consistent with the results of references [6, 7, 23]. The stable deformation moduli of lime solidified saline soil, lime + MPA solidified saline soil and lime+fly ash+ MPA solidified saline soil are 14, 11 and 61 MPa, respectively, which are higher than that of saline soil (3 MPa). Though separate solidification with lime, fly ash and MPA can improve the deformation resistance of saline soil to a certain extent under freeze-thaw cycles, the combined solidification is more efficient.

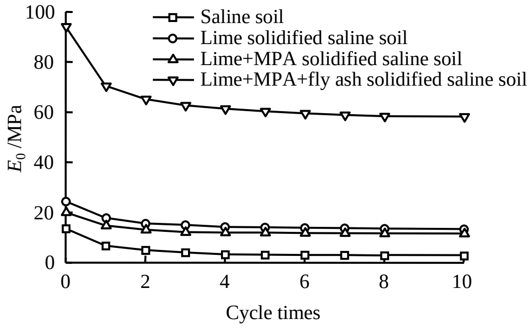


Fig. 4 Variation of deformation modulus of soil with freeze-thaw cycles

3.2 Preliminary selection of materials content

Taking the strength in the main descent zone (the initial four cycles) as the research object, and the appropriate content ranges of various solidification materials are obtained, as shown in Figs. 5–7.

With the increase of lime content, The UCS of the lime solidified saline soil increases rapidly, and the effect of freeze-thaw cycle is weakened (Figs. 5(a)–5(b)). The products of hydration reaction, calcium silicate and calcium aluminate, can produce more needle-like substance, which can cross with the soil particles, and then restraint and restrict the movement of soil particles (Fig. 5(c)). From the view of strength distribution and freeze-thaw resistance, when the lime content is more than 8%, the strength increases slowly and the freeze-thaw resistance is more stable, indicating that the appropriate content scope of lime should be greater than 8%.

The UCS and the freeze-thaw resistance of MPA solidified soil also increase gradually with the increase of MPA content (Figs. 6(a)–6(b)). MPA can form a network system under the interaction of bonding, chelation, adsorption, and bridging (Fig. 6(c)). The network structure, formed by MPA wrapped soil particles, is relatively sparse in the low content of

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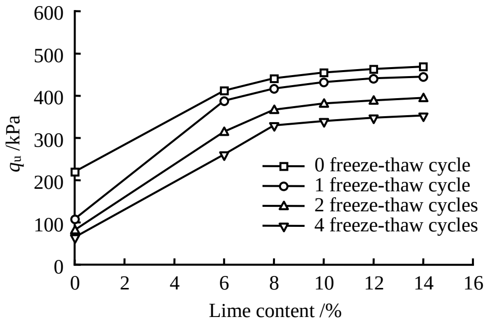
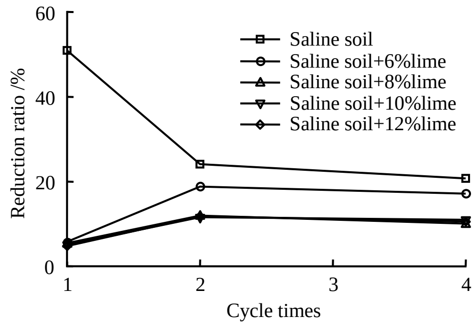
MPA condition, which is easy to be damaged under the freeze-thaw cycles. However, the network structure is denser and the freeze-thaw resistance is stronger in the high content of MPA condition, indicating that the appropriate content of MPA should be greater than 1.0%.

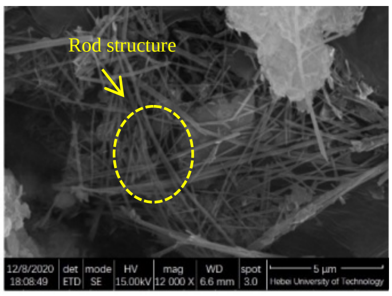
With regard to fly ash solidified saline soil, the UCS and the freeze-thaw resistance increase constantly with the increase of fly ash content when the range of fly ash content is 0–30% (Figs. 7(a)–7(b)). The porous structure of fly ash has obvious adsorption, and a series of hydrated calcium silicate and calcium aluminate products can be formed under the pozzolanic reaction (Fig. 7(c)). These products cement soil particles and help to improve the strength[31]. Considering the fly ash content in engineering application and the research results of relevant references [18, 32, 33], the fly ash content can be fixed at 30%.



(a) Strength distribution

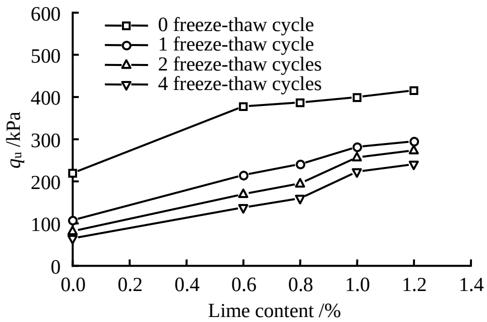


(b) Reduction ratio

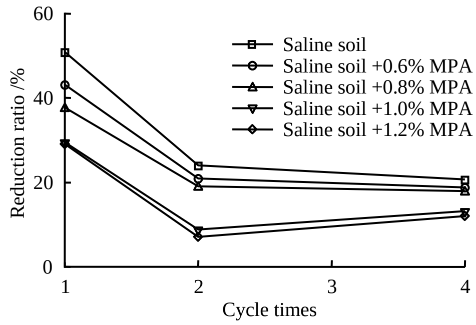


(c) SEM

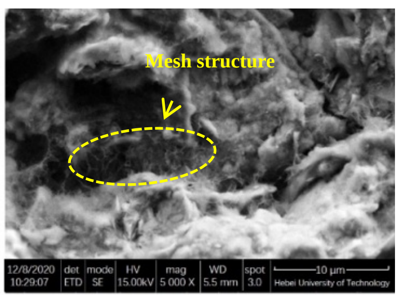
Fig. 5 Strength distribution, reduction ratio and SEM of lime solidified soil with freeze thaw cycles



(a) Strength distribution

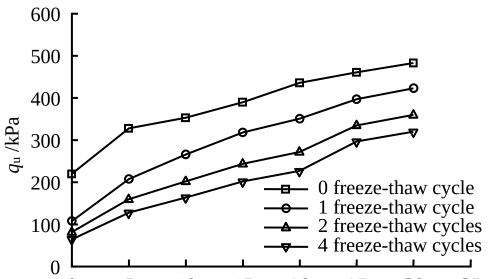


(b) Reduction ratio

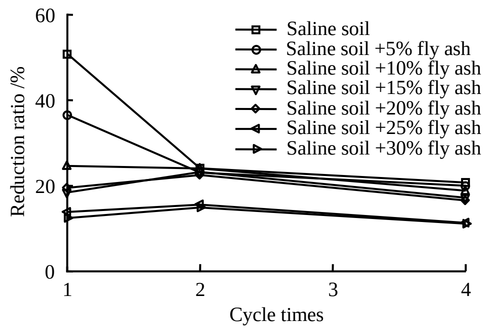


(c) SEM

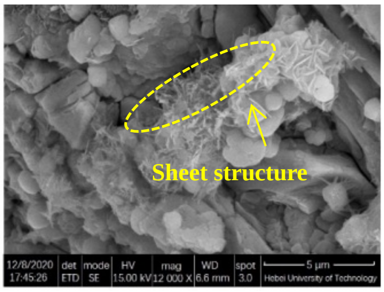
Fig. 6 Strength distribution, reduction ratio and SEM of MPA solidified soil with freeze thaw cycles



(a) Strength distribution



(b) Reduction ratio



(c) SEM

Fig. 7 Strength distribution, reduction ratio and SEM of fly ash-solidified soil with freeze thaw cycles

3.3 Shear strength distribution and orthogonal test analysis

According to the orthogonal test (Table 7), under the interaction of six factors, the optimal combination of parameters is group 17, whose curing time is 28 d, lime content is 14%, MPA content is 0.9%, dry density is 1.65g/cm^3, the salt content is 1%, and the freeze-thaw cycles is 3 times., The cohesion and internal friction angle in this combination reach the maximum, and their values are 208.2 kPa and 38.56°, respectively.

Table 7 Orthogonal test results

No.	Curing time /d	Freeze-thaw cycles	Lime content /%	MPA content /%	Salt content /%	Dry density /(g • cm^{-3})	c_u /kPa	φ_u /(°)
1	7	1	6	0.7	1	1.50	13.65	11.34
2	7	3	8	0.8	3	1.55	55.42	12.72
3	7	5	10	0.9	5	1.60	77.32	24.89
4	7	7	12	1.0	7	1.65	36.96	15.94
5	7	9	14	1.2	9	1.70	79.88	26.87
6	14	1	8	0.9	7	1.70	63.55	17.55
7	14	3	10	1.0	9	1.50	10.68	17.34
8	14	5	12	1.2	1	1.55	29.09	29.18
9	14	7	14	0.7	3	1.60	84.18	23.95
10	14	9	6	0.8	5	1.65	29.24	15.47
11	21	1	10	0.9	3	1.65	42.10	24.85
12	21	3	12	1.0	5	1.70	92.33	29.03
13	21	5	14	1.2	7	1.50	30.03	24.16
14	21	7	6	0.7	9	1.55	37.88	17.68
15	21	9	8	0.8	1	1.60	57.26	17.29
16	28	1	12	0.8	9	1.60	164.57	32.55
17	28	3	14	0.9	1	1.65	208.20	38.56
18	28	5	6	1.0	3	1.70	65.11	28.49
19	28	7	8	1.2	5	1.50	38.81	24.66
20	28	9	10	0.7	7	1.55	53.60	25.55
21	35	1	14	1.0	5	1.55	75.07	24.81
22	35	3	6	1.2	7	1.60	40.59	28.64
23	35	5	8	0.7	9	1.65	49.31	19.17
24	35	7	10	0.8	1	1.70	132.14	37.14
25	35	9	12	0.9	3	1.50	100.03	29.48

According to the results of cohesion and internal friction angle (Tables 8–9), the sensitivity of factors is in the order of decreasing importance: curing time, lime content, MPA content, dry density, salt content, and freeze-thaw cycle. The *R*-values of cohesion are 62.71, 58.178, 54.56, 47.962, 43.122, and 31.272 kPa, respectively; and the *R*-values of internal friction angle are 11.61°, 9.392°, 7.528°, 6.42°, 4.334° and 3.038°, respectively. It confirms that the solidified reaction determine the strength stability, and the effect of freeze-thaw cycle can be weakened by the solidified action. The sensitivity order is consistent with UCS results and visual analysis.

Table 8 Range analysis results of cohesion (unit: kPa)

Factors	$\bar{K}_1$	$\bar{K}_2$	$\bar{K}_3$	$\bar{K}_4$	$\bar{K}_5$	R
Curing time	52.646	43.348	51.920	106.058	79.428	62.710
Freeze-thaw cycle times	71.788	81.444	50.172	65.994	64.002	31.272
Lime content	37.294	52.870	63.168	84.596	95.472	58.178
MPA content	47.724	87.726	98.240	56.030	43.680	54.560
Salt content	88.068	69.368	62.554	44.946	68.464	43.122
Dry density	38.640	50.212	84.784	73.162	86.602	47.962

Note: $\bar{K}_i$ is the average of the results corresponding under various factors of level *i*; *R* is the difference between the maximum value and the minimum value of $\bar{K}_i$ corresponding to each factor.

Table 9 Range analysis results of the friction angle (unit:°)

Factors	$\bar{K}_1$	$\bar{K}_2$	$\bar{K}_3$	$\bar{K}_4$	$\bar{K}_5$	R
Curing time	18.352	20.698	22.602	29.962	27.848	11.610
Freeze-thaw cycle times	22.220	25.258	25.178	23.874	22.932	3.038
Lime content	20.324	18.278	25.954	27.236	27.670	9.392
MPA content	19.538	23.034	27.066	23.122	26.702	7.528
Salt content	26.702	23.898	23.772	22.368	22.722	4.334
Dry density	21.396	21.988	25.464	22.798	27.816	6.420

The curing time is determined by the process of curing reaction, which is the most sensitive factor affecting the shear strength of combined solidified saline soil. The most suitable curing time is still 28d for freeze-thaw resistance, which is consistent with the results of [18, 31, 33] without considering freeze-thaw effect. There is no special requirement for the curing time. The content of solidified material is closely related to the curing reaction. The effectiveness of the solidified materials and the adequacy of the curing reaction are the guarantee of structural stability, which are the two most important factors for the freeze-thaw resistance.

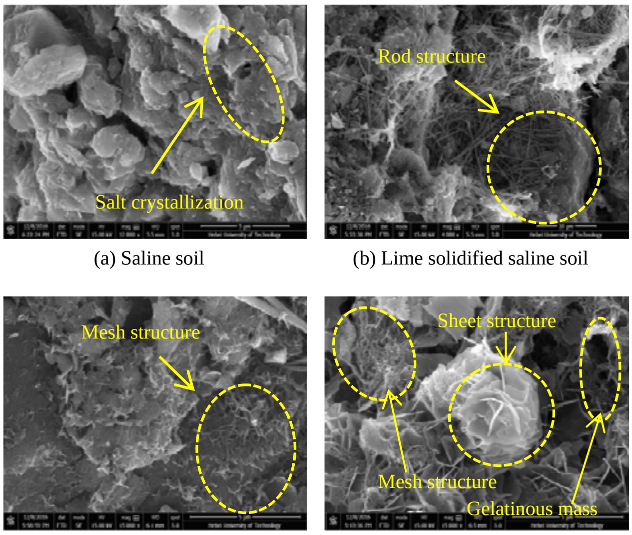
Salt causes serious engineering problems, such as salt expansion and corrosion [23], which is also adverse to the stability of solidified soil. LÜ et al. [10] pointed out that salt affected the solidification effect of materials on saline soil, and then reduced the soil strength. Then salt content should be considered in the saline soil treatment. It suggests that the salt content of soil should be less than 1% when it is applied in freeze-thaw environment.

The freeze-thaw environment is the weakest factor for the strength of solidified soil, and the damage caused by freeze-thaw environment is mainly concentrated in the initial 3 cycles. The combined action of lime, fly ash and MPA take advantage of the inorganic solidification reaction and the network bridging function of organic polymer material, which is helpful for the integral structure formation, and the structural stability enhancement of saline soil in freeze-thaw environment.

4 Discussion

In order to improve the freeze-thaw resistance of saline soil in engineering application, this study puts forward a combined treatment method with lime + fly ash + MPA. The results have verified that the UCS of solidified saline soil can reach to 1130.25 kPa, and the stable value is 700 kPa after five freeze-thaw cycles. It is higher than 584 kPa of lime solidified saline soil [6] and 475 kPa of cement solidified saline soil without freeze-thaw experience [22]. During the same 28 day curing conditions (Groups 16–20 in Table 7), the average cohesion and internal friction angle of combined solidified saline soil are 106.06 kPa and 29.96° under freeze-thaw cycle, which is also higher than the lime solidified soil (86.2 kPa and 27.9°) [34] and fly ash solidified soil (64.3 kPa and 15.9°) [35] without freeze-thaw effect. Combined solidified saline soil meets the relevant requirements of engineering specification (JTG 3430-2020), which is a better way to improve of saline soil properties.

In order to clarify the applied range of different solidified methods, the unconfined compressive strength (Fig.3), shear performance (Table 7), deformation resistance (Fig. 4) and microstructure of solidified soil (Fig.8) are joint systematically to elaborate the advantages and disadvantages.



(a) Saline soil (b) Lime solidified saline soil
(c) Lime + MPA solidified soil (d) Lime+ MPA + fly ash solidified soil

Fig. 8 SEM of saline soil and different solidified saline soil

For the saline soil without treatment, its soil particles are mainly granular, loosely connected, and salt crystals exist in the pores (Fig. 8(a)). The soil structure is destructed and easy to collapse in the freeze-thaw environment due to the water and salt phase transition. Only 50 kPa of the UCS is remained in saline soil after five freeze-thaw cycles, which decreases by 77.06% (218 kPa) (Fig. 3(a)). Therefore, the saline soil is susceptible to freeze-thaw environment and cannot be directly used in engineering.

When lime contacts with water and air, carbonation reaction occurs to form fibrous and columnar crystals. These crystals fill the soil pores, which is helpful for improving the density and strength of soil (Fig. 8 (b)). Though the stable UCS of lime solidified saline soil is much higher than that of saline soil after 5 freeze-thaw cycles, it still decreases by 43% (Fig. 3 (b)). Additionally, the failure deformation has not been improved. Therefore, the separate lime treated method is not suitable for improving the mechanical property of saline soil in freeze-thaw environment.

The lime + MPA solidification forms an elastic mesh spatial structure (Fig. 8(c)), which is mainly caused by the complexation reaction among hydroxyl and carboxyl groups in the main chain of MPA. In addition, the thickness of water film is reduced since MPA film wraps on soil particles. Compared with separate lime treated method, lime+MPA treated saline soil has a higher deformation resistance (Figs. 3(b)–3(c)). While the lime+MPA treated method has little effect on strength enhancement (Fig. 4), so it is limited in engineering application.

The combined treatment method with lime + fly ash + MPA can produce more cementations substances, and then form flake crystals and spatial mesh structure in the soil (Fig. 8(d)). Compared with the other methods, fly ash can accelerate the water-insoluble compounds formation such as hydrated calcium silicate, further tamp the stability of soil structure. By combining the results of strength with deformation (Figs. 3(d)–(4)), the combined treatment method can achieve double improvement between strength and deformation. The strength can reach 700 kPa after five freeze-thaw cycles. The combined treatment method with lime + fly ash + MPA meets the construction and application requirements of highway engineering in freeze-thaw environment, which is suitable for the saline soil solidification in coastal areas.

5 Conclusions

This paper proposed a combined treatment method to improve the freeze-thaw resistance of saline soil. Lime, fly ash and MPA are used as solidified materials. Unconfined compressive strength, shear strength, microstructure, and orthogonal experiment are used to evaluate the solidified effect and determine the optimal solidified parameters. The conclusions are as follows:

(1) The combined treatment with lime, fly ash and MPA is helpful for improving the strength of saline soil. The UCS of the combined solidified saline soil is 1 130.25 kPa, which is 5.18 times that of saline soil. The combined solidified saline soil has good freeze-thaw resistance. The UCS is stable at 700 kPa after five freeze-thaw cycles, and the UCS fluctuation range is about 5% after three cycles. As to the shear strength (cohesion and internal friction angle), the values of combined solidified saline soil after three freeze-thaw cycles are 208.2 kPa and 38.56° . The mechanical properties of lime+ fly ash + MPA solidified saline soil meet the requirements of highway geotechnical test specification (JTG 3430-2020).

(2) The sensitivity of factors is in an order of decreasing importance: curing time, lime content, MPA content, dry density, salt content, and freeze-thaw cycles. Curing time and solidified material content have positive influence on solidified effect. With the increasing of lime, fly ash and MPA content, the strength of combined solidified saline soil increases and then tends to be stable. The content of lime, fly ash and MPA should be greater than 8%, 25% and 1%, respectively. Salt and freeze-thaw cycles have some negative impacts on the stability of solidified saline soil. Their influence can be weaken by optimizing solidified parameters.

(3) Combined with the compressive strength and shear strength tests, it suggests that the optimal combination of solidified parameters is 14% of lime, 30% of fly ash, 1% of MPA, 28 d of curing time, and a dry density of 1.65 g/cm^3.

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