A laboratory test study on effect of freeze-thaw cycling on strength and hydraulic conductivity of high water content stabilized dredged sediments

<table>
<thead>
<tr>
<th>Journal:</th>
<th>Canadian Geotechnical Journal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID:</td>
<td>cgj-2015-0295.R3</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Note</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>16-Dec-2015</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Makusa, Gregory; Luleå University of Technology, Civil, Environmental and Natural Resources Engineering; Mácsik, Josef; Ecoloop, Holm, Göran; Swedish Geotechnical Institute, Knutsson, Sven; Luleå University of Technology, Civil, Environmental and Natural resources engineering</td>
</tr>
<tr>
<td>Keyword:</td>
<td>Freeze-thaw, unconfined compressive strength, hydraulic conductivity, durability, thaw weakening, thaw consolidation</td>
</tr>
</tbody>
</table>
A laboratory test study on effect of freeze–thaw cycles on strength and hydraulic conductivity of high water content stabilized dredged sediments

Gregory Makusa¹*, Josef Mácsik², Göran Holm³, Sven Knutsson⁴

¹PhD Student, Department of Civil, Environmental and Natural resources engineering, Luleå University of Technology, SE-97187, Luleå, Sweden. Email: gmakusa@yahoo.com

²Ecoloop, Stockholm, Sweden, josef.macsik@ecoloop.se

³Swedish Geotechnical Institute, Linköping, Sweden, goran.holm@swedgeo.se

⁴Professor, Department of Civil, Environmental and Natural resources engineering, Luleå University of Technology, SE-97187, Luleå, Sweden. Email: sven.knutsson@ltu.se

*Corresponding author: alternative email: gmakusa@yahoo.com
Abstract: Dredged sediments with initial water content between 200% and 400% were treated with single and composite binders. Samples were subjected to open and semi-closed freeze-thaw (f-t) cycles to investigate the impact of f-t cycling on hydraulic conductivity (HC) and unconfined compressive strength (UCS). A grace period (GP) for thaw consolidation is included to assess healing potential of the affected stabilized mass. The findings of this study show that the impact of f-t cycles depend on initially achieved UCS and HC values prior to the f-t cycling and time of testing after f-t cycles. The HC of specimens with initially UCS value of 87 kPa increased with number of f-t cycles. The UCS values decreased in the range of 50%-80% when specimens were tested directly after the thaw period and values decreased in the range of 14%-60% when specimens were tested at the end of GP. The HC of specimens with initial UCS value of 299 kPa remained almost the same. These samples experienced permanent loss in the UCS values, irrespective of time of testing. Detrimental effects of the freezing action on the UCS were greater under semi-closed than open freezing conditions.

Keywords: Freeze–thaw cycle; dredging; hydraulic conductivity; stabilization-solidification; unconfined compressive strength, thaw weakening, thaw consolidation; durability.
Introduction

In cold regional climates, repetitive freeze–thaw (f-t) cycles can have a detrimental effect on mechanical properties of stabilized soft soils and sediments. Researchers have shown that f-t cycling has significant effects on strength and hydraulic conductivity of stabilized soils (Al-Tabbaa and Evans 1998a; Topolnicki 2004; Maher et al. 2006; Jamshidi et al. 2014; Holm et al. 2015; Jamshidi and Lake 2015). Freezing water in stabilized materials produces expansive forces, which cause formation of micro-cracks, an increase in volume, and bonds breakage. Maher et al. (2006) concluded that the increase in volume and bond fracture on stabilized dredged sediments resulted in permanent loss of strength. However, Jamshidi and Lake (2015) reported both increase and decrease in unconfined compressive strength (UCS) of cement–stabilized silty sand. Al-Tabbaa and Evans (1998a, 1998b) carried out a treatability study on made ground comprising of soils ranging from clayey silty to fine and coarse sand with water content between 9.4% and 9.9%. Using percentage dry mass loss as criteria for assessing the impact of f-t cycles on stabilized soils (ASTM D 650), Al-Tabbaa and Evans (1998a) reported failure for all laboratory treated soils at freezing temperature of -20°C. However, for the same design recipes treated in-situ, all samples survived the f-t criteria at freezing temperature of 0°C and -10°C and failed at -20°C (Al-Tabbaa and Evans 1998b). When the hydraulic conductivity (HC) becomes of major concern, especially on stabilized contaminated dredged sediments, both increase and decrease in HC with number of f-t cycles have been reported (Al-Tabbaa and Evans 1998b; Jamshidi and Lake 2015; Jamshidi et al. 2014). These contradictory results are partly due to: (i) absence of common testing methods and interpretation of the test results, (ii) different mix designs used in these studies, initial water contents of soils, and achieved strength (iii) incomplete f-t cycles during the laboratory test studies.
In cold weather regions, during the four seasons of a year, the actual field weather condition involves freezing phase–thaw weakening phase–thaw consolidation phase and back to freezing phase. Physical effects for each phase are defined in ASTM D7099 as follows:

Freezing phase is associated with changing of phase from water to ice in soil or rock. Frozen water (ice) produces expansive forces, which cause an increase in soil volume, and some bonds breakage in stabilized soils. Thaw weakening phase refers to a reduction in shear strength due to the decrease in effective stress as a result of slow dissipation of excess pore pressures when frozen cohesive soils containing ice are thawing under load. During this period it can be difficult for pore water to dissipate downward because as thaw progresses from the ground surface downward, the soil at a certain depth below the ground surface may remain frozen. Simonsen and Isacsson (1999) observed that (i) the frozen sub-layer can restrict drainage and prolong the thaw weakening period, and (ii) increasing amount of percolating melt water can further decrease the bearing capacity and extend the thaw weakening period of natural soils. Thaw consolidation phase refers to the process by which the density and effective stress increases due to the escape of pore water under the weight of soil itself or an applied load, which cause reduction in void ratio and increase in effective stress.

Based on the literature, traditional f-t cycling does not define or consider the period for thaw consolidation. Though freezing action involves weakening of the stabilized material; we postulate that thaw consolidation may act as a healing phase. Jamshidi and Lake (2015) reported a wide range of potential healing for damaged hydraulic conductivity values of stabilized mass after a post-exposure curing period of over 120 days.

The aim of the present laboratory test study is to investigate the impact of f-t cycling on the UCS and HC of the high water content stabilized dredged materials (SDM). The intent of this
study is to simulate and evaluate a five year period of field performance for stabilized dredged material (SDM) utilized as structural backfill material in northern parts of the world. In these applications the stabilized dredged materials are placed below groundwater level and surrounded by natural soils. Thus, a test program was developed to assess the effect of open and semi closed f-t cycling. Extended thaw period (grace period) is allowed prior to testing to assess the healing potential on the SDM with reduced UCS values.

Material

The use of composite binders for stabilization–solidification of the dredged sediments (DS) is increasing due to artificial pozzolanas that can be utilized as supplementary cementitious materials (SCM). Primary binders such as cement can be blended with pozzolanic materials such as fly ash (FA) and ground granulated blast furnace slag (GGBS). However, according to Wang and Lee (2009) the hydration of cement incorporating SCM such as FA and GGBS is complicated due to the co-existence of cement hydration and the pozzolanic reactions of the mineral admixtures. In this study, dredged sediments were treated with both a composite (ternary) binder and single binder.

Dredged sediments

Dredged sediments (DS) were obtained from Port of Oskarshamn, which is located in the south-eastern coast of Baltic Sea in Sweden. The salinity of water in the Baltic Sea is between 0 and 10 parts per thousand along the Swedish coast (Al-Hamady and Reker 2007). The studied DS had received water contents between 200% and 400%. Based on the received water content, the DS were categorized as two distinct materials, namely; DS-A and DS-B. The average initial water content was 283% and 356%, for DS-A and DS-B, respectively. The DS were not analyzed for presence of the contaminants. Physical properties of the studied DS
are shown in Table 1. Generally, the studied DS were mainly of organic nature. Wet sieving was carried out on the DS to obtain the particle size distributions and cumulative organic matter. The DS particles retained on all sieve sizes less than 4 mm were dried and pulverized. The pulverized powders were then burnt in a furnace at 800°C to determine the percentage of organic matter, which was utilized to compute losses of ignition (LOI). The LOI was conservatively utilized to obtain the actual soil particles by subtracting percentage LOI from each retained dry mass to obtain particle size distribution curve shown in Fig. 1. On average, the studied DS comprised about 4% clay, 76% silty and 20% fine sand particles. Consequently, the studied DS could be classified as highly organic silt. The cumulative percentage LOI for the DS with particles diameters less than 4 mm were 235% and 413% for DS-A and DS-B, respectively (Table 1).

**Binders**

Binders used were either a combination of Byggcement (BC), fly ash (FA) and ground granulated blast furnace slag (GGBS) or single binder by BC only. BC is produced in Sweden by Cementa AB. FA and GGBS were obtained from Billerud Karlsborg paper mill (Billerud Korsnäs) and SSAB steel industry, respectively. Billerud Korsnäs and SSAB are all located near Luleå City in northern part of Sweden. FA and GGBS were utilized as supplementary cementitious materials (SCM). Table 2 presents the average mineral compositions for individual binder components.

Two composite binder (CB) recipes, namely CB1 and CB2 were prepared and utilized to amend the DS at received water content. CB1 was prepared by mixing BC:FA:GGBS at a ratio of 1:1:0.5, respectively by weight of total binder. CB1 was utilized to amend both DS-A and DS-B to obtain stabilized samples A-CB1 and B-CB1 with water contents of 180% and 210%, respectively (Fig 2). CB2 was prepared at reduced amount of FA by blending
BC:FA:GGBS at a ratio of 1:0.5:0.5, respectively. The single binder by BC only was utilized to amend DS-A to determine the effect of incorporating SCM on strength development and resistance to f-t processes. The amounts of CB2 and BC were estimated such that the same initial water content of 160% could be achieved on stabilized mass immediately after mixing (within a period of less than 3 hours) in accordance with Makusa (2015). As a result of different initial water contents of the studied DS, DS-A was treated with BC at a dosage of 260 kg/m$^3$ to produce A-BC. DS-B was blended with CB2 at a dosage of 320 kg/m$^3$ of DS-B to produce B-CB2. A summary of design recipes that were utilized in this laboratory test study is presented in Fig. 2 and Table 3.

**Methods**

**Sample preparations**

Samples for the UCS assessment were prepared by packing the stabilized dredged material (SDM) in polyvinyl chloride (PVC) tubes of size 50 mm by 170 mm without mechanical compaction. The SDM samples were placed in the PVC tubes and allowed to fall freely to the bottom of the tubes by applying a vibratory force at the bottom end of the tube. The SDM samples were then cured under water in a curing container as shown in Fig. 3 (At this time only curing water was used without saturated sand). Tap water was utilized as the curing water. At the bottom of the curing container, a filter was placed to facilitate continuous exchange of pore water. This curing system was adopted to simulate field conditions, where the SDM may be deposited below ground water level. In Sweden, it is customarily required to preload the stabilized volume immediately after mixing with a minimum preloading weight of 18 kPa. The initial preloading weight serves two purposes: firstly, to squeeze out air and water trapped during mixing; secondly, to speed up consolidation of the stabilized mass and to
ensure particle contact for effective hydration reactions (EuroSoilStab 2002). Accordingly, at the top of the PVC sample tube, a plug with filter (see Fig. 3) was inserted and a preloading weight of 22 kPa was applied on top. Literature (Taylor 1997) has shown that at least 28 days of curing is needed to attain 90% of hydration reactions for cement treated soil. However, partial substitution of cement for pozzolanic materials may require curing period in excess of 28 days for pozzolanic reactions to take place and contribute to strength development. Thus, samples A-CB1 and B-CB1 were subjected to a curing period of 91 days. Sample A-BC and B-CB2 were cured for 28 and 50 days, respectively. After the prescribed curing periods, samples were subjected to 1, 3, and 5 open and semi-closed f-t cycles as will be discussed shortly.

Samples for hydraulic conductivity (HC) measurements were molded in rigid wall permeameter of Proctor molds of dimensions 102 mm x 112 mm without mechanical compaction. The inner surfaces of the Proctor molds were lined with a layer of bentonite clay to prevent any possible seepage along the interface. Thin layers of fresh DS were placed on top and bottom end of the stabilized mass surfaces to prevent filter clogging due to cementation. The top and bottom cap with double filters were finally covered on the Proctor molds. Samples were mounted for the HC measurement, which was carried out using a constant head method at a hydraulic gradient of about 7 in accordance with ASTM D 5856. Thus, curing of these samples took place concurrent with permeation to establish baseline HC values prior to f-t cycling.

**Freeze-thaw methods**

Freeze-thaw cycling was carried out in a freezer cabinet with a maximum capability of freezing to –30°C and thawing to 30°C. The freeze-thaw air temperature of the freezing cabinet could be manually altered to a desired air temperature. A minimum freezing and
maximum thawing air temperature of –25°C and 20°C, respectively was utilized. Open and closed freeze-thaw conditions were desired.

During open freeze-thaw cycling, specimens were kept in their original curing container and placed in the freezing cabinet. The PVC sample tubes were sandwiched between saturated sand (Fig. 3), which was utilized to minimize expansive forces of freezing water on the sides of the curing container. The intent was to simulate the field conditions where the stabilized mass will be placed below ground water level and surrounded by natural soils of different thermal conductivity. Both stabilized mass and saturated curing sand were subjected to freeze-thaw cycling. Because of different thermal conductivity, continuous interchange between pore water in stabilized mass and the surrounding would occur. This phenomenon could cause delay in freeze-thaw process on the stabilized mass.

Considering a closed freeze-thaw system, loss or gain of water in the sample should be precluded (ASTM D 653). However, during this study a fully closed freeze-thaw was not achieved. Although, the bottom part of PVC tubes were covered with tight vinyl cap to prevent loss of water to the surrounding. It was assumed that water will be lost through the top filter where the preloading weights were kept. Thus, this f-t condition was considered to be semi-closed freeze-thaw condition. During this freeze-thaw system, specimens were kept in their curing container without curing water. The purpose was to mimic stabilized mass that can be located away from ground water and the interface of surrounding natural soils.

**Freeze–thaw process**

Copper wire thermocouple instrumentation was utilized to determine the period for a complete f-t cycle on samples under both open and semi-closed curing conditions. Evolution of temperature on the samples under UCS assessment only is shown in Fig. 4. Thermocouple instrumentation shows that it would take about 24 hours (Fig. 4a) and 12 hours (Fig. 4b) to
complete one f-t cycle under open and semi–closed f-t systems, respectively. Nonetheless, 24 hour period was utilized to define a complete f-t cycle on UCS samples under both open and semi–closed f-t conditions. Samples for hydraulic conductivity (HC) measurement required 48 hours to complete one open f-t cycle. The thermocouple data are not presented due to problems in data storage.

Based on the thermocouple instrumentation data (Fig. 5a), one can deduce that the actual freeze and thaw conditions occur when the temperature of freezing and thawing air is below and above 0°C, respectively. Furthermore, the freeze-thaw rate of the stabilized dredged material (SDM) relative to the surrounding saturate sand was low. An enlarged pictorial view of f-t cycle can be depicted in Fig. 5(b), which indicates that, the traditional f-t cycle is an incomplete cycle.

Generally, in northern regions of the world, the four seasons of the year (i.e. winter, spring, summer, and autumn) are fixed with small variations. This is to say, winter and spring seasons are the only part of a year that make the depicted semi f-t cycle in Fig. 5b. Consequently, the resistance to repetitive f-t cycles of the SDM cannot be assessed based on two seasons only. For a complete f-t cycle, a grace period (GP) which can be associated with summer and autumn weather conditions was considered. It was postulated that during the GP, the SDM will strive to regain its original strength values after the impact of freeze-thaw. Thus, a pair of the SDM sample tubes was removed from freezing cabinet at the end of prescribed f-t cycles. One specimen was prepared and tested immediately at the end of thaw period (TP). The remaining SDM sample tube was placed in an external curing container and subjected to prescribed grace period (GP) under initial curing conditions before testing.
Testing and evaluations

100 mm SDM sample height was extruded from PVC tubes and cut to obtain specimens for unconfined compression test, which was carried out using a strain–controlled method at a deformation rate of 1 mm/min. The compression tests were conducted on unfrozen specimens after the prescribed curing period (CP) to establish control strength (CS). Subsequent tests were carried out after 1, 3, and 5 f-t cycles to assess the UCS values immediately after the end of (i) TP and (ii) GP. The UCS values obtained at the end of TP and GP were compared with the CS values to assess the impact of the f-t cycles on the UCS and healing potential of the SDM. Figure 6 presents a schematic diagram for the UCS testing and conditions.

Samples for hydraulic conductivity (HC) evaluations were subjected to 1, 3, 4 and 5 open f-t cycles with intermittent permeation (Fig. 7). The HC values were compared to the baseline line HC value (HC prior to f-t cycles). At the end of fifth f-t cycles, cylindrical specimens with dimensions 50 mm x 90 mm were extruded, trimmed and subjected to unconfined compression test at a deformation rate of 0.9 mm/min to determine the UCS values.

Test results and discussion

Unconfined compressive strength

The measured control strength (CS) values for sample A-CB1 and B-CB1 were 28 kPa and 24 kPa, respectively. Specimens from sample A-CB1 were subjected to 3 f-t cycles to assess preliminary results. Regardless of number of f-t cycles, a grace period (GP) for thaw consolidation (TC) of 24 hours only was utilized. However, it was found that the GP for TC should be defined based on the number of f-t cycles and thaw period (TP). Thus, results from sample A-CB1 were not included. The CS values for samples A-BC and B-CB2 were 299 kPa and 87 kPa, respectively (Fig. 8). The UCS value for sample A-BC was about 3.4 times the
The measured UCS indicated decreased values for all specimens tested immediately at the end of thaw period (TP) under both open and semi-closed f-t systems (Fig. 8). Freeze-thaw process induces phase changes of water without dehydration (Makusa et al. 2014). The reduced UCS value immediately after thaw period could be associated with increased amount of free water content, which generated excess pore pressure at the time of testing as a result of undrained condition. Wang et al (2011) observed that the compressive strength decreases due to the weakening effect of water on calcium silicate hydrate. Thus, the effect of thaw weakening on the UCS could be regarded as temporary phenomenon waiting for dissipation of released pore water. Delay in dissipation of pore water and ultimate increase in UCS was significant under semi-closed f-t conditions (Fig 8). Specimens tested after grace period (GP) of thaw (i.e. thaw consolidation) showed improved UCS values under both open and semi-closed f-t systems. These results suggest that thaw consolidation (TC) may act as healing phase after detrimental effects of freezing action have taken place. Furthermore, under semi-closed f-t systems, TC can be limited due to slow dissipation of released water.

**Hydraulic conductivity**

The baseline hydraulic conductivity \( (H_{C0}) \) values were established prior to freeze-thaw (f-t) cycles. The values for \( H_{C0} \) were 4.6 x \( 10^{-8} \) m/s and 2.6 x \( 10^{-8} \) m/s for A-BC and B-CB2, respectively. The lowest \( H_{C0} \) value was measured on sample B-CB2 (Fig. 9) probably due to the presence of fly ash and GGBS. Marsh et al. (1985) observed that fly ash in general can
cause substantial reduction in HC of unfrozen stabilized soils. The high HC$_0$ value on sample A-BC may have been contributed by cement hydration, which usually causes aggregation of particles and increased pore sizes. According to Quang and Chai (2015), the HC of a porous medium is a function of the microstructure of the pores (sizes and distribution) and pore water properties. Hydration of cement agglomerates several small aggregates into a large one. Larger pore size and uniform pore distribution are associated with high HC.

Freezing action can result in formation of a network of cracks and micro-cracks (Jamshidi and Lake 2015; Jamshidi et al. 2014; Benson and Othman 1993; Chamberlain et al. 1990; Chamberlain and Gow 1979; Kraus et al. 1997). Well-connected micro-cracks result in increased hydraulic paths, which cause increased hydraulic conductivity (HC) values. The HC values for A-BC sample remained almost the same during intermittent permeation following 1, 3, 4, and 5 f-t cycles (Fig. 9). On the other hand, the HC for B-CB2 sample decreased by a factor of 0.3 of the baseline value after 1 f-t cycle. The HC values increased by a factor of 1.7, 2.3 and 3.5 times the baseline value after 3, 4 and 5 f-t cycles, respectively (Fig. 9). It can be postulated that the connectivity of formed cracks and increased HC values depend on the achieved UCS values prior to freeze-thaw cycling.

**Effect of initial unconfined compressive strength on hydraulic conductivity**

Frozen water produces expansive forces, which cause the increase in volume, formation of micro-cracks and some bond breakage in stabilized mass. Depending on the initially achieved unconfined compressive strength (UCS) values (prior to freeze-thaw cycling), the formed micro-cracks may become continuous interconnected or disconnected. For the stabilized dredged material (SDM) with low initial strength value, f-t cycles may result in formation of interconnected micro-cracks. As a result the HC will show increased values as shown in Fig. 9 for sample B-CB2 with control UCS of 87 kPa. The measured HC value on sample A-BC
with control UCS value of 299 kPa remained almost the same (Fig. 9). This phenomenon suggests that the initial UCS value of 299 kPa was significantly high to cause increased brittleness and formation of discontinuous micro-cracks on sample A-BC. These results indicate that the HC value and UCS are mutually dependent. Guthrie et al. (2012) observed that for cement–treated soils, there can be a correlation between the UCS and HC values.

**Effect of hydraulic conductivity on unconfined compressive strength**

High water content stabilized dredged material (SDM) with a low hydraulic conductivity (HC) will experience significant loss in strength with prolonged thaw weakening regardless of achieved UCS values. If the hydraulic conductivity is significantly low, the water released during thaw will generate excess pore pressure during loading (Simonsen and Isacsson 1999). As a result, failure will occur under undrained condition and the measured strength will show decreased values. Jamshidi and Lake (2015) reported decreased HC values (i.e. improved performance) hand in hand with reduction of 30% in UCS value (i.e. performance degradation). According to Knutsson (1983), the water accumulated as ice during freezing is released during thaw. Depending on the hydraulic conductivity, the released water can be trapped within the soil. Increased water content leads to a potential risk of water saturation and high pore pressure, which in turn reduces the shear strength of the soil. Prolonged thaw period (thaw consolidation, TC) allows released water to dissipate and reduce the amount of free water, which in turn reduces the excess pore pressure and increases effective stress. It follows that, during loading, the rate of dissipation of excess pore water pressure turns out to be proportional to the rate of loading. Consequently, the effect of undrained condition becomes insignificant. Knutsson and Rydén (1984) reported that if the HC value is high, the water will drain at the same rate as new water is released, and the decrease in strength of the soil will be limited. Jamshidi and Lake (2015) reported increased HC value of up to 50 times
baseline value hand in hand with a strength gain of about 14% on compacted stabilized sand. These arguments were supported by the findings of this study as shown in Fig. 8 in relation to Fig. 9. Results show that the UCS values for sample B–CB2 increased with increasing HC for specimens tested at the end of TP, GP and HC measurement. On the other hand, the UCS values for sample A-BC remained at reduced value of 60% at the end of TP, GP and HC measurement for the same number of freeze-thaw cycles.

Conclusions

The effect of freeze-thaw (f-t) cycles depends on initially achieved unconfined compressive strength (UCS) and hydraulic conductivity (HC) values prior to f-t cycles in addition to the time of testing. This study has shown that:

- Stabilized mass with an initially low UCS experienced a temporary loss of UCS with increased HC. The increase in HC was hypothesized to be a result of increasing hydraulic paths due to formation of continuous micro-cracks. Improved UCS occurred with increasing HC or extended thaw period as a result of reduced excess pore pressure.

- Stabilized mass with initially high UCS showed permanent loss in UCS without increase in HC value. This was due to increased brittleness, which caused discontinuity of hydraulic paths, which caused increased excess pore pressure.

- Open freeze-thaw system allows quick dissipation of the pore water and shortens the effect of thaw weakening. Closed system of freezing impedes the movement of pore water and prolongs the period for thaw weakening, which results in strength reduction.

- The knowledge of the effect of freeze–thaw cycles on the mechanical properties of the stabilized soils is very limited. This study proves that thaw consolidation (TC) has to
be considered in the current testing methods in order to get a better understanding of the impact of freeze–thaw processes. TC can be implemented either intermittently (i.e. between f-t cycles) or at the end of f-t cycles.

Acknowledgments

The authors would like to acknowledge Mr. Mats-Johan Rostmark at FriGeo Company for providing us with the dredged sediments for investigation. The Sustainable Management of Contaminated Sediments (SMOCS) project, Luleå University of Technology, Swedish Geotechnical Institution (SGI), Ecoolop Consultancy Company are hereby acknowledged for their technical and financial supports. Special thanks remain to laboratory technician Mr. Thomas Forsberg, Senior research engineer Kerstin Pousette for their help during laboratory experiments.

References


*Cold Regions Science and Technology*, 29, 135-151.


List of Tables

Table 1. Physical properties of studied dredged sediments: LOI is the loss of ignition on DS with particles size <= 2mm, Gs is the specific gravity, w is the average initial water content. LL is liquid limit. PL is the plastic limit, and ρ is the bulk density.

Table 2. Mineral composition for individual binder: FA for off-specified fly ash (Svensson and Andreas, 2012), GGBS for ground granulated blast furnace slag (Courtesy of SSAB), and BC for Byggcement (Holm et al. 2015).

Table 3. Design recipes utilized to prepare samples of stabilized dredged materials (SDM) for freeze–thaw tests.
List of Figures

Fig. 1. Particle size distribution for the studied DS after has been corrected for organic matter content and debris.

Fig. 2. Schematic view of design recipes utilized during this laboratory test study.

Fig. 3. A cross section view through a curing container showing the PVC tube, SDM, bottom and top filters, preloading weight, curing water level, PVC tubes, and bottom and top guard rails.

Fig. 4. Evolution of temperature in the SDM during (a) open five freeze–thaw cycles (b) one semi-closed freeze–thaw cycles for samples under UCS assessment. RT = Room temperature; TT = Temperature at the top of the sample; BT = Temperature at the bottom of the sample, and ST = Temperature of water saturated sand.

Fig. 5. Freeze–thaw process (a) Example of freeze–thaw cycle and required grace period for thaw consolidation. (b) visualized traditional freeze–thaw cycle and grace period for a complete freeze–thaw cycle. TT = Temperature at the top of the sample; BT = Temperature at the bottom of the sample, F-TT =Temperature of freezing/thawing air, and ST = Temperature of water saturated sand.

Fig. 6. Schematic diagram for testing and evaluation of unconfined compressive strength (UCS).

Fig. 7. Schematic diagram for hydraulic conductivity (HC) and unconfined compressive strength (UCS) testing and evaluations on A-BC and B-CB2 samples.

Fig. 8. Variations in average unconfined compressive strength (UCS) with number of freeze-thaw cycles during (left) open freeze–thaw condition (right) semi-closed freeze–thaw conditions.
Fig. 9. Measured hydraulic conductivity during open freeze–thaw cycles on samples A–BC and B–CB2.
Table 1. Physical properties of studied dredged sediments: LOI = loss of ignition on DS with particles size <= 2mm, Gs = specific gravity, w = average initial water content. LL = liquid limit. PL = the plastic limit, and ρ = average bulk density.

<table>
<thead>
<tr>
<th></th>
<th>w (%)</th>
<th>LL (%)</th>
<th>PL (%)</th>
<th>ρ (g/cm³)</th>
<th>LOI (%)</th>
<th>Gs</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-A</td>
<td>283</td>
<td>120</td>
<td>88</td>
<td>1.19</td>
<td>235</td>
<td>2.53</td>
</tr>
<tr>
<td>DS-B</td>
<td>356</td>
<td>122</td>
<td>85</td>
<td>1.17</td>
<td>413</td>
<td>2.37</td>
</tr>
</tbody>
</table>
Table 2. Mineral composition for individual binder: FA = off-specified fly ash (Svensson and Andreas, 2012), GGBS = ground granulated blast furnace slag (Courtesy of SSAB), and BC = Byggcement (Holm et al. 2015).

<table>
<thead>
<tr>
<th>Chemical compound (%)</th>
<th>FA</th>
<th>GGBS</th>
<th>BC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>21.0</td>
<td>31</td>
<td>63</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>42.8</td>
<td>34</td>
<td>18</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>9.5</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>MgO</td>
<td>3.5</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>K$_2$O</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Design recipes utilized to prepare samples of stabilized dredged materials (SDM) for freeze–thaw tests. w/b = water-binder ratio; w/c = water-cement ratio.

<table>
<thead>
<tr>
<th>DS</th>
<th>Binder</th>
<th>Dosage kg/m³</th>
<th>Ratio BC/FA/GGBS</th>
<th>w/b ratio</th>
<th>w/c ratio</th>
<th>Assumed water content (%)</th>
<th>Number of samples</th>
<th>Curing period (days)</th>
<th>Type of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>CB1</td>
<td>180</td>
<td>1:1:0.5</td>
<td>4.9</td>
<td>12.3</td>
<td>-</td>
<td>8</td>
<td>91</td>
<td>UCS</td>
</tr>
<tr>
<td>A</td>
<td>BC</td>
<td>260</td>
<td>1:0:0</td>
<td>4.4</td>
<td>4.4</td>
<td>160</td>
<td>4</td>
<td>28</td>
<td>UCS</td>
</tr>
<tr>
<td>A</td>
<td>BC</td>
<td>260</td>
<td>1:0:0</td>
<td>4.4</td>
<td>4.4</td>
<td>160</td>
<td>1</td>
<td>-</td>
<td>HC</td>
</tr>
<tr>
<td>B</td>
<td>CB1</td>
<td>180</td>
<td>1:1:0.5</td>
<td>5.2</td>
<td>13.0</td>
<td>-</td>
<td>8</td>
<td>91</td>
<td>UCS</td>
</tr>
<tr>
<td>B</td>
<td>CB2</td>
<td>320</td>
<td>1:0.5:0.5</td>
<td>2.8</td>
<td>5.6</td>
<td>160</td>
<td>8</td>
<td>50</td>
<td>UCS</td>
</tr>
<tr>
<td>B</td>
<td>CB2</td>
<td>320</td>
<td>1:0.5:0.5</td>
<td>2.8</td>
<td>5.6</td>
<td>160</td>
<td>1</td>
<td>-</td>
<td>HC</td>
</tr>
</tbody>
</table>
Fig. 1. Particle size distribution for the studied DS after has been corrected for organic matter content and debris.
86x65mm (150 x 150 DPI)
Fig. 2. Schematic view of design recipes utilized during this laboratory test study.
155x88mm (150 x 150 DPI)
Fig. 3. A cross section view through a curing container showing the PVC tube, SDM, bottom and top filters, preloading weight, curing water level, PVC tubes, and bottom and top guard rails.

400x245mm (72 x 72 DPI)
Fig. 4. Evolution of temperature in the SDM during (a) open five freeze–thaw cycles (b) one semi-closed freeze–thaw cycles for samples under UCS assessment. RT = Room temperature; TT = Temperature at the top of the sample; BT = Temperature at the bottom of the sample.
Fig. 5. Freeze–thaw process (a) Example of freeze–thaw cycle and required grace period for thaw consolidation. (b) visualized traditional freeze–thaw cycle and grace period for a complete freeze–thaw cycle. TT = Temperature at the top of the sample; BT = Temperature at the bottom of the sample, F-TT = Temperature of freezing/thawing air, and ST = Temperature of water saturated sand.
Fig. 6. Schematic diagram for testing and evaluation of unconfined compressive strength (UCS).

916x768mm (96 x 96 DPI)

M & P = Mixing and packing.
CP = Curing period.
UCS = Unconfined compressive strength.
CS = Control strength.
f-t = Freeze-thaw cycle(s).
TP = Thaw period.
GP = Grace period.
d = Days
CP = 50d for B-CB2; 28d for A-BC.
f-t = 1, 3, 5 for B-CB2; 3 for A-BC.
Fig. 7. Schematic diagram for hydraulic conductivity (HC) and unconfined compressive strength (UCS) testing and evaluations on A-BC and B-CB2 samples.

M & P = mixing and packing; f-t = freeze-thaw; d = days;

HC = Hydraulic conductivity measurement; HC0 = baseline values; UCS = Unconfined compressive strength
Fig. 8. Variations in average unconfined compressive strength (UCS) with number of freeze-thaw cycles during (left) open freeze–thaw condition (right) semi-closed freeze–thaw conditions.
186x163mm (150 x 150 DPI)
Fig. 9. Measured hydraulic conductivity during open freeze–thaw cycles on samples A–BC and B–CB2.

86x88mm (150 x 150 DPI)