Influence of low temperature curing and freeze-thaw-cycles on the stiffness of stabilised silt

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Abstract: *Silt is a highly frost susceptible soil. In moderate climate conditions in opposite to cold climates, it is common to improve silt and other fine-grained soils by mixing with hydraulic binder. Here, a laboratory study of a Swedish clayey silt stabilised with Petrit T, a by-product from sponge iron production is presented. The samples were cured at +4°C for 14, 28 and 90 days, representing conditions in northern Sweden. Further samples were exposed to 12 freeze-thaw-cycles as well as subsequent curing time. A third of the samples were cured under a surcharge, while for another third the surcharge has been applied during the freeze-thaw-cycles and subsequent curing. The last third had no surcharge. Focus is given here on the stress-strain-relations obtained during unconfined compression tests to establish the strength (UCS).*
The results show differences in both stiffness and strength, with lower values of both for the samples that had endured freeze-thaw-cycles. The results of the samples with surcharge show higher stiffness and strength than those without surcharge at the same testing time

Kurzfassung: *Feinkörnige weiche Böden werden in Ländern mit gemäßigtem Klima häufig mit hydraulischen Bindemitteln behandelt, um z.B. die Tragfähigkeit zu erhöhen oder die Frostempfindlichkeit zu verringern. Frost während der Erhärtungszeit beeinflusst die Erhärtungsreaktion hydraulischer Bindemittel und kann den Effekt der Verbesserung beeinflussen. Um den Einfluss einer niedrigen Lagerungstemperatur und Frost-Tau-Wechseln während der Erhärtung zu untersuchen, wurde eine Laborstudie durchgeführt. Probekörper eines schwedischen Schluffs wurde mit einem Recyclingbindemittel, Petrit T, stabilisiert. Die Erhärtung fand bei +4°C fur 14, 28 bzw. 90 Tage statt. Anschließend wurden einaxiale Druckversuche zur Aufzeichnung der Spannungs-Dehnungs-Kurve und zur Ermittlung der Druckfestigkeit durchgeführt. Weitere Proben bei gleicher Erhärtungszeit wurden zwölf Frost-Tau-Wechsel ausgesetzt. Zusätzlich wurden Proben untersucht, die nach zwölf Frost-Tau-Wechseln und einer weiteren Erhärtungszeit von 28 Tagen ausgesetzt wurden Ein Drittel der Proben hatte eine Auflast während der gesamten Zeit, ein Drittel für die Dauer der Frost-Tau-Wechsel und der Nacherhärtungszeit, das weitere Drittel hatte keine Auflast.Die Ergebnisse zeigen Unterschiede in der Steifig- wie auch in der Festigkeit. Proben ohne Frost-Tau-Wechsel erreichen die höchsten Festigkeiten im Vergleich zu Proben, die Frost-Tau-Wechseln ausgesetzt waren, Die Auflast hat einen deutlichen Einfluss auf die Festigkeit und Steifigkeit der Proben nach Frosteinfluss.*

1 Introduction

Silt is classified as frost susceptible because it cause frost heave or thaw weakening or both phenomena. The volume expansion of the pore water in transition to ice cause heaving while freezing. The heave caused by ice-lenses is the major problem. Ice lenses occur when the freezing temperature isotherm remains at the same level for a certain time and water is transported to this level so that more water freezes than what has been in the soil at that level before. In silt, water can be transported long way to the freezing zone through capillary transport. Thaw weakening occurs when the pore water thaws, but is trapped by the underlying ground, which may be frozen or slowly permeable. The pore pressure rises and this reduces the effective stress. As a consequence the bearing capacity is decreased. (Andersland and Ladanyi, 2004; Zeinali, 2018)

A common solution in Sweden to avoid these problems is to excavate silt and replace by coarser material before building constructions on top. The mass transport, the need for suitable replacement material, and the need to landfill the excavated material, are the major drawbacks of that solution. A beneficial technique to enhance the properties of the soil in place is the treatment with hydraulic binder. The new European standard for earthworks EN 16907-4 (2018a) includes, besides lime and cement, also binders like fly ash and granulated blast furnace slag or mixtures of those, so called hydraulic road binders. The binder material reacts with the water and with the clay particles in the soil and forms new minerals. The reaction as well as their products are similar to the hardening reaction in concrete. The new formed minerals connect soil particles together, which improves the engineering properties of the soil. (Bell, 1996; Lottmann et al., 2008; Al-Jabban, 2017; Rothhämel, 2018).

The technique of soil treatment with hydraulic binders is very common in regions with moderate climate. The reaction process of the binder is temperature-dependent: the higher temperature, the faster is the reaction (Åhnberg et al., 1995; Deschner et al., 2013). The most reference values in the literature are given for room temperature (+20°C +/-2K), but in Northern Europe this temperature is not relevant for the average soil temperature. The standard laboratory mixing test for Swedish Lime Cement Columns is therefore done by +7°C. A surcharge is usually applied on the lime cement columns to accelerate the settlements in the soil, but also to rise the strength in the columns. (SGF Report 4:95E, 1997).

Frost has an influence on improved soil since the properties of soil and the chemical reactions between the soil and the binder depend significantly on the water content. Several researchers have worked with the influence of frost on cement-stabilised soft soils and found that the strength after freezing and thawing is decreased but still several times higher than the one of the untreated material (among others: Kujala, 1989; Eskişar et al., 2015)

Two recent publications investigated the stabilised soil a certain time after the influence of freeze-thaw, Jamshidi and Lake (2015) for cement-stabilised silty sand and Tebaldi et al. (2016) for lime-stabilised clay. Both publications describe a healing potential or recovering of the UCS values at a given measured time after freeze-thaw.

The stiffness of a soil describes the deformation behaviour of a material and is usually defined by an elastic modulus. Wang et al. (2017) found that the stiffness of stabilised silt samples decreased with increasing number of freeze-thaw-cycles. The binder composition had an influence on the decrease rate: higher strength and ductility with fly ash-cement mixture compared to lime-cement mixtures or cement alone.

In the present study, the unconfined compressive strength (UCS) was used as indicator for the effect of low curing temperatures and freeze-thaw cycles on the cementitious reactions. The stiffness was evaluated from the stress-strain-curves measured during the UCS test. The curing temperature has an influence on the applicability of soil stabilisation methods in cold climate. Therefore the curing temperature in the present study was chosen to +4°C. The reported healing potential is interesting for the application of stabilisation in the frost-active part of the soil. This present study includes also a curing time at low temperature after 12 freeze-thaw-cycles.

2 Laboratory work

Samples were prepared from a natural soil from Gothenburg, Sweden. The soil consists of 16% clay, 55% silt and 29% fine sand. The natural moisture content (w_n) was 30%, the liquid limit (w_L) 37% and the plastic limit (w_p) 20%. The optimum moisture content (w_{opt}) is 12%, and the proctor density is 1.97 g/cm³. The soil is classified as a medium plasticity fine soil according to EN 16907-4 (2018b). The soil was mixed with Petrit T, a by-product from sponge iron production that is not commercially used as binder yet. An X-ray diffraction test (XRD) of Petrit T (provided by the manufacturer) shows dicalcium silicate (57%), calcium-silicon-aluminate (28%), quartz (11%) and calcium hydroxide (3%) as mineral components. The mineral part displays 74% of the whole mass, the rest consists of amorph carbon (21%) and iron (5%). The soil and the binder as well as the sample production are described more detailed in Al-Jabban et al. (2017), the binder in Rothhämel et al. (2019).

The soil, at its initial water content, was crumbled by hand to appr. 2 cm^3 siezed pieces. Petrit T (4% of dry mass of the soil) was added as dry powder and the materials were mixed for ten minutes in a machine. The mixture was filled in five layers in tubes (inner diameter 50mm) and compacted with a Proctor stamp: each layer with 25 blows, following a combination of the Swedish recommendations for soil stabilisation (Larsson, 2006) and the modified proctor density test (EN13286-2, 2010). Three samples were prepared from the same blend within one hour from adding the binder. The samples had a height of 100mm and remained in the tubes for the whole time until the UCS test.

The samples were stored vertically for three different curing times (14, 28 and 90 days) under cold conditions (+4°C). The samples were placed in individual plastic cups on a totally soaked sand bed with a visible water table. One third of the samples was tested without freeze-thaw-cycles, one third was exposed to twelve freeze-thaw-cycles and tested directly after the last thawing. The rest have been conducted under twelve freeze-thaw-cycles and then kept under similar curing conditions as before (+4°C) for another 28 days before testing. The temperature was measured continuously between sample and sand filter for some samples, to make sure that the thawing was completed before testing. One of the triplet samples had a surcharge from the beginning and one of the triplet samples had a surcharge during the freeze-thaw-cycles and the subsequent curing time. The samples were pressed out of the tubes with the help of a mechanical jack directly before testing. The UCS was tested according to EN ISO 17892-7 (2017) with a velocity of 1 mm/min. The stress was measured automatically and the stress-strain curves were plotted. The stiffness was determined both as maximum tangent modulus (E_{max}) and as secant modulus at half of the maximum strength value (E_{50}) in the stress-strain curve.

3 Results

The stress-strain-curves for the samples with binder are presented in figure 1 and for the samples without binder in figure 2. The row on top presents the samples with 14 days of curing time before the freeze-thaw-cycles, the middle row those with 28 days of curing and the row at the bottom in both figures those with 90 days of curing. The figures in the left column show the samples without freeze-thaw-cycles, the ones in the middle show the samples after the freeze-thaw-cycles, and the figures in the right column show the samples after the subsequent curing time. The dash-dot-lines symbolise the samples without surcharge, the dashed lines the samples with surcharge from the start of the freeze-thaw-cycles and the continuous lines the samples with surcharge during the whole time.

The general tendency for the samples with binder (figure 1) is that the strength and stiffness decreases from the upper left diagram to the lower right diagram: The 14- and 28-days-samples before the freeze-thaw-cycles show the highest strength and stiffness, the 90-days-samples after the recovering time the lowest strength and stiffness. The 14-days-samples after the recovering show higher strength than the 14-days-samples after the freeze-thaw-cycles. The 28-days-samples after the freeze-thaw-cycles and after the recovering show higher values for the samples with surcharge than without surcharge. The 90-days-samples show lower strength and stiffness before the freeze-thaw-cycles than the samples with less curing time. The values of final strength after the freeze-thaw-cycles are not much lower than before them.

The stiffness changes from more brittle for the younger samples without freeze-thaw-cycles to more ductile for the samples with longer curing time. A change in stiffness is visible for the 14- and 28-days-samples as they show higher stiffness at low strain rates, whereas the stiffness is lower for higher strain rates. This tendency is much lower for 90-days samples, where the difference in stiffness in the beginning is not as distinct.

The general tendency for the samples without binder (figure 2) is that the load deformation curves are almost straight lines except for the samples with

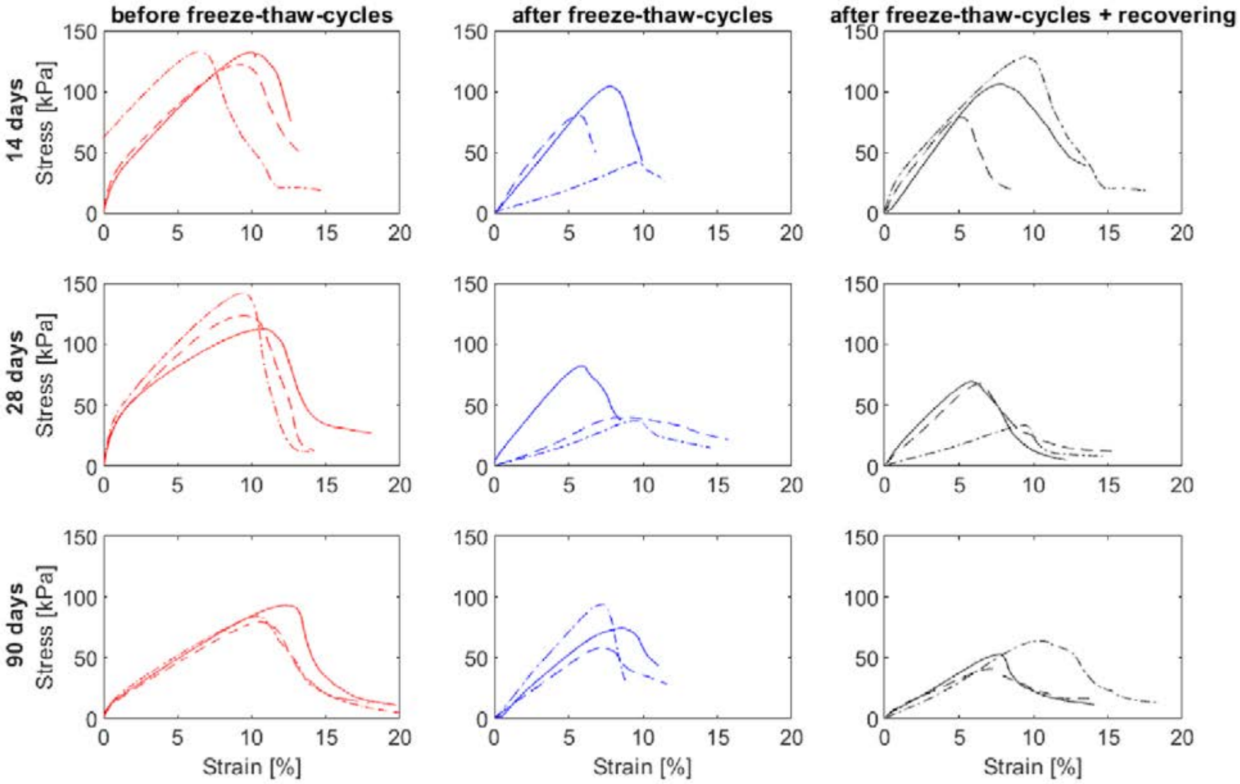

Figure 1: Stress-strain-curves for the samples with 4% of binder: continuous lines symbolise samples with surcharge from the beginning, dashed lines symbolise samples with surcharge from the start of the freeze-thaw-cycles and dash-dot-lines symbolise samples without surcharge. (Spannungs-Dehnungs-Kurven der Proben mit 4% Bindemittel: durchgezogene Linien symbolisieren Proben mit Auflast während der gesamten Zeit, gestrichelte Linien symbolisieren Proben mit Auflast ab Beginn der Frost-Tau-Zyklen und Strich-Punkt-Linien symbolisieren Proben ohne Auflast.)

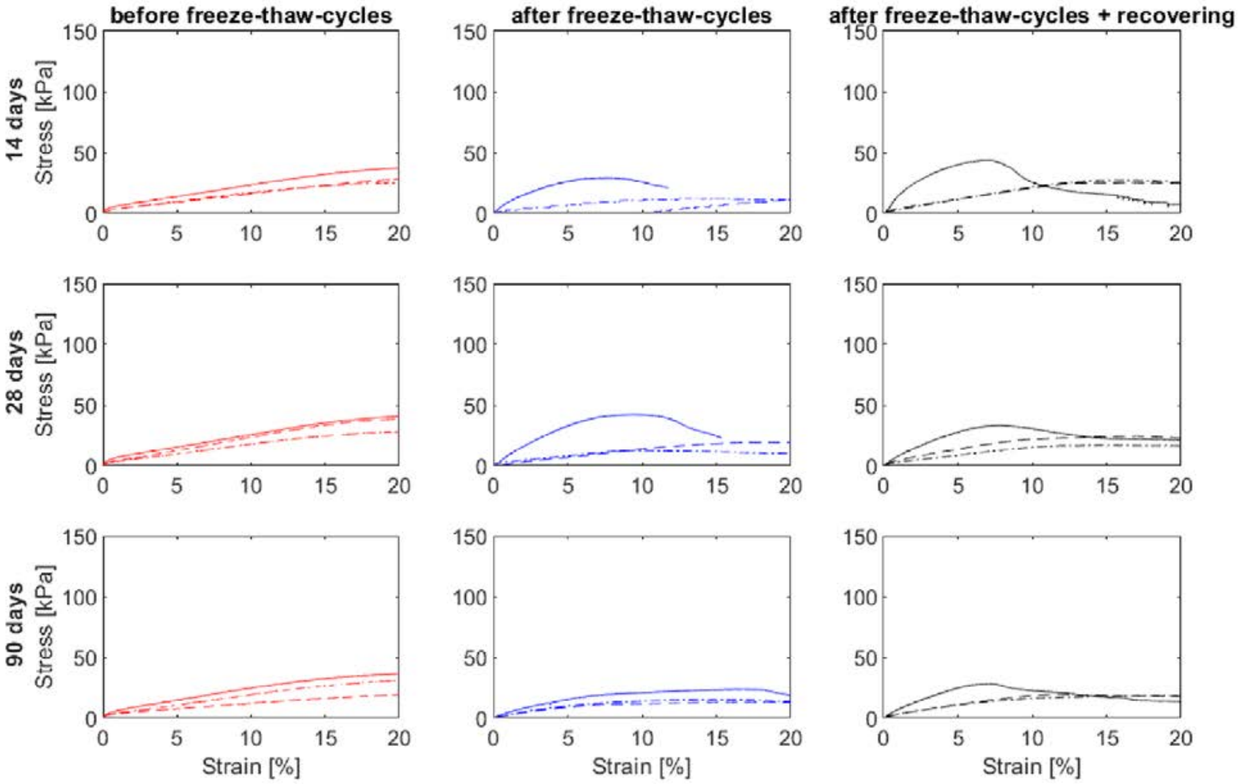

Figure 2: Stress-strain-curves for the samples without binder: continuous lines symbolise samples with surcharge from the beginning, dashed lines symbolise samples with surcharge from the start of the freeze-thaw-cycles and dash-dot-lines symbolise samples without surcharge. (Spannungs-Dehnungs-Kurven der Proben ohne Bindemittel: durchgezogene Linien symbolisieren Proben mit Auflast während der gesamten Zeit, gestrichelte Linien symbolisieren Proben mit Auflast ab Beginn der Frost-Tau-Zyklen und Strich-Punkt-Linien symbolisieren Proben ohne Auflast.)

surcharge from the beginning, which show a different strength and stiffness after the freeze-thaw-cycles and after the recovering. The values are in general much lower than for the samples mixed with binders.

The modulus of elasticity was calculated both as maximum tangent modulus (E_{max}) and as secant modulus at half of the maximum strength value (E_{50}). The results are shown in figure 3, to the left for the samples without binder, to the right for the samples with 4% of binder; on the top E_{50}, in the bottom E_{max}. Circles symbolise samples with surcharge from the beginning, triangles symbolise samples with surcharge from the start of the freeze-thaw-cycles and stars symbolise samples without surcharge. Red symbols stand for samples before the freeze-thaw-cycles, blue symbols for samples after the freeze-thaw-cycles and black symbols for samples after the recovering.

The tendency is that the moduli decrease with the age of the samples. However, the E_{50} of the samples without binder is about the same over time except for the samples with surcharge, which show higher values. The span is much wider for the E_{max} than for the E_{50}. The values of the E_{50} for the samples with binder are three to ten times higher than the values of the samples without binder.

4 Discussion

The expectations are (i) that the strength increase over time (ii) that the strength is lower after freeze-thaw-cycles, (iii) that the stiffness after freeze-thaw-cycles is lower than before, (iv) that a surcharge leads to higher strength and stiffness and (v) that the strength increase during recovering is higher for the younger samples (where more reactive material is left).

The strength of the samples after the freeze-thaw-cycles is lower than before the cycles, but still higher as without binder. The drop in strength is lower for the 90-days-samples. The strength values of the 90-days samples are significantly lower than the values of the 28-days samples. This is unexpected, as the strength is assumed to increase continuously with time. The composition of the binder in combination with the cold curing temperature is supposed to be the reason for this strength drop, as discussed in Rothhämel et al. (2019): The calcium-silicon-aluminate reacts in cold temperature to high-strength minerals, which do not stay stable in the

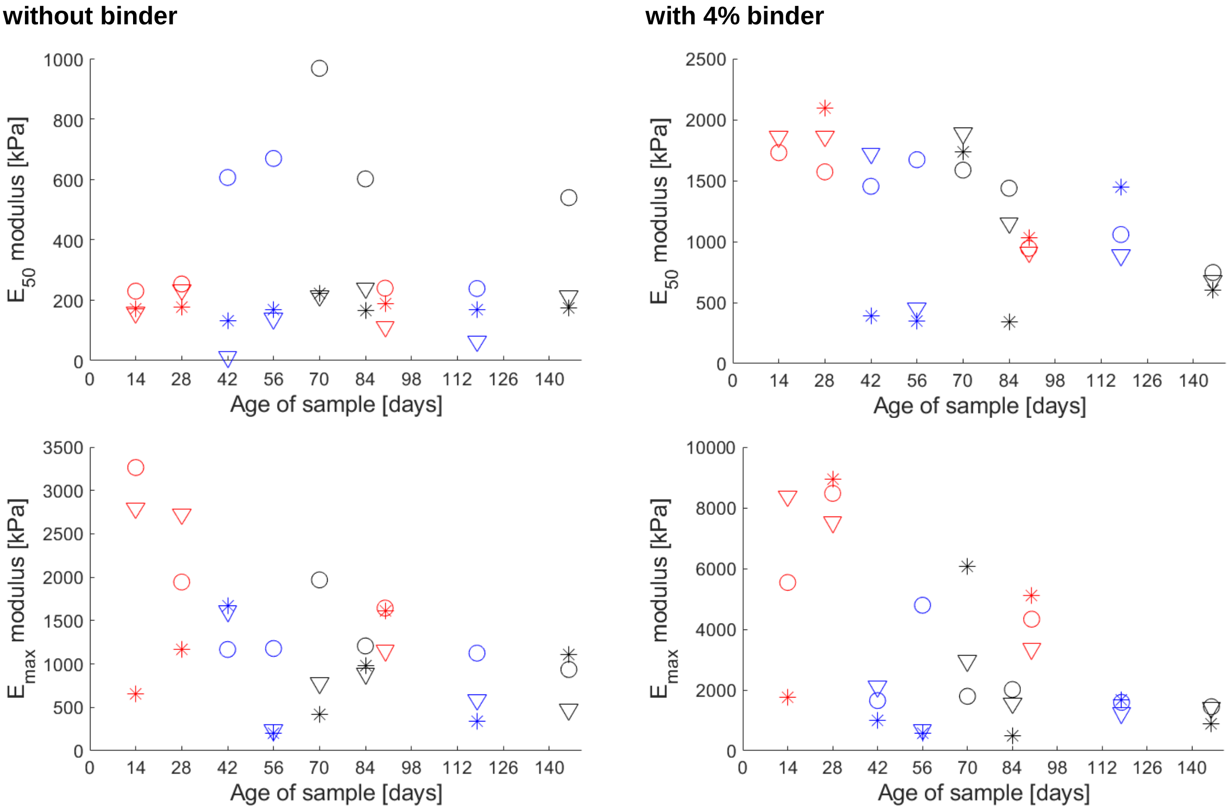

Figure 3: Modulus of elasticity: circles symbolise samples with surcharge from the beginning, triangles symbolise samples with surcharge from the start of the freeze-thaw-cycles and stars symbolise samples without surcharge. (Elastizitätsmoduln: Kreise symbolisieren Proben mit Auflast während der gesamten Zeit, Dreiecke symbolisieren Proben mit Auflast ab Beginn der Frost-Tau-Zyklen und Sterne symbolisieren Proben ohne Auflast.)

long term. Instead, a process called "conversion" takes place, where minerals with a more dense crystal structure are formed, resulting in a lower strength caused by the pores that remain in between the minerals (Hewlett and Lea, 2003). The "conversion" could also explain the lower strength of the samples with surcharge: the load during the conversion possibly destroy the structure more than in the samples without surcharge.

The stiffness after the freeze-thaw-cycles is lower than before for the samples cured for 14- and 28-days. The 90-days-samples show about the same or higher values of E_{50} after the freeze-thaw-cycles. The decreasing trend of the stiffness (E_{50}) of the stabilised soil with age of the sample is in opposite to the findings of Al-Jabban et al. (2017), where an increase in stiffness over time was found. The values of the stiffness in the beginning are about the same as found by Al-Jabban et al. (2017), but the values of the older samples differ. A possible explanation is that the stiffness of the stabilised samples is affected by the "conversion" process as well, as it seems to be case for the strength.

Without binder, the samples with surcharge from the beginning show higher values than the other samples at the same time of testing (continuous lines in figure 2). With binder, the samples with surcharge from the beginning show about the same strength after the recovering than the samples directly after the last thawing (continuous lines in figure 1). The strength of the samples with surcharge from the start of the freeze-thaw-cycles is lower compared to the samples with surcharge from the beginning. This difference is highest for the 14-days-samples. The surcharge and the time when it is applied is important. The samples without surcharge show the highest strength after recovering for both the 14- and the 90-days-samples.

A strength increase during recovering is visible for the 14-days-samples. The strength does not increase during recovering for the 90-days-samples.

5 Conclusion

The current study presents a laboratory investigation of a silt stabilised with a by-product originated binder, Petrit T. The samples were cured in low temperature (+4°C), to simulate natural conditions in cold regions, and exposed to 12 freeze-thaw-cycles as well as a subsequent curing time. The strength and the stiffness was evaluated from UCS-tests.

The results show lower values of both strength and stiffness for the samples that were exposed to freeze-thaw-cycles. The samples with short curing time before the freeze-thaw-cycles show higher strength values again after the recovering time. The samples with surcharge showed higher strength and stiffness values for the samples with 14 and 28 days of curing before the freeze-thaw-cycles, but not for the samples with 90 days of curing. The strength of the samples with 90 days of curing without freeze-thaw-cycles was generally lower than the others, which might be caused by the binder in combination with cold curing conditions.

The strength increase of the samples with binder is higher after the freeze-thaw-cycles and recovering compared to the natural soil, in general by factor two for the chosen binder content of 4%.

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