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Uniaxial Compressive Strength of the Saturated Frozen Silt at Constant Strain Rates

(饱和冻结粉土在常应变速率下的单轴抗压强度)

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Abstract: Uniaxial compressive strength tests were conducted on the saturated frozen Lanzhou silt (loess) at various constant strain rates and at various constant temperatures. It is concluded from the test results that: the compressive strength (σ_f) is very sensitive to temperature (θ) and increases with the temperature decreasing as a power law. Compressive strength is sensitive to strain rate ($\dot{\varepsilon}$) and increases with strain rates increasing within a certain range of strain rates as a power law. Compressive strength decreases when time to failure (t_f) increases, also following a power law. Finally, Compressive strength of frozen silt with higher dry density (γ_d) is higher than that of frozen silt with lower dry density. The difference between them is mainly influenced by strain rate.

Key words: the saturated frozen silt; compressive strength; constant; strain rate

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1 Introduction

Compressive strength is one of the major mechanical properties of frozen soil and an important basis for designing foundations in cold regions. Many studies on the compressive strength of frozen soil have been conducted. Early in 1930, Tsytovich[1], a founder of mechanics of frozen ground in Russia, conducted uniaxial compress tests on frozen sand at various temperatures and at various stress rates, and found that the compressive strength of frozen sand increases with stress rate increasing and temperature decreasing. Afterwards many famous researchers in geocryology had studied the compressive strength of frozen soil, such as Vialov[2] and Ladanyi *et al.*[3]. In China, Wu Ziwang *et al.*[4,5]. firstly tested the uniaxial compressive strength of frozen sand, and found that it related to temperature, stress rate and water content. Thereafter Zhu Yuanlin *et al.*[6~11]. in detail studied on the uniaxial compressive strength of frozen sand, and proposed that the compressive strength closely relates to strain rate, time to failure and temperature, and established quantitative relations among them. Li Hongsheng[12] *et al.* investigated the sensitivity of compressive strength to strain rate for frozen silty loam, and found that strain rate and temperature are vital factors in affecting compressive strength. They divided the sensitivity into three different levels from low to

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high with the strain rate changing, and set up a strength models with strain rate and temperature as variables for frozen silty loam.

Many researchers have studied compressive strength for frozen sand and frozen clayey soil, but few tests were conducted on compressive strength of frozen silt. The uniaxial compressive strength of saturated frozen silt (Lanzhou loess) at constant strain rate and at constant temperature was investigated in this paper.

2 Experimental

2.1 Specimen preparation

The soil used in this experiment was remolded Lanzhou silt (loess). Process of preparing specimens is as follows. Firstly distilled water was added to air-dried soil to make initial water content of 12% by weight. Then the soil was put in a cylindrical gang mold with diameter of 61.8mm and compacted to the desired dry density (1.76 $g \cdot cm^{-3}$ and 1.58 $g \cdot cm^{-3}$ in this test). These specimens were then saturated with deaerated, distilled water under a vacuum of 73 mm Hg (the corresponding saturated water content is 15.5 and 24.5%). After saturation they were quickly frozen from top to bottom in a freezing cabinet. Then the specimens were taken out from the molds after freezing and machined to 150 mm in length.

2.2 Experiment methods

Firstly, the prepared specimens were kept at the same temperature as the test for 12 hours in a constant temperature cabinet. Then it was placed on screw-driven universal material testing machine to perform uniaxial compressive tests at constant deformation rate. Data taker automatically recorded axial load and deformation in the course of compression. Computer calculated the stress and strain, and plotted the corresponding stress-strain curves at last. Density and water content of the specimen were measured after test. The density and water contents reported in the paper is the averaged value.

3 TEST RESULTS

The test results are listed in Table 1.

4 Discussion

4.1 $\sigma_m - \theta$ Relationship

The curves of compressive strength against temper-ature for the frozen silt with different dry densities at various strain rates are shown in fig. 1 and fig. 2. From the figures we can see that compressive strength is very sensitived to temperature and it strongly increases with temperature descending. By regression analysis, their relationship can be described by:

$$\sigma_m = K(\theta/\theta_0)^h \tag{1}$$

where θ is native temperature (℃), $\theta_0 = -1$ ℃ is a reference temperature, K and h are parameters. The values of K and h are listed in table 2. From the table, it is clear that the parameter h is almost not related to temperature, strain rate and dry density. And it's averaged values is 0.7182. However, K is closely related to strain rate.

4.2 $\sigma_m - \dot{\varepsilon}$ Relationship

Fig. 3 and fig. 4 show the relationship between comp-ressive strength and strain rate at various temperatures for the frozen silt with different dry densities. From the figures, it s clear that compressive strength generally increases with strain rate increasing in a power law within a certain range of strain rate.

By regression anlysis, the relation between compressive strength and strain rate in a certain range of strain rate can be expressed by

$$\sigma_m = A(\dot{\varepsilon}/\dot{\varepsilon}_0)^m$$

where: $\dot{\varepsilon}$ is strain rate (s^{-1}), $\dot{\varepsilon}_0 = 1$ s^{-1} is a reference strain rate, A and m are parameters. The values of A and m are listed in table 3.

From Table 3, it's clear that m is almost not related to temperature. In the range of temperature from -15 to -2 ℃, the average values of m are 0.059 and 0.098 for the frozen silt with dry density of 1.76 $g \cdot cm^{-3}$ and 1.58 $g \cdot cm^{3}$, respectively. However, A is closely related to temperature. By regression, their relation can be described by

$$A = \sigma_0(\theta/\theta_0)^i \tag{3}$$

Table 1　Test results of uniaxial compressive strength for frozen silt

No.	Strain rate /s^{-1}	Strength /MPa	Time to failure /min	No.	Strain rate /s^{-1}	Strength /MPa	Time to failure /min
			$\gamma_d=1.76\ g\cdot cm^{-3}$, $W=15.5\%$				
	Temperature= −2 ℃				Temperature= −5 ℃		
LS-316	6.45×10^{-4}	2.50	1.08	LS-344	6.52×10^{-4}	4.69	1.45
LS-322	6.48×10^{-4}	2.53	1.10	LS-346	6.57×10^{-4}	4.69	1.50
LS-313	9.76×10^{-5}	2.30	7.00	LS-345	9.96×10^{-5}	4.17	7.23
LS-324	9.77×10^{-5}	2.20	6.33	LS-347	1.01×10^{-4}	4.09	8.33
LS-314	8.56×10^{-6}	1.65	58.00	LS-348	7.70×10^{-6}	3.56	71.00
LS-317	8.58×10^{-6}	1.82	53.00	LS-352	$8.09\ 10^{-6}$	3.60	62.00
LS-321	1.06×10^{-6}	1.65	390.00	LS-349	1.05×10^{-6}	3.33	530.00
LS-323	$1.07\ 10^{-6}$	1.48	420.00	LS-350	1.06×10^{-6}	3.32	510.00
LS-325	5.20×10^{-7}	1.71	1 150.00	LS-351	5.12×10^{-7}	3.37	1 000.00
LS-326	5.34×10^{-7}	1.65	1 020.00	LS-353	4.81×10^{-7}	3.28	973.00
	Temperature= −10 ℃				Temperature= −15 ℃		
LS-354	6.29×10^{-4}	7.60	1.65	LS-384	6.74×10^{-4}	9.85	2.55
LS-358	6.30×10^{-4}	7.22	1.76	LS-391	6.63×10^{-4}	9.97	2.60
LS-355	9.37×10^{-5}	6.84	9.43	LS-388	1.02×10^{-4}	9.22	14.05
LS-357	9.66×10^{-5}	6.56	9.58	LS-389	1.11×10^{-4}	9.27	12.81
LS-356	8.79×10^{-6}	5.75	87.00	LS-385	8.72×10^{-6}	7.90	125.00
LS-359	8.16×10^{-6}	5.37	88.00	LS-387	8.75×10^{-6}	7.88	125.00
LS-360	1.03×10^{-6}	4.96	615.00	LS-383	1.06×10^{-6}	7.10	610.00
LS-364	1.05×10^{-6}	5.44	630.00	LS-386	1.05×10^{-6}	7.42	800.00
LS-361	$5.06\ 10^{-7}$	5.47	1 200.00	LS-392	5.16×10^{-7}	7.48	1 900.00
LS-362	4.95×10^{-7}	5.81	1 240.00	LS-393	5.45×10^{-7}	7.43	2 130.00
			$\gamma_d=1.58\ g\cdot cm^{-3}$, $W=24.5\%$				
	Temperature= −2 ℃				Temperature= −5 ℃		
LS-327	7.64×10^{-4}	2.32	5.15	LS-335	7.38×10^{-4}	4.05	5.12
LS-331	7.45×10^{-4}	2.14	5.20	LS-338	7.46×10^{-4}	4.19	5.15
LS-328	1.12×10^{-4}	1.63	29.50	LS-337	1.14×10^{-4}	3.25	31.80
LS-330	1.08×10^{-4}	1.67	29.40	LS-339	1.11×10^{-4}	3.20	31.70
LS-329	$9.26\ 10^{-6}$	1.38	255.00	LS-340	9.54×10^{-6}	2.47	269.00
LS-332	9.65×10^{-6}	1.31	273.00	LS-342	9.44×10^{-6}	2.42	231.00
LS-333	1.12×10^{-6}	1.17	1 790.00	LS-336	1.11×10^{-6}	2.12	1 800.00
LS-334	1.11×10^{-6}	1.08	1 450.00	LS-341	1.10×10^{-6}	2.14	1 620.00
	Temperature= −10 ℃				Temperature= −15 ℃		
LS-371	7.09×10^{-4}	6.75	5.40	LS-375	7.40×10^{-4}	8.65	4.80
LS-367	7.11×10^{-4}	6.58	5.51	LS-378	7.03×10^{-4}	8.34	4.00
LS-368	1.05×10^{-4}	5.36	34.00	LS-374	1.14×10^{-4}	7.06	32.70
LS-369	1.09×10^{-4}	5.61	30.60	LS-377	1.13×10^{-4}	7.13	28.80
LS-366	$9.53\ 10^{-6}$	4.36	300.00	LS-376	1.00×10^{-5}	5.90	302.00
LS-370	9.28×10^{-6}	4.27	306.00	LS-379	9.43×10^{-6}	5.58	264.00
LS-372	1.11×10^{-6}	3.58	1 370.00	LS-380	1.14×10^{-6}	5.06	2 170.00
LS-373	1.05×10^{-6}	3.36	1 720.00	LS-381	1.15×10^{-6}	4.62	2 160.00

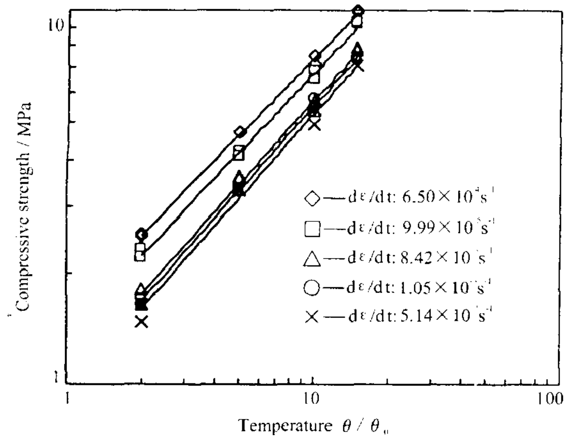

Fig. 1 Compressive strength vs. temperature
(γ_d=1.76 g·cm^{-3}, W=15.5%)

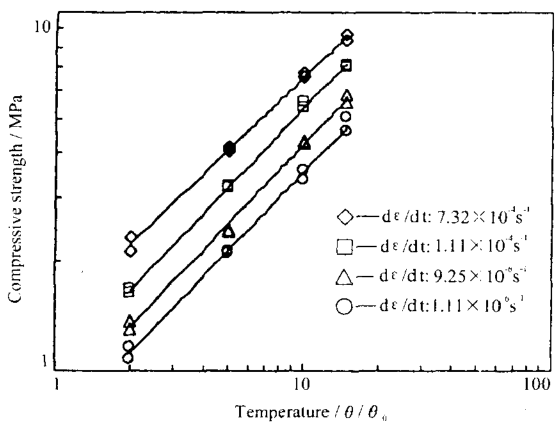

Fig. 2 Compressive strength vs. temperature
(γ_d=1.58 g·cm^{-3}, W=24.5%)

Table 2 Values of K and h in eq. (1)

Strain rate/s^{-1}	K/MPa	h
γ_d=1.76 g·cm^{-3}, W=15.5%		
6.50×10^{-4}	1.53	0.6992
9.99×10^{-5}	1.37	0.6971
8.42×10^{-6}	1.05	0.7396
1.05×10^{-6}	1.01	0.7433
5.14×10^{-7}	0.95	0.7455
γ_d=1.58 g·cm^{-3}, W=24.5%		
7.32×10^{-4}	1.41	0.6690
1.11×10^{-4}	1.00	0.7306
9.52×10^{-6}	0.80	0.7274
1.11×10^{-6}	0.68	0.7185

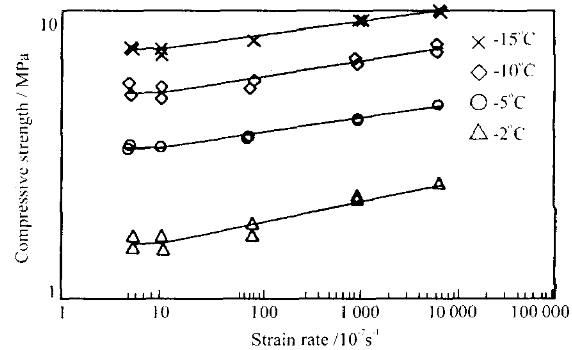

Fig. 3 Compressive strength vs. strain rate
(γ_d=1.76 g·cm^{-3}, W=15.5%)

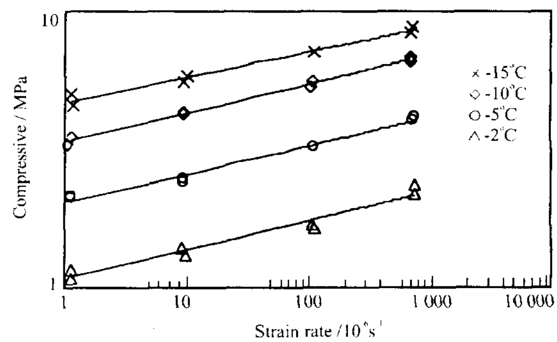

Fig. 4 Compressive strength vs. strain rate
(γ_d=1.58 g·cm^{-3}, W=24.5%)

Table 3 Vlaues of A and m in eq. (2)

θ /℃	γ_d= 1.76 g·cm^{-3} W = 15.5%		γ_d= 1.58 g·cm^{-3} W = 24.5%	
	A/MPa	m	A/MPa	m
−15	14.396	0.050	15.818	0.087
−10	10.876	0.053	13.782	0.100
−5	6.858	0.054	8.396	0.103
−2	4.496	0.078	4.432	0.102

where: σ_0 is the compressive strength as $\theta=-1$ ℃ and $\dot{\varepsilon}1$ s^{-1}, and the value of which has no relation with dry density and equals to 2.896. i is a parameter related to dry density, and it's value is 0.578 and 0.648 for frozen silt with dry density 1.76 g·cm^{-3} and 1.58 g·cm^{-3}, respectively.

Combining Eqs(2) and (3), the compressive strength can be evaluated by the following model according to $\dot{\varepsilon}$ and θ:

$$\sigma_m = \sigma_0(\theta/\theta_0)^i(\dot{\varepsilon}/\dot{\varepsilon}_0)^m \quad (4)$$

If take the values of parameters into Eq. (4), then we get the following models:

For the satured frozen silt with dry density of

1.76 g.cm^{-3}($\dot{\varepsilon}\geqslant 1.1\times10^{-6}$ s^{-1}),

$$\sigma_m = 2.896(\theta/\theta_0)^{0.578}(\dot{\varepsilon}/\dot{\varepsilon}_0)^{0.059} \quad (5)$$

For frozen silt with dry density of 1.58 g · cm^{-3},

$$\sigma_m = 2.896(\theta/\theta_0)^{0.648}(\dot{\varepsilon}/\dot{\varepsilon}_0)^{0.098} \quad (6)$$

4.3 $\sigma_m - t_f$ Relationship

Compressive strength against time to failure in logarithm for frozen silt with different dry densities at various temperatures is plotted in fig. 5 and fig. 6, respectively. From the two figures, it can be seen that compressive strength decreases with time to failure increasing also following a power law within a certain range of the time to failure.

By regression analysis, in a certain range of the time to failure, their relationship can be written as:

$$\sigma_m = B(t_f/t_{f0})^{-n} \quad (7)$$

where: $t_{f0}=1$ min is a reference time to failure, B and n are parameters and their values are listed in table 4.

Table 4 Vlaues of *B* and *n* in eq. (7)

θ/℃	γ_d= 1.76 g · cm^{-3} W = 15.5%		γ_d= 1.58 g · cm^{-3} W = 24.5%	
	B/MPa	n	B/MPa	n
−15	10.525	0.056	9.698	0.091
−10	7.633	0.063	8.146	0.114
−5	4.716	0.059	4.875	0.116
−2	2.555	0.085	2.584	0.116

From table 4, the value of n has no relation to temperature for the frozen silt with same dry density. In the range of test temperature, the average value of n is respectively 0.066 and 0.109 for γ_d= 1.76 g · cm^{-3} and 1.58 g · cm^{-3} respectively. B is closely related to temperature. By regression, their relation can be expressed by

$$B = \sigma_0'(\theta/\theta_0)^j \quad (8)$$

where: σ_0' is the compressive strength at $\theta=-1$ ℃ and $t_f=1$ min, and j is parameter. In the test conditions, for the frozen silt with dry density of 1.76 g · cm^{-3} and 1.58 g · cm^{-3}, σ_0' is 1.557 and 1.644, and j is 0.698 and 0.672, respectively.

Combining Eqs. (7) and (8), the compressive strength model for frozen silt can be expressed as follows:

$$\sigma_m = \sigma_0'(\theta/\theta_0)^j(t_f/t_{f0})^{-n} \quad (9)$$

Taking the values of parameters into eq. (9), this model can be expressed as:
for frozen silt with dry density of 1.76 g · cm^{-3},

$$\sigma_m = 1.557(\theta/\theta_0)^{0.698}(t_f/t_{f0})^{-0.066} \quad (10)$$

for frozen silt with dry density of 1.58 g · cm^{-3},

$$\sigma_m = 1.664(\theta/\theta_0)^{0.672}(t_f/t_{f0})^{-0.109} \quad (11)$$

4.4 $\sigma_m - \gamma_d$ Relationship

According to the test results, compressive strength of the saturated frozen silt with higher dry density is higher than that of the frozen silt with lower dry density at same strain rate and same temperature. The difference betwene the two compressive strengthes with different dry densities is divided by the compressive strength of frozen silt with lower dry density at the same strain rate and temperature is defined as increasing rate of strength R_σ, expressed by percentage. The increasing rate of strength against strain rate at various temperatures is plotted in figure 7. From this figure, it can be seen that the increasing rate decreases whith strain rate increasing. Their relationship can be expressed by

$$R_\sigma = \log(1/\dot{\varepsilon})^h + k \quad (12)$$

where: h and k are parameters, and in the test conditions, they have the values of 5.059 and −21.098.

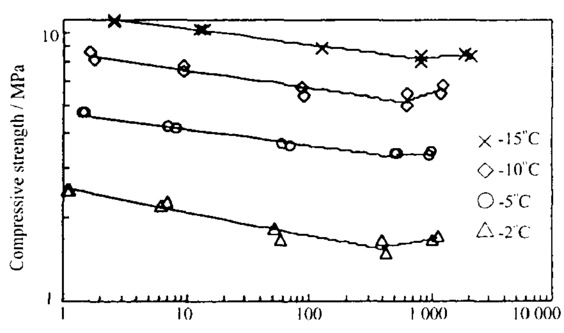

Fig. 5 Compressive strength vs. time to failure
(γ_d=1.76 g · cm^{-3}, W=15.5%)

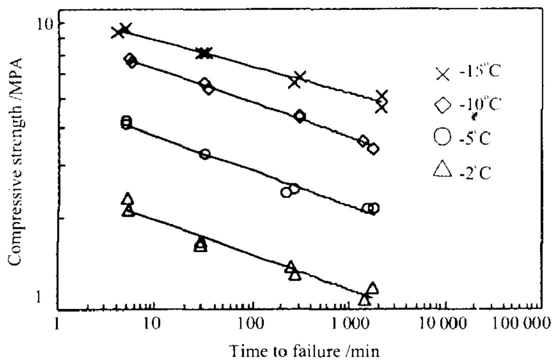

Fig. 6 Compressive strength vs. time to failure ($\gamma_d = 1.58\ g \cdot cm^{-3}$, $W = 24.5\%$)

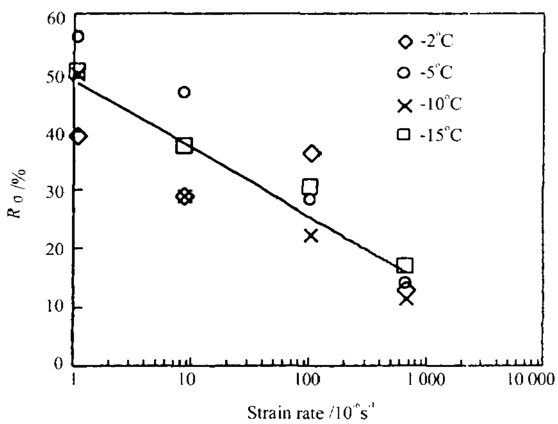

Fig. 7 Increasing rate of strength vs. stra n rate

5 Conclusions

It can be concluded from this investigation that:

(1) Compressive strength of the saturated frozen silt is quiete sensitive to temperature and strain rate. It can be evaluated by the follow ng model according to temperature and strain rate in a certain range of strain rate:

$$\sigma_m = \sigma_0 (\theta/\theta_0)^i (\dot{\varepsilon}/\dot{\varepsilon}_0)^m$$

(2) Compressive strength of the satt rated frozen silt decreases with time to failure increasing also in a power law. In a certain range of time to failure, the strength model, with time to failure and temperature as variables, can be written as:

$$\sigma_m = \sigma_0{}' (\theta/\theta_0)^j (t_f/t_{f0})^{-n}$$

(3) At the same strain rate and temperature, compressive strength of the saturated frozen soil with higher dry density is higher than that of the frozen silt with lower dry density. The increasing rate of strength R_σ is mainly influenced by strain rate. Their relations can be described by

$$R_\sigma = \log(1/\dot{\varepsilon})^h + k$$

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