Frozen Loess Mechanical Behavior Based on Structural Characteristics

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ABSTRACT

The structural characteristics is a basic attribute of soil, which has a strong influence on engineering properties of soil. The effect of structural characteristics on the mechanical properties of frozen loess has been investigated. Based on triaxial compression tests of remolded frozen loess and artificial structured frozen loess with different content of cement, this paper studied how the confining pressure, initial water content, temperature and the cement amount had influenced the frozen loess' strength behavior. The experimental results showed that in the same experiments, there were some differences of the stress-strain relationship between the unsaturated and saturated frozen loess. The temperature and confining pressure were the main important factors that influenced the shearing strengths of frozen soil. The lower the temperature is, the higher the failure strength is. The shearing strengths of unsaturated frozen loess are increasing with confining pressure, but that of saturated frozen loess has little relationship with confining pressure. The initial water content is another main factor affecting the frozen loess strength. As the increase of water content, the frozen loess strength is also increasing, but there is a peak point. After it the frozen loess strength would decrease gradually with the water content increasing, and the strength of saturated frozen loess reached the lowest. With regard to the unsaturated frozen loess, the yield strength and failure strength are both increasing with the content of cement. For the saturated frozen loess, the yield strength is increasing with the content of cement, too. However, the failure strength has little relationship with the cement content. The mentioned factors have obvious influence on the structural characteristics of frozen loess, but the cement content and water content are the dominating factors. The mechanical properties and structural characteristics of frozen loess depend on not only the single factor, such as confining pressure, initial water content, temperature and the cement amount etc., but also on possible interaction of the various factors. At last, the comprehensively structural coefficient M which correlates closely with parameters of shear strength was presented. By regression analysis, the exponential function relationship between M and c, as well as M and tan , were obtained, respectively. Moreover, the exponential functions were validated feasible.

KEYWORDS: Structural characteristics; Frozen loess; Artificial structured soil; Triaxial tests; Strength behavior

INTRODUCTION

The soil structural characteristics are how soil structures have interacted with mechanical properties under the action of external load (Kavvadas and Amorosi, 2000). Broadly speaking, any soil has its own unique structural characteristics, which is the basic attribute of soil and has a strong influence on engineering properties of soil. The structural characteristics of natural soil varies depending on its geologic forming and ambient environments, etc. The main factors controlling the structural characteristics are interference connection and arrangements of the soil particles, and the external environments such as water, temperature, humidity, weathering and load can change and even destroy the structural property. The soil constitutive model, as theory foundation of numerical computation in Geotechnical Engineering, must include the soil structural characteristics. Shen (1996) has thought that it is the central subject of soil mechanics to establish a structural mathematical model in the 21st century. As undisturbed soil and remolded soil possess their own structural features, they demonstrate different mechanical properties, and which has drawn the attention of many scientists in recent years.

As an compound multiphase medium, the strength property and deformation behavior of frozen soil not only relate directly to soil property, but also are intensively influenced by factors such as temperature and water content, which complicates any structure-related research on frozen soil. Through collecting the relative literatures, the study on frozen soil structural characteristics is rare both at home and abroad. And these researches have focused on micro/fine structure of remodeling frozen soil. But few studies have focused on structure evaluation through comparative analysis between undisturbed frozen and remolded soil. The microstructure is an important quality characteristic of soil. Early, by means of CT and SEM , the microstructure of frozen soil was tested and made many achievements(Wu et al., 1995; Wu et al., 1996; Wu et al., 1997; Miao et al., 1995; Shen et al., 1996; Xu et al., 2003). Qi et al. (2003) performed soil mechanics tests and SEM quantitative analysis on the saturated Lanzhou loess and Tianjin silty clay, and found that both mechanical properties and microstructure of the two soils are changed by freezing-thawing. Deng et al. (2008) investigated structural changes of saline soil during the freezing process, and the experimental result is that there existed some apparent differences in the internal structures of the samples due to different temperatures and saline soils. Based on different ways of freezing and sample preparation methods, Zheng et al. (2010) analyzed the microstructure of silty clay under load by CT.

The mechanical characteristics of natural soils are significantly affected by their structure. There are only a few people studying structure of the frozen soil by soil mechanics in the research. Based on the experiments in strength and creep, Yang (1996) discussed the differences of compression, tensile, shear strength and creep between original and disturbed frozen clays. According to the experiments, the strength and creep deformation of original frozen caly are lower and the modulus is larger as compared with that of disturbed frozen clay. The original frozen soil has roughly the same compressive strength as disturbed frozen soil, but the failure strain of original frozen soil is different from that of disturbed frozen soil in Lianghuai Regions (Wu et al., 1988). Li et al. (2003) showed that the compressive strength of the undisturbed frozen clay is slightly lower than that of the remolded frozen clay, and the elastic modulus of the former is slightly higher than that of the later. There are significant differences of the failure mode and failure strain between the undisturbed and remolded frozen clay. The undisturbed frozen clay usually takes on typical brittle failure character, and its failure strain is smaller. Whereas, the remolded frozen clay usually takes on typical ductile plastic failure character, and its failure strain is greater. He et al. (2003) explored the frozen soil structural characteristics and put forward the conception of the ice efficiency for the first time. The structure evolvement regularity of Aeolian soil in the western area of Liaoning Province during the period of freezing and thawing was studied under different moisture fields and different stress fields by using the ice efficiency as the structure parameter (Zhang et al., 2008). Huo et al. (2011) analyzed that the strength of the undisturbed frozen clay was higher than that of the remolded frozen clay, and the differences in elastic modulus may be due to temperature.

Currently, many researchers have analyzed the structure properties of loess and clay through soil mechanics. Moreover, the structural constitutive models are put forward, and which have been applied to numerical computation and geotechnical design. However, as far as frozen ground engineering is concerned, for example, it does not consider how the structure properties effect on the design of artificial freezing wall. The mechanics parameters of artificial frozen soil are used in many articles instead of those of undisturbed frozen soil because there are no related documents, which is not compatible with the actual conditions. Therefore, this paper will simulate the bonding strength between the particles of undisturbed soil by adding a little cement to remolded soil-that is to say, artificial structured soil. We study on frozen soil structure evaluation through comparative analysis based on undisturbed frozen (artificial structured soil) and remolded soil. This study will have complemented and enriched the structural theory of soil. Also, it will have developed and deepened frozen ground mechanics.

PREPARATION OF SPECIMENS AND TEST PROCEDURE

Specimen preparation

The test materials are Lanzhou loess, whose main physical parameters are listed in Table1. The water content and the dry unit weight of the natural soil were 9.06% and 1.69 g/cm3, respectively. Cylindrical specimens nominally with 61.8 mm in diameter and 125 mm in length were prepared by packing a split copper mold. There are two types of sample: (1) pure loess sample (remolded soil) ; (2) Composite sample consisted of loess and ordinary Portland cement (artificial structured soil) . The specimen preparation is shown in Table 2. And the saturated soil samples are obtained by pumping.

Table 1: The basic physical properties of Lanzhou loess

Soil type	Composition of grains(%)				Liquid limit(%)	Plastic limit(%)
	>0.5	0.5-0.05	0.05-0.005	<0.005		
Lanzhou loess	6.10	16.35	51.34	26.21	24.6	16.2

Table 2: The specimens preparation

Water content	8%	16%	Saturation
Cement content	0%	0%	0%
	2%	2%	2%
	5%	5%	5%

Test procedure

All specimens were carried out the triaxial shear test under different temperature and initial confining pressure. The test pattern is axis-symmetry (namely), with the test temperatures of -3

℃ and -10 ℃, respectively. And the confining pressures are 1MPa, 3MPa, 5MPa, respectively. The axial deformation was automatically measured by axial pressure system monitoring the changes of axial displacement, and the data were collected continually by the computer. The test procedure consists of three stages: (1) freezing the specimens for 24h, and then adjusting the temperature to a certain test degree (-3 ℃ and -10 ℃) and keeping the temperature more than 24 h; (2) consolidating the specimens for 2h under the corresponding test temperature and confining pressures(1MPa, 3MPa and 5MPa), and (3) performing the axial loading tests until the specimen failure. During the entire experiment, the shear rate has remained 1.25mm/min. When the axial strain reaches 20%, the specimen is considered to be destroyed.

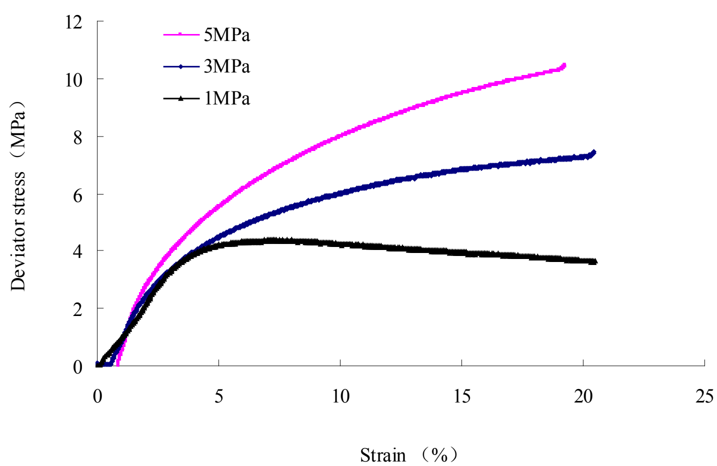
RESULTS AND ANALYSIS

The strength of frozen soil varies according to soil types, temperature, moisture content, confining pressure and other factors. There in no obvious shear broken surface in destroyed specimens, which look like drums (Figure 1). The shearing process is analyzed as follows.

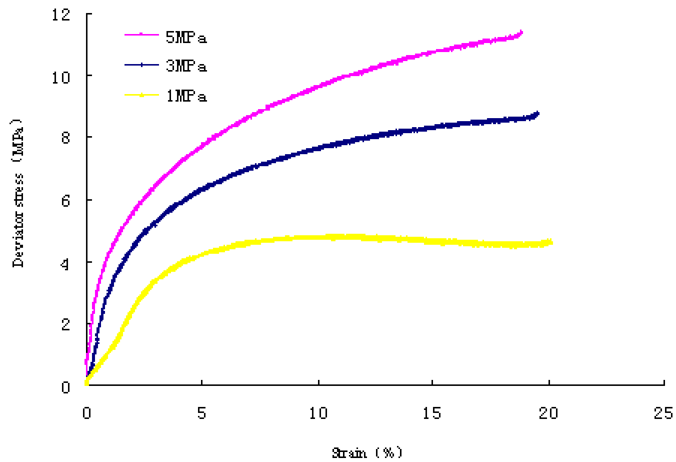
Figure 1: The related photos of this experiment

The confining pressure versus stress–strain

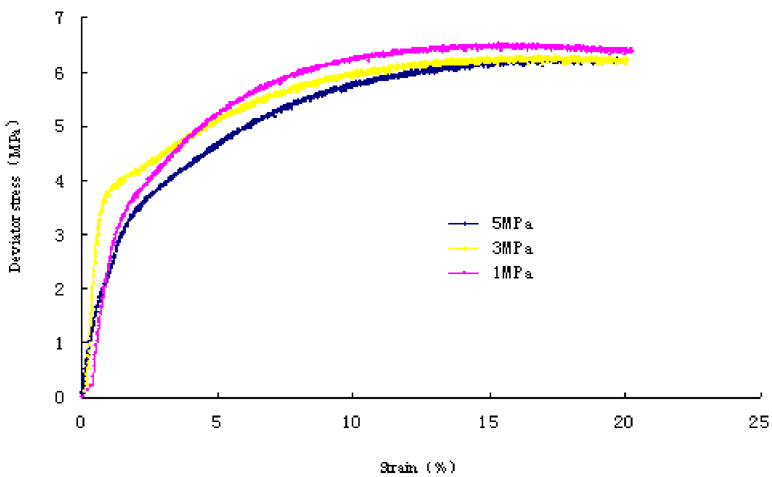
Here, we take the consolidation-end-confining pressure as the confining pressure σ_3, and the deformation does not include the section which happened in the period of consolidating. When the cement content is 2% and at the temperature of -10℃, a series of axial loading test results of different water content with confining stress varying from 1 to 5MPa is shown in Figure 2. These curves present the changes of the deviator stress ( ) versus axial strain ε1. It can be seen, there are obvious differences between unsaturated specimens and saturated specimens with regard to their stress–strain curves. For the unsaturated specimens, the stress–strain curves appear to be hyperbolical in shape under higher confining pressure (3MPa and 5MPa). But under both lower confining pressure (1MPa) and lower water content (8%), the stress–strain curves appear weak softening. And under the same confining pressure (1MPa), the stress–strain characteristic is analogous to ideal elastic - plastic material when the water content is 16%. Based on the analysis of yield and failure of materials, it is concluded that the two conceptions are different, and they are two different steps in the deformation process of materials. Initial yield is a symbol of materials to first enter into plastic state from elastic state, and it is the upper limit of materials′ elastic deformation. So yield is the dividing point of elastic state and plastic state. However, failure is the final result of plastic process, and it is the limit state that plastic deformation can arrive, showing materials′ limit deformation ability. It is not definite for materials to fail after being yielded, because there is a plastic deformation process between yield and failure (Gao et al., 1994). And according to the studying method on the material stress–strain behavior in the material mechanics (Sun et al., 1994; Wang et al., 2004), supposing the point corresponding to maximum inflexion point represents the yield point of frozen soil, which is also the corner point of curves, the deviator stress that corresponds to this point is the yield strength of frozen soil. When the axial strain reaches 20%, the deviator stress is considered to the failure strength. In view of these, the other factors being kept constant, with the confining pressure increasing the yield strength and failure strength of frozen soil increases, and the stress–strain curves gradually begin the transition from weak softening to hyperbolical. This is because under the effect of external loads all elements beyond the strain - softening region were always in a state of strain hardening. However, for the all saturated specimens, on all occasions the stress–strain curves show hardening. The stress-strain behavior is affected by confining pressure which has changed the soil particles arrangement. In this experiment, how the confining pressure effects on soil strength is affected by water content. For unsaturated specimens, the higher the confining pressure , the higher the failure strength. For saturated specimens, that the confining pressure influences over failure strength is small. Also, it can be found that the strain appears not to be affected by the increase of deviator stress when the stress is less than the yield strength. But when the stress goes beyond the yield strength, there is a big increment in deformation under a little increment of the deviator stress. Through a study of other cases, the same conclusions have been reached.



(a) The water content is 8%



(b) The water content is 16%

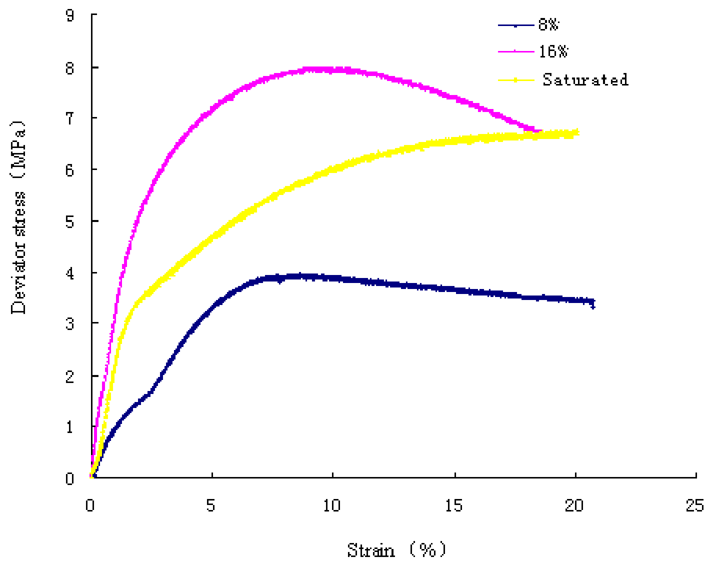


(c) The water content is saturated

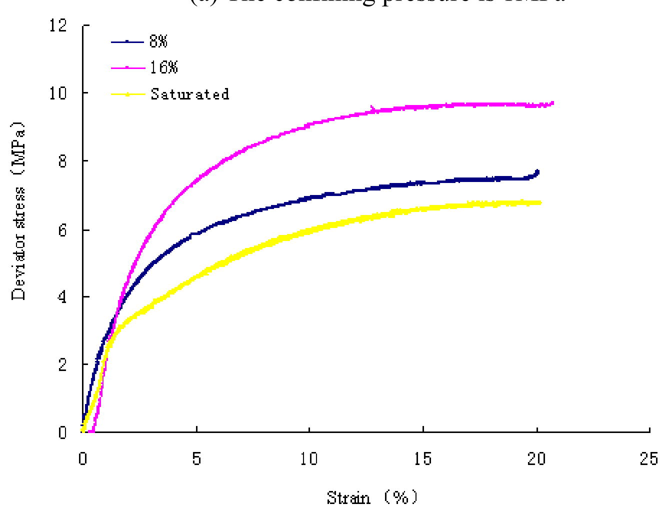
Figure 2: Stress–strain curves under different confining pressures at -10℃

The water content versus stress–strain

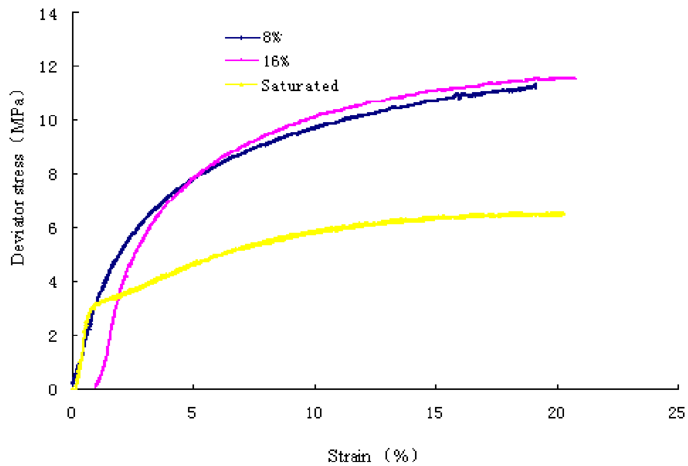
The strength of frozen soil depends on the join strength among soil particles as well as the join strength between soil particles and ice. Ice content or initial water content and dry density are the factors that contro1 the strength of unsaturated frozen soil. The greater the dry density is, the greater the load—bearing area of soil particles is, and the greater the strength of frozen soil will be. For a given dry density, the more the ice content is, the greater the strength of frozen soil is under unsaturated conditions. Figure 3 shows the stress-strain curves of frozen loess under different water contents and at -10 ℃ with confining pressure of 1MPa, 3 MPa and 5 MPa, respectively. It can be seen, the frozen loess strength of 16% water content is the maximum, and the saturated frozen loess strength is the minimum under the same confining pressure. The frozen loess strength of 8% water content is between these two extremes. Specimen of other conditions shows the same law. Our findings are consistent with literature (He et al., 2002): the unsaturated frozen soil strength increases with the initial water content increasing and there exists peak, and after the peak which decreases with the initial water content increasing. The water content of peak strength is often uncertain. The frozen soil strength depends on the ice content. The initial water content reflects the ice content and the ice binding degree among soil particles. The pore which can not initially bear load has been filled by ice and can bear load. Ice and soil particles are joined to bear shear load. Therefore, under the same initial water content and dry density, the greater the ice content is, the greater the strength of unsaturated frozen soil will be. Under saturated condition, the lower the dry density is, the lower the strength of frozen soil will be. Eventually the frozen soil strength will be tending towards the ice strength, and the dry density is seen as zero.



(a) The confining pressure is 1MPa



(b) The confining pressure is 3MPa



(c) The confining pressure is 5MPa

Figure 3: Stress–strain curves under different water content at-10℃

The temperature versus stress–strain

Temperature is one of the major factors that influence on the stability and strength of frozen soil. It not only decides the formation or thaw of frozen soil but decides the mechanical characteristic as well. Figure 4 shows the stress-strain curves of frozen soil containing 2% cement and 16% water content with confining pressure of 3 MPa under different temperature. We could see the two curves are both hyperbolas, and the lower the temperature, the higher the failure strength. The same conclusion has been arrived at through the other experiments. The specimen presents the properties of a rigid body. These results were caused by the action of temperature and confining pressure. The unfrozen water content and ice content in frozen soil is affected heavily by the temperature change. The unfrozen water content decreases with the temperature declining, while the ice content increases, which strengthen the bonding strength between ice and particles of soil, and further improve the capability of resistance to deformation. Therefore, the specimen, under lower temperature, presents that the deformation will not increase or has a little increment with the increasing stress. For the role of initial confining pressure in the present tested range, many studies manifested that the strength of the frozen soil increases with the increasing initial confining pressure (Wang et al., 2004).

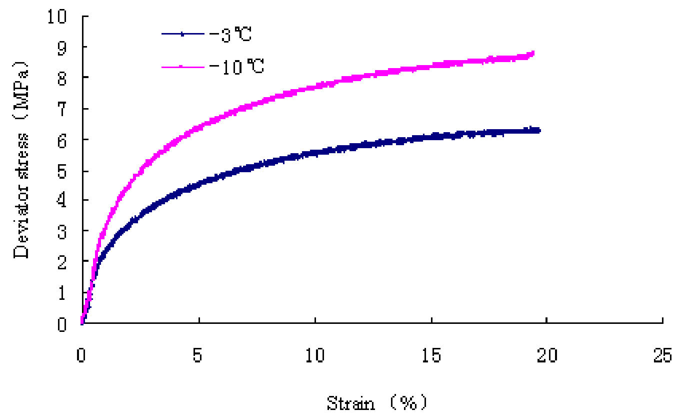
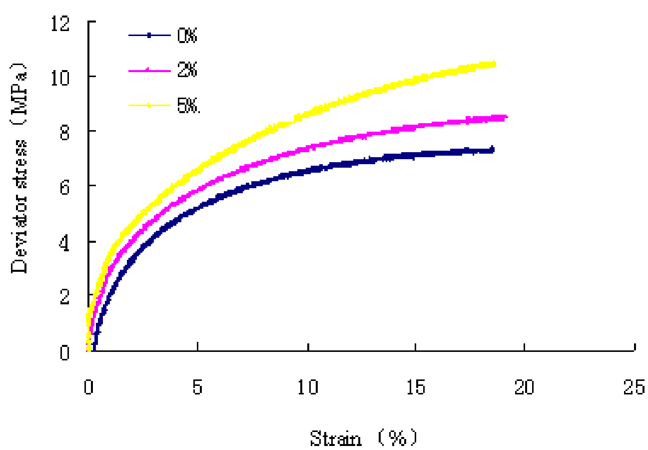


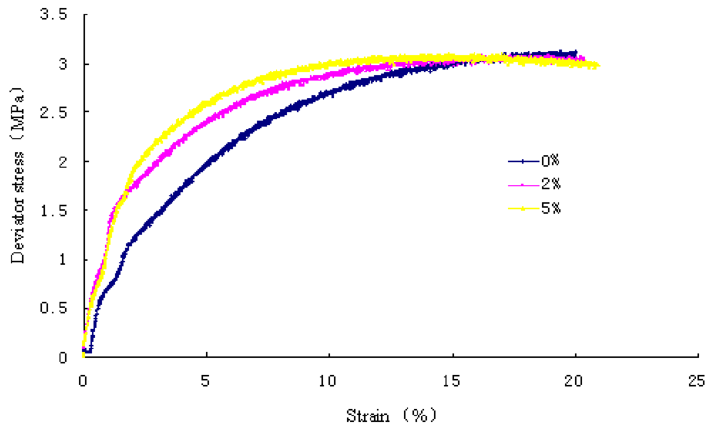
Figure 4: Stress–strain curves under different temperatures

The cement content versus stress–strain

Certain cement incorporated into soil has changed the structure of soil and leads to the variation of soil strength. As far as frozen soil is concerned, the cement not only has changed arrangement and connection of soil particles, but also has made a great impact on the bonding strength between ice and soil particles. Figure 5 gives the stress-strain curves at -3℃ with confining pressure of 5 MPa and the water content is 16% and saturated, respectively. It can be seen, there are obvious differences between unsaturated specimens and saturated specimens with regard to their stress–strain curves. For the unsaturated specimens, in the same conditions, the larger the cement content is, the greater the strength of frozen soil is. And the stress–strain curves obviously appear to be hyperbolical in shape. The yield strength and failure strength both increases with cement content. However, with regard to saturated specimens, the cement content has great influence on the yield strength. And the cement content has no effect on the failure strength. Water content is closely related with the frozen soil structure. The strength of saturated frozen soil is mainly carried by ice, so which have little relationship to the structure. Especially, when the dry density is lesser, the strength of frozen soil will be smaller. Eventually the frozen soil strength will be tending towards the ice strength.



(a) The water content is 16%



(b) The water content is saturated

Figure 5: Stress–strain curves under different cement content at -3℃

PARAMETERS OF SHEAR STRENGTH

The soil structure includes shape, size and distribution of particles and the connection of particles. The mechanical characteristics of natural soils are significantly affected by their structure. Considering the particularities of frozen soil, its structure may include arrangement and connection between soil particles and ice particles, which has made a great impact on the bonding strength between ice and soil particles. Based on physical - mechanical properties of frozen soil, temperature is an important factor in controlling its strength. By changing water forms in soil, including the conversion between liquid and solid, temperature takes the soil strength in this way. Therefore, both temperature and water content interactively influence in the soil strength.

At a higher temperature, the water in soil exists in state of liquid. Liquid against external force is very small, and in this case, the load was placed on the soil particles. At a lower temperature, the water develops into ice. The compressive strength of ice reaches 0.3~5.5MPa. So the strength of soil is increasing with the increase in ice. On the other hand, there is volume expansion when water turns into solid ice, which makes soil pore become smaller. From a connection of particles standpoint, the bonding strength between ice and soil particles has an advantage over that between water and soil particles. Therefore, as the water turns into ice the soil structure becomes strong and the soil strength increase. From the above analysis, we can see that the mechanical properties and structural characteristics of frozen loess mainly depend on initial water content, temperature, the cement amount and dry density. Laying a lot of emphasis on these four factors and analyzing the experimental data, we found there is a good correlation between the four factors and the strength parameters of frozen soil. Accordingly, a synthetic parameter M which characterizes parameters of shear strength is put forward.

$$\mathrm{M}=\rho_d \frac{100+c_a}{100}\,\omega\,\mathrm{T} \tag{1}$$

where, ρ_d -dry density, c_a -the cement content, ω - initial water content, T- temperature absolute value.

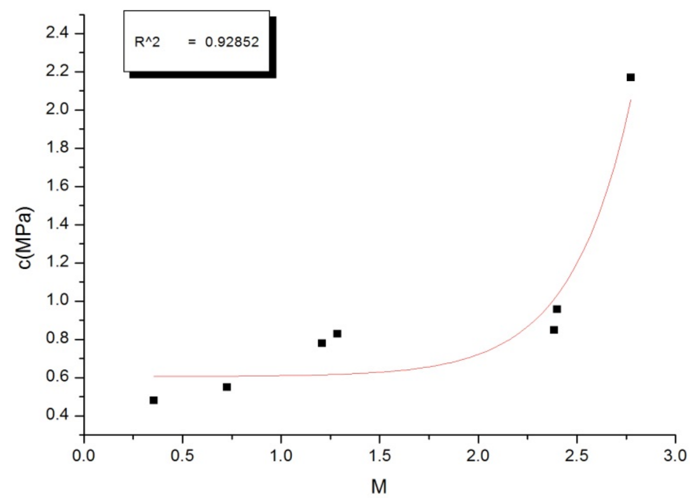


Figure 6: The relationship between c and M

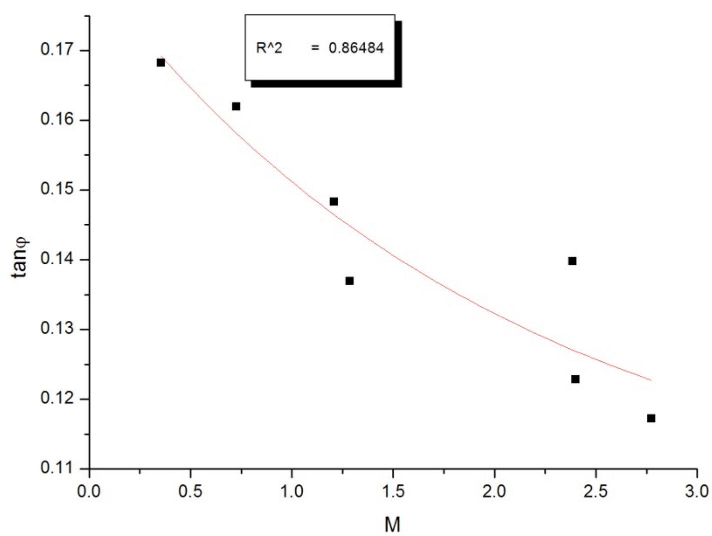


Figure 7: The relationship between $\tan\varphi$ and M

According to the mechanics of frozen soil and based on the experimental data, the relationships between C (or tan) and M can be described as an exponential function, which are shown as shown in Figure 6 and in Figure 7. Moreover, the regressions are as follows. Table3 gives the comparison between the calculated values and experimental results. Compared with the experimental results, the theory shows a good agreement and high precision.

$$c = 0.60573 + 0.00017e^{\frac{M}{0.3061}} \tag{2}$$

$$\tan\varphi = 0.10139 + 0.08032e^{-\frac{M}{2.09216}} \tag{3}$$

Table 3: Comparison between the calculated values and experimental results

Soil	*Confining pressure (MPa)*	*Cement content (%)*	*Water content(%)*	*Tempe-rature(℃)*	*Experimental results*		*Calculated values*	
					c(MPa)	$\tan\varphi$	c(MPa)	$\tan\varphi$
1	1.0	5	8.4	-10	0.83	0.136958	0.617103	0.144816
2	1.0	2	8.0	-10	0.78	0.14829	0.614589	0.146485
3	1.0	5	15.66	-3	0.5817	0.16195	0.607512	0.164349
4	5.0	2	8.0	-3	0.48	0.168227	0.606273	0.169155
5	3.0	5	15.66	-10	0.9577	0.122834	1.03937	0.126882
6	3.0	2	15.50	-10	0.8493	0.139789	1.01795	0.127071
7	3.0	0	16.9	-10	2.1711	0.117199	2.07626	0.122711
8	5.0	0	16.9	-3	0.5832	0.147613	0.60855	0.154638
9	3.0	2	16.75	-3	0.5741	0.15032	0.60805	0.156187
10	5.0	5	8.0	-3	0.5736	0.160938	0.606303	0.168626

CONCLUSION

(1) There are obvious differences between unsaturated specimens and saturated specimens with regard to their stress–strain curves. For the unsaturated specimens, the stress–strain curves appear to be hyperbolical in shape under higher confining pressure (3MPa and 5MPa). But under lower confining pressure (1MPa), the stress–strain curves appear weak softening and are analogous to ideal elastic - plastic material. However, for the all saturated specimens, on all occasions the stress–strain curves show hardening.

(2) For unsaturated specimens, confining pressure can enhance frozen loess anti-damage strength. But for saturated specimens, confining pressure only affected failure strength very weakly. And therefore, in the process of freezing wall design, the influence of the confining pressure can be neglected when the design pressures are in the scope of this study.

(3) For the unsaturated specimens, the larger the cement content is, the greater the strength of frozen soil is. And the stress–strain curves obviously appear to be hyperbolical in shape. The yield strength and failure strength both increases with cement content. However, with regard to saturated specimens, the cement content has great influence on the yield strength, and the cement content has no effect on the failure strength.

(4) The cement content and water content are the dominating factors which have obvious influence on the structural characteristics of frozen loess. The mechanical properties and structural characteristics of frozen loess depend on not only the single factor, such as confining pressure, initial water content, temperature and the cement amount etc., but also on the possible interaction between the mentioned factors.

(5) On the basis of the above, a synthetic parameter M which characterizes parameters of shear strength is put forward. By regression analysis, the relationships between c (or tan) and M can be described as an exponential function. Moreover, the functions are validated feasible, by

which the shear strength parameters of frozen loess can be better calculated. The equation may provide a dependable scientific basis for the construction of the project.

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