Freeze-thaw Performance of Phase Change Material (PCM) Incorporated Canal Foundation Expansive Soil

Yong Chen (chenyong@nhri.cn)
Nanjing Hydraulic Research Institute https://orcid.org/0000-0002-8062-1397
Yinghao Huang
Nanjing Hydraulic Research Institute
Shuo Wang
Nanjing Hydraulic Research Institute
Rui Zhu
Nanjing Hydraulic Research Institute
Xiaohan Liu
Water Affairs Center of Xiqing District

Research Article

Keywords: Phase change material, PCM-modified soil, freeze-thaw cycle, Volume deformation, unconfined compressive strength, differential scanning calorimetry

Posted Date: July 7th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-401566/v1

Abstract

Drought and water shortages severely restrict the development of agriculture in China. The complex process of freezing and thawing experienced by the canal foundation soil in cold regions will cause leakage and loss of canal water. It is a common measure to improve the foundation soil of canals in cold regions. Phase change material (PCM) store or release heat in the form of latent heat during the phase change process, which is a new type of temperature control material. In this study, PCM-modified soil was used as the research object. Volume deformation measurement, unconfined compressive strength test, differential scanning calorimetry, and scanning electron microscopy tests were carried out on modified soil samples with different PCM content after freeze-thaw (F-T) cycles. The influence of the number of F-T cycles and the content of PCM on the expansion-shrinkage deformation and mechanical properties of the modified soil was revealed. The results show that: the greater the PCM content, the smaller the volume change, but there will be an optimal mixing ratio. The stress-strain curve characteristics, the failure strain with the number of F-T cycles and the PCM content have a great relationship. The effects of F-T cycles have a greater impact on the mechanical properties of PCM-modified soil. Among them, the first cycle is the most obvious, and it stabilizes after the third cycle. PCM can inhibit the attenuation of soil strength, and the greater the amount, the better the effect. The freezing time of PCM-modified soil has been increased, the supercooling phenomenon is no longer obvious, and the thermal stability has been improved. PCM reduces the connectivity of pores, and macroscopically suppresses the expansion and shrinkage characteristics and strength attenuation of expansive soil. The studies have shown that 8% PCM-modified soil has obvious advantages in resisting the harsh weather in cold regions, which can provide a reference for actual engineering design.

1. Introduction

The long-distance water conveyance canal is a strong guarantee for agricultural development in northern Xinjiang. The expansive soil section accounts for about 32% of the total length of the canal. The annual average temperature along the canal is 3.4°C, the highest temperature is 40.6°C, and the lowest temperature is -41.7°C. These factors (Zhu et al.2020) work together to form an obvious F-T cycle process, causing deformation and failure of the expansive soil of the canal foundation (*see* Fig. 1), which has a serious impact on the stability of the canal.

Expansive soil has poor properties and difficulty in improvement due to its fissure, expansion and contraction, strength attenuation, and over-consolidation. It is called an "engineering cancer" in civil engineering and is a cosmopolitan technical problem (Chaduvula et al.2020). In cold regions, influenced by repeated F-T cycles, foundations containing expansive soils are usually subject to engineering geological hazards such as subsidence, deformation, and cracking. Therefore, it must be treated. To overcome these problems, scholars have adopted some measures to improve the properties and structure of expansive soil to weaken the expansion and contraction of expansive soil and restrain soil strength attenuation. Through a series of laboratory experiments, Lu et al. (2019) found that cement can reduce the expansion and contraction deformation of expansive soil under F-T cycles. Mohanty (2016) used

XRD, SEM, and EDX to find that the plasticity index, expansive, and expansive pressure of the soil were significantly reduced after adding waste ash. Zhou (2019) studied fly ash's influence on the stability of expansive soil and gave the best mixing ratio. Ene (2009) added pyroclastic rock to the expansive soil to change its particle gradation, thereby enhancing the physical properties and strength properties of the soil. Soltani et al. (2017) used two types of fibers to test the expansive properties of expansive soils and found that 0.5% is the best content.

It can be found that although the scholars mentioned above have studied the improvement of expansive soils a lot, they still have disadvantages such as insufficient applicability in cold regions and easy to cause secondary pollution to the environment. Therefore, more advanced and effective treatment technologies need to be explored. As a new type of temperature control material, phase change materials (PCM) can be divided into organic, inorganic and composite PCM, which can generate a large amount of latent heat during the phase change process. Due to its high energy storage density, small volume change before and after phase change, constant temperature, non-toxicity, and many other advantages, it has achieved more results in saving energy (Samimi et al. 2017; Aftab et al. 2020; Behrooz et al. 2017) and improving the internal temperature field of the engineering structure (Bryan et al. 2015; Sanfelix et al. 2019; Plytaria et al. 2019). It shows that PCM have certain feasibility in controlling the positive and negative changes of temperature. At present, there are relatively few researches on soil treatment using PCM, only Mahedi (2019) has initially studied in this direction, so it is of great significance to carry out experimental research on phase change temperature control treatment of expansive soil in cold regions.

This article takes the expansive soil along a certain water conveyance canal in northern Xinjiang as the research object. Through a series of laboratory tests, the changes in the volume and mechanical properties of PCM-modified expansive soil under the action of F-T cycles are studied, and the thermal stability and microscopic point of view are analyzed to clarify the influence of PCM on the F-T performance of soil.

2. Test Materials And Sample Preparation

2.1 Test materials

2.1.1 Expansive soil

The soil for the test was taken from a construction site of a large-scale irrigation canal in the northern Xinjiang region. The sampling depth is about 1.5m. The soil material is representative at this depth and is yellowish-brown. According to the geotechnical test specification (GB/T 50123 – 2019), the particle size distribution curve is shown in Fig. 2, the main physical indicators measured are shown in Table 1. Among them, the free expansive rate of soil materials is 86%, which belongs to medium expansive soil. The unevenness of the soil is 16, and the coefficient of curvature is 1.56, indicating that the gradation of the soil is good. The mineral composition of the soil material was analyzed by X-ray diffraction, and the main components are shown in Table 1.

Table 1
Physical indexes and mineral components of the expansive soil.

Property	Index	Value
Physical Properties	Specific gravity (G_s)	2.7
	Liquid limit (W_L, %)	52.6
	Plastic limit (W_P, %)	18.4
	Plasticity index (I_P, %)	34.2
	Maximum dry density (ρ_{dmax}, g/cm^3)	1.71
	Optimum moisture content (w_{op}, %)	18.4
	Free expansion rate (δ_{ef})	71
Mineral composition	Clay (Mainly montmorillonite) (%)	61.5
	Quartz (%)	31.9
	Feldspar (%)	6.1
	Calcite (%)	0.5
	Albite (%)	0.5

2.1.2 phase change material (PCM)

According to the local climate characteristics, a commercial microcapsule PCM with a phase change point of about 5°C and an enthalpy value of 198.1J/g was selected for the experiment, as shown in Fig. 3. Compared with the method of direct incorporation, microcapsules as a PCM carrier can effectively solve the problem of leakage during paraffin solid-liquid transformation. PCM is composed of core material and shell material. The core material is paraffin wax, the shell material is melamine resin, and the core-to-wall mass ratio is about 9:1. The physical appearance of PCM is a slightly off-white powder with a particle size of about 10 μm. PCM has stable performance at extremely high and low temperatures. When heated to 200°C, the leakage rate is less than 1%, and the expansion and contraction during the phase change process can also be ignored.

2.2 Sample preparation

The soil material transported back from the construction site, after natural air drying, is crushed through a 2mm sieve, and the initial moisture content of the sieved soil is determined to be 3.71%. Add PCM to the air-dried soil according to 5%, 8%, and 10% of the weight of the dry soil and mix them evenly, then spray a certain amount of distilled water into the soil according to the optimal moisture content of the soil material, mix it evenly, and put it in a plastic film Keep it airtight for a day and night to make the water in the mixture evenly distributed. When samples are prepared by the conventional sublayer compaction method, there is easily a weak band between layers. Therefore, our research group has developed a sample preparation method with one-time forming and two-end compaction, as shown in Fig. 4. Compared with the experiment, this method has less initial damage to the sample than the sample preparation methods such as the layered compaction method, and can better ensure the uniformity of the sample. This test also adopted this sample preparation method to control the dry density of all samples to 1.62g/cm^3, the moisture content to be 18.4%, and the sample size to h = 80mm, d = 39.1mm. Wrap the prepared sample with plastic wrap and place it in a sealed bag slightly larger than the sample for later use to ensure that the sample does not come into contact with the outside world to avoid water loss.

3. Test Programme Design

3.1 Freeze-thaw (F-T) cycle tests

Different freezing temperatures and lengths have a greater impact on the results of F-T cycle tests (Orakoglu et al. 2016), and most of the current F-T cycle tests adopt methods: freezing time is 12h, the temperature is -20°C; thawing time is 12h, the temperature is 20°C, which is too general and not targeted. It is not easy to fully simulate the complex F-T cycle process experienced on-site in laboratory tests. Refer to Huang YH et al. (2020) to first generalize the actual boundary conditions on-site, and then determine the simulated temperature and duration based on similar theories. Figure 5 shows the temperature distribution along the canal observed by a weather station (from November 2013 to November 2014). Therefore, the ambient temperature control process can be confirmed, and the temperature ranges and elapsed time of every phase are shown in Table 2. According to the previous test conclusions [21–23], the number of F-T cycles of the sample is designed to be 7 times. The F-T cycle test is carried out in a programmable high and low temperature test device.

Table 2
Ambient temperature control process.

Phases		Temperature ranges/°C	Elapsed time/h
Cooling phase	Phase 1	0 to -21	3
	Phase 2	-21 to -21	2
	Phase 3	-21 to 0	3
Warming phase	Phase 1	0 to 22.5	6
	Phase 2	22.5 to 22.5	4
	Phase 3	22.5 to 0	6

3.2 Volume change tests

The method in reference (Lu et al. 2019) uses digital vernier calipers to measure the diameter of each sample 3 times along 1/3 of the height, and measure the height 3 times along the vertical direction of the upper and lower ends, and then take the average value of each sample, as shown in Fig. 6. The sample volume is calculated according to the formula, and 5 parallel groups are set for each group of samples. After each sample size measurement is over, weigh it with an electronic balance to monitor the quality change of the sample during the F-T cycle. The results show that the moisture content loss of the sample after 7 F-T cycles is less than 0.5 %.

3.3 Unconfined compressive strength (UCS) tests

This UCS test was carried out using an electronic universal testing machine, as shown in Fig. 7. The instrument can be used to test and analyze static mechanical properties such as tension and compression, with a maximum load of 50kN. The speed adjustment range of the beam is 0.001-500mm/min, and the accuracy is very high, which is 1/300000 of the maximum deformation. The shear test is stopped when the axial strain reaches 20%, and the strain rate is set to 1%/min. UCS tests are carried out on the samples after 0 (initial state), 1, 3, and 7 F-T cycles. Three parallel tests are designed under each test condition, and the computer automatically collects the test data. Figure 7 shows representative photographs of PCM at the time of damage during the test.

3.4 Differential scanning calorimeter (DSC)

A differential scanning calorimeter (DSC) QL-2000 with an operating range of-160℃~700℃ (see Fig. 8), was used to determine the thermal properties of the PCM. The pneumatic diaphragm pump was equipped with nitrogen cooling, and the purge gas flow rate was kept between 8 ~ 12 mL/ min. The measured sample weight was 10 ± 2mg, and a high-precision balance with an accuracy of 10^{-4}g was used for sample weighing. The rate of cooling and heating was 5℃/min. The test was started by holding the temperature at -20℃ for 2 min and then increasing temperature to 20℃. Sample was kept at 20℃ for 2 min and followed by cooling back to -20℃.

3.5 Scanning electron microscope (SEM) tests

Quanta450 electron microscope scanner was used to test the samples under different freezing and thawing times. The maximum magnification of the instrument is 1 million times, and the resolution is ≥ 1.0nm. The liquid nitrogen vacuum cooling and drying method is used to ensure the original pores and structural characteristics of the soil to the greatest extent. Then, the dried soil sample is broken apart to obtain an undisturbed fresh structure surface, and the fresh structure surface to be observed is coated with a gold film using a sputtering ion instrument. Then, the dried soil sample is broken apart to obtain an undisturbed fresh structure surface, and the fresh structure surface to be observed is coated with a gold film using a sputtering ion instrument. Put it into the sample area of the scanning electron microscope together with the base, and focus on the observation area by adjusting the sample's position. Select representative points to take pictures, and set the scanning magnifications to 100, 1000, and 5000. The specific operation steps are shown in Fig. 9.

4. Test Results And Analysis

4.1 Volume change

Figure 10 shows the volume change of the sample after undergoing F-T cycles. "F" means that the sample is completely frozen, and "T" means that it has melted. It can be seen from Fig. 10 that the overall change in the volume of the sample during the entire F-T cycle is "freeze heave and thaw shrinkage", and it only appears as "thaw heave" during the first thawing. As the number of F-T cycles increased to 3, the volume change range remained stable. After 7 F-T cycles, the volume of all samples increased slightly. According to calculations, during the entire F-T cycle test, 5% PCM content can reduce the volume change by about 9%, and 8% PCM content can reduce the volume change by about 34%. As the content increases to 10 %, the reduction in volume change increased to 39%. This shows that when the doping amount of PCM is small, the effect on the volume change of the sample is small; when the doping amount is increased to 8%, the sample's volume change has been significantly improved. With the further increase of the dosage, the decrease in volume change is no longer obvious.

The effects of F-T cycles on the volume deformation of expansive soil are mainly reflected in two aspects: On the one hand, the volume of solid ice is 9% larger than the volume of liquid water of equal mass. When freezing occurs, the liquid water transforms into solid ice, the growth of ice crystals expands in volume, and the melting is the reverse process. On the other hand, during the freezing process, the expanded clay particles will shrink due to loss of water, and the continuous growth of ice crystals will squeeze the surrounding soil particles, which will cause the soil particles to shift and the pores between the soil particles will become smaller and melt. The effect is the reverse process. Because the initial water content of the sample is large, the volume expansion of the liquid water phase into solid ice when frozen is greater than the shrinkage of the expansive soil particles when they lose water, and the opposite is true when they are melted. Therefore, the macroscopic performance is "freeze expansion and thawing shrinkage". After 7 F-T cycles, the volume of all samples increased slightly, which can be explained by the fact that the initial dry density of the expansive soil sample is relatively large (compactness 95%), and the water phase becomes ice, which will cause the sample to expand plastic deformation is usually irreversible (Xu et al. 2019).

During the F-T cycle, PCM can undergo phase change with positive and negative temperature changes to produce and store heat. Due to the large free water content inside the sample, when the PCM content is low, the energy released by the PCM is not enough to resist the influence of the external temperature change on the volume change of the expansive soil particles and the volume change caused by the water phase change. PCM is mainly distributed in the pores of soil particles, and the released energy reduces the migration and freezing of free water between soil particles. With the increase of the content, due to the greater degree of compaction of the sample, the release ability and penetration ability are limited. In addition to improving the volume change of free water in the pores, only the volume change of some clay particles around the pores is suppressed.

4.2 Exploration of mechanical properties

4.2.1 Stress-strain relationship

The stress-strain relationship curve is the most intuitive method for evaluating soil deformation and strength characteristics. Figure 11 shows the stress-strain curve of PCM-modified expansive soil, where *N* represents the number of F-T cycles. In this test, the stress-strain curves all show a strain-softening type. Taking the pure soil sample as an example, the entire stress-strain curve can be divided into four stages. In the first stage, because the uneven surfaces at both ends of the sample cannot make good contact with the loading end, it cannot reflect the true mechanical properties of the sample. In the second stage, as the strain increases, the stress rises approximately linearly. As the number of F-T cycles increases, the rising rate slows down, which is regarded as the elastic stage. In the third stage, the stress rise rate gradually slows down, and then the stress peak appears. Due to the gelation between the expanded clay particles, the sample undergoes obvious and uniform plastic deformation, but the soil is damaged by the F-T cycle. The duration of plastic deformation is significantly reduced, and it stabilizes after 3 times, which is regarded as the damage stage. In the fourth stage, the stress gradually decreases as the strain increases, which is regarded as the brittle fracture stage. From Fig. 11(b), (c), (d), it can be found that the changing trend of the stress-strain curve of PCM-modified expansive soil is quite different under different content. With the increase of PCM content, the approximate linear increase of stress in the elastic phase becomes more obvious. The plastic characteristics are weakened in the damage stage; the greater the amount, the more obvious the weakening degree. In the brittle fracture stage, the rate of stress decrease increases. When the content is 10%, it decreases linearly until the strength is completely lost.

4.2.2 Failure strain

Failure strain is an important index to measure the deformation characteristics of the soil. For general strain-softening soils, the strain corresponding to the maximum stress value is considered the failure strain (Gao et al. 2019). Figure 12 reflects the relationship between the failure strain of the sample and the number of F-T cycles. It can be seen from Fig. 12 that the first F-T cycle has a greater impact on the failure strain of the pure soil sample, and then tends to be stable. For the expansive soil treated by PCM, the failure strain is less affected by F-T cycles and remains unchanged. This shows that the PCM improved expansive soil is stable in a certain sense. Under various PCM contents, the failure strain value of the sample is lower than that of pure soil. The overall trend of failure strain is decreasing with the increase of PCM content. The above phenomenon can be explained as PCM shell is a polymer material (Ashraf 2019), which has a certain degree of brittleness, and the compressive strength of PCM is small, thus aggravating the brittleness of soil.

4.2.3 Effect of freeze-thaw cycles on soil mechanical strength

For general strain-softening soils, the stress corresponding to the peak of the stress-strain curve is taken as the UCS (Cao et al.2019). The variation of the unconfined compressive strength of the sample with the number of F-T cycles is shown in Fig. 13. It can be seen from Fig. 13 that the first F-T cycle has the most significant attenuation effect on the strength of the soil, which can account for more than 53.4% of the entire F-T cycle test. This is because under the dual influence of the complex ice-water phase change and the expansion and shrinkage of soil grains, the soil structure is severely damaged, and the pore distribution changes. With the increase in the number of F-T cycles, the soil strength's attenuation gradually slowed down and stabilized after the third time. PCM can inhibit the attenuation of soil strength due to freezing and thawing cycles. The greater the PCM content, the better the inhibition effect. After 7 cycles, the strength attenuation rates of the samples with PCM content of 5%, 8%, and 10% were 60.7%, 46.7%, and 37.7%, respectively, and the unconfined compressive strengths were all higher than those of pure soil samples. This is because PCM can store or release heat in the form of latent heat during the F-T cycle to resist damage to the soil caused by external temperature changes, thus slowing soil strength attenuation.

Regression analysis was carried out on the unconfined compressive strength test results of PCM-modified expansive soil under different PCM content and different F-T cycles. A mathematical model between the unconfined compressive strength and the number of F-T cycles is established, which can be described by an exponential equation, and the fitting curve is shown in Fig. 13. The specific fitting function is shown in the following formula: $q_u = \mathrm{A} + \mathrm{B}e^{CN_{\mathrm{FT}}}$. In the formula:

q_u is the unconfined compressive strength;

A, *B*, and *C* are the coefficients related to the PCM content, whose values are shown in Table 4;

N_{FT} is the number of F-T cycles.

Combining Table 4 and Fig. 13 shows that under the same PCM content, the unconfined compressive strength and the natural index of the number of F-T cycles have an obvious linear negative correlation. The coefficient A + B is the theoretical value of the unconfined compressive strength in the initial state (0 cycles) under a certain PCM content. The coefficient C reflects the rate at which the unconfined compressive strength at a certain PCM content decreases with the increase in the number of F-T cycles. The absolute value of the coefficient C shows a decreasing trend with the increase of PCM content, which shows that the greater the PCM content affected by the effects of F-T cycles, the slower the unconfined compressive strength of the sample decays. In the three sets of data, R2 is close to 1, indicating that the fitting effect is better and can more truly reflect the functional relationship between the two.

Table 4 Function fitting results.

Content (%)	Functional relationship	R^2
0	$q_u = 59.2165 + 138.4512e^{-1.1605N_{FT}}$	0.9876
5	$q_u = 72.9775 + 107.1332e^{-1.0949N_{FT}}$	0.9845
8	$q_u = 89.3329 + 75.5333e^{-0.7444N_{FT}}$	0.9954
10	$q_u = 96.4056 + 57.3321e^{-0.7371N_{FT}}$	0.9954

4.3 Thermal stability

The expansive soil sample in a dry state is tested, and it is found that the dehydrated soil particles do not undergo energy conversion during the DSC test. Therefore, it can be considered that only water undergoes a phase change. The DSC curves of expansive soil and PCM-modified expansive soil are shown in Fig. 14. Due to the enormous energy released during freezing, the temperature of the sample rises again so that the DSC curve will be bent back. In Fig. 14, the upward peak represents the endothermic curve peak, the downward peak represents the exothermic peak, and the curve peak area represents the phase change latent heat. Because the DSC curves of different PCM content are similar in shape, limited to space, only the DSC curves with 0 and 10% PCM content are listed. It can be seen from Fig. 7 that the incorporation of PCM reduces the latent heat of phase change of the expansive soil by about 10.93%, which means that the heat released by the phase change of PCM at 4.61 ~ 1.63°C is "stored" in the soil particles, which may cause some water did not phase into ice. After adding PCM, the starting point of the "primitive peak" phase transition temperature changed from − 7.61°C to -6.30°C, which indicates that the soil body mixed with PCM has increased in temperature during freezing and melting. At the same time, it can be found that the width of the phase transition peak has also increased slightly, and the supercooling phenomenon has also been slowed down. This indicates that the incorporation of PCM delays the formation of ice lenses in the test temperature range, which helps improve the internal temperature field of the canal soil. It is beneficial to improve the thermal stability of the soil.

Table 5
thermal properties of samples.

Property	pure soil	10% PCM-modified soil	
Melting			
Temperature Range	-7.61 °C to -10.83 °C	4.61 °C to 1.63 °C	-6.30 °C to -10.71 °C
Peak Temperature	-7.74 °C	2.58°C	-6.34°C
Enthalpy	60.82J/g	19.34J/g	54.17J/g
Crystallization			
Temperature Range	-2.18 °C to 2.42 °C	4.73°C to 7.55 °C	-1.24 °C to 2.62 °C
Peak Temperature	0.93 °C	6.15 °C	0.97 °C
Enthalpy	61.74J/g	18.78J/g	54.36J/g

4.4 Micro mechanism

Figure 15 are 100X scanning electron microscope images of the sample with pure soil and 8% PCM content, where black represents pores or cracks and white represents soil. It can be seen that in the initial state (0 cycles), the soil particles are cemented and connected to form a whole, and the soil sample shows good integrity. After the sample undergoes a F-T cycle, the pores of the sample begin to develop. The pores after 7 F-T cycles were significantly larger than the pores after 1 F-T cycle, and obvious through-fractures formed inside the soil after 7 F-T cycles. The incorporation of PCM allows the large pores of the soil to be filled, and the many fine pores formed to make the pore canals narrow and tortuous, reducing the connectivity of the pores, hindering the flow of water, and inhibiting the expansion and contraction characteristics of the expansive soil. Figure 16 is obtained after local magnification of the PCM-modified soil sample by 1000 and 5000 times. It can be seen that the low content of PCM is mainly distributed in the pores of the soil. As the content increases, PCM begins to aggregate into a granular structure, which is one of the important reasons for the slight decrease in the mechanical strength of the soil in the initial state.

Based on the professional image processing software PCAS, quantitative analysis of the image scanned by the electron microscope can be used to extract parameters such as soil shape coefficient, pore direction and size. In this paper, we select an appropriate threshold to binarize the image under 100 times, and reduce the noise to segment the pores, and obtain the surface porosity of the sample after different F-T times (the proportion of pores on a certain plane of the soil), such as Shown in Fig. 17. With the increase in the number of F-T cycles, the surface porosity of the soil sample gradually increased, and the increase gradually slowed down after 3 cycles. After the end of the 7 cycles, the porosity of the soil samples with the four PCM content increased by 15.40%, 12.78%, 9.29% and 6.01%. Macroscopically, PCM weakens the effect of F-T cycles on the degradation of soil mechanical properties; that is, the greater the PCM content, the slower the unconfined compressive strength attenuation. At the same time, it can be found that in the early stage of the test, the lower the PCM content, the faster the soil porosity increases. When the PCM content is low, the heat released is not enough to resist the liquid water phase changing into ice crystals and the damage to the surrounding soil particles, the more obvious the changes in the microstructure of the soil after the F-T cycle.

5 Prospect

Along with the positive and negative fluctuations of the ambient temperature, PCM stores or releases heat in the form of latent heat, which can control the internal temperature field of the expansive soil sample and reduce the expansion and contraction of soil particles and the repeated freezing and thawing of pore water. To a large extent, the fatigue damage of the soil's microstructure (pore coarsening, loose structure, etc.) is alleviated. However, the amount of earthwork in actual engineering construction is huge, and considering the economic cost of PCM, it is impossible to mix in the entire frozen soil layer. Therefore, after determining the optimal mixing amount, it is necessary to determine the optimal mixing depth, to provide a reference for the actual engineering design of the expansive soil canal in the cold area.
Figure 18 is a schematic diagram of PCM's resistance to external temperature changes. PCM is added to the foundation surface of the canal. When the external temperature changes, heat is released through a phase change, which changes the internal temperature field of the canal and changes the temperature gradient of the frozen soil layer. The soil temperature at the same depth is higher than before treatment, to achieve the overall treatment effect.

6. Conclusion

In this paper, the influence of phase change materials (PCM) on the damage performance of Beijiang Canal Foundation's expansive soil in reducing freezing and thawing cycles is studied. The main findings are as follows:

1. During the F-T cycle, the overall volume change of the sample is shown as "freeze heave and thaw shrinkage". The larger the PCM content, the smaller the volume change, but with the increase of the PCM content, the volume change is basically the same, which shows that PCM suppresses the expansion and contraction deformation of the expansive soil within a certain range.
2. The UCS of the sample gradually decreases with the increase of the number of F-T cycles, and the first cycle is the most obvious, and it stabilizes after the third cycle. PCM reduces the attenuation of UCS, but as PCM's content increases, the decrease gradually slows down. With the increase of PCM content, the samples changed from brittle failure to plastic failure, and the failure strain gradually decreased. Tests show that the best use amount of phase change materials when dealing with soils with higher plasticity requirements and strength is 8%.
3. The microstructure shows that the effects of F-T cycles make the microscopic pores in the soil gradually develop into cracks, and the macroscopic manifestation is the attenuation of mechanical strength. The incorporation of PCM reduces the connectivity of pores, reduces the impact of freezing

and thawing on soil pore damage, and macroscopically improves the expansion and shrinkage characteristics of expansive soil and the attenuation of mechanical strength.

4. The microstructure shows that the effects of F-T cycles make the microscopic pores in the soil gradually develop into cracks, and the macroscopic manifestation is the attenuation of mechanical strength. The incorporation of PCM reduces the connectivity of pores, reduces the impact of freezing and thawing on soil pore damage, and macroscopically improves the expansion and shrinkage characteristics of expansive soil and the attenuation of mechanical strength.
5. Applying PCM to expansive soils stores or releases heat in the form of latent heat during the phase change process, which can control the internal temperature field of expansive soil, reduce its expansion and contraction characteristics, and improve soil stability. It is recommended to select PCM with appropriate melting point and latent enthalpy according to regional climate conditions and target temperature in actual engineering.

7. Declarations

Acknowledgments

It was great appreciated that this work was financed by “National Natural Science Foundation of China” (Grant Nos. 51879166) and “Open Fund of the State Key Laboratory of Frozen Soil Engineering of China” (Grant Nos. SKLFSE201909).

8. References

1. Ashraf W (2016) Carbonation of cement-based materials: challenges and opportunities. Construction Building Materials 120:558–570. https://doi.org/10.1016/j.conbuildmat.2016.05.080
2. Aftab W, Khurram M, Shi J, Tabassum H, Zou R (2020) Highly efficient solar-thermal storage coating based on phosphorene encapsulated phase change materials. Energy Storage Materials 32:199–207. https://doi.org/10.1016/j.ensm.2020.07.032
3. Bryan JMA, Paul RBB et al (2015) Assessing the feasibility of incorporating phase change material in hot mix asphalt. Sustainable Cities Society 19:11–16. https://doi.org/10.1016/j.scs.2015.06.005
4. Behrooz M, Ziapour Amir H (2017) Performance study of an enhanced solar greenhouse combined with the phase change material using genetic algorithm optimization method. Appl Therm Eng 110:253–264. https://doi.org/10.1016/j.applthermaleng.2016.08.153
5. Cao ZG, Zhang DW (2015) Research on characterization parameters of unconfined compressive strength of cement-soil. Chin J Rock Mechan Eng S1:3446–3454. https://doi.org/10.13722/j.cnki.jrme.2014.0031
6. Chaduvula U, Viswanadham BVS, Kodikara J (2017) A study on desiccation cracking behavior of polyester fiber-reinforced expansive clay. Appl Clay Sci 142(jun.):163–172. https://doi.org/10.1016/j.clay.2017.02.008

7. Ene E, Okagbue C (2009) Some basic geotechnical properties of expansive soil modified using pyroclastic dust. Eng Geol 107(1–2):61–65. https://doi.org/10.1016/j.enggeo.2009.03.007
8. Gao F, Kaiser PK, Stead D, Eberhardt E, Elmo D (2019) Strainburst phenomena and numerical simulation of self-initiated brittle rock failure. Int J Rock Mech Min Sci 116:52–63. https://doi.org/10.1016/j.ijrmms.2019.03.021
9. Huang YH, Cai ZY et al (2020) Development of centrifugal simulation test equipment for wet-drying, freezing and thawing of channels in seasonal frozen areas. Chinese Journal of Geotechnical Engineering 07: 1181–1188. https://doi.org/cnki:sun:ytgc.0.2020-07-003
10. Lu Y, Liu S, Zhang Y, Li Z, Xu L (2019) Freeze-thaw performance of a cement-treated expansive soil. Cold Reg Sci Technol 170. https://doi.org/10.1016/j.coldregions.2019.102926
11. Mohanty SK et al (2016) Consolidation and drainage characteristics of expansive soil stabilized with fly ash and dolochar. Geotech Geol Eng 34(5):1435–1451. https://doi.org/10.1007/s10706-016-0053-3
12. Mahedi M, Cetin B, Cetin KS (2019) Freeze-thaw performance of phase change material (PCM) incorporated pavement subgrade soil. Constr Build Mater 202:449–464. https://doi.org/10.1016/j.conbuildmat.2018.12.210
13. Orakoglu ME, Liu J, Niu F (2016) Experimental and modeling investigation of the thermal conductivity of fiber-reinforced soil subjected to freeze-thaw cycles. Appl Therm Eng 108:824–832. https://doi.org/10.1016/j.applthermaleng.2016.07.112
14. Plytaria MT, Bellos E, Tzivanidis C, Antonopoulos KA (2019) Numerical simulation of a solar cooling system with and without phase change materials in radiant walls of a building. Energy Conversion Management 188:40–53. https://doi.org/10.1016/j.enconman.2019.03.042
15. Soltani A, Deng A, Taheri A (2018) Swell–compression characteristics of a fiber–reinforced expansive soil-sciencedirect. Geotext Geomembr 46(2):183–189. https://doi.org/10.1016/j.geotexmem.2017.11.009
16. Samimi F, Babapoor A, Azizi M, Karimi G (2016) Thermal management analysis of a li-ion battery cell using phase change material loaded with carbon fibers. Energy 96(Feb1): 355–371. https://doi.org/10.1016/j.energy.2015.12.064
17. Sanfelix SG, Santacruz I, Szczotok AM, Belloc LMO et al (2019) Effect of microencapsulated phase change materials on the flow behavior of cement composites. Constr Build Mater 202:353–362. https://doi.org/10.1016/j.conbuildmat.2018.12.215
18. Xu L, Liu SH, Lu Y, Song YJ, Yang Q (2016) Research on the physical and mechanical properties of expansive soil under freeze-thaw cycles. Rock and Soil Mechanics S2: 167–174. https://doi10.16285/j.rsm.2016.S2.020
19. Zhou SQ, Zhou DW, Zhang YF et al (2019) Study on physical-mechanical properties and microstructure of expansive soil stabilized with fly ash and lime. Advances in Civil Engineering 2019(1):1–15. https://doi.org/10.1155/2019/4693757

20. Zhu X, Cai ZY, Huang YH et al (2020) Experimental study on the effects of wet-dry freeze-thaw coupling cycles and dry density on the mechanical properties of expansive soils. J Hydraul Eng 051(003):286–294. https://doi.org/10.13243/j.cnki.slxb.20190362

Figures

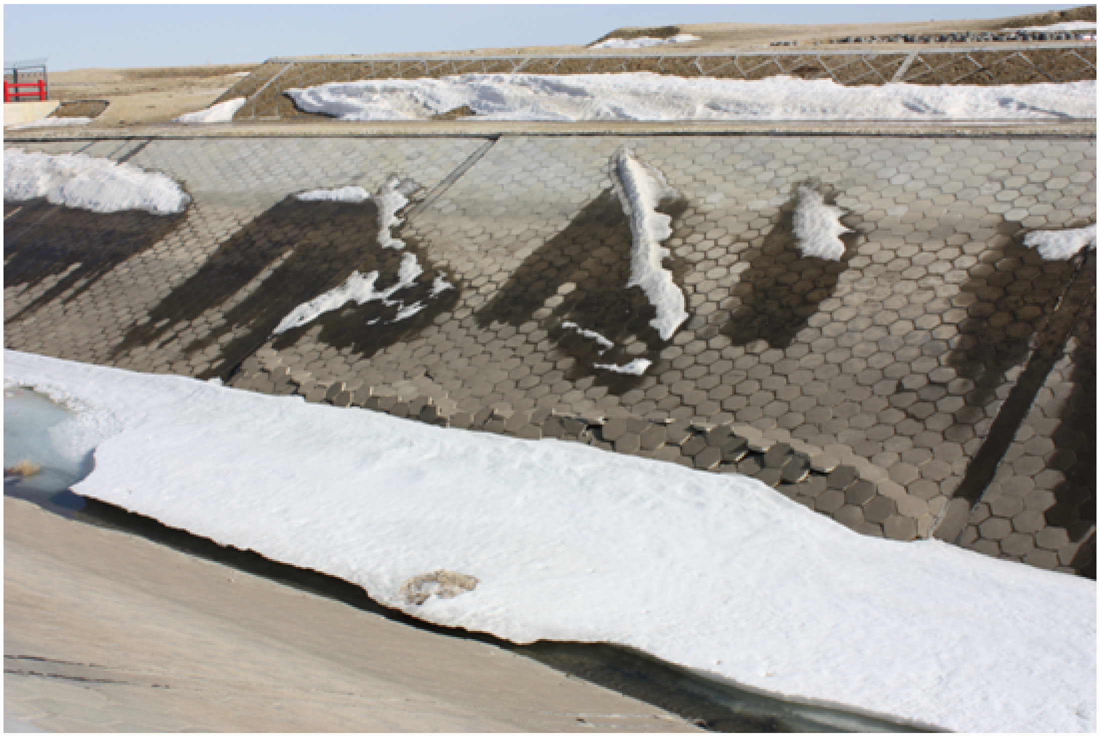

Figure 1

Typical deterioration photo of a main canal in northern. Xinjiang.

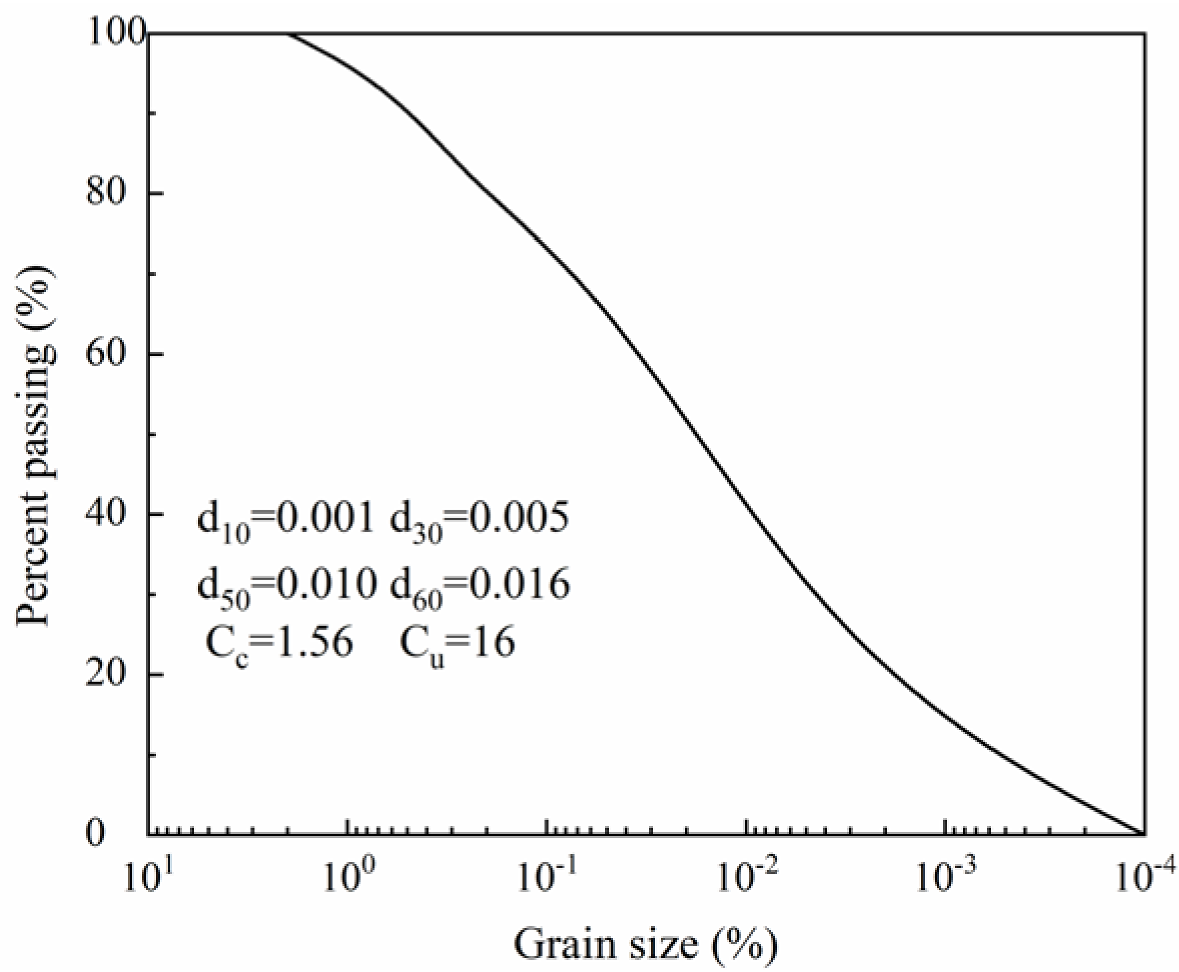

Figure 2

Particle distribution curve of soil.

Figure 3

Phase change material

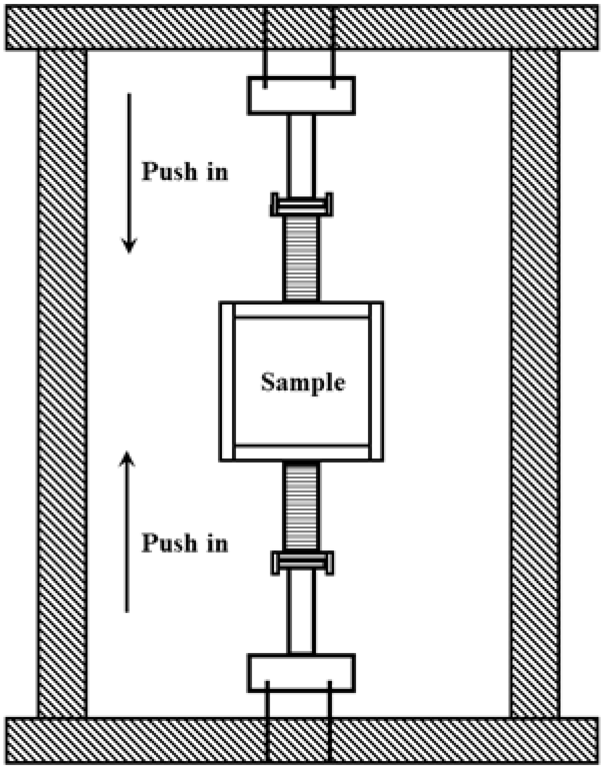

Figure 4

Schematic diagram of sample preparation device.

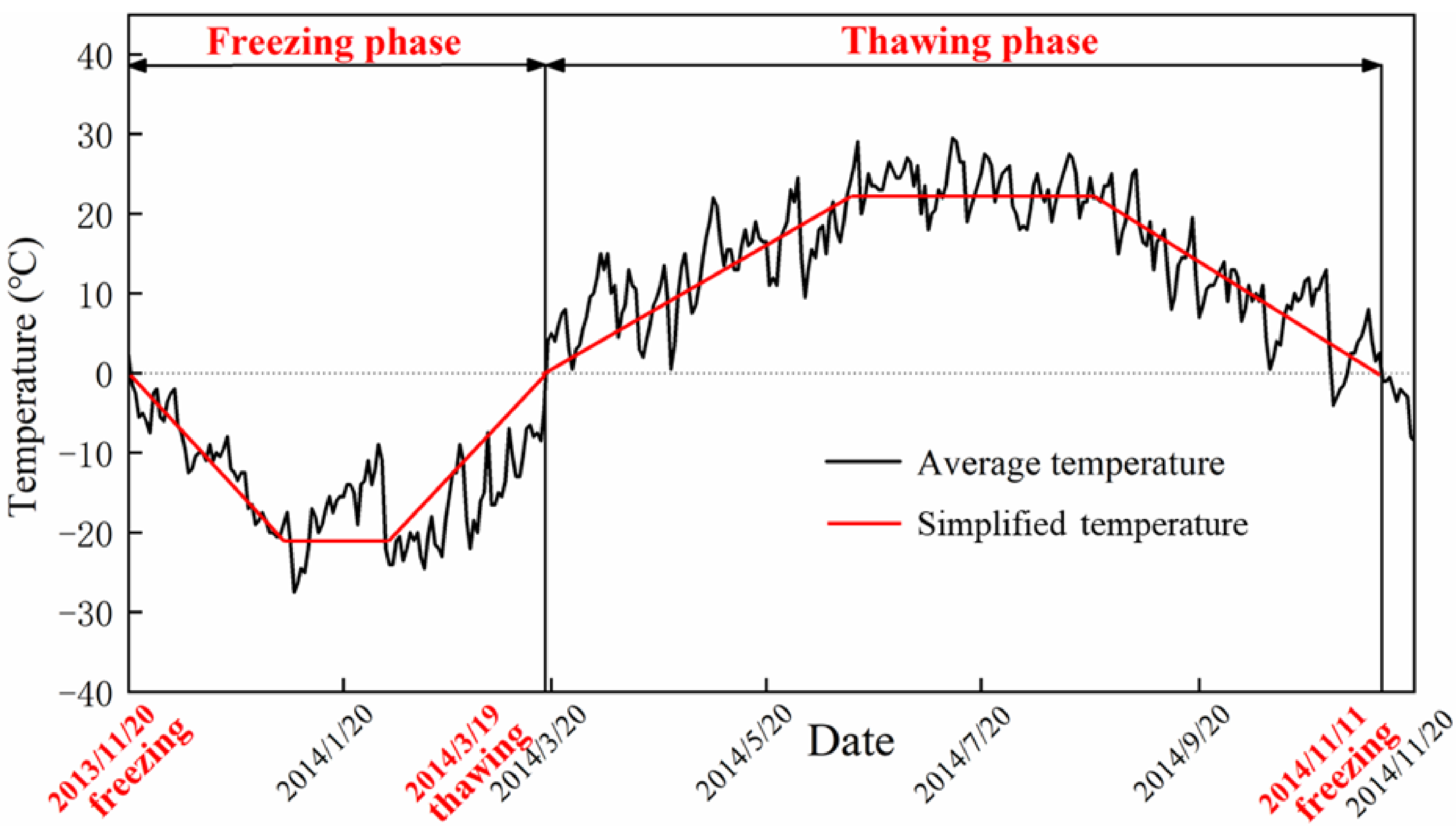

Figure 5

Simplified and actual ambient temperature of the canal (2013 to 2014).

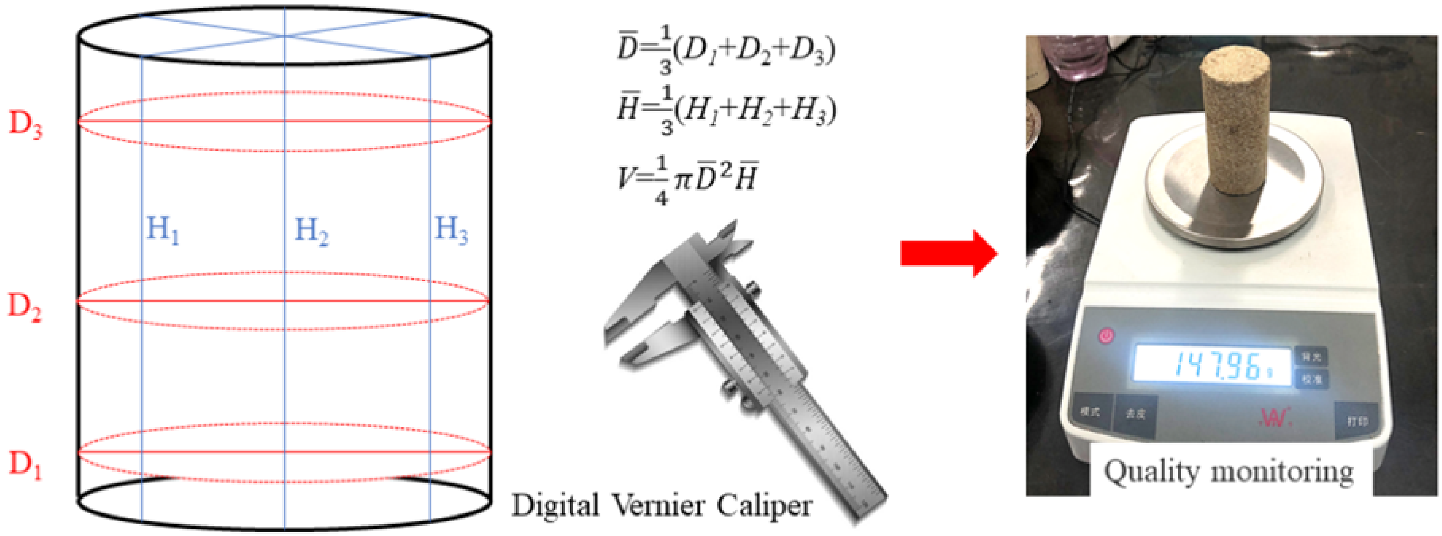

Figure 6

Volume measurement and quality control.

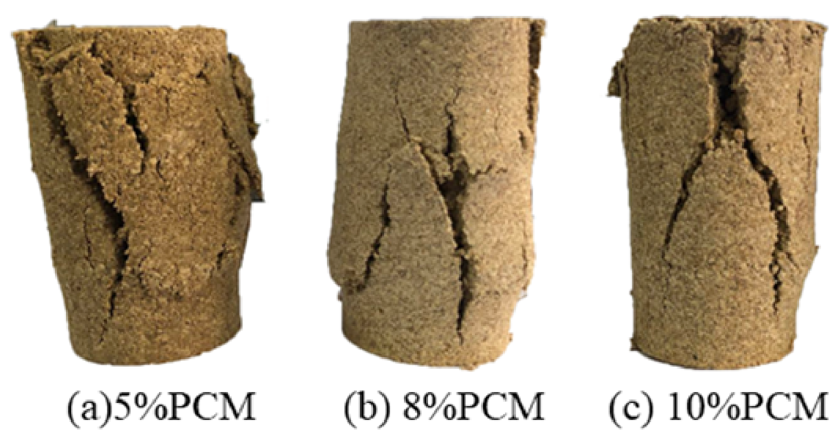

Figure 7

Photo of unconfined compressive strength test equipment.

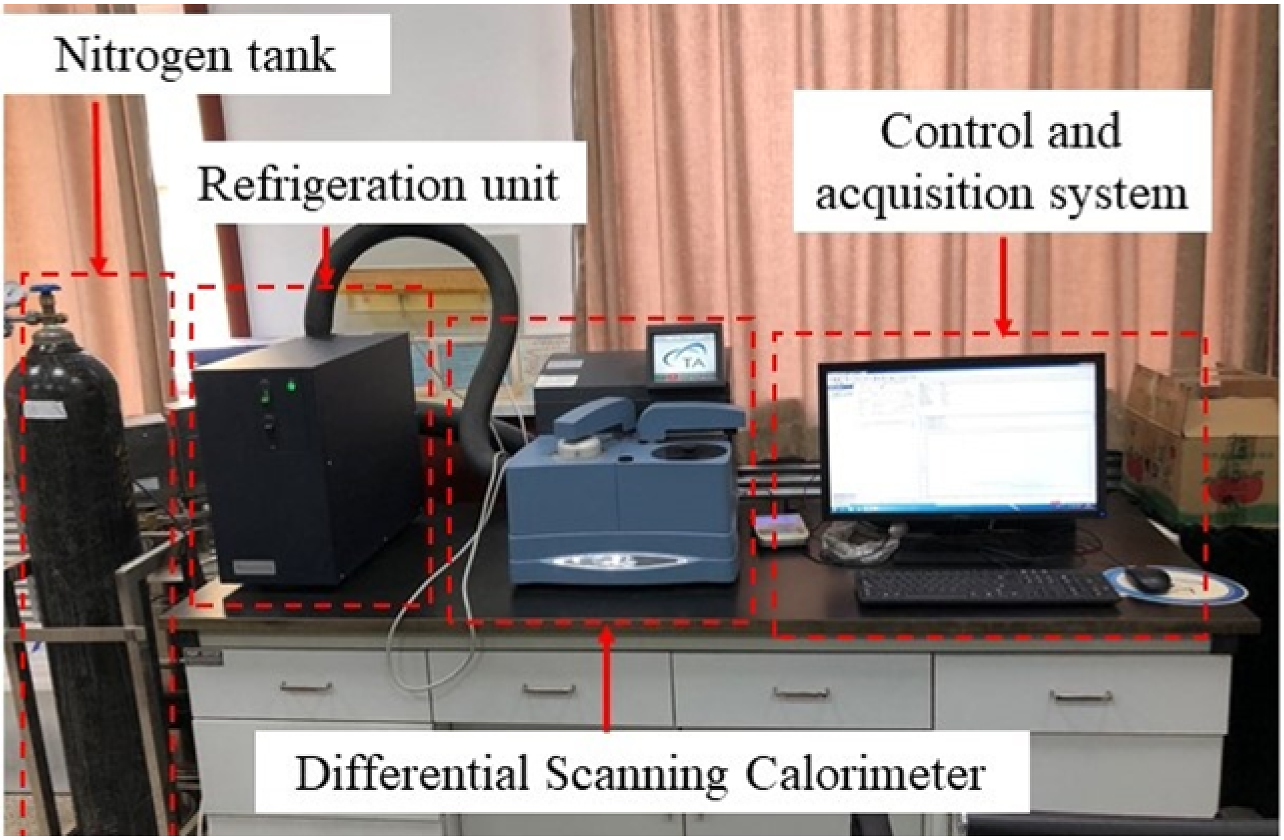

Figure 8

Photo of differential scanning calorimetry test equipment.

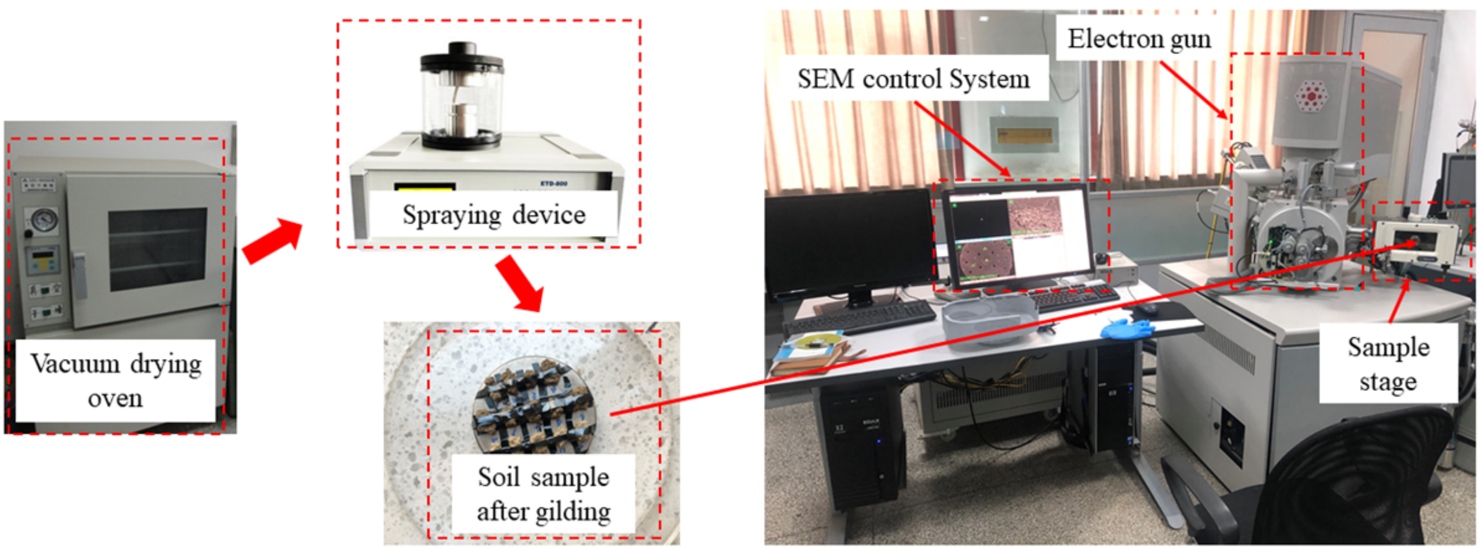

Figure 9

Scanning electron microscope test steps.

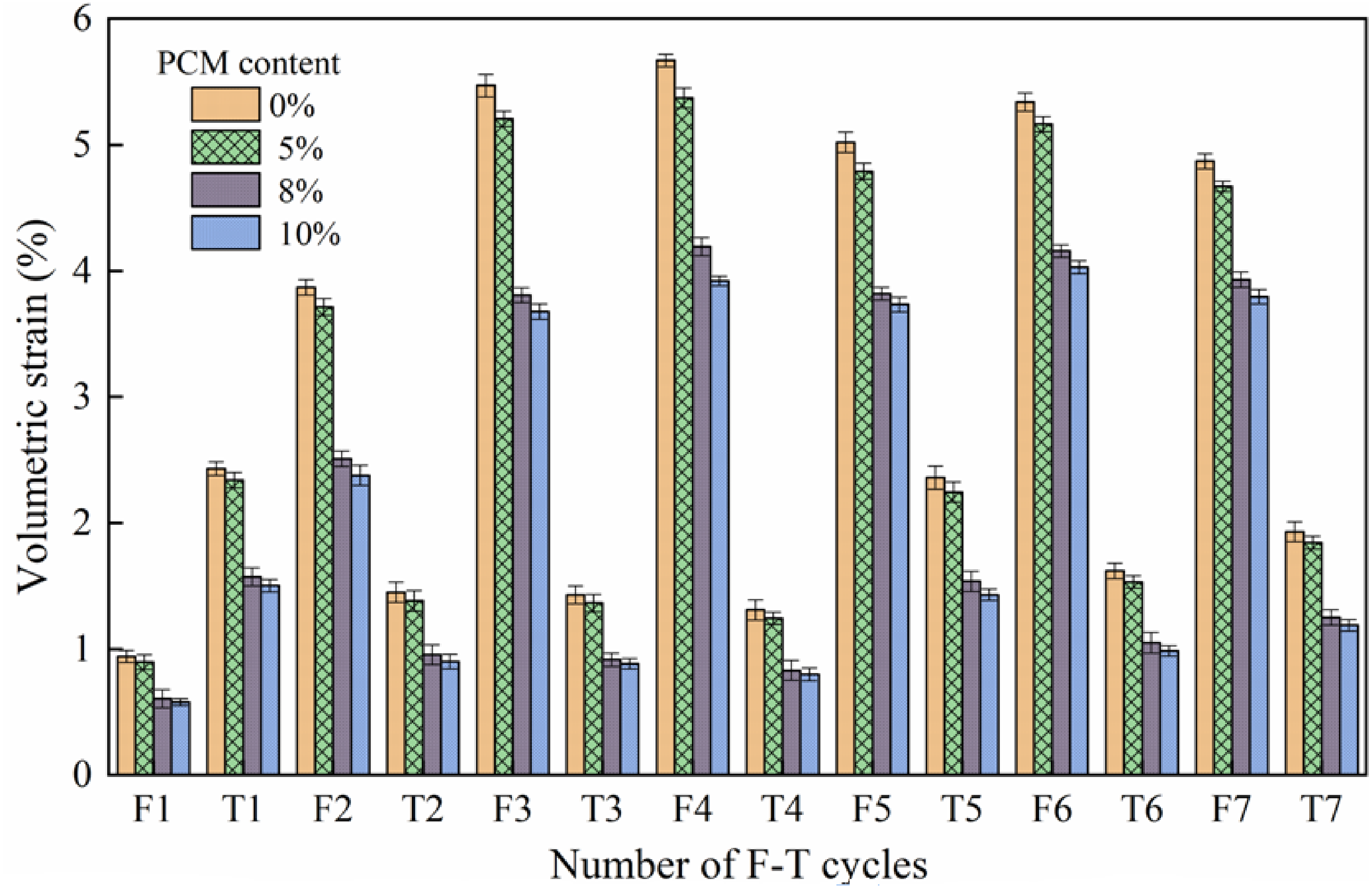

Figure 10

Volume changes of samples during F–T cycles.

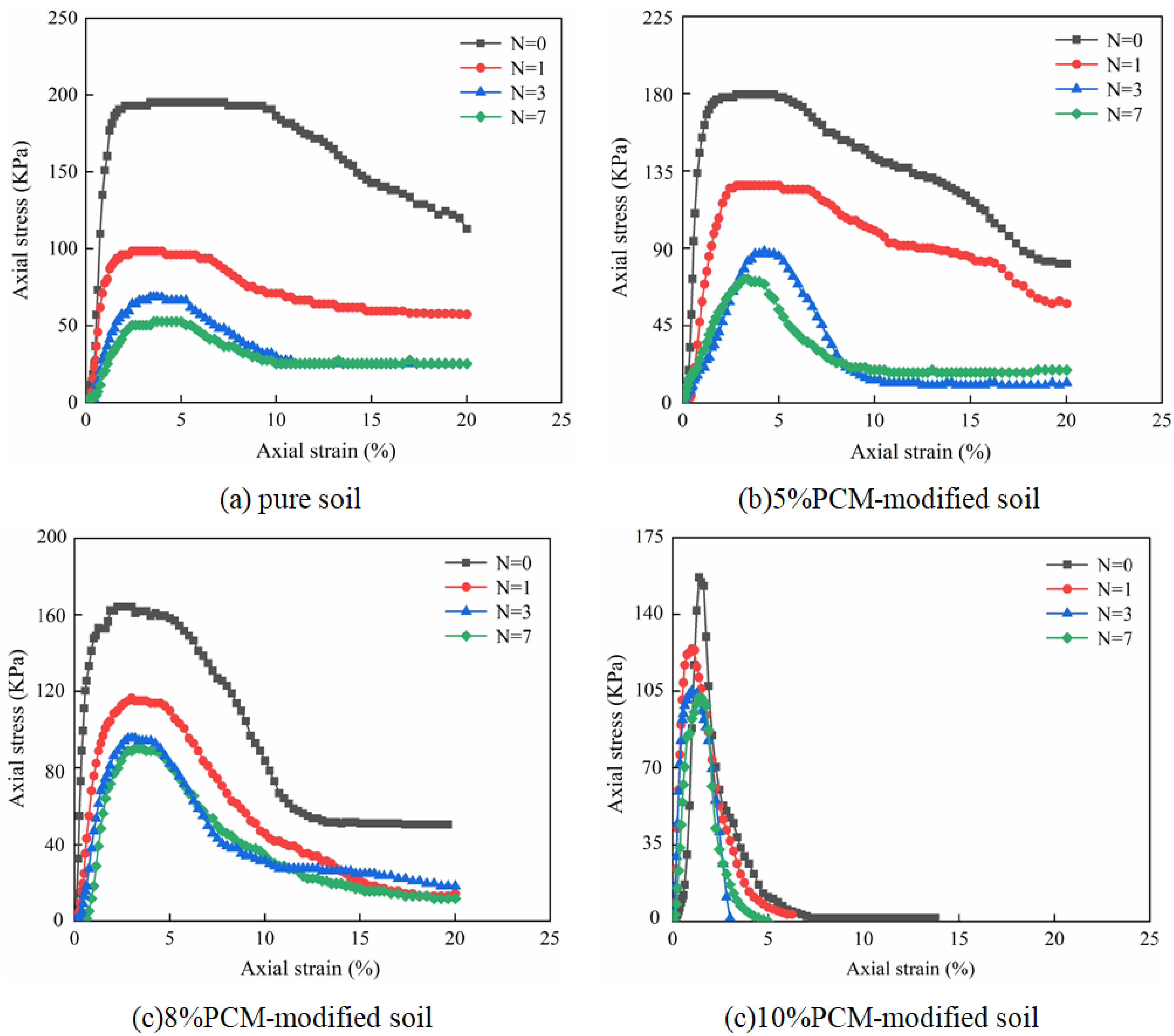

Figure 11

Stress-strain relationship curve for samples under different F−T cycle.

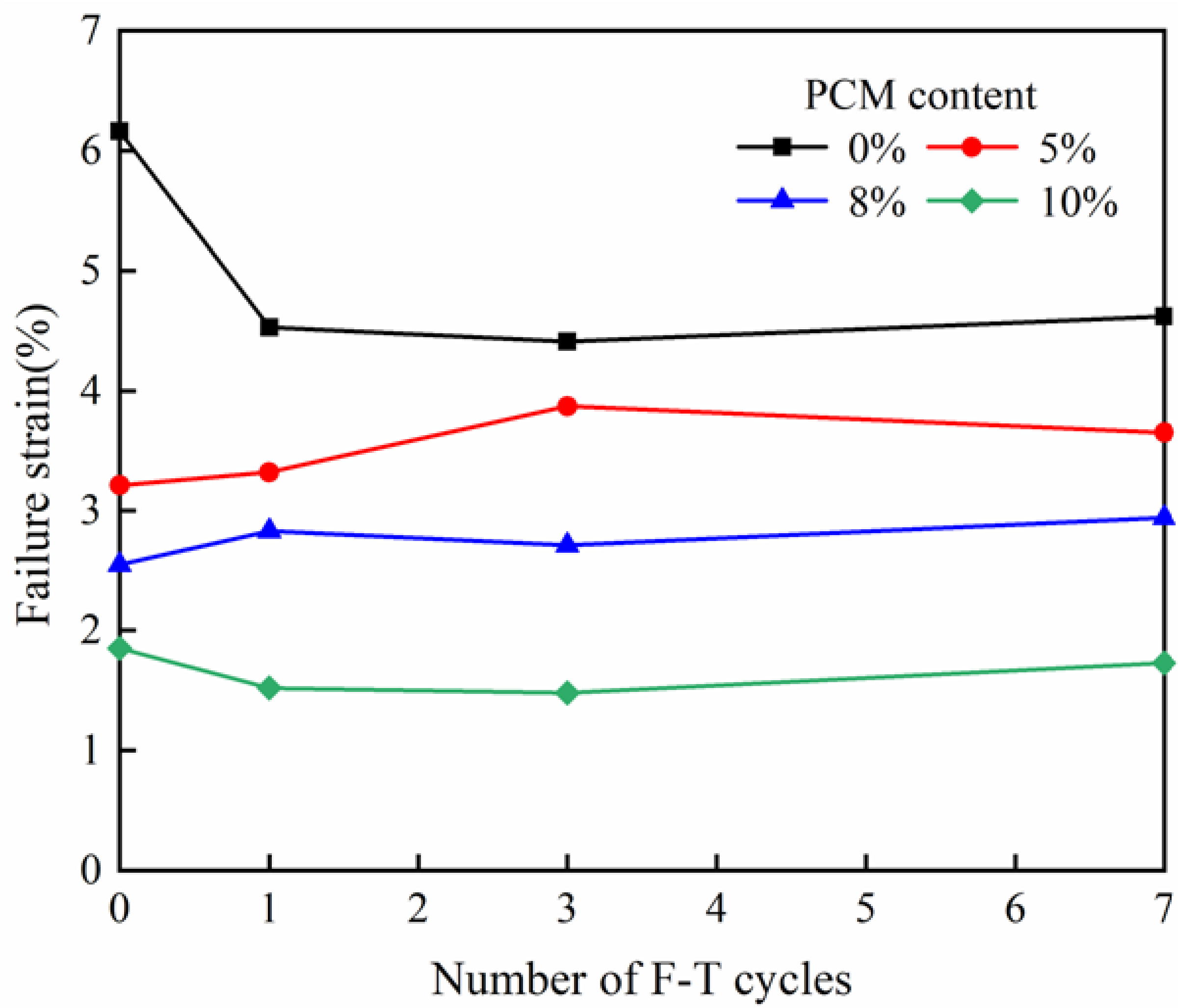

Figure 12

Changes of failure strain with the number of F-T cycles.

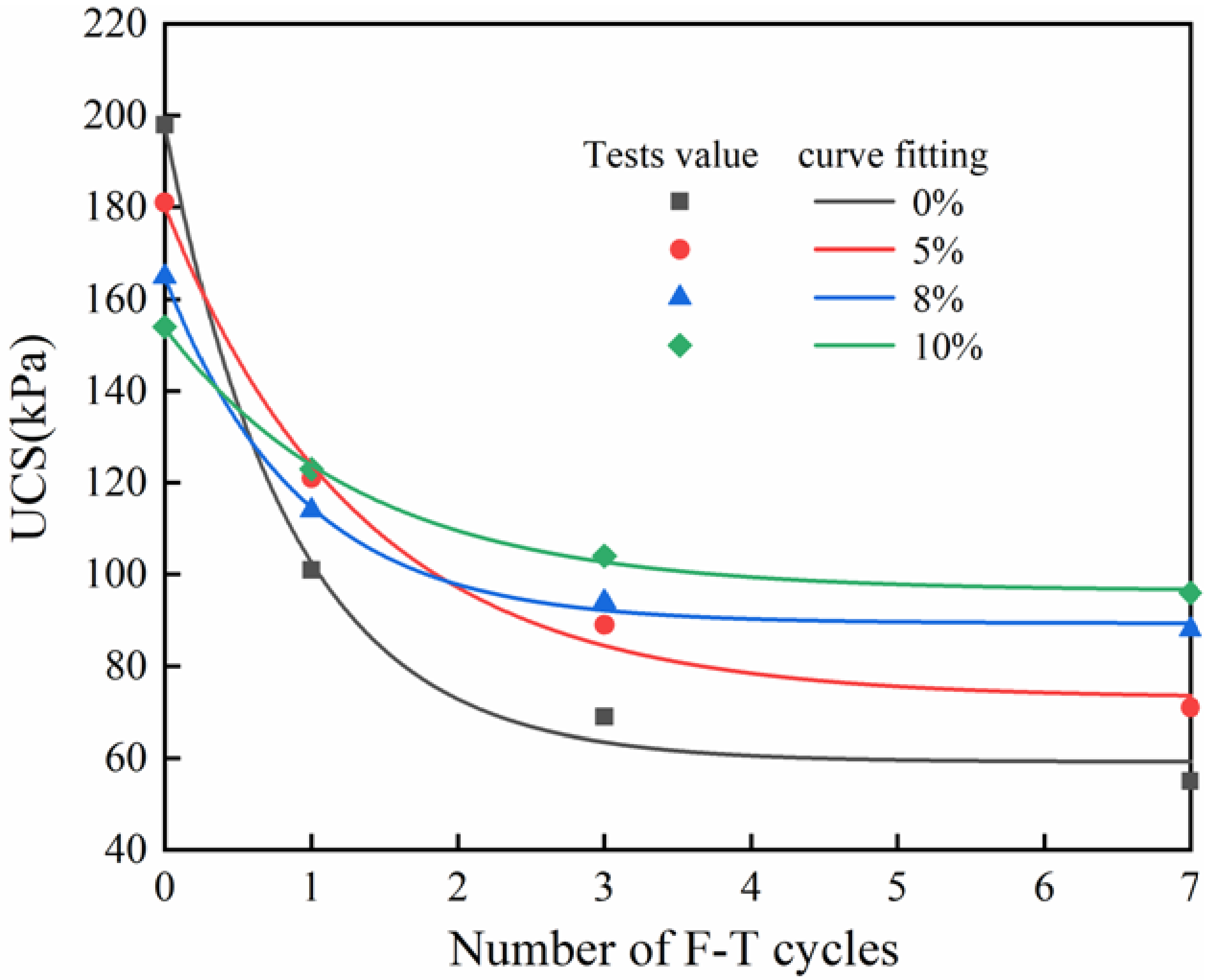

Figure 13

Changes of UCS with the number of F-T cycles.

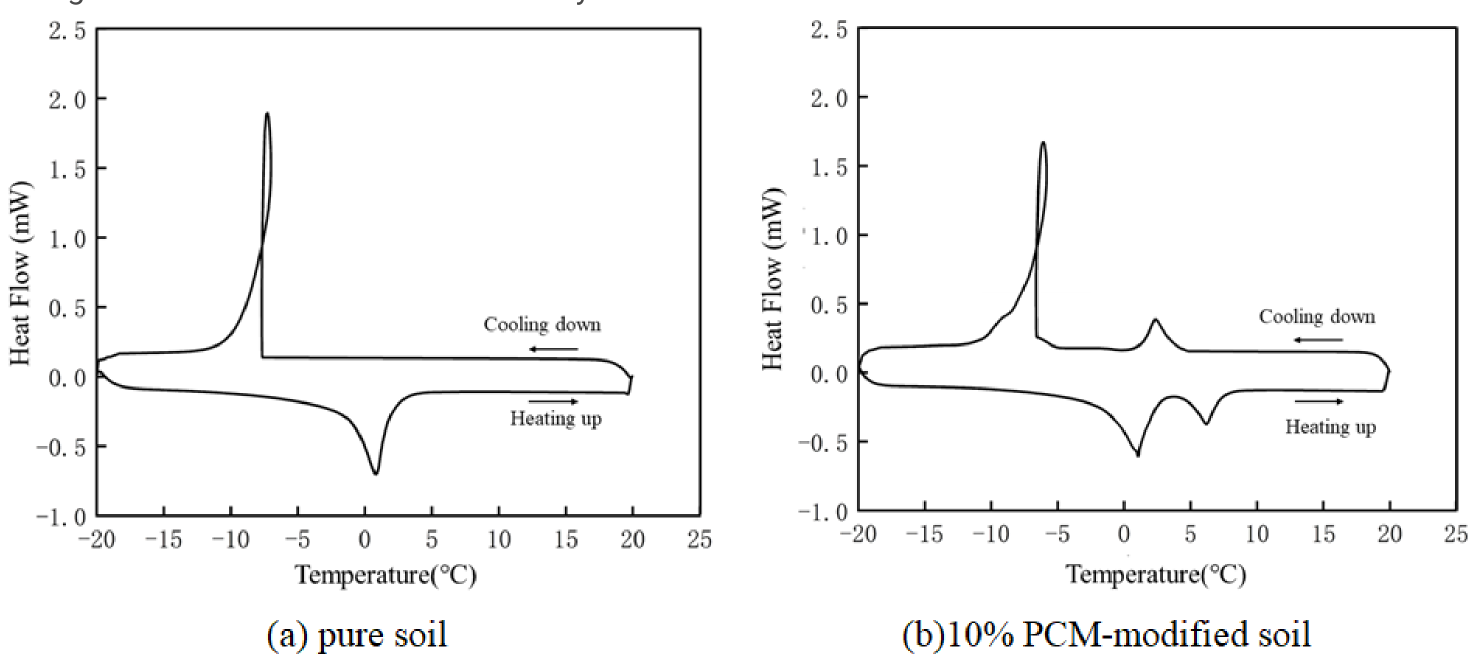

Figure 14

DSC curves

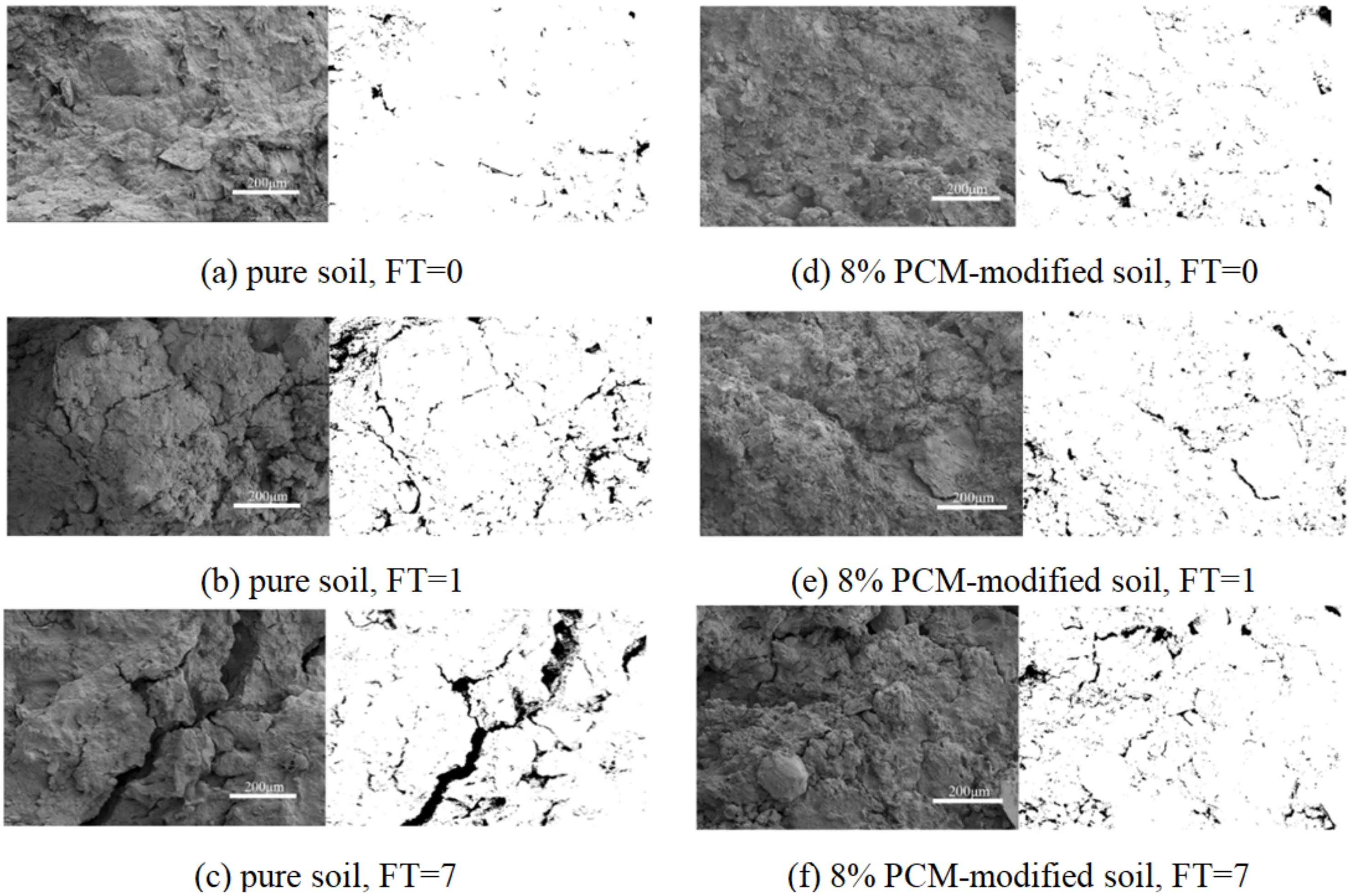

Figure 15

SEM photos of pure soil and 8% mPCM-modified soil at 100x.

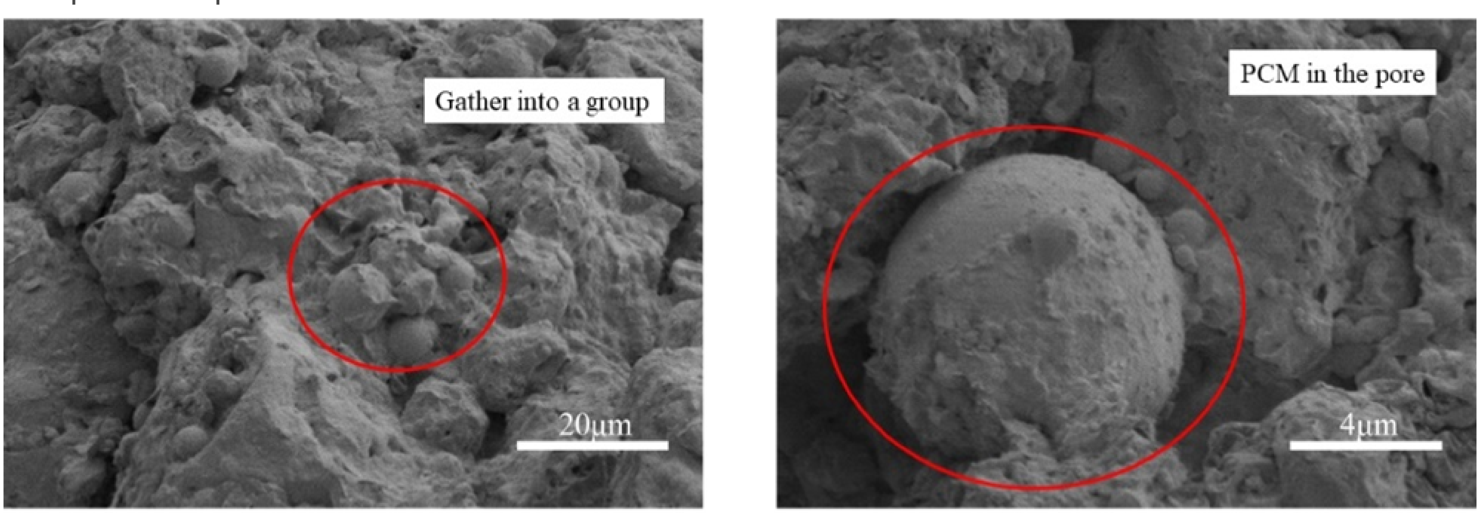

Figure 16

Micromorphology of 8% mPCM-modified soil.

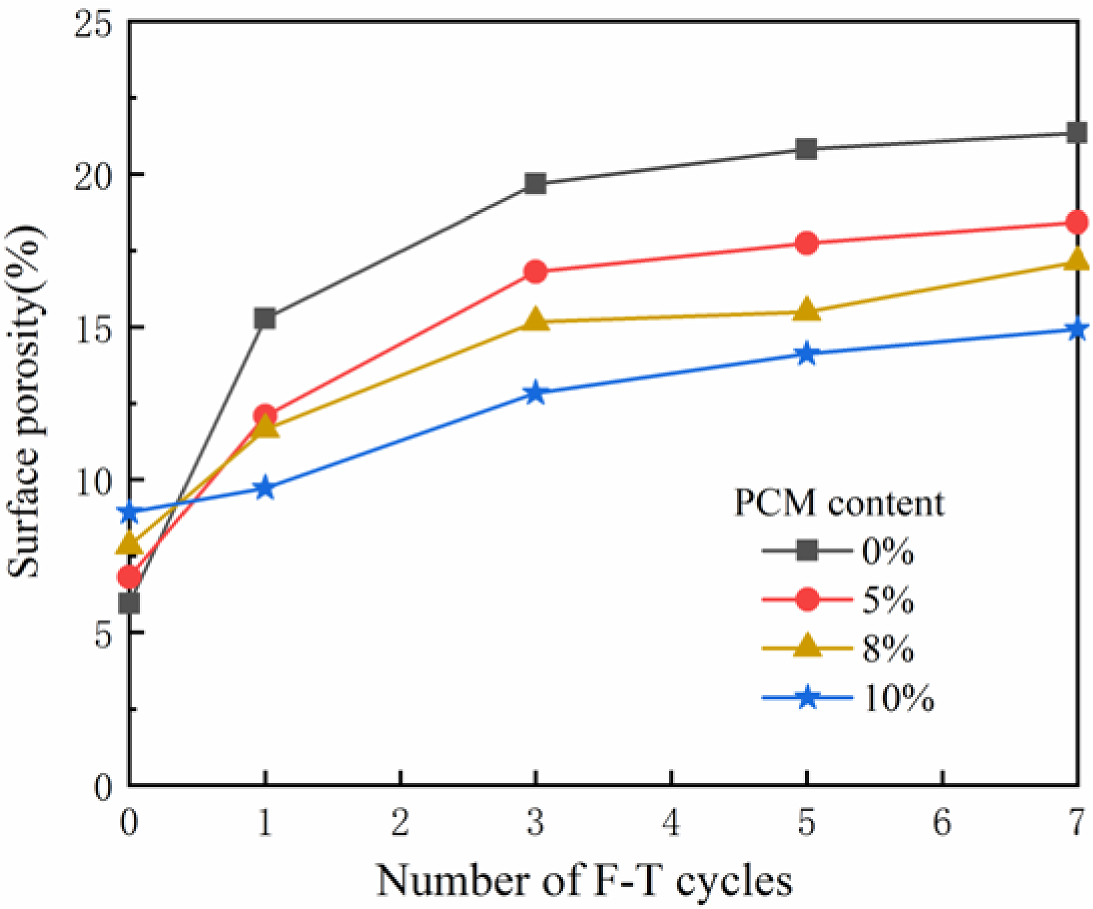

Figure 17

The porosity of the sample surface porosity with the number of F–T cycles.

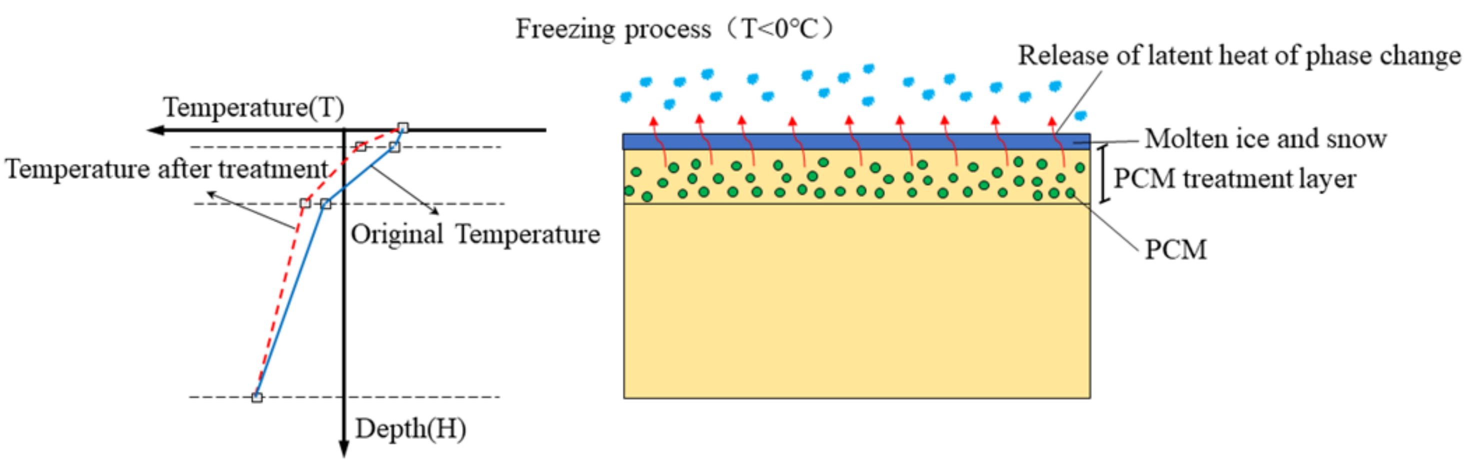

Figure 18

Schematic diagram of the PCM treatment mechanism of the foundation soil of the expansive soil canal in the cold region.