Cold Regions Science and Technology 99 (2014) 38–45

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

# Impact of freeze–thaw cycles on mechanical behaviour of lime stabilized gypseous soils

Abdulrahman Aldaood [a,b], Marwen Bouasker [a], Muzahim Al-Mukhtar [a,*]

[a] Centre de Recherche sur la Matière Divisée, CRMD- CNRS, Polytech Orléans - Université d'Orléans, 1b rue de la Férollerie, 45071 Orléans Cedex 2, France
[b] Department of Civil Engineering, College of Engineering, Mosul University, Al-Majmooah Street, Mosul, Iraq

ARTICLE INFO

*Article history:*
Received 14 February 2013
Accepted 5 December 2013

*Keywords:*
Gypseous soil
Lime stabilization
Freezing–thawing
Unconfined compressive strength
Volume change

ABSTRACT

In seasonally frozen regions, earth structures such as embankments and roads are exposed to periodic freezing–thawing. Most problems with these structures arise from the fact that design approaches are based only on strength without consideration of long-term stability or durability. This study was conducted to investigate the impact of freeze–thaw cycles on the mechanical and mineralogical behaviour of gypseous soils stabilized with lime. The laboratory research associated with this study involved fine-grained soil of different gypsum contents (0, 5, 15 and 25%). The soil samples were stabilized with 3% lime and cured for 28 days at 20 °C. The soil samples were subjected to freeze–thaw cycles following the ASTM procedure. A series of unconfined compression and wave velocity tests were performed. pH, electrical conductivity, water content and volume changes were evaluated. Mercury porosimetry tests and scanning microscopy observations (SEM images) were carried out to determine changes at the microscopic and mineralogical level. Analyses indicated that freeze–thaw cycles reduce the unconfined compressive strength of all the tested samples. Gypseous soil samples lose a substantial amount of their strength after a limited number of freeze–thaw cycles. Moreover, water content during the applied cycles increases and induces significant volume changes with the gypsum content in the soil. The dissolution of gypsum due to water infiltration, crack propagation and ettringite formation was revealed by pH, electrical conductivity and microstructural measurements. These changes in the structure and the mineralogy reduce the durability of gypseous soil samples when subjected to freeze–thaw cycles.



## 1. Introduction and scientific background

Cyclic freezing–thawing is known to be the major source of deterioration in pavement structures in cold regions. Freeze–thaw is considered to be one of the most destructive actions, which can induce significant damage in pavement structures. Damage due to freeze–thaw cycling can take various forms, the most common ones being cracking and spalling on different scales (Yarbasi et al., 2007). Other forms of damage are attributed to the formation of ice lenses during the freezing period which tend to segregate in soils, resulting in a modified soil structure on the micro- and macro-scale (Hohmann-Porebska, 2002).

Gypseous soils are problematic soils in which the gypsum content ($CaSO_4 \cdot 2H_2O$) affects physical and chemical properties, thus limiting their uses in the engineering applications. The gypsum content in these soils varies widely from less than 5% to over 50% (Adams et al., 2008; Al-Dabbas et al., 2012).

Gypseous soils are used in road construction mainly as the sub-grade layers due both to their widespread availability in many areas of the world and to the lack of economical alternative materials (Adams et al., 2008; Aibn et al., 1998). The amount of gypsum in a soil is crucial in determining its properties, especially volume change and strength. Smith and Robertson (1962) (FAO, 1990) found that a gypsum content of less than 10% does not significantly affect the soil characteristics (structure, texture and water retention), whereas in soils containing between 10 and 20% gypsum, gypsum crystals tend to break the continuity of the soil mass. In addition, several studies on gypseous soils, have shown that, the onset of problems associated with these soils depends on the initial sulphate levels in soils prior to chemical stabilization (Adams et al. 2008; Hunter, 1988; Petry and Little, 1992). Based on their studies, researchers determined various initial amounts of sulphates (i.e. gypsum) at which problems such as; reduction in strength and an increasing in swelling can be expected. Hunter (1988) mentioned that an initial sulphate level of 10,000 ppm in soils would lead to sulphate-induced heave distress problems when such soils were stabilized with calcium-based stabilizers. Adams et al. (2008) reported that the lime–soil mixtures of soils having high sulphate contents (greater than 8500 ppm) showed a significant increase in swell, while soils with low sulphate contents (less than 200 ppm) showed a significant reduction in swell when stabilized by lime. Wild et al. (1998) worked on lime-treated kaolinite clayey samples with and without the presence of gypsum and/or slag. They reported that the strength properties of lime-treated soil samples were enhanced by the presence of gypsum. The unconfined compressive strength varied

* Corresponding author.
*E-mail address:* muzahim.al-mukhtar@univ-orleans.fr (M. Al-Mukhtar).

0165-232X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coldregions.2013.12.003

slightly when the gypsum content increased from (1% $SO_3$ ~ 2% gypsum) to (3% $SO_3$ ~ 6% gypsum) especially for 28 days of curing, while there was no effect of gypsum addition on the strength properties when the soil samples were treated with slag alone.

Fine-grained and gypseous soils are known to be problematic when exposed to different freeze–thaw cycles (Ahmed and Ugai, 2011; Gullu and Hazirbaba, 2010; Kamei et al., 2012; Khoury and Zaman, 2007; Simonsen et al., 2002). In cold regions, the one major concern associated with road construction materials is their durability against freeze–thaw cycles. The durability of soil can be improved by chemical stabilisation (Liu et al., 2010; Paige, 2008). Chemical stabilisation of soils involves substances such as cement, lime and other chemical additives (e.g. fly ash) (Ingles and Metcalf, 1972). Lime stabilisation is one of the most economic techniques to improve the engineering behaviour of clayey soils (Ingles and Metcalf, 1972; Little, 1995). The addition of lime to a soil causes two basic sets of reactions; one is a short-term reaction while the second is a long-term reaction (Al-Mukhtar et al., 2010a, 2010b; Little, 1995). The immediate effect of lime addition to soil is the trigger of flocculation and agglomeration of the clay particles caused by cation exchange at the surface of the soil particles. The result of this short-term reaction is to enhance workability and plasticity (Little, 1995; Mathew and Rao, 1997). The long-term reactions that are accomplished over a period of time may require weeks, months or even years for completion, depending on the rate of chemical decomposition and hydration of the silicates and aluminates (Al-Mukhtar et al., 2012; Khattab et al. 2007). This results in the formation of cementitious materials, which bind the soil particles together (Ingles and Metcalf, 1972; Little, 1995).

The durability and strength properties of natural and stabilized soils under freeze–thaw cycles have been investigated by many researchers. Dempsey and Thompson (1968) studied the durability of lime stabilized soil samples, and reported that the unconfined compressive strength of soil samples could be used as indicator of the freezing–thawing durability of the lime–soil mixtures. The same conclusion was drawn by Shihata and Baghdadi (2001) during their work on the durability of cement–soil mixtures. Moreover, in another study carried out by Dempsey and Thompson (1973), they determined that vacuum saturation testing prior the freeze–thaw test provides a rapid and economic method for accurately predicting the freezing–thawing durability of the stabilized material. Simonsen et al. (2002) investigated the effect of one freeze–thaw cycle on the resilient modulus of five different types of soil (glacial till, silty fine sand, coarse gravelly sand, fine sand and marine clay) using a closed system (no inflow or outflow of water). A reduction in resilient modulus was observed for all types of soil, resulting in a looser soil structure (due to the increased volume of soils during the freeze–thaw cycles, which causes a lower resilient modulus). The same negative effect (i.e. reduction in resilient modulus) of freezing–thawing on aggregate stability was observed by Öztas and Fayetorbay (2003). Zaman and Khoury (2003) evaluated the effect of freeze–thaw cycles on Oklahoma base aggregate blended with fly ash. The resilient modulus and unconfined compressive strength tests of cured samples for 3 and 28 days were conducted after different freeze–thaw cycles up to 30 cycles. The results indicated that the resilient modulus of the 28 day cured samples increased with freeze–thaw cycles up to 12 cycles, then decreased up to 30 cycles of freezing–thawing. On the other hand, the resilient modulus of the 3 day cured samples increased with up to 30 cycles. An increase in freeze–thaw cycles also resulted in an increase in the unconfined compressive strength for all cases. The effect of freezing–thawing on the resilient modulus and unconfined compressive strength was attributed to the retardation or acceleration of cementitious reactions. Similar results were noted by Khoury and Brooks (2010). Wang et al. (2007) pointed out that the physical and mechanical properties of compacted clay drastically changed with freeze–thaw cycles. The strength of the soil samples reached minimum values after 3 to 7 cycles of freezing–thawing. Therefore they suggested that the designed strength of soils in cold regions must be taken into account after 7 freeze–thaw cycles. Liu et al. (2010) studied the dynamic properties of cement and lime modified soils under different stabiliser percentages ranging between (3% to 12%) and under different freeze–thaw cycles. In general, the dynamic stress increased from 0.1 MPa of natural soil to 0.29 and 0.85 MPa of soil samples treated with lime and cement, respectively, under freeze–thaw cycles.

The study of durability of lime stabilized gypseous soil against freeze–thaw action is particularly important due to the increasing application of gypseous soils in pavement structure construction. Research work presented in this paper is an attempt to analyse the mechanical and mineralogical properties of lime stabilized gypseous soils under freeze–thaw cycles. A series of unconfined compression and wave velocity tests were carried out. Water content and volume change variations were calculated after each freeze–thaw cycle. pH and electrical conductivity tests were also performed with respect to these cycles.

## 2. Materials and testing methods

### 2.1. Materials

The soil tested is a fine-grained soil from an area near the Jossigny region in eastern Paris, France. Various physical and geotechnical indexes as well as mineralogical and grain size distributions of the soil are presented in Table 1. Based on the Atterberg limit values and according to the Unified Soil Classification System (USCS), the soil was classified as a low plasticity clay (CL).

The quicklime added is supplied by the French company LHOIST, is a very fine lime and passes through an 80 μm sieve opening. The activity of the lime used was 94%.

The gypsum used in this study, supplied by the Merck KGaA company, Germany, is a very fine gypsum and passes through an 80 μm sieve opening, and with a purity of more than 99%.

### 2.2. Samples preparation

A standard Proctor compaction effort (ASTM D-698) was adopted in the preparation of the soil samples. To prepare the soil samples, the oven-dried soil (2 days at 60 °C) was first crushed and passed through a 4 mm sieve. Studies in the literatures showed that gypsum content in the nature varies widely, that is why, to control the exact percentage of gypsum in the different samples tested and in order to study an important range of gypsum soil behaviour, we decided to prepare our soil samples in the laboratory with three percentages of gypsum: 5, 15 and 25% by dry weight of soil. After grinding, the required amount of

**Table 1**
Some physical and index properties of natural soil.

| Property | | Value |
|---|---|---|
| Liquid limit (%) | | 29 |
| Plastic limit (%) | | 21 |
| Plasticity index (%) | | 8 |
| pH | | 8.0 |
| Electrical conductivity (mS/cm) | | 0.4 |
| Natural moisture content in situ (%) | | 18.5 |
| Specific gravity Gs | | 2.66 |
| Standard compaction | Max. dry density ($kN/m^3$) | 17.7 |
| | Optimum moisture content OMC (%) | 11 |
| Grain size distribution | Sand (%) | 17 |
| | Silt (%) | 64 |
| | Clay (%) | 19 |
| USCS | Group symbol | CL |
| | Group name | Sandy lean clay |
| Unconfined compressive strength (MPa) | | 0.19 |
| Wave velocity (m/s) | | 618 |