EVALUATION OF THERMAL EFFECTS AND STRAIN-RATE SENSITIVITY IN FROZEN SOIL

by

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Temperature variation is one important factor that affects the dynamic mechanical properties of frozen soil under impact loading. Thermal damage is a collective phenomenon that can be caused by temperature variation. This paper investigates the effects of thermal damage on strain course. A split Hopkinson pressure bar was employed to investigate the dynamic mechanical characteristics of frozen soil at different temperatures and different strain rates. The stress-strain curves were obtained under impact loading. The compressive strength of frozen soil showed a negative temperature sensitivity and positive strain-rate trend. Specifically, the strength of frozen soil increased with decreasing temperatures and increasing strain rates.

Key words: *thermal effect, compressive, temperature, yield, crack*

Introduction

Frozen soil is abundant in China. The permafrost area accounts for 23% of the territory, and seasonal frozen soil is widely distributed throughout the country. Studies of the mechanical properties of frozen soil are increasing in importance because of construction demands for more and more engineered facilities in cold regions.

Previous research has mainly focused on the static and quasi-static mechanical properties of frozen soil [1-3]. However, the dynamic mechanical properties have not been studied in detail yet, especially for high velocity impact loading conditions. Ma [4] and Chen [5] conducted preliminary research on impact mechanical properties of artificial frozen soil. They found that frozen soil has certain sensitivities for different strain rates and temperatures. Furthermore, researchers at the Sandia Laboratory [6, 7] studied impact mechanical properties of undisturbed frozen soil in Alaska under different stress states and obtained some preliminary results. However, so far, research on impact mechanical properties cannot be directly used to describe those of frozen soil. Hence, it is necessary to observe the dynamic mechanical behaviors of frozen soil experimentally and theoretically.

Temperature variation is one of the main factors that affect the strength of frozen soil. In this paper, we investigated the effects of temperature and strain rate on the strength of frozen soil. First, the theoretical relationship between thermal damage and strain course was derived. Then, impact experiments under passive confining pressure were conducted on fro-

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zen soil by using a split Hopkinson pressure bar. The dynamic stress-strain curves at different temperatures and different strain rates are reported in this paper.

Evaluation of thermal damage and strain course

There can be apparent temperature rises and volume changes in frozen soil under impact loading. The weakening strength of frozen soil caused by increases in temperature can lead to thermal damage. This can be shown from the Hugoniot curve, which has a complicated form for complex porous media such as frozen soil [8]. If each parameter can be determined from experiments, the dynamic properties of frozen soil can be presented clearly. However, the complicated nature of frozen soil has continued to puzzle researchers; therefore, a reduced form was applied to this thesis [9]:

$$P_H = \frac{\left(1-\dfrac{V}{V_0}\right)c_0^2}{\left[1-\lambda\left(1-\dfrac{V}{V_0}\right)\right]^2 V_0} \tag{1}$$

where V is the current specific volume, V_0 – the initial specific volume, and P_H – the Hugoniot curve. c_0 and λ are Hugoniot constants for the material and also represent actual measurement data for shock waves.

A second fundamental equation [9] was also applied:

$$\frac{1}{2}(V_0 - V)\mathrm{d}P + \frac{1}{2}P\mathrm{d}V = c_v\mathrm{d}T + \frac{\gamma}{V}c_v T\mathrm{d}V \tag{2}$$

where P is the impact load, T – the thermodynamic temperature, and c_v – the specific heat capacity.

The boundary conditions are $\theta = 1 - V/V_0$ and $[\theta, T] = [0, T_0]$.

The actual temperature is a function of specific heat capacity at a constant volume c_v and volumetric strain θ, and from eq. (1) and eq. (2), it can be formulated as:

$$T = T_0\mathrm{e}^{\gamma_0\theta} + \frac{c_0^2}{c_v}\mathrm{e}^{\gamma_0\theta}\int_0^\theta \frac{\lambda x^2}{(1-\lambda x)^3}\mathrm{e}^{-\gamma_0 x}\mathrm{d}x \tag{3}$$

where T_0 is the initial temperature and T – the current thermodynamic temperature.

Applying the Cauchy inequality to the integral part, we get:

$$\left[\int_0^\theta \frac{\lambda x^2}{(1-\lambda x)^3}\mathrm{e}^{-\gamma_0 x}\mathrm{d}x\right]^2 \le \left[\int_0^\theta \frac{\lambda x^2}{(1-\lambda x)^3}\mathrm{d}x\right]^2 \left(\int_0^\theta \mathrm{e}^{-\gamma_0 x}\mathrm{d}x\right)^2 \tag{4}$$

Considering the limit of such a weakening effect, it would be an upper bound:

$$T \approx T_0\mathrm{e}^{\gamma_0\theta} + \frac{c_0^2}{c_v}\sqrt{\frac{\mathrm{e}^{2\gamma_0\theta}-1}{2\gamma_0}\frac{\lambda^2\theta^5}{5(1-\lambda\theta)^5}} \tag{5}$$

The volume strain is equal to multiplex strain $\theta \approx k\varepsilon$. Supposing c_v is a constant, c_0 and λ can be determined by the Hugoniot curve, and the equation $T = F(\varepsilon)$ is obtained. The experiment was conducted at 255.15 K, and the $T-\varepsilon$ curve shown in fig. 1 describes the low bound and upper bound of such equations.

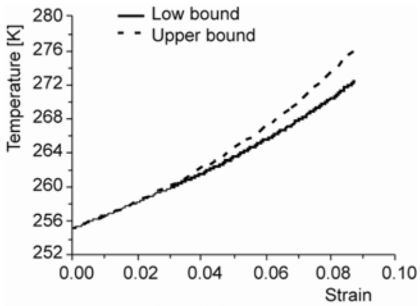

Figure 1. The Kelvin temperature interval of the experiment results

Experimental procedure

The material used in the impact compression experiments was a disturbed soil sample. The moisture content was 20%, and the bulk density was 1.6 g/cm^3. First, the sample was dried for 12 h in an oven at 105 °C prior to use. Following that, distilled water was added to produce a soil sample with a moisture content of 20%. The sample was then sealed and stored for 6 h to ensure uniform moisture content.

A 64.13 g sample of soil was compacted and placed into a device with an inner diameter of 45 mm. After compaction, an initial and original specimen of ∅ 45 × 21 mm was obtained and the bulk density was 1.6 g/cm^3. Then, by using a cutting ring, which was 30 mm in diameter and 18 mm in height, the original specimen was split. By removing the protruding parts from the two ends of the specimen, the final specimen size obtained was ∅ 30 × 18 mm. A thin layer of vaseline was applied to the specimen surface to prevent water evaporation. Each specimen was numbered. Then, the samples were placed into a refrigeration box and frozen at various temperatures for 24 h.

A split Hopkinson pressure bar apparatus was used in the frozen soil experiments under impact loading. In order to match the specimen (30 mm in diameter and 18 mm in length), the incident bar adopted used a variable cross-section bar with a right cone; the bar was 30 mm in diameter and 525 mm in length. The transmitted bar was 400 mm long. Strain gages were mounted on both the incident bar and transmitted bars. Based on one-dimensional stress wave theory and assumptions of homogeneity, the stress, strain, and strain rate were calculated by the classical two-wave method.

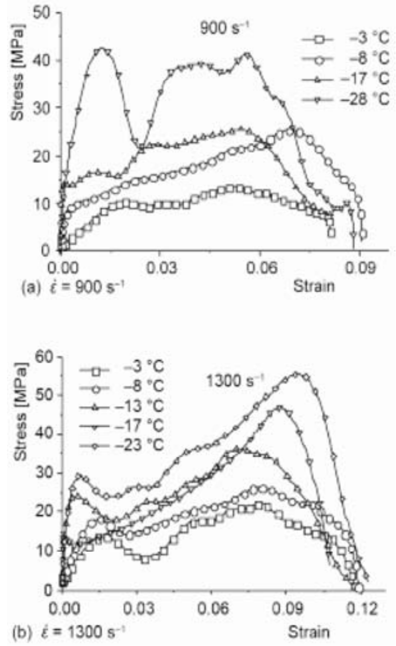

Figure 2. The dynamic stress-strain curves of frozen soil at different temperatures

Experimental results

Two different temperatures, –3 °C and –28 °C, were selected for analysis. At each of the different temperatures, the impact loading experiments were carried out for three to five different high strain rates. Again, all specimens were ∅ 30 × 18 mm in size. Because of the short dynamic loading time, we assumed that the process was adiabatic.

Temperature effect

In order to investigate the effects of temperature, the stress-strain curves of frozen soil under impact loading at different temperatures were determined; the results are shown in fig. 2.

At the same strain rate, the strength of frozen soil increased when temperatures decreased. Hence, the dynamic mechanical property of frozen soil exhibited a temperature effect. As temperatures decrease, the ice strength increases [10], and the cementation strength of ice and mineral particles increases as well. Thereby, the strength of frozen soil increases. All the curves demonstrated convergence behavior or showed a converging trend.

Strain rate effect of frozen soil

Figure 3 shows the stress-strain curves of artificial frozen soil under passive confining pressure at two different temperatures for different strain rates.

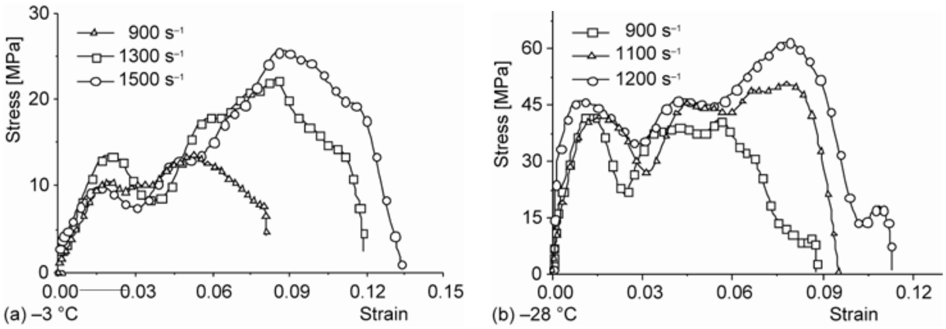

Figure 3. The dynamic stress-strain curves of frozen soil at different strain rates

When subjected to impact loading in passive confining pressure conditions, the specimens are in a one-dimensional strain state. The data presented in fig. 3 show that all stresses decreased as the strain approached 0.03. After that, the stresses rose again, and then fell after reaching a peak. Here, we define the peak stress reached before the stress started to decrease for the first time as the initial strength. The first time decreases observed in the stress-strain curves may have been caused by tiny gaps between the specimens and the mould. With continued loading, the specimens deformed. After reaching the initial strength, the stress began to fall. However, the gaps were not filled up then. When the gaps were filled up, the specimen was under a quasi-one-dimensional strain state, and its transverse deformation could be confined. Hence, as the internal holes collapsed, the specimens were consolidated. As depicted in the stress-strain curves, the stress then increased until a maximum value was reached. From the curves in fig. 3, it can be seen that artificial frozen soil shows an obvious strain rate effect. That is, the peak stress and the final strain increase uniformly with increasing strain rates.

In order to further investigate the strain rate effect, the relationship between peak stress and strain rate, as well as final strain and strain rate, are shown in fig. 4. In regards to the strain rate, both the peak stress and the final strain displayed linear trends. Albeit, the linear trends for the final strain were more significant than those of the peak stress, and all final stresses at different temperatures had rather consistent linear trends.

After impact loading, the specimens were compressed. Under these conditions, obvious damage did not appear and the specimens still had a relatively high strength. The specimens showed plastic behavior. The microscopic mechanism at work here is that as internal holes in the specimens collapsed, small cracks appeared on the partially cemented surface of ice and soil grains. Meanwhile, because of pressure-melting [11, 12], the process was accompanied by a local phase transformation, *i. e.* the melting ice was converted into water. This enabled the specimens to have plastic behavior.

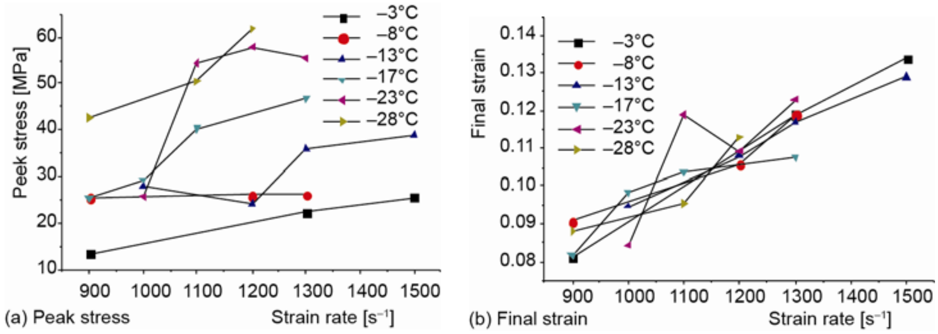

Figure 4. Relations between strain rate and peak stress, or final strain

When the strain rate was relatively low, the stress-strain curves were mostly at the same stress level. As the temperatures decreased, both the initial strength and the peak stress increased. Our results were somewhat different from previous research results [4, 5] in that the stress-strain curves for these experiments did not finally converge. The final strain and the peak stress basically increased with increasing strain rates. The amplitude of the stress pulse in the incident bar was proportional to the impact speed of a bullet. Therefore, the stress amplitude would be larger if the strain rate was larger.

Conclusions

- Temperature variation is one of the main factors that affect the strength of frozen soil. The weakening strength of frozen soil caused by rising temperatures can result in thermal damage. The results presented here describe the actions leading to thermal damage on the strain course in a precise manner.
- Frozen soil showed obvious temperature and strain rate effects. Its strength increased with decreases in temperature and increases in the strain rate. In addition, frozen soil did not show typical yield behavior at high strain rates.
- Under impact loading with passive confining pressure, stress resulted in decreases on the stress-strain curves. The length of the specimens significantly decreased, the radial dimension slightly changed, and the specimens showed no obvious signs of damage after impact compression.

Acknowledgments

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References

[1] Zhao, S. P., *et al.*, Recent Progress and Suggestion in the Research on Dynamic Response of Frozen Soil, *Journal of Glaciology and Geocryology, 24* (2002), 10, pp. 681-685
[2] Qi, J. L., Ma, W., State-of-Art of Research on Mechanical Properties of Frozen Soils, *Rock and Soil Mechanics, 21* (2010), 1, pp. 133-143
[3] Ma, Q. Y., Research Status of Dynamic Properties of Artificial Frozen Soil and Its Significance, *Rock and Soil Mechanics, 20* (2009), 1, pp. 10-14

[4] Ma, Q. Y., Study on the Dynamic Mechanical Properties of Frozen Soil under Impact Loading, Ph. D. thesis, University of Science and Technology, Beijing, 2005
[5] Chen, B. S., *et al.*, Experimental Research of Dynamic Mechanical Behaviors of Frozen Soil (in Chinese), *Chinese Journal of Theoretical and Applied Mechanics, 11* (2005), 11, pp. 724-728
[6] Michael, D. F., Measuring Static and Dynamic Properties of Frozen Silty Soils, Sandia Report No. 98, Sand, USA, 1998
[7] Moo, Y. L., *et al.*, Frozen Soil Material Testing and Constitutive Modeling, Sandia Report No. 524, Sand, USA, 2002
[8] Gao, Z. P., The Real Equation of State of Materials in Explosion and Shock, *Advances in Mechanics, 21* (1991), 2, pp. 176-189
[9] Tang, W. H., *et al.*, Approximation Calculation Methods of Shock Temperature, *Advances in Mechanics, 28* (1998), 4, pp. 479-487
[10] Monstafa, S., *et al.*, High Strain-Rate Behavior of Ice under Uniaxial Compression, *International Journal of Solids and Structures, 46* (2007), 7, pp. 1499-1515
[11] Yang, Y. G., *et al.*, The Strength Criterion and Elastoplastic Constitutive Model of Frozen Soil under High Confining Pressures, *Cold Regions Science and Technology, 60* (2010), 1, pp. 154-160
[12] Shen, Z. Y., Zhang, J. Y., Effect of Confining Pressure on the Dynamic Features of Frozen Silt, *Journal of Glaciology and Geocryology, 19* (1997), 4, pp. 245-251

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