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Research Article

Comparison of Mechanical Properties and Sensitivity of Compressive and Flexural Strength of Artificial Frozen Sand

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Some zones of freezing curtains of subway contact channels are subjected to compression and tension. Thus, understanding the mechanical properties and relationship between the compressive and flexural strengths of frozen soil is crucial. In this regard, this study considered sandy soil from Fuzhou as an example to perform uniaxial compressive and three-point flexural strength tests under different moisture content and curing conditions. The results showed that the uniaxial compressive and three-point flexural strengths of frozen soil were directly correlated with the moisture content and inversely correlated with curing temperature. Moreover, the compressive strength was significantly higher than the flexural strength, and the ratio was between 1.68 and 3.41. The sensitivity analysis for two factors affecting the strength was performed using the grey correlation analysis method. The moisture content showed a stronger effect on the uniaxial compressive strength of frozen sand. In contrast, the curing temperature substantially affected the three-point flexural strength. This study provides a reference for optimizing the freezing scheme for subway connection channels.

1. Introduction

Artificial freezing is a technique that uses artificial refrigeration technology to freeze water in the soil, thereby increasing the strength and stability of the soil and isolating the soil from groundwater. This process further forms an impermeable freezing curtain with good integrity and high strength to develop geotechnical constructions under freezing curtain protection. Artificial freezing has been widely used in coastal soft soil layer reinforcement. However, in-depth research on the mechanical properties of artificially frozen soil is required to determine the mechanical properties and stability of frozen curtains.

Firstly, Tritovitch et al. determined, via the uniaxial compressive strength test, that the compressive strength of frozen sand increased when the temperature decreased [1]. Recently, Cai et al. and Sun et al. discussed the relationship between the uniaxial compressive strength of frozen soil and moisture content and temperature. These authors reported that the compressive strength increased when the moisture content increased and increased when the temperature decreased. In particular, Sun et al. also proposed that the strength of artificially frozen soil has a peak value when the moisture content changes at the same temperature level [2–4]. Moreover, Wang et al. evaluated the unconfined compressive strength of frozen soils. The authors observed that the elastic modulus of the remolded frozen soil was negatively correlated with the freezing temperature [5]. Zhang et al., Zhou et al., and Yu et al. successfully performed triaxial compression tests on frozen rock and soil. The experimental results showed that different freeze-thaw cycles had different effects on the strength of frozen rock and soil, and the stress-strain curve of frozen rock and soil under different initial freezing temperatures also differed [6–8]. Huang et al., Gao et al., and Cui et al. analyzed uniaxial compressive strength test results of frozen soil using the grey correlation analysis approach. These studies discovered that moisture content and freezing temperature substantially affected the uniaxial compressive strength, and the temperature was inversely correlated with compressive strength [9–11]. Liu et al., Jia et al., and Liu et al. studied the flexural strength of frozen soil under different moisture contents and different temperatures. The results showed that the flexural strength of artificially frozen soil was inversely proportional to the temperature and proportional to the moisture content [12–15]. Wu et al. observed the average compressive and flexural strength of silty clay and silty sand at −10°C [16]. Subsequently, Huang et al. and Zhao et al. evaluated the compressive and flexural strength characteristics of frozen soil and frozen rock at different temperatures. Their results showed that the temperature effect of compressive strength of the same frozen soil is more evident than that of flexural strength [17, 18].

However, most studies have focused on the mechanical properties of frozen soil at home and abroad. These studies have mainly focused on analyzing the compressive properties of frozen soil, and less attention has been paid to the flexural strength of frozen soil [19–25]. Due to the combined action of the upper and lateral earth pressure, in the subway contact channel using the freezing method to reinforcement, the arch of the formed freezing curtain is in compression, while the side wall is in tension. Thus, studying both compression and flexural fracture strength of frozen soil is crucial. In this regard, this study establishes a relationship between compressive and flexural strength of frozen sandy soil; a typical sandy soil stratum in the Fuzhou area was considered in the study. The relationship between the compressive and flexural strengths of frozen sand was established by conducting compressive and flexural strength tests at different temperatures and moisture contents. Simultaneously, the sensitivity of different factors to frozen soil was also studied. This study can lay the foundation for designing and developing artificial freezing methods for reinforcement projects in the Fuzhou area.

2. Mechanical properties test of artificial frozen sand

2.1. Test Scheme. The mechanical properties test of artificial frozen sand was conducted on a custom-made frozen soil comprehensive test system using an ETM205D microcomputer-controlled. The system can perform a uniaxial compressive test and flexural strength test of frozen soil by replacing the loading pressure head, as seen in Figure 1. The axial load of the test system can reach 200 KN with an accuracy of ±1.0%. The temperature range varies between −40 and 150°C with a fluctuation of ±0.2°C. The test load and deformation data can be automatically collected by setting parameters, and the stress-strain curve can be obtained in real time. The test was performed by strain controlled loading. In particular, the test considered that it could be stopped when the force reaches the peak value or stabilizes. If the force value continues to increase, the test can be stopped when a specified strain is reached or is greater than 25%.

The compressive and flexural strengths of artificial frozen sand are affected by numerous factors. In this study, two influencing factors of curing temperature (−10°C, −15°C, and −20°C) and moisture content (12%, 15%, and 18%) were selected for the experiments. Each of the two experiments was divided into nine groups; each considered three samples for 54 valid data. The test process was numbered; "*C#a-b*" and "*F#a-b*" were used to represent the compressive test and flexural strength test, respectively. Moreover, "*a*" was used to represent the group number and "*b*" was used to represent the test sequence in each group. If the difference between the maximum and minimum compressive (flexural) strength of the three samples and the intermediate value exceeded 15% of the intermediate value, the test of this group was repeated.

2.2. Specimen Preparation. The test sand samples were from Fuzhou Metro Line 4. In this study, the mechanical properties of remolded soil samples at low temperatures were studied. The diameter and height of the uniaxial compressive strength specimen dimension were 50 mm and 100 mm, respectively. The three-point flexural specimen dimensions were 400 mm × 100 mm × 100 mm. Following the "Artificial Frozen Soil Physics Mechanics Performance Test" (MT/T593-2011), the sandy soil was first dried for 8 h at 105–120°C. Subsequently, the sandy soil was pulverized, placed in the shaking sieve machine, and fed through a 2-millimeter sieve to remove foreign materials. After that, the soil was configured and mixed thoroughly according to the moisture content of 12%, 15%, and 18%. Finally, the material was placed into a mold coated with three layers of Vaseline (Mingde Medical, Shandong province, China) on average, compacted in layers, and chiseled. The sample with the mold was placed into a presetting curing temperature environment for constant temperature curing for 6 h and subsequently sealed with plastic film to maintain it for 18 h. The compressive and flexural strength test samples of frozen soil are shown in Figure 2.

2.3. Data Processing. When calculating the uniaxial compressive strength, the cross-sectional area of the sample must be corrected. The calculation method is as follows:

$$A_a = \frac{A_0}{(1 - \Delta h/h_0)}, \tag{1}$$

where A_a is the sample cross-sectional area after calibration in mm^2, A_0 is the sample cross-sectional area before the test in mm^2, Δh is axial deformation in mm, and h_0 is the sample height before the test in mm.

The calculation method of the uniaxial compressive strength of frozen soil is as follows:

$$\sigma = \frac{F}{A_a}, \tag{2}$$

where σ is the uniaxial compressive strength in MPa, F is the maximum axial load in N, and A_a is the section area of the corrected sample in mm^2.

The calculation method of the three-point flexural strength of frozen soil is as follows:

$$f_f = \frac{Pl}{bh^2}, \tag{3}$$

(a) Uniaxial compression test fixture (b) Three point flexural test fixture

Figure 1: Loading pressure head of the frozen soil test system.

(a) Uniaxial compressive strength test (b) Three point flexural strength test

Figure 2: Mechanical property test sample of artificial frozen soil.

where f_f is the flexural strength in MPa, P is the tested maximum axial load in N, l is the bearing spacing in mm, b is the section width of the specimen in mm, and h is the section height of the sample in mm.

2.4. Test Results. The test results regarding the mechanical properties of artificially frozen soil at different moisture contents and temperatures were analyzed. The uniaxial compressive strength and three-point flexural strength of frozen soil under the action of two factors are shown in Table 1.

3. Factors Affecting the Mechanical Properties of Artificial Frozen Sand

3.1. Effect of the Moisture Content on the Mechanical Properties of Artificial Frozen Sand. Further analysis of the test results listed in Table 1 shows that the moisture content affects the mechanical properties of artificially frozen sand soil, as shown in Figure 3. Moreover, the increase in the mechanical property index of artificially frozen soil in different moisture content zones was calculated. The results are listed in Table 2.

Figure 3 shows that the uniaxial compressive and three-point flexural strengths of frozen soil under different curing temperature conditions increase with the water content. Moreover, they are all positively correlated. The results in Table 2 indicate that when the moisture content increases from 12% to 15%, the three-point flexural strength of frozen soil increases by 38.8% under the condition of −10°C. Furthermore, the uniaxial compressive and three-point flexural strengths of frozen soil under other conditions increased significantly, both higher than 73.5%. When the moisture content increased from 15% to 18%, the three-point flexural strength of frozen soil increased significantly at −10°C, reaching 76.4%. However, the uniaxial and flexural strengths under other conditions increased by less than 28.4%.

3.2. Effect of Curing Temperature on Mechanical Properties of Artificially Frozen Sandy Soil. The effects of curing

Table 1: Test results of mechanical properties of artificial frozen soil.

Moisture content (%)	Curing temperature (°C)	No.	Compressive strength (MPa)	Mean value (MPa)	No.	Break off strength (MPa)	Mean value (MPa)
12	−10	C1#-1	3.00	3.17	F1#-1	1.05	1.16
		C1#-2	3.23		F1#-2	1.19	
		C1#-3	3.27		F1#-3	1.23	
	−15	C2#-1	3.06	3.57	F2#-1	1.46	1.63
		C2#-2	3.60		F2#-2	1.69	
		C2#-3	4.04		F2#-3	1.75	
	−20	C3#-1	3.79	4.24	F3#-1	1.94	2.06
		C3#-2	4.45		F3#-2	2.03	
		C3#-3	4.47		F3#-3	2.21	
15	−10	C4#-1	5.41	5.50	F4#-1	1.47	1.61
		C4#-2	5.52		F4#-2	1.59	
		C4#-3	5.56		F4#-3	1.78	
	−15	C5#-1	6.37	6.87	F5#-1	3.49	3.77
		C5#-2	7.04		F5#-2	3.82	
		C5#-3	7.21		F5#-3	3.99	
	−20	C6#-1	10.37	10.79	F6#-1	5.28	5.65
		C6#-2	10.80		F6#-2	5.73	
		C6#-3	11.20		F6#-3	5.95	
18	−10	C7#-1	6.02	6.15	F7#-1	2.73	2.84
		C7#-2	6.07		F7#-2	2.82	
		C7#-3	6.35		F7#-3	2.97	
	−15	C8#-1	8.12	8.27	F8#-1	4.43	4.84
		C8#-2	8.26		F8#-2	4.83	
		C8#-3	8.42		F8#-3	5.26	
	−20	C9#-1	10.73	10.83	F9#-1	5.90	6.44
		C9#-2	10.83		F9#-2	6.56	
		C9#-3	10.92		F9#-3	6.87	

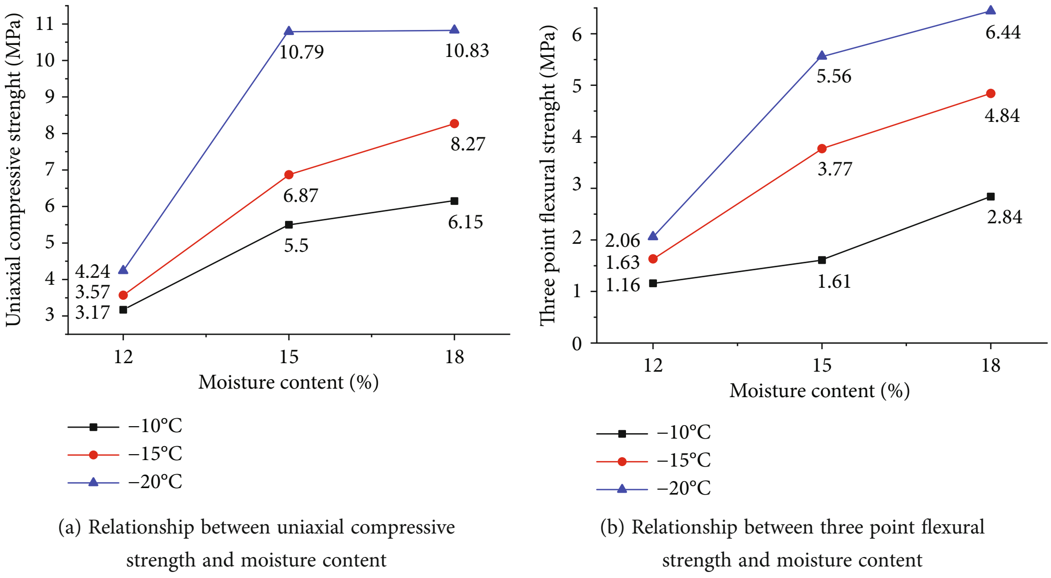
temperature on the mechanical properties of artificially frozen sandy soil can be derived by further analyzing the test results listed in Table 1, as shown in Figure 4. In addition, the increase in the mechanical properties of artificially frozen soil in different curing temperature ranges can also be calculated. The results are shown in Table 3.

As observed in Figure 4, the uniaxial compressive and three-point flexural strengths of permafrost under different moisture content conditions increase with decreasing temperature and are inversely correlated. The results listed in Table 3 show that while the temperature increment in flexural strength fluctuates, the effect is mostly reflected in the range from −10°C to −15°C. In contrast, the uniaxial compressive strength slightly fluctuates.

3.3. *Comparison between the Compressive and the Flexural Mechanical Properties of Artificial Frozen Sand.*

If φ is considered as the compression ratio of frozen soil, then, $\varphi = \sigma / f_f$. In particular, the compression ratio of frozen soil under different conditions can be determined, as shown in Table 4.

The results listed in Table 4 show that under the same external factors, the compressive strength of frozen sand is significantly higher than the flexural strength, and the compression-flexural ratio φ is between 1.68 and 3.41. For a curing temperature higher than −15°C and moisture content lower than 15%, the compression ratio of frozen soil is greater than 2.0. Moreover, for a curing temperature lower than −15°C and moisture content higher than 15%, the compression ratio of frozen soil is slightly less than 2.0. In this case, the curing temperature and moisture content affect the compression ratio of frozen soil. Comparing the failure modes of frozen soil in the two tests (see Figure 5), the compressive strength test of frozen soil results in a shear failure and the flexural strength test of frozen soil in a tensile failure. The failure mode for the two tests differs significantly. As the ice crystals in frozen soil are anisotropic, under tensile stress, the pore cracks in frozen soil will rapidly expand and become wider, resulting in fracture. Under the action of compressive stress, cracks in frozen soil tend to seal and are difficult to rupture.



(a) Relationship between uniaxial compressive strength and moisture content

(b) Relationship between three point flexural strength and moisture content

Figure 3: Effect of the moisture content on mechanical properties of artificial frozen sand.

Table 2: Percentage increase of mechanical properties of artificial frozen soil with different moisture contents.

Curing temperature (°C)	Increased percentage of compressive strength in different intervals (%)		Percentage increase of flexural strength in different intervals (%)	
	Moisture content 12%~15%	Moisture content 15%~18%	Moisture content 12%~15%	Moisture content 15%~18%
−10	73.5	11.8	38.8	76.4
−15	92.4	20.4	131.3	28.4
−20	154.5	0.4	174.3	14.0

4. Sensitivity Analysis Based on Grey Correlation Analysis

The essence of gray correlation analysis is to determine whether a series of curves are closely related to each other based on the similarity of their geometric shapes. That is, the closer the curves are, the greater the correlation between the corresponding series and vice versa. Therefore, grey correlation analysis can be used to quantitatively analyze several factors affecting a complex system, provide the correlation degree of each factor, and determine major and minor factors. The specific approach is to normalize the original observation data of the evaluation index, calculate the correlation coefficient and degree, and finally rank the evaluation index according to the magnitude of the correlation degree.

4.1. Dimensionless Series. The reference sequence reflecting the characteristics of the system behavior should be determined. Moreover, the comparison sequence affecting the system behavior before performing gray correlation analysis on the test results should be determined. The average values of the uniaxial compressive and three-point flexural strengths of permafrost were used as the reference series, i.e.,

$$Y = \{Y(k), k = 1, 2, \cdots, n\}. \tag{4}$$

Considering each significant factor listed in Table 2 to form a comparative series, i.e.,

$$X_i = \{X_i(k), k = 1, 2, \cdots, n\}, \quad i = 1, 2, \cdots, m. \tag{5}$$

Here, k is the level number, i is the factor sequence, $n = 9$, and $m = 2$.

The usual methods used for dimensionless processing include equalization, initialization, and inversion. In this study, the initial value method was used to analyze the factors affecting the uniaxial compressive and flexural strengths of permafrost. The method can provide the sequence X_i after priming, i.e.,

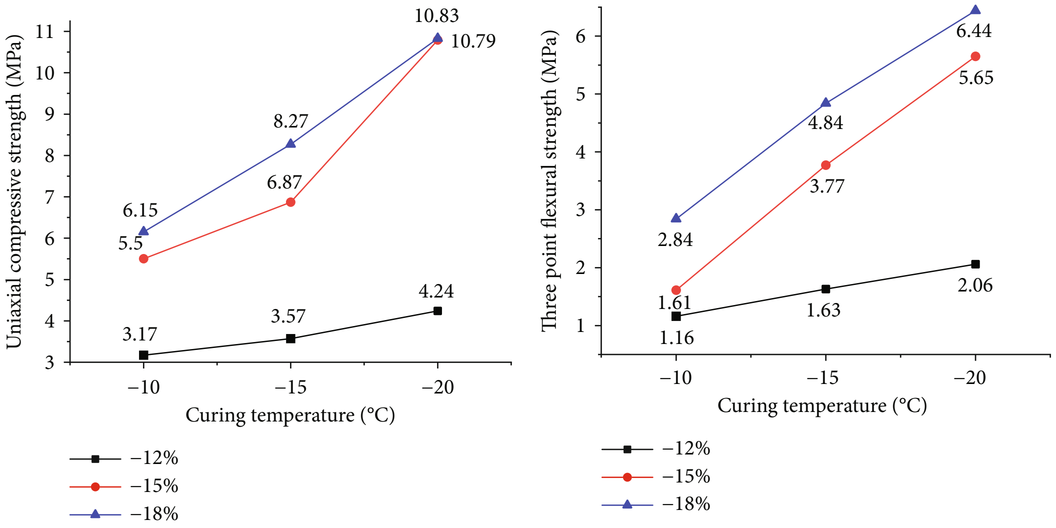
$$X_i^0 = \frac{X_i}{x_i(1)} = \left(x_i^0(1), x_i^0(2), \cdots, x_i^0(n)\right). \tag{6}$$

4.2. Grey Correlation Calculation. The absolute difference series is obtained from the test results, i.e.,

$$\triangle_i(k) = |y(k) - x_i(k)|, \quad k = 1, 2, \cdots, n\,; i = 1, 2, \cdots, m. \tag{7}$$

The maximum absolute difference M and the minimum absolute difference m are obtained simultaneously, i.e.,

$$M = \max_i \max_k \Delta_i(k), \quad m = \min_i \min_k \Delta_i(k). \tag{8}$$



(a) Relationship between uniaxial compressive strength and curing temperature

(b) Relationship between three point flexural strength and curing temperature

Figure 4: Effect of the water content on mechanical properties of artificially frozen sandy soil.

Table 3: Percentage of the increase in mechanical properties of artificial frozen sand at different curing temperatures.

Moisture content (%)	Increased percentage of compressive strength in different intervals (%)		Percentage increase of flexural strength in different intervals (%)	
	Curing temperature −10°C to −15°C	Curing temperature −15°C to −20°C	Curing temperature −10°C to −15°C	Curing temperature −15°C to −20°C
12	12.6	18.8	40.5	26.4
15	24.9	57.1	134.2	49.9
18	34.5	31.0	70.4	33.1

Table 4: Compression ratio of frozen soil under different influencing factors.

Curing temperature (°C)	−10			−15			−20		
Moisture content (%)	12	15	18	12	15	18	12	15	18
Compressive to flexural ratio	2.74	3.41	2.16	2.18	1.82	1.71	2.06	1.91	1.68

(a) Uniaxial compression

(b) Three point flexural

Figure 5: Failure mode of specimen.

Table 5: Uniaxial compressive strength correlation coefficient results.

No.	$\gamma_{01}(k)$	$\gamma_{02}(k)$
1	1	1
2	0.90	0.74
3	0.76	0.62
4	0.69	0.59
5	0.54	0.62
6	0.33	0.43
7	0.71	0.53
8	0.49	0.49
9	0.36	0.43
Relevance	0.64	0.61

Table 6: Three point flexural strength correlation coefficient results.

No.	$\gamma_{01}(k)$	$\gamma_{02}(k)$
1	1	1
2	0.83	0.96
3	0.72	0.90
4	0.94	0.84
5	0.50	0.54
6	0.36	0.41
7	0.68	0.58
8	0.43	0.43
9	0.33	0.36
Relevance	0.64	0.67

Subsequently, the gray correlation coefficients of $y(k)$ and $x_i(k)$ are obtained as follows:

$$\gamma_{0i}(k) = \frac{m + \zeta M}{\Delta_i(k) + \zeta M}. \quad (9)$$

Considering that the orthogonal test has uniform dispersion characteristics, ζ was set to 0.5 for calculation and analysis to improve the significant difference between the correlation coefficients.

Calculate the correlation degree as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \gamma_{0i}(k). \quad (10)$$

4.3. Sensitivity Analysis of Influencing Factors. In this study, $i = 1$ corresponds to the moisture content and $i = 2$ corresponds to the freezing temperature. After the dimensionless processing of Table 1, the correlation coefficients of each series were obtained using equations (7)–(9) and the correlation degree of each series was obtained using equation (10). The results are listed in Tables 5 and 6.

The results listed in Tables 5 and 6 show that the correlation between the two influencing factors, as discussed before, and the compressive strength is higher than 0.5 (50%). These results indicate that all of the above factors significantly affect the uniaxial compressive strength of frozen sandy soils. The correlation between uniaxial compressive strength and moisture content is 0.64, whereas the correlation between uniaxial compressive strength and temperature is 0.61, indicating that the moisture content has a relatively strong effect on uniaxial compressive strength results. The correlation between three-point flexural strength and temperature is 0.67, while the correlation between flexural strength and moisture content is 0.64, indicating that temperature is the primary factor affecting flexural strength.

5. Conclusions

This study conducted uniaxial compressive and three-point flexural strength tests on frozen sandy soils from the Fuzhou, China, region. Moreover, gray correlation analysis was used to assess the sensitivity of factors affecting the compressive and flexural strengths of frozen sandy soil. The following findings were obtained:

(1) The uniaxial compressive and three-point flexural strengths of frozen sandy soil showed an increasing trend with increasing water content. That is, both showed positive correlations. The strength changes were mainly obtained for 12–15% water content. The strength increased with decreasing temperature with inverse correlations. Particularly, the strength changes occurred for −10°C and −15°C

(2) The compressive strength of frozen sand was significantly greater than the flexural strength, and the compressive flexural ratio φ was affected by both the curing temperature and water content, ranging from 1.68 to 3.41

(3) The effect of the water content on the uniaxial compressive strength of frozen sandy soil was stronger than the curing temperature. However, the opposite effect occurred on the three-point flexural strength test

Data Availability

The data required has been included in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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