Construction and Building Materials 149 (2017) 861–868

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Effect of cement additives on unconfined compressive strength of warm and ice-rich frozen soil

Mingtang Chai [a,b,1], Hu Zhang [a,*], Jianming Zhang [a], Zhilong Zhang [a,b]

[a] State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

## HIGHLIGHTS

- Effects on modification of nine cement additives in frozen soils is analyzed.
- Change of water content relative to hydration reaction at −1 °C in frozen soils is proposed.
- Optimum dosage of additives which increased unconfined compressive strength of frozen soils is calculated.

## ARTICLE INFO

*Article history:*
Received 14 February 2017
Received in revised form 16 May 2017
Accepted 24 May 2017

*Keywords:*
Additive
Modification
Frozen soil
Compressive strength
Water content

## ABSTRACT

The effect of nine cement additives on the unconfined compressive strength (UCS) of warm and ice-rich frozen soils was analyzed. After 7 days of curing at −1 °C, the UCS at −1 °C, the freezing-point depression and changes in the water content of soil samples were measured to explore the additive effect and mechanism. The optimum additive dosage was determined to improve engineering applications. The conclusions were: (1) attapulgite, metakaolin, nano-silicon dioxide ($SiO_2$), silica fume and hardener accelerator increased the UCS by reducing the water content of frozen soils; (2) sodium hydroxide (NaOH), sodium silicate ($Na_2SiO_3$) and sodium lignosulfonate thawed the ice and reduced the UCS of frozen soil samples; (3) when frozen soil with a water content of 30% and 90% was mixed with 15% cement, the optimum dosages were 2% and 8% metakaolin and 0.49% and 0.62% hardening accelerator, respectively.

## 1. Introduction

Warm and ice-rich frozen soil ranges from −1.0 °C to 0 °C and has an ice content larger than 25% [1,2]. Large amounts of unfrozen water result in weak cementation between soil particles and ice crystals in warm and ice-rich frozen soil, which results in a low strength. Warm and ice-rich frozen soils can produce extensive creep and compressive deformation on loading [3]. Because of the poor engineering performance of warm and ice-rich frozen soils, subgrade constructions in permafrost regions on the Qinghai–Tibet Plateau settle extensively. The deformation of warm and ice-rich frozen soil threatens operations and the service life of constructions [3–5].

To improve the performance of warm and ice-rich frozen soil, numerous cooling measures have been adopted in permafrost regions, such as thermosyphons, ventilated ducts, crushed rock, and pile foundations [6–8]. These measures retard the thawing of frozen soils but they cannot prevent the thawing of permafrost that will result from future global warming. Some novel methods or techniques, such as soil improvements, should be proposed to improve the mechanical behavior of the frozen soils.

Chemical stabilization has been adopted widely to improve the mechanical behavior of soft clay and residual soil. Additives such as basanite [9], fly ash [10], metakaolin [11], rice husk [12], silicon dioxide ($SiO_2$) nanoparticles [13] and epoxy resin [14] have been mixed with cement and added to the soils. After curing, the addition of additives increased the plastic limit and the optimum moisture content of soil samples, and the amount of hydration products. Thus, modified soils had a larger density and a better cementation. The unconfined compressive strength (UCS) of soil samples is usually measured at a maximum dry density and optimum moisture content to evaluate the stabilization effect of additives in cement.

In seasonally frozen ground regions, additives have also been used to reduce the strength loss of soil from freezing and thawing cycles [15], including fibers (geofiber, jute fiber, polymer fiber and steel fiber) [16–19], lime [20], basanite [21], fly ash [22] and crumb

---

[*] Corresponding author at: Donggang West Road 320, Lanzhou 730000, China.
*E-mail addresses:* cmt620422@163.com (M. Chai), zhanghu@lzb.ac.cn (H. Zhang), zhangjm@lzb.ac.cn (J. Zhang), 573289332@qq.com (Z. Zhang).
[1] Address: Donggang West Road 320, Lanzhou 730000, China.

http://dx.doi.org/10.1016/j.conbuildmat.2017.05.202
0950-0618/

**Table 1**
Particle-size distribution of the soil samples.

| Soil type | Particle–size distribution /% | | | |
|---|---|---|---|---|
| Silty clay | >0.1 mm | 0.1–0.05 mm | 0.05–0.005 mm | <0.005 mm |
| | 3.69 | 11.96 | 52.83 | 31.52 |

**Table 2**
Chemical components of attapulgite, metakaolin, nano-$SiO_2$ and silica fume.

| Components /% | $SiO_2$ | MgO | $Al_2O_3$ | CaO | $Fe_2O_3$ | $K_2O$ | $Na_2O$ | C |
|---|---|---|---|---|---|---|---|---|
| Attapulgite | 48.5–68.5 | 4.0–16.5 | 2.5–12.5 | 0.45–6.5 | 0.1–2.5 | 0.05–2.5 | 0.06–1.0 | 0 |
| Metakaolin | ≤41 | 0.3 | 43.5 ± 1.0 | 0.4 | ≤0.4 | 3.2 | 0.4 | 0 |
| Nano-$SiO_2$ | ≥99.8 | 0 | 0 | 0 | ≤0.01 | 0 | 0 | 0.6–1.2 |
| Silica fume | 75–98 | 0.7 ± 0.1 | 1.0 ± 0.2 | 0.3 ± 0.1 | 0.9 ± 0.3 | 0 | 1.3 ± 0.2 | 0 |

**Fig. 1.** Sample-preparation procedure in the refrigeration house, (a) frozen soil, (b) crushed frozen soil, (c) samples.

**Table 3**
Dosage grades of each additive by dry weight of cement.

| Dosage grade | Attapulgite | Metakaolin | Nano-$SiO_2$ | SF | HA | NaOH | $Na_2SiO_3$ | SL | SAP |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.0% | 2.0% | 0.5% | 2.0% | 0.1% | 0.4% | 2.0% | 0.5% | 1.0% |
| 2 | 4.0% | 4.0% | 1.0% | 4.0% | 0.5% | 0.8% | 4.0% | 1.0% | 2.0% |
| 3 | 8.0% | 8.0% | 2.0% | 8.0% | 1.0% | 1.2% | 6.0% | 2.0% | 4.0% |

rubber [23]. Therefore, the addition of cement and additives could increase the compressive strength effectively and cause changes in physical properties. All soil samples were cured at 20 °C, and therefore, the test results cannot be applied to frozen ground in permafrost regions. No literature exists on soil samples cured below 0 °C.

Nine additives that are used widely to modify seasonally frozen ground and soft clay were used to increase the UCS of warm and ice-rich frozen soil. We proposed a modified method of sample preparation below 0 °C by mixing additives, cement and frozen soil. The effects of additives in cement on the UCS were analyzed. The freezing-point depression of water and changes in the water content of soil samples after curing were measured to analyze the improvement mechanism. Optimum dosages of additives that could maximize the UCS of warm and ice-rich frozen soils were acquired by a response-surface methodology (RSM).

## 2. Materials and method

### 2.1. Soil, cement and additives

The tested soil is a silty clay and was from the Beiluhe basin on the Qinghai–Tibet Plateau, China. The soil particle-size distribution is shown in Table 1. The cement was ordinary Portland cement (cement I 42.5) in accordance with China National Standard GB 175-2009. The nine additives were attapulgite, metakaolin, nano-$SiO_2$, silica fume (SF), hardening accelerator (HA), sodium hydroxide (NaOH), sodium silicate ($Na_2SiO_3$), sodium lignosulfonate (SL) and super-absorbent polymer (SAP). Attapulgite and metakaolin were from Xingtang County, Hebei, China. Nano-$SiO_2$ (AEROSIL R972) is hydrophobic and was imported from Germany. HA is anti-freezing to −20 °C and the suggested mixture ratio is 0.1% by weight of cement. SF, NaOH and $Na_2SiO_3$ are analytically pure. The chemical components and proportions of attapulgite, metakaolin, nano-$SiO_2$ and SF are shown in Table 2. SL is a dispersant that distributes the water more uniformly in the cement. SAP has a water-absorption capacity of 400 g per gram for distilled water or 50 g per gram for saline water (0.5% NaCl).

### 2.2. Sample preparation

The soil, which was crushed and ground after air-drying and filtered through a 2-mm sieve, was mixed with water in a ratio of 1:0.3 by mass to provide an initial water content of 30%. Humid soil was placed into plastic bags in a −20 °C environment for 24 h. When the soil was frozen, it was crushed in a cold room at approximately −5 °C. Cement and additives were added to the crushed frozen soil. The cement content was 15% by weight of the frozen soil. To ensure hydration of the cement, a certain amount of water was added to the cement during sample preparation. Mixtures of water, cement, additive and frozen soil were placed into a cylindrical mold (61.8 mm diameter, 126 mm height), compacted homogeneously and tapped with a rubber hammer to remove bubbles in the samples. Vaseline was greased on the inner surface of the mold to allow for easier sample extraction from the mold. To prevent the soil moisture from evaporating, the time used