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# Effect of Composite Erosion on Physical Variability of Microbial Solidified Engineering Muck

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**Abstract:** To study the influence of freeze-thaw and wind erosion on the physical properties variability of microbiologically solidified engineering soil and further promote the application of Microbially Induced Calcium Carbonate Precipitation (MICP) anti-wind erosion dust technology in seasonal frozen soil areas, freeze-thaw cycling tests and indoor wind tunnel tests after freeze-thaw were carried out on microbiologically solidified engineering soil. Two parameters related to variability analysis (variation and coefficient of variation) were introduced to systematically analyze the physical and mechanical properties indicators of microbiologically solidified engineering soil after different freeze-thaw cycles and wind erosion. The results showed that the combined effects of freeze-thaw and wind erosion on the surface strength of microbiologically solidified soil samples were complex and related to the initial porosity of the engineering soil. With an increase in the number of freeze-thaw cycles, the soil density continuously increased, while the solidified surface thickness gradually decreased. The absolute values of the changes in density, solidified surface thickness, and surface strength of microbiologically solidified engineering soil increased with the increase in the number of freeze-thaw cycles. The coefficients of variation of the density, surface thickness, and surface strength of microbiologically solidified engineering soil under the combined effects of freeze-thaw and wind erosion decreased with the increase in the number of freeze-thaw cycles, and the physical and mechanical properties of microbiologically solidified engineering soil tended to stabilize after undergoing more than 7 freeze-thaw cycles.

**Keywords:** Freeze-thaw cycles; wind erosion; microbiological solidification; physical property; variability.

## 1. Introduction

Microbial-induced calcium carbonate precipitation (MICP) consolidation technology utilizes the metabolic activities of microorganisms to induce the formation of calcium carbonate crystals, which cement loose soil particles and thereby achieve the reinforcement and improvement of soil. As an emerging green reinforcement technology in geotechnical engineering [1], microbial consolidation can effectively improve the structure, strength, stiffness, compressibility, and permeability of rock and soil [2], endowing them with excellent functions such as anti-seepage [3-4], anti-liquefaction [5-6], anti-erosion and anti-scouring [7-8], and can be applied to solve problems such as windbreak and sand fixation, slope reinforcement, and the restoration of geotechnical materials [9-11]. Among these applications, its use in the consolidation of loose soil to resist wind erosion is considered the most likely to be realized first, and many scholars have conducted research in this area and applied it in engineering practice. The microbial consolidation technology is a new method suitable for large-scale treatment of engineering waste soil against wind erosion, but this method is currently mainly at the laboratory research stage and lacks sufficient field tests and natural environment tests. The regions north of Guangdong, Guangxi, and Fujian in China are all freeze-thaw zones [12], and the freeze-thaw action in these areas is an important environmental factor affecting the anti-wind erosion and dust control effect of microbial consolidated engineering waste soil.

Freeze-thaw action alters the structure of soil, thereby changing its physical and mechanical properties [13]. Zheng Yun et al. [14-15] studied the impact of freeze-thaw action on the structural properties of silty clay, indicating that during repeated freeze-thaw cycles, soil samples experienced particle breakage, which led to an increase in the liquid limit, plastic limit, plasticity index, and specific surface area of the soil. Zhao Luqing et al. [16-18] investigated the variation laws of the microstructure of loess under freeze-thaw action, suggesting that the number of freeze-thaw cycles affects the microstructure characteristics of soil particles, causing continuous flaking of soil debris until complete flaking, and the microstructure morphology and arrangement of soil particles change to form a new structural system. Additionally, freeze-thaw action has a significant impact on soil strength. Cui Honghuan et al. [19] studied the influence of freeze-thaw cycles on the strength of unsaturated clay in seasonally frozen areas, indicating that with an increase in the number of freeze-thaw cycles, the strength of unsaturated silty clay first decreases and then stabilizes, and the first freeze-thaw cycle has the most significant impact on soil strength. The above studies are all based on the single-factor effect of freeze-thaw cycles on the physical properties of undisturbed soil samples or remolded soil samples. However, freeze-thaw action is often accompanied by other actions such as wind erosion and water erosion. Currently, there are few studies on the variability characteristics of the physical properties of microbial-cured soil samples under the combined erosion of freeze-thaw and wind. Studying the variation laws of the physical properties of microbial-cured soil samples under the combined erosion of freeze-thaw and wind is of great significance for the application and development of microbial curing technology in geotechnical engineering.

Based on the previous research, this paper prepares microbial solidified engineering waste soil samples using the optimized microbial solidification parameters. Different working conditions of freeze-thaw cycles and wind tunnel tests are designed to reveal the variation characteristics of surface strength, solidified layer thickness and density of microbial solidified soil under the combined erosion of freeze-thaw and wind. Two statistical parameters, variation and coefficient of variation, are introduced to study the influence of the combined erosion of freeze-thaw and wind on the physical property variability of microbial solidified engineering waste soil. The anti-freeze-thaw and anti-wind erosion characteristics of microbial solidified engineering waste soil are systematically analyzed.

# 2. Experimental Design

## 2.1. Selection of Experimental Materials and Sample Preparation

The soil used for the experiment is engineering waste soil. Considering the impact of void ratio on the density and water retention capacity of the soil, the samples were divided into three groups based on their void ratios (e1=1.1, e2=1.2, e3=1.3). The natural moisture content of the undisturbed soil sample was 11.91%, with a pH value of 7.7. The maximum dry density and minimum dry density were recorded as 1.48 g/cm³ and 0.93 g/cm³, respectively. The particle size distribution curve of the undisturbed soil sample is illustrated in Figure 1. Using a controlled dry density method, the experimental soil was spread evenly within an organic glass box measuring 350 mm × 250 mm × 100 mm; its surface was then leveled off before applying microbial solidification treatment via spraying methods. This model box allows for direct observation of both the infiltration behavior of bacterial solution during microbial solidification and the thickness of the solidified layer on the surface of the soil sample. The MICP curing solution consists of bacterial liquid and cementing liquid [20]. In this experiment, Sporosarcina Pasteurii (CGMCC1.3687) was cultured to obtain bacterial liquid; its culture medium primarily consisted of yeast extract, NH4Cl, MnSO4·H2O, and NiCl2·6H2O. The pH value of this prepared culture solution was adjusted to approximately 9 using a NaOH solution at a concentration of 1 mol/L; subsequently, high-temperature steam sterilization was performed under conditions set at 121°C and 0.1 MPa using an autoclave apparatus followed by ultraviolet sterilization for thirty minutes in a sterile operating environment prior to inoculation with bacteria from this culture medium placed in an incubator set at constant temperature with shaking (30°C and rotation speed at 200 r/min) for twenty-four hours to yield original bacterial liquid thereafter mixed urea with calcium chloride in equal concentrations to produce cementing liquid.

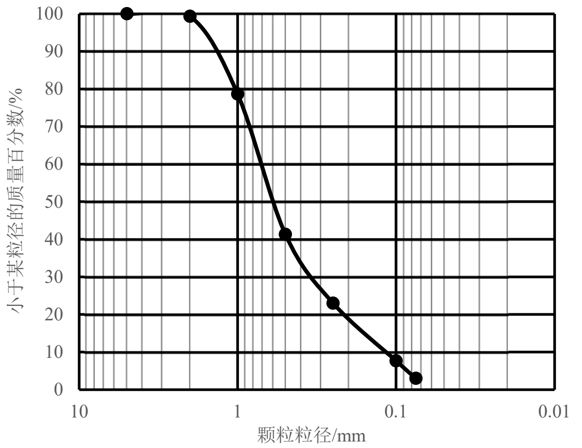

**Figure 1.** The gradation curve of soil particle size

## 2.2. Freezing and Thawing Cycle Test

The soil samples were subjected to freezing and thawing cycles using a freezing and thawing cycle test chamber. Based on meteorological data (the average minimum temperatures in winter and summer in northern China are -20.7°C and 21.5°C respectively [21]), the freezing and thawing temperatures were set at -25°C and 25°C, and the freezing and thawing times were both set at 12 hours. The number of freezing and thawing cycles was set at 0, 1, 3, 5, 7, and 9 times, and the samples were divided into 6 groups according to the number of cycles. During the test, the sample groups that reached the specified number of cycles were taken out in sequence for physical property tests, while the remaining groups continued the freezing and thawing tests in the test chamber.

## 2.3. Wind Tunnel Test

Freezing and thawing can intensify wind erosion. Wind tunnel tests were conducted after setting the number of freezing and thawing cycles. An indoor wind tunnel test machine was used for the test. Existing studies have shown that the threshold wind speed for soil dust emission is 4 to 7 m/s [22], and the number of days with wind speeds above 8 m/s in northern regions is relatively small [23-24]. Therefore, four wind speeds were designed for the wind tunnel test, namely 6 m/s, 9 m/s, 12 m/s, and 15 m/s, corresponding to wind forces of 4 to 7 levels. The wind tunnel test lasted for 10 minutes at each wind force level, and the mass loss due to wind erosion was recorded each time.

## 2.4. Measurement of Surface Strength and Thickness of the Cured Layer

The surface strength of the microbial-cured soil samples was tested using a WXGR-2 type micro penetration tester. During the measurement, the tester's probe was vertically and steadily inserted into the soil layer from the surface of the cured soil sample until the marked line on the probe touched the soil surface, and then the reading could be taken. Multiple measurements were conducted on each sample and the average value was taken. The thickness of the surface layer of the cured soil sample could be measured by placing a ruler against the outside of the acrylic box at multiple points and taking the average value.

# 3. Analysis of the Physical Properties Variability of Microbial Solidified Soil under the Combined Erosion of Freeze-Thaw and Wind

The variability of the engineering properties of microbial solidified soil under the combined erosion of freeze-thaw and wind requires the combination of the number of freeze-thaw cycles and the changes in the physical property parameters of the soil samples before and after the freeze-thaw cycle and wind tunnel tests. Traditional statistical measures for describing the degree of variation, such as variance, standard deviation, and range, cannot reflect this dynamic change characteristic. Zhou Hong et al. [25] introduced two new calculation parameters, namely the change quantity and the coefficient of variation, when studying the variability characteristics of the physical properties of loess under freeze-thaw action, to analyze the variability of the physical properties of loess caused by freeze-thaw. Based on this method, this paper explores the variability characteristics of the physical properties of microbial solidified construction waste soil under the combined erosion of freeze-thaw and wind.

The calculation formula for the change quantity is:

$$\Delta D_i = Y_i^n - X_i \tag{1}$$

The formula for calculating the coefficient of variation is:

$$K_{var} = \frac{1}{n}|X_i - Y_i| \tag{2}$$

Where X represents the physical property parameter values of the microbial solidified engineering waste soil samples without freeze-thaw cycles; Y represents the physical property parameter values of the microbial solidified engineering waste soil samples under the combined action of freeze-thaw and wind erosion; i represents different physical property indicators when it is different letters, such as strength, thickness of the solidified layer and density, etc.; n represents the number of freeze-thaw cycle tests and wind tunnel tests. ΔDi represents the difference in the corresponding physical property parameters under different numbers of freeze-thaw cycle tests and wind tunnel tests, describing the magnitude of the change. If ΔDi > 0, the corresponding parameter value increases; if ΔDi < 0, the corresponding parameter value decreases. Kvar represents the coefficient of variation, which indicates the intensity of the changes in various physical property parameters under the combined action of freeze-thaw and wind erosion. Based on this, the strength of the changes in various physical properties under the combined action of freeze-thaw and wind erosion can be judged. When Kvar > 1, the corresponding parameter changes are strong, indicating high variability; when 0.1 ≤ Kvar ≤ 1, the corresponding parameter changes are moderate, indicating medium variability; when 0 ≤ Kvar < 0.1, the corresponding parameter changes are weak, indicating low variability.

# 4. Experimental Results and Analysis

## 4.1. Physical property test results and analysis

Firstly, freeze-thaw cycle tests were conducted on the microbial solidified engineering waste soil, and indoor wind tunnel tests were carried out on the samples after each freeze-thaw action. The surface strength of the microbial solidified engineering waste soil after freeze-thaw cycles and wind tunnel tests was tested, and the results are shown in Figure 2: After one freeze-thaw cycle and wind tunnel test, the surface strength of all soil samples increased. Subsequently, with the increase in the number of freeze-thaw cycles, the surface strength of the soil samples with a porosity of 1.1 continuously decreased, while that of the samples with a porosity of 1.3 continuously increased. The surface strength of the samples with a porosity of 1.2 showed a trend of first increasing, then decreasing, and then increasing again. After one freeze-thaw cycle test and wind tunnel test, the surface strength of the solidified soil samples significantly increased. The reason is that in the -25°C environment, the water molecules in the samples quickly froze into ice, expanded in volume and squeezed the surrounding soil, causing the structural connection between soil particles to be destroyed, becoming looser, and the surface adhesion of the soil samples decreased. However, after the wind tunnel test, the loose soil particles on the surface of the solidified layer gradually moved downward under the action of external force, the volume settled, the density increased, the contact area between soil particles increased, and the mechanical interlocking force increased, resulting in an increase in the surface strength of the samples instead of a decrease.

The thickness of the solidified layer of the microbial solidified engineering waste soil after freeze-thaw cycles and wind tunnel tests was tested, and the results are shown in Figure 3: The thickness of the solidified layer of the microbial solidified soil samples decreased with the increase in the number of freeze-thaw and wind force combined erosion actions. This is because the MICP solidification method used is the spraying method. As the surface adhesion of the solidified soil samples decreases, the calcium carbonate's binding effect on soil particles gradually weakens from top to bottom, and the less adhesive soil particles gradually peel off. At the same time, the wind force also causes the loose soil particles to gradually move downward, thereby resulting in a gradual decrease in the thickness of the solidified layer.

The density of the microbial solidified engineering waste soil after freeze-thaw cycles and wind tunnel tests was tested, and the results are shown in Figure 3: The density of the solidified soil samples is positively correlated with the number of freeze-thaw and wind force combined erosion actions. After 0-9 freeze-thaw and wind force combined erosion actions, the soil particles and ice crystals gradually connected closely under the continuous action of squeezing force, thereby causing the density of the soil samples to gradually increase.

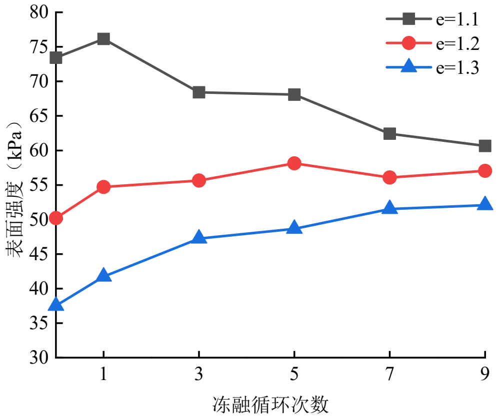

**Figure 2.** The effect of freeze-thaw cycles on the surface strength of solidified soil samples

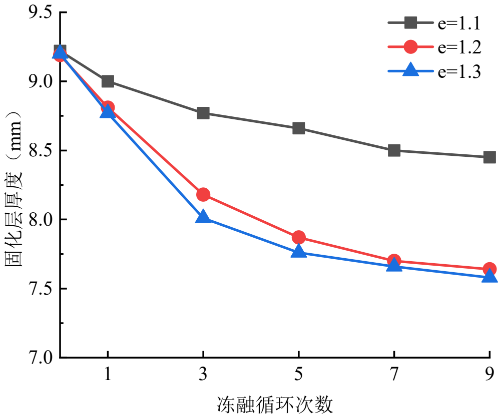

**Figure 3.** Effect of freeze-thaw cycles on the thickness of solidified layer of solidified soil samples

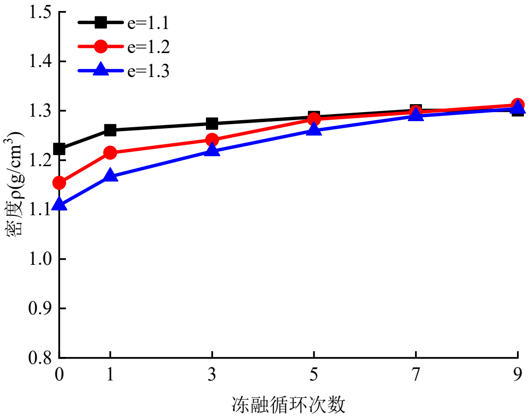

**Figure 4.** Effect of freeze-thaw cycles on the density of solidified soil samples

## 4.2. Analysis of Changes in Physical Properties

The bar chart of the variation in surface strength of microbially solidified soil with the number of freeze-thaw and wind erosion cycles is shown in Figure 5. The variation values of the surface strength of the solidified soil samples are both positive and negative. Taking the absolute values of these data reveals that the absolute value of the variation in surface strength of the solidified soil samples generally increases with the increase in the number of freeze-thaw and wind erosion cycles. At the same time, based on the positive and negative values of the variations, it can be seen that the variations in surface strength of the solidified soil samples with void ratios of 1.2 and 1.3 are positive, indicating that the surface strength of the solidified soil samples increases after more than one freeze-thaw and wind erosion cycle. The variation in surface strength of the solidified soil sample with a void ratio of 1.3 is negative, indicating a decrease in surface strength. Therefore, the effect of freeze-thaw and wind erosion cycles on the surface strength of microbially solidified soil samples is complex and related to the original void ratio of the engineering soil.

The bar chart of the variation in the thickness of the solidified layer of microbially solidified soil with the number of freeze-thaw and wind erosion cycles is shown in Figure 6. All the variations are negative, indicating that the thickness of the solidified layer of the solidified soil samples gradually decreases with the increase in the number of freeze-thaw and wind erosion cycles. By comparing the absolute values of the variations, it can be found that the absolute value of the variation in the thickness of the solidified layer increases with the increase in the number of freeze-thaw and wind erosion cycles, and the change amplitude between adjacent cycles gradually decreases, indicating that the thickness of the solidified layer of the solidified soil samples gradually approaches a stable value, which to some extent reflects that the microbially solidified engineering soil has good resistance to freeze-thaw and wind erosion.

Figure 7 is the bar chart of the variation in the density of the solidified soil samples with the number of freeze-thaw and wind erosion cycles. During the first five freeze-thaw cycles, the density of the solidified soil samples increases with the increase in the number of freeze-thaw and wind erosion cycles. After that, the density of the solidified soil sample with a void ratio of 1.1 basically remains unchanged, while the density of the solidified soil samples with void ratios of 1.2 and 1.3 continues to increase, but at a smaller rate, indicating that the density of the solidified soil samples gradually approaches a stable value. The height of the bars reflects the magnitude of the variation. Based on this, it can be found that the smaller the void ratio of the engineering soil samples, the smaller the variation in density, and the weaker the effect of freeze-thaw on the density.

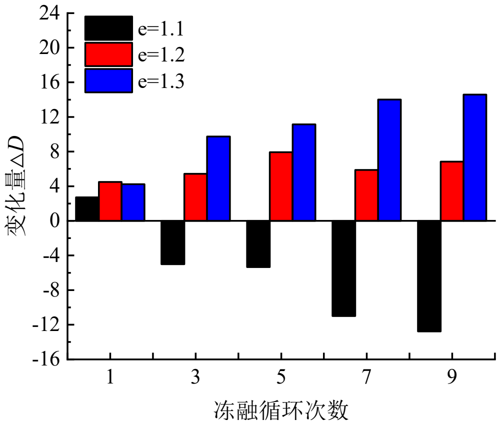

**Figure 5.** Variation of surface strength of solidified soil samples under freeze-thaw cycles

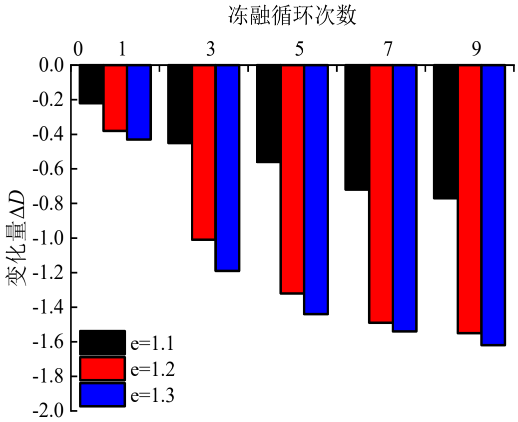

**Figure 6.** Variation of solidified layer thickness of solidified soil sample under freeze-thaw cycles

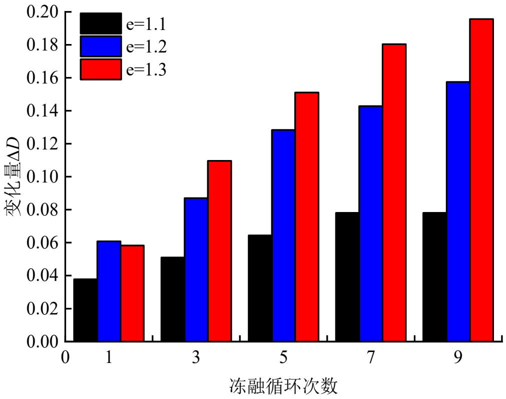

**Figure 7.** Variation of solidified soil sample density under freeze-thaw cycles

## 4.3. The variation law of the coefficient of variation of physical properties

Based on the above analysis of the measurement of physical property parameters of microbial solidified engineering waste soil and their variations, this paper introduces the coefficient of variation as a statistical quantity to analyze the variability of physical properties of microbial solidified engineering waste soil under the combined action of freeze-thaw and wind erosion. By analyzing the variation of surface strength of microbial solidified engineering waste soil samples, the coefficient of variation of surface strength of microbial solidified soil samples under the combined action of freeze-thaw and wind erosion is obtained, as shown in Figure 8. According to Figure 8 and the variability classification standard: after one freeze-thaw cycle test and wind tunnel test, the surface strength variability of the solidified soil samples is relatively high (Kvar>1). After three freeze-thaw cycle tests and wind tunnel tests, the coefficient of variation of the solidified soil samples decreases. Subsequently, the coefficient of variation of the solidified soil samples with void ratios of 1.2 and 1.3 continues to decrease, while that of the solidified soil sample with a void ratio of 1.1 first decreases, then increases, and then decreases. After seven combined erosion actions, the coefficient of variation of the solidified soil samples with all three void ratios decreases.

By analyzing the variation of the thickness of the solidified layer of microbial solidified waste soil samples, the coefficient of variation of the thickness of the solidified layer of microbial solidified soil samples under the combined action of freeze-thaw and wind erosion is obtained, as shown in Figure 9. It can be seen from Figure 9 that the coefficient of variation of the thickness of the solidified layer of the soil samples is almost all between 0.1 and 1, which is medium variability. The coefficient of variation of the thickness of the solidified layer of the soil samples with three void ratios gradually decreases with the increase of the number of freeze-thaw cycles and wind erosion actions. Among them, the coefficient of variation of the solidified soil samples with void ratios of 1.2 and 1.3 is always between 0.1 and 1. The coefficient of variation of the solidified soil sample with a void ratio of 1.1 decreases to low variability (Kvar<0.1).

By analyzing the variation of the density of microbial solidified engineering waste soil samples, the coefficient of variation of the density of microbial solidified soil samples under the combined action of freeze-thaw and wind erosion is obtained, as shown in Figure 10. It can be seen from Figure 10 that the coefficient of variation of the density of the solidified soil samples is all relatively low (Kvar<0.1), and the coefficient of variation gradually decreases with the increase of the number of freeze-thaw cycles and wind erosion actions, indicating that with the increase of the number of combined freeze-thaw and wind erosion actions, the soil particles gradually form a new stable arrangement structure, which makes the coefficient of variation of the density of the microbial solidified soil samples gradually decrease.

After seven combined erosion actions, the coefficient of variation of all physical property parameters of the solidified soil samples decreases (Figures 8-10), indicating that the physical properties of the solidified soil samples gradually tend to be stable after experiencing multiple freeze-thaw and wind erosion actions.

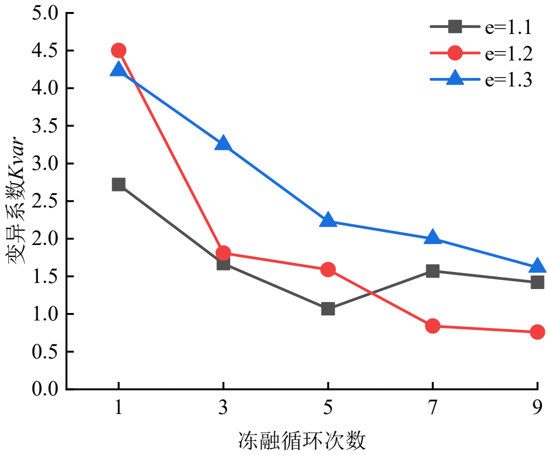

**Figure 8.** Effect of freeze-thaw cycles on variation coefficient of surface strength of solidified soil samples

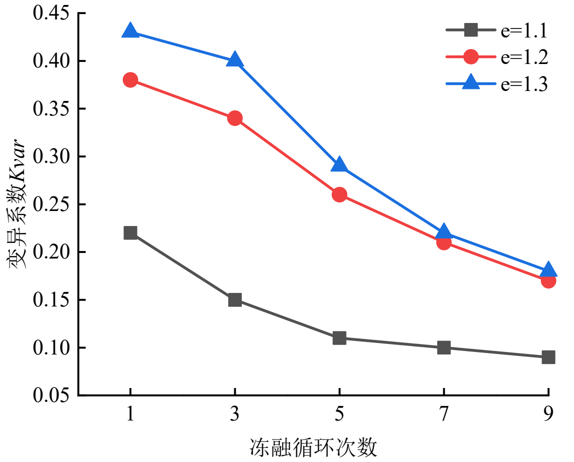

**Figure 9.** Effect of freeze-thaw cycles on variation coefficient of solidified layer thickness of solidified soil samples

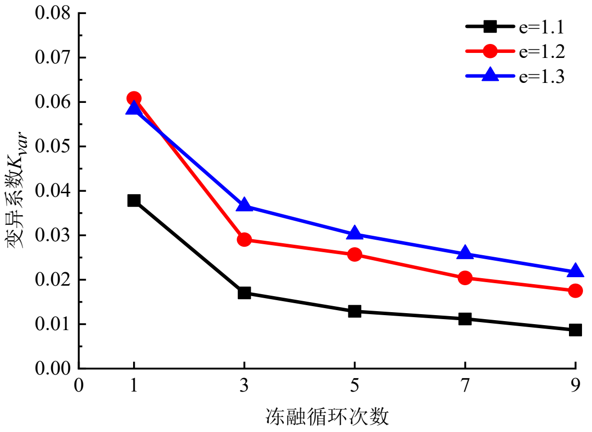

**Figure 10.** Effect of freeze-thaw cycles on density variation coefficient of solidified soil samples

## 5. Conclusion

To study the influence of freeze-thaw and wind erosion on the physical property variability of microbial immobilized construction waste soil, the construction waste soil was first treated with MICP. Freeze-thaw cycles and indoor wind tunnel tests were designed. Two statistical measures, the change amount and the coefficient of variation, were used to describe and analyze the variability characteristics of the physical properties of the treated soil samples after freeze-thaw and wind erosion. The following conclusions were drawn:

(1) The surface strength of the treated soil samples increased significantly after one freeze-thaw cycle and wind tunnel test, and then the changes became relatively complex. Under the combined action of freeze-thaw and wind erosion, the changes in the density and surface thickness of the treated soil samples were opposite. With the increase in the number of combined erosion cycles, the soil density continuously increased, while the thickness of the treated surface gradually decreased. After three freeze-thaw and wind erosion cycles, the changes in soil density and treated surface thickness tended to stabilize.

(2) The influence of freeze-thaw and wind erosion on the surface strength of the treated soil samples was variable, with both enhancing and weakening effects, which was related to the initial void ratio of the construction waste soil. The absolute values of the changes in surface strength, density, and treated surface thickness increased with the increase in the number of combined erosion cycles. The amplitude of changes in each parameter between adjacent cycles gradually decreased, indicating that the physical properties of the treated soil samples gradually stabilized after multiple combined erosion cycles.

(3) Under the combined action of freeze-thaw and wind erosion, the variability of the surface strength of the treated construction waste soil was relatively high ($Kvar > 1$), the variability of the treated layer thickness was moderate ($0.1 < Kvar < 1$), and the variability of density was relatively low ($Kvar < 0.1$). After seven combined erosion cycles, the coefficient of variation of each physical property parameter of the treated soil samples decreased, and the variability gradually stabilized. That is, the combined action of freeze-thaw and wind erosion would change the erosion resistance performance indicators of the treated construction waste soil samples, thereby affecting the soil's resistance to freeze-thaw and wind erosion. However, as the number of freeze-thaw cycles increased, the damage degree of the combined action of freeze-thaw and wind erosion on the samples gradually decreased.

## References

[1] HE X, MA G L, WANG Y et al. Visualization investigation of bio-cementation process based on microfluidics[J]. Chinese Journal of Geotechnical Engineering, 2020,42(06):1005-1012.

[2] DEJONG J, TORTENSEN M B, MARTINEZ B C, et al. Bio-mediated soil improvement [J]. Ecological Engineering,2010, 36(2):197-210.

[3] LIU L, LIU H L, STUEDLEIN A, et al. Strength Stiffness, and Microstructure Characteristics of Bio-cemented Calcareous Sand [J]. Canadian Geotechnical Journal, 2019, 56(10):1502-1513.

[4] Nader H, Alireza B. Reducing Soil Permeability Using Microbial Induced Carbonate Precipitation (MICP) Method: A Case Study of Shiraz Landfill Soil[J]. Geomicrobiology Journal,2020,37(2):147-158.

[5] Meghna S, Neelima S, R. K R. Investigation of various gram-positive bacteria for MICP in Narmada Sand, India[J]. International Journal of Geotechnical Engineering, 2021, 15(2):220-234.

[6] SHAN Y, ZHAO J T, TONG H W, et al. Effects of activated carbon on liquefaction resistance of calcareous sand treated with microbially induced calcium carbonate precipitation[J]. Soil Dynamics and Earthquake Engineering, 2022,161(Oct.):1-11.

[7] Wang Z, Zhang N, Jin Y, et al. Application of microbially induced calcium carbonate precipitation (MICP) in sand embankments for scouring/erosion control[J]. Marine Georesources and Geotechnology, 2020(11):1-14.

[8] SUN X H, MIAO L C, WANG H X, et al. Bio-cementation for the mitigation of surface erosion in loess slopes based on simulation experiment[J]. Journal of Soils and Sediments, 2022, 22(6):1-15.

[9] WANG Y X, LI C, WANG C Y, et al. Improving the Erosion Resistance Performance of Pisha Sandstone Weathered Soil Using MICP Technology[J]. Crystals,2021,11(9):1112-1112.

[10] KOU H L, LIU J H, ZHANG P, et al. Ecofriendly improvement of coastal calcareous sandy slope using recycled shredded coconut coir (RSC) and bio-cement[J]. Acta Geotechnica,2022,17(12):5375-5389.

[11] LIU H L, XIAO P, XIAO Y et al. State-of-the-art review of biogeotechnology and its engineering applications [J].Journal of Civil and Environmental Engineering, 2019, 41(01):1-14.

[12] ZHANG R F, WANG X, FAN H M et al. Study on the regionalization of freeze-thaw zones in China and the erosion characteristics [J]. Science of Soil and Water Conservation, 2009,7 (02): 24-28.

[13] FANG L L, QI J L, MA W. Freeze-Thaw Induced Changes in Soil Structure and Its Relationship with Varitions in Strength [J]. Journal of Glaciology and Geocryology, 2012,34 (02):435-440.

[14] ZHENG Y, MA W, BING H. Impact of freezing and thawing cycles on structure of soils and its mechanism analysis by laboratory testing [J]. Rock and Soil Mechanics, 2015, 36 (05) : 1282-1287+1294.

[15] ZHAI J B, ZHANG Z, MELNIKOV A, et al. Experimental Study on the Effect of Freeze—Thaw Cycles on the Mineral Particle Fragmentation and Aggregation with Different Soil Types[J]. Minerals,2021,11(9):913-913.

[16] ZHAO L Q, YANG G S, WU D et al. Micro Structure and Fractal Characteristics Loess under Freeze-thaw Cycles [J]. Chinese Journal of Underground Space and Engineering, 2019, 15 (06): 1680-1690.

[17] LONG J H, ZHANG L L, XING X L et al. Study on strength and microstructure of loess under freeze-thaw based on temperature path [J]. Coal Geology & Exploration, 2021,49 (04):242-249.

[18] YANG X L, HE W S, LIU S K. Effect of freezing-thawing Cycle on Shear Strength of Undisturbed Unsaturated Loess and Its Microscopic Interpretation [J]. Water Resources and Power, 2022,40(09): 194-197.

[19] CUI H H, QIN X P, WANG W T et al. Effect of Freeze-thaw Cycle on SWCC and Strength of Unsaturated Silty Clay [J]. Chinese Journal of Underground Space and Engineering, 2020， 16(06):1722-1728+1745.

[20] LIU Z, XIAO S M, LIU F F, et al. Experimental Study on Influence Factors of Anti-Wind Erosion and Anti-Dust for Construction Debris Cemented by MICP [J]. Industrial Construction, 2022,52(11):71-78.

[21] WANG L, XIE X Q, SU W et al. Changes of maximum and minimum temperature in northern China over the second half of the 20th century [J]. Journal of Natural Resources, 2004(03):337-343.

[22] Nanjing Forestry University. China Forestry Dictionary [M]. Shanghai Scientific and Technical Publishers, 1994.

[23] WANG Y Q. Study on blown dust characteristics of PM10 and PM2.5 from bare agricultural soils based on wind tunnel experiment [D]. Tianjin Normal University, 2019.

[24] LU Y M, WU B F, YAN N N, et al. Quantifying the Contributions of Environmental Factors to Wind Characteristics over 2000-2019 in China[J]. ISPRS International Journal of Geo-Information,2021,10(8):515-515.

[25] ZHOU H, ZHANG Z, QIN Q, et al . Research on variability of basic physical properties of loess under freeze-thaw cycles [J]. Journal of Glaciology and Geocryology, 2015, 37 (01): 162-168.