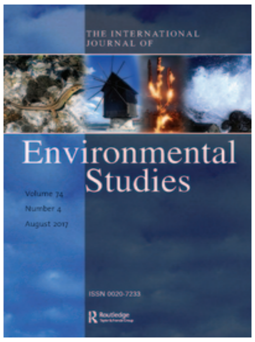

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Freeze-thaw resistance of stabilized soils in Flanders

Glenn Strypsteen, Zeger Sierens, Miquel Joseph, Jelle Benoot and Luc Boehme

Department of Civil Engineering, Technology Cluster Construction, KU Leuven, Technology Campus Ostend, Ostend, Belgium

ABSTRACT

Clayey and loamy soils, in Flanders, are improved with a wide range of stabilizing products. This paper reports an investigation into the impact of 12 freeze-thaw cycles on the mechanical properties of stabilized soils. Results indicate that freeze-thaw cycles reduce the unconfined compressive strength of all the test specimens by 10%. A weak stabilized material, with a small compressive strength, has a great material loss and a big drop in compressive strength. In this study, the various stabilized test pieces do not undergo volume change after eight cycles. The water content of all test pieces decreases, until equilibrium between forward and reverse water migration.

KEYWORDS

Frost; soils; cement; lime; resistance; durability

Introduction

Frost is one of the harsh weather elements that can affect structures and pavements. Especially when rapid freeze-thaw cycles occur, frost is one of the most destructive events that may cause significant structural damage. Sufficiently stabilized ground material is usually resistant to the influence of repeated frost and thaw. Yet severe weather conditions affect soil material that is badly composed or not properly processed. Damage caused by freeze-thaw cycles can take several forms. The most common are: cracking and chipping of the material [1,2]. Other forms of damage can be attributed to the formation of ice lenses in the material during the period of frost. This modifies structure, both at micro and macro scale [3].

Fine-grained soils are known to be problematic when they are exposed to freeze-thaw cycles [4–7]. In cold areas, the main concern for materials used in road construction is their durability in freeze-thaw cycles. The durability of the soil can be improved by chemical stabilization [8,9]. Soil stabilization includes binders such as cement, lime and other chemical additives such as fly ash [10]. Lime stabilization is one of the most economical techniques to improve the mechanical behaviour of clayey soils [10,11]. The addition of lime in soil causes short-term and long-term reactions [11–13]. The immediate effect of lime on soil is the flocculation and agglomeration of the clay particles. This is caused by cation exchange on the surface of the soil particles. The result of this reaction is to improve the workability [11,14]. Depending on the degree of chemical degradation and hydration

CONTACT Glenn Strypsteen glenn.strypsteen@kuleuven.be

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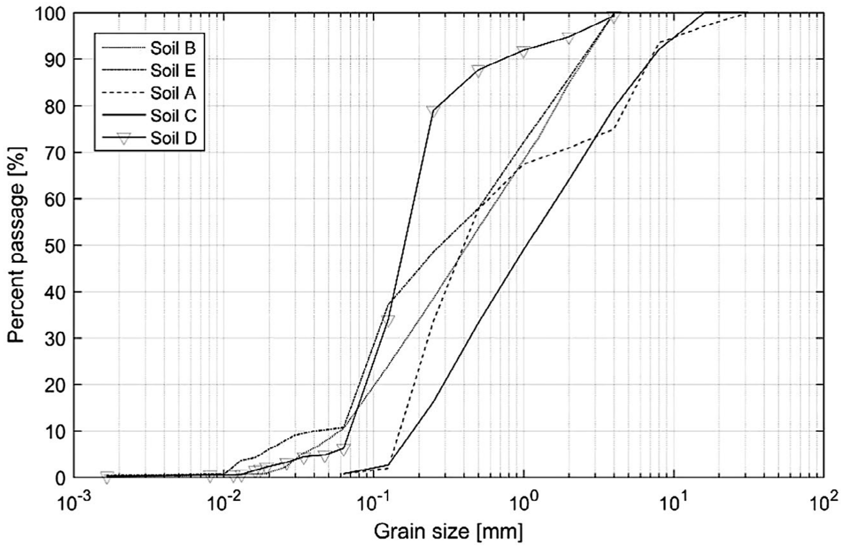

Figure 1. Grain size distribution of the tested soils.

of silicates and aluminates, the long-term responses are achieved weeks, months or even years after implementation [15,16]. There follows a formation of cementitious materials which bind the soil particles together [10,11]. In Flanders, stabilized soil is mainly used in road construction as a supplement for sewer trenches, covering of drains, subbase and base foundations under industrial floors.

There have been to date only a few studies on the relation of the mechanical properties of stabilized soil subjected to freeze-thaw cycles. The elasticity characteristics of soils subjected to freeze-thaw cycles can be significantly improved by the addition of lime or cement [17]. Janoo et al. [18] conducted a practical study of soil stabilized with Portland cement. After repeated freeze-thaw-load, the results showed that the material had a compressive strength loss of 50%. The compressive strength is one of the most important indicators to evaluate the freeze-thaw resistance of stabilized soils [19]. Yarbasi et al. [20] showed that after successive freeze-thaw cycles, the compressive strength, the California Bearing Ratio and the resonance frequency of lime, fly ash, and cement treated soil lead to high freeze-thaw resistance, in comparison to untreated test pieces. In China, Ning and Chen [21] analysed the unconfined compressive strength of cement-stabilized soil under different freeze-thaw cycles. The results show that freeze-thaw cycles have a significant effect on the properties of cement-treated soil. The effect of freeze-thaw load on the modulus of elasticity and compressive strength was attributed to the deceleration and acceleration of cementing reactions.

Used materials

Five materials were used in this study: four types of soil and sieving sand. The tested soils were derived from different construction sites in Flanders where soil and drainage works were in progress. Most of these soils were found to be mainly plastic with high water content. These types of soil were problematic for the contractor to process. The soils expand in volume when they absorb a large amount of water. The sieving sand was taken from the

Table 1. Some physical and geotechnical properties of the five tested materials, each characterized by a letter.

Properties	A	B	C	D	E
Absolute density	2.29	2.57	2.64	2.50	2.59
D_{10} (mm)	0.16	0.06	0.19	0.07	0.04
D_{30} (mm)	0.24	0.171	0.45	0.12	0.12
D_{60} (mm)	0.61	0.675	1.85	0.185	0.55
Fines (%)	0.64	10.06	1.15	6.21	10.69
Uniformity coefficient	4	11	10	3	14
Curvature coefficient	0.6	0.7	0.6	1.1	0.7
Plasticity of the fines	–	12	–	11	14
Max. dry density (kg/m^3)	1723	1863	1870	1743	1897
Optimum water content (%)	10.98	12.83	10.12	10.38	11.35
Natural water content (%)	11.22	12.30	11.83	16.18	11.75
Organic material (%)	1.35	1.56	–	1.67	1.88
Classification by SB250	M-SS[a]	LSb	SS[c]	TS[d]	LS[c]

[a]The abbreviation M-SS stands for medium sandy soil.
[b]The abbreviation LS stands for loamy sand.
[c]The abbreviation SS stands for sieving sand.
[d]The abbreviation TS stands for topsoil.

Figure 2. Stabilized test pieces located in the freeze-thaw cabinet.
Notes: The test pieces are placed on a water saturated plate. There are two test pieces per type of soil. One is used for the determination of the compressive strength, and the other is used for mass and volume changes.

depot of a contractor and it was the fine fraction which is released during the breaking process of concrete and stone rubble. Of the various materials, the grain size distribution was determined (Figure 1). Table 1 shows other physical and geotechnical properties, such as the liquid limit, plastic limit, optimum water content and optimum density. By use of the Atterberg limits, the absolute density, organic matter content and grain distribution, the different types of soil are classified according to the standard specifications in SB250.

Experimental procedure

The materials were sampled in natural state, of which the water content was determined. By taking into account that the material has an assumed wet density of 1800 kg/m^3 and that a

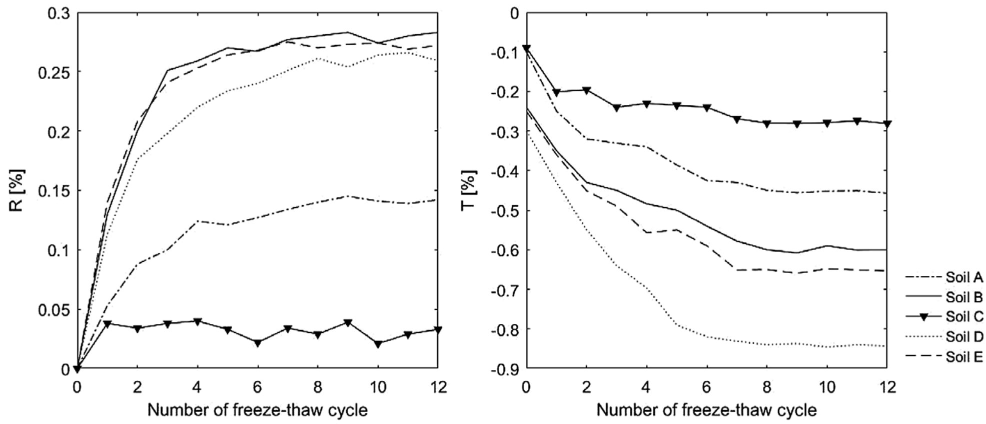

Figure 3. Variation in volume and water content during freeze-thaw cycles.

cement dose of, respectively, 100 and 150 kg/m^3 is used, the total amount of cement could be calculated. Afterwards, the treated material was dynamically compacted into a cylindrical stainless steel formwork. The stabilized materials had final dimensions of 100 ± 1 mm in diameter and 120 ± 1 mm in height (or a volume of 942 ml). After compaction each test piece was placed in a closed humid environment (RH 94 ± 2%) at 20 °C.

At the end of the 28 days curing time, the stabilized test pieces were subjected to 12 freeze-thaw cycles described in ASTM D560-03. These pieces, located in the freeze-thaw cabinet, were placed on a water saturated plate (Figure 2). The freeze-thaw cycle started at a negative temperature of −23 °C for 24 h. Subsequently, the test pieces were subjected to a thaw cycle at 21 °C for 23 h. The masses and water contents were determined at the end of each cycle. In addition, variations in volume were determined by measurement of the height and diameter of the test pieces. Each volume and mass change, which is considered in the study, is the average of four measurements. Previous research shows that 8–12 frost and thaw cycles are sufficient to evaluate the effect of freeze-thaw on different mechanical parameters, including the unconfined compressive strength [22–24].

Results and discussion

Change in volume- and water content of stabilized soils subjected to freeze-thaw cycles

In order to identify the effect of freeze-thaw cycles on the mechanical properties of stabilized soils, the volume and the water content of each test piece was determined. These measurements always took place at the end of a freeze-thaw cycle. In order to evaluate changes in volume, a dimensionless parameter, R, is introduced. This is defined as the ratio of increase or decrease of the stabilized soil volume (ΔV) after n cycles relative to the initial volume (V_0). Equation 1 shows this ratio.

$$R = \frac{\Delta V}{V_0} \times 100\% \tag{1}$$

Another dimensionless parameter, T, is introduced in order to demonstrate the effect on the water content caused by freeze-thaw cycles. According to:

$$T = \frac{\Delta w}{w_0} \times 100\% \tag{2}$$

In which:

- Δw is the increase or decrease of the thawed specimens water content after n cycles.
- w_0 is the initial water content of the stabilized material.

Figure 3(a) and (b) shows the variation in volume and water content during freeze-thaw cycles. Figure 3(a) indicates that the volume of each stabilized specimen gradually increases after each cycle. At the eighth cycle, the volume change stops.

Simultaneously, the water content of the stabilized test pieces decreased because of rapid freeze-thaw cycles. The minimum water content was achieved after approximately nine cycles. When minimum water content and volume changes are considered, stabilized soils appear to have reached a new dynamic state after eight, respectively, nine cycles. This is a state where no more changes occur in the internal structure of the material.

Water begins to freeze when the stabilized soil is cooled to below 1 °C. Before the stabilized soil begins to freeze, there must be two conditions. The first condition is that it must be sufficiently cold. The second condition is that the material should contain sufficient water [25]. The pore water starts to freeze when the material is exposed to negative temperatures. At that time, a transition zone between the frozen and non-frozen material exists. As a result, a capillary suction of water from the not yet frozen zone is transported through the transition zone, into the frozen zone [25]. There, the water starts to accumulate and freeze. Upon freezing, the water undergoes a volume increase of about 9% and ice lenses are formed. This leads to hairline cracks in the material. If the thaw cycle starts, first, the surface of the test piece, which is exposed to the air, starts to melt. During the defrosting process, the temperature in the core of the test piece is always lower than the temperature at the surface. This leads to a migration of water from the surface to the core of the material.

This process will stop more quickly as a result of the increase in the core temperature. When the internal temperature rises, the water in the test specimen starts to melt. This leads to the shrinkage of the test piece. Owing to the cohesion of the stabilized soil, the extent of the shrinkage during thaw is smaller than the swell during frost. After several freeze-thaw cycles, the material reaches a constant volume change. Equilibrium is reached in the internal structure of the material. In this study, the various stabilized test pieces reach equilibrium after eight cycles (Figure 3(a)). But there is no volume change noticeable after the first freeze-thaw cycle for sieving sand (soil C).

The movement of water from the inside out, during the freeze cycle, is called forward migration. During the thaw cycle, the movement of the water is reversed. This is called reverse migration. The amount of water that migrates during forward migration is always greater than in reverse migration. Hence, the water content of all the test pieces decreases. After several freeze-thaw cycles, the migrations reach equilibrium. In this study, equilibrium was reached after nine cycles (Figure 3(b)).

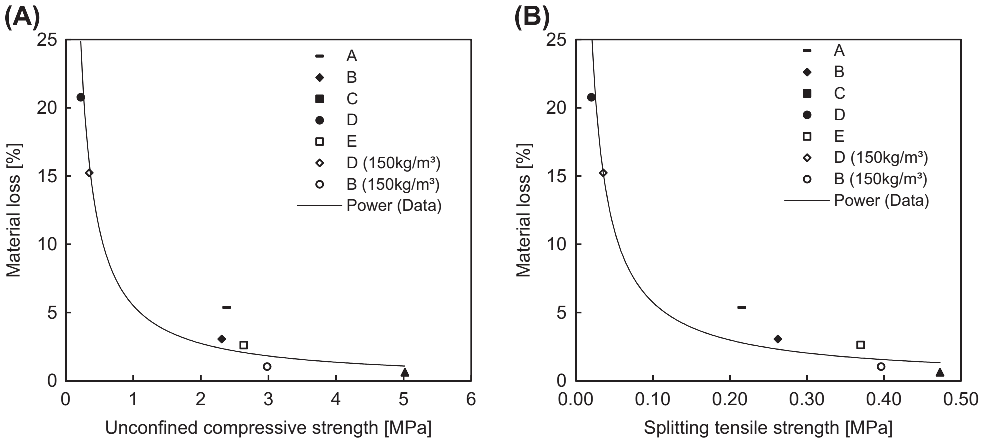

Figure 4 (A) Comparison between the unconfined compressive strength and the loss of material. (B) Comparison between the splitting tensile strength and the loss of material.

Material loss of stabilized soils subjected to 12 freeze-thaw cycles

Figure 4(a) shows the comparison between the unconfined compressive strength of the test pieces at 28 days of age and the loss of material after 12 freeze-thaw cycles. Figure 4(b) shows the comparison between the splitting tensile strength at 28 days curing and the loss of material after 12 freeze-thaw cycles. A negative power function describes these relationships. A small compressive strength and tensile strength, such as stabilized topsoil, has a large loss of material. For larger compressive and tensile strengths smaller losses were measured. Hence, with a known compressive strength or even tensile strength, the material loss that occurs after a series of freeze-thaw cycles can be estimated.

Based on the compressive and tensile strengths, the frost resistance of stabilized material can be estimated. It is assumed that treated soil is frost resistant if at the date of expected frost, a compressive strength higher than 2.5 MPa and a tensile strength higher than 0.25 Mpa is reached [26]. Figure 4 indicates that above those boundaries, the material loss is minimal (i.e. <3%). Consequently, these materials may be considered to be frost-resistant.

Unconfined compressive strength of stabilized soils after 12 freeze-thaw cycles

As shown in Figure 5, the compressive strength for all the test specimens decreases with an average value of 10% after 12 freeze-thaw cycles. Note that the compressive strength was not measured for stabilized topsoil (100 kg/m^3 cement). The decrease in compressive strength is attributed to the changes in the structure when exposed to freeze-thaw cycles. This finding is observed as a result of the development of internal cracks between the material particles. As is known, stabilized soil and sieving sand are porous materials and they have the ability to absorb capillary water during the defrosting process. At this stage, all the cavities (micro- and macro-pores) are partially saturated. When the material encounters negative temperatures (±−23 °C), the retained water freezes, increasing in volume. This causes internal tensions in the cavities, which leads to internal cracks [27,28]. Consequently, the cracks lead to a change in the arrangement of the particles. This result is in agreement

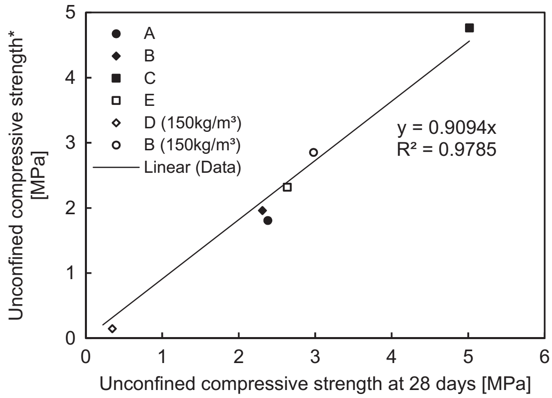

Figure 5. Comparison between the unconfined compressive strength after 28 days of curing and the unconfined compressive strength after 28 days of curing plus 12 freeze-thaw cycles.
Note: All the test pieces are stabilized with 100 kg/m^3 cement, or with 150 kg/m^3 if mentioned.

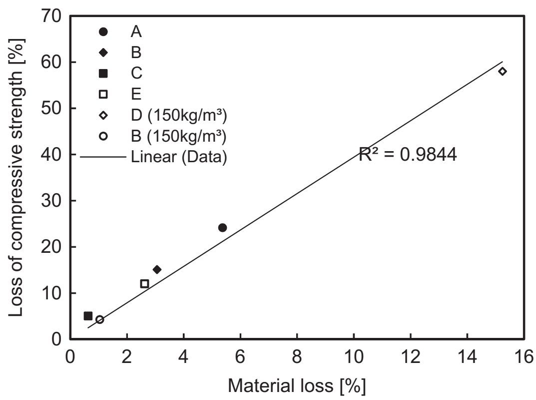

Figure 6. Comparison between the loss in material and the loss in unconfined compressive strength after 12 freeze-thaw cycles.
Notes: All the test pieces are stabilized with 100 kg/m^3 cement, or with 150 kg/m^3 if mentioned.

with previous studies where the effects of freeze-thaw cycles on stabilized soils and other geotechnical materials were investigated [29–32].

Figure 6 shows the relationship between the unconfined compressive strength loss and the loss of material after 12 freeze-thaw cycles. A link between the two can be found. A weak stabilized material, with a small compressive strength, has a great material loss and a big drop in compressive strength after a series of freeze-thaw cycles. It can be concluded that the converse is also true.

Conclusions

This paper reports a study of the freeze-thaw resistance of stabilized soils in Flanders; mainly, the impact of freeze-thaw cycles on the durability and on the mechanical properties of cement-stabilized soil. Based on the results, the following conclusions can be drawn:

(1) After several freeze-thaw cycles, the stabilized soils reach a constant volume change. The internal structure of the material reaches equilibrium. In this study, the various stabilized test pieces reach equilibrium after eight cycles. No volume change is noticeable after the first freeze-thaw cycle for sieving sand.
(2) The movement of water from the inside out, during the freeze cycle, is called forward migration. During the thaw cycle, the process is reversed. This is called reverse migration. The amount of water that moves during forward migration is always greater than the reverse migration. Hence, the water content of all the test pieces decreased. After several freeze-thaw cycles, the migration between forward and reverse migration reaches a balance. In this study, equilibrium was reached after nine cycles.
(3) A negative power function describes the relationship between the unconfined compressive strength, splitting tensile strength and the loss of material. A small compressive strength and tensile strength has a large loss of material. For larger compressive and tensile strengths smaller losses were measured. Hence, with a known compressive strength or even tensile strength, the material loss that occurs after a series of freeze-thaw cycles can be estimated. Based on the compressive and tensile strength, the frost resistance of stabilized material can be estimated. It is assumed that treated soil is frost resistant if at the date of expected frost, a compressive strength higher than 2.5 MPa and a tensile strength higher than 0.25 Mpa are reached [26]. Analysis indicates that above those boundaries, the material loss is minimal (i.e. <3%). Consequently, these materials may be considered to be frost-resistant.
(4) The compressive strength for all the test specimens decreases with an average value of 10% after 12 freeze-thaw cycles. The decrease in compressive strength is attributed to the changes in the structure when exposed to freeze-thaw cycles. This finding is observed as a result of the development of internal cracks between the material particles. A weak stabilized material, with a small compressive strength, has a great material loss and a big drop in compressive strength after a series of freeze-thaw cycles. It can be concluded that the converse is also true.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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