Laboratory and field investigation of cement-stabilized organic soil near flood-prone area

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Abstract. Cement stabilization of very high plasticity organic soils (gyttja) near flood-prone areas, is a key to constructing water-retaining structures with optimized foundation works. The company Geo has documented the strength of cement stabilized gyttja samples from the area Jyllinge Nordmark in Denmark, for Keller Funderingsteknik Danmark ApS, who have carried out the stabilization. The strength was determined by Unconfined Compressive Strength (UCS) tests, with support of Consolidated Undrained Triaxial (CU) tests and field vane tests to determine undrained shear strength of the stabilized soil. In the laboratory, specimens were prepared with five different cement contents (60, 80, 100, 125, 150 kg/m³) and the strength determined after curing times of 7, 28 and 91 days. To document the in-situ strength and correlate laboratory and in-situ measurements, two UCS tests and three undrained triaxial tests were carried out on intact specimens taken from the cement stabilized soil. The investigation showed a good correlation between cement content, water content, curing time and compressive strength. Further, comparison with similar tests from Sweden, where cement stabilization is a far more common method, shows good correlation to the Jyllinge Nordmark results.

1. Introduction
Climate changes and rise of sea level have made it necessary to establish flood protection in the area Jyllinge Nordmark, north of Roskilde in Denmark. The flood protection will consist of dikes and a water lock system where a stream from the inland meets Roskilde Fjord. The soil condition in the area is very poor and so soil improvement was chosen to increase the bearing capacity for the new constructions.

The soil at Jyllinge Nordmark comprised a 2-10 meter thick layer of gyttja (organic clay), that was required to have an increased undrained shear strength after 28 days of curing. The undrained shear strength was documented by laboratory tests and in-situ field vane tests.

The improvement method was Dry Deep Mixing (DDM), where the binder (the additive) can be a dry powder of cement, quick lime (CaO), blast furnace slag, fly ash, gypsum, bentonite or a combination of the different binders. The reaction process was aided with only the natural occurring moisture content. This method of stabilizing soil has found use in Sweden since the late 60’s and since spread to Finland and Norway. In Denmark there are still very few experiences with this method.

2. Soil stabilization at Jyllinge Nordmark
The stabilization units used at Jyllinge Nordmark consisted of a drilling rig and a shuttle, which carried the binder tank. See Figure 1. The drilling rig and shuttle had wide tracks, providing low ground pressure. The shuttle carrying the binder had a storage capacity of 12 ton and was pressurized with 4 to 12 bar.
The drilling rig was equipped with a mixing tool of the type “pinnborr” with three sets of wings. The diameter of the tool was 800mm. The stabilization in Jyllinge Nordmark was carried out in a pattern of interlocking columns, as seen in Figure 2. The depth of the columns were 2 – 10 meters equivalent to the thickness of the gyttja layer.

Binder was fed from the shuttle to the top of the drilling shaft and blown out by the outlet hole at the mixing tool by air pressure. Rotational speed of the drilling shaft was in the interval of 100 to 200 rpm, depending on the ground conditions. Downward movement was manually controlled by the operator and continuously corrected due to ground conditions and risk of hitting obstacles. Typical downward movement was 100mm/rotation. During downward movement, the shaft was pressurized by air to prevent water and soil from entering the drilling shaft. During upward movement binder was fed out by air pressure. The amount of binder was regulated by feed out valves in the shuttle. The upward movement was generally 15 to 25mm/rotation, depending on the required mixing work. The binder feed was shut off at 0.3m below the surface to prevent blow out in to the open air. The binder used for stabilizing the soil at Jyllinge Nordmark was Lavalkali Cement.

### 3. Laboratory tests

#### 3.1. Characterization of the gyttja

The material used for the laboratory tests consisted of four bulk samples from two locations at the site. The samples were taken from a depth of ~3m and ~5m. Classification tests were conducted on the samples for determination of basic properties prior to mixing with cement. Results are summarized in Table 1.

The samples have similarly geological description, with variation in amount of shells and plant fibres. The sample from B101-3m have lower liquid limit and plasticity index than the other three samples. This is also seen in Figure 3, where the Atterberg limits are plotted in the Casagrande diagram. The results plot below the A-line, indicating organic clay or gyttja. The soil samples had water content almost equal to or exceeding the liquid limit. The organic content determined by loss on ignition (LoI) varied from 13.9 to 20.9 %. All samples had pH above 5, which is considered the lower limit for stable cementation of the soil [1].
### Table 1. Results from classification tests on the four bulk samples of gyttja.

| Borehole | Depth [m] | Geological Description | Moisture content [%] | W_L [%] | W_P [%] | I_P [%] | LoI [%] | pH |
|----------|-----------|------------------------|----------------------|---------|---------|---------|--------|----|
| B101     | ~3        | Gyttja, sl. sandy, with shells and shell fragments, with few plant fibres, dark olive grey | 134 | 126 | 63    | 13.9   | 7.9  |
| B101     | ~5        | Gyttja, sl. sandy, rich in shells and shell fragments, dark olive grey | 183 | 207 | 91    | 15.2   | 7.6  |
| B102     | ~3        | Gyttja, sl. sandy, with few plant fibres, with shells and shell fragments, dark olive grey | 198 | 220 | 95    | 20.9   | 7.6  |
| B102     | ~5        | Gyttja, sl. sandy, with shells and shell fragments, with few plant fibres, dark olive brown | 215 | 208 | 79    | 15.1   | 7.7  |

![Figure 3. Results from Atterberg limits shown in Casagrande's diagram.](image)

3.2. **UCS tests on specimens stabilized in the laboratory**

For each sample, specimens for unconfined compressive strength (UCS) testing were prepared with five different cement contents (60, 80, 100, 125, 150 kg/m³). The binder used was Lavalkali Cement, CEM I 42.5N - SR5 (EA). Two specimens were prepared for double determination of the strength after curing times of 7, 28 and 91 days. The specimens were casted in a cylindrical mould with dimensions of approximately (height x diameter) 10.8cm x 5.1cm. Specimens hardened in the cylinders with only the natural water from the soil to help the curing process, to imitate conditions used in-situ. To simulate the expected in situ heat development, the specimens were set to cure two days at ~24˚C and the remaining time at 6˚C. The UCS tests were carried out according to DS/CEN ISO/TS 17892-7 with a shear rate of 1 mm/min, resulting in shear failure after 3-5 minutes. Bulk density and moisture content were determined after UCS testing by drying the specimens in an oven at 105˚C.
In Figure 4, Figure 5 and Figure 6 the undrained shear strength for the four different samples are shown as a function of the cement concentration after curing time of 7, 28 and 91 days, respectively. As expected, the undrained shear strength increases with increasing cement content. It is seen that specimens from B101 ~3m that consisted of gyttja with significantly lower plasticity index, had undrained shear strength comparable with the undrained shear strength determined for the remaining specimens. One specimen (B102~5m, cement content of 60 kg/m$^3$), showed significantly higher strength than what was seen from the other tests with similar cement content.

The mean undrained shear strength as a function of the cement content is shown in Figure 7.

![Figure 4. Undrained shear strength as a function of cement content after 7 days of curing.](image4)

![Figure 5. Undrained shear strength as a function of cement content after 28 days of curing.](image5)

![Figure 6. Undrained shear strength as a function of cement content after 91 days of curing.](image6)

![Figure 7. Mean undrained shear strength as a function of cement content.](image7)

In Figure 8, the prepared bulk density of the 120 UCS tests are shown as a function of the cement content. The figure shows that with increasing binder content, an increase in bulk density will occur. There are variations in bulk density for all samples and cement concentrations. The bulk densities of The high undrained shear strength of B102~5m with a cement content of 60 kg/m$^3$ is not explained by a correspondingly higher bulk density. The samples from BH101-3m has an overall larger range of bulk densities than the other three samples. The change in density across all five cement concentrations is approximately 3 times higher for BH101-3m than the other three samples.
Figure 8. Comparison of binder content and bulk density of all 120 samples prepared for UCS testing.

Figure 9 shows the undrained shear strength as a function of the bulk density for the tested material. As expected, the undrained shear strength increased with increasing bulk density.

Each cement concentration shows a development of strength over time. In Figure 10, each cement concentration is presented with the mean undrained shear strength of the four bulk samples. The concentration of 80 kg/m³ acts different from the other concentrations, showing almost no hardening from 28 to 91 days. After 91 days it is as hardened as the 60 kg/m³ concentration. From Figure 8 it shows that sample BH101-3m with concentration 80 kg/m³ is a clear outlier from other concentrations. This may explain the low hardening of this particular combination of sample and concentration, and also a bad mix compared to other mixes from sample BH101-3m.
Figure 10. Development of Undrained Shear Strength, mean cu, over time for each cement concentration.

From Figure 10 it is seen that 91 days of curing time with a cement concentration of 100 kg/m³ results in almost equal shear strength as 28 days with 150 kg/cm³. The hardening time shows increased effect with a higher cement concentration, except for a concentration of 80 kg/m³.

3.3. Tests on specimens stabilized in-situ

Intact material was taken from the soil stabilized in-situ using Shelby tubes and were brought to the laboratory for shear strength testing. Shelby tubes consist of an empty steel pipe, which is pushed in to the soil and filled with material. After filling, the tube is retrieved with intact material contained in the Shelby tube. A total of five Shelby tubes were retrieved.

Testing consisted of triaxial tests, UCS tests, laboratory vane tests and pocket penetrometer tests. The Shelby tubes taken from the soil stabilized in-situ contained material with varying amount of strength and where possible, specimens were taken for triaxial and UCS tests. The remaining material was used for laboratory vane tests and pocket penetrometer tests. The intact specimens were tested after ~28 days of in-situ curing.

The results from the UCS tests on specimens stabilized in-situ are summarized in Table 2.

| Specimen no. | Depth [m] | Moisture content [%] | Bulk density [g/cm³] | Undrained shear strength [kPa] |
|--------------|-----------|----------------------|----------------------|-------------------------------|
| 1            | 4.90      | 147                  | 1.24                 | 142                           |
| 2            | 3.60      | 132                  | 1.26                 | 23                            |

The triaxial tests were carried out as isotropically consolidated undrained tests according to CEN ISO/TS 17892-9:2004. The tests were conducted with four phases: installation, saturation, consolidation and shear. The consolidation stress imitated the in-situ stress, approximately 13 kPa. The shear phase was undrained with a constant rate of strain. The results are summarized in Table 3.

| Specimen no. | Depth [m] | Moisture content [%] | Bulk density [g/cm³] | Undrained shear strength [kPa] |
|--------------|-----------|----------------------|----------------------|-------------------------------|
| 3            | 3.80      | 132                  | 1.26                 | 40                            |
| 4            | 2.25      | 91                   | 1.36                 | 109                           |
| 5            | 3.90      | 175                  | 1.17                 | 18                            |
The results from all the index strength tests are shown in Table 4. For specimen no. 9 it was not possible to insert the vane in the sample, therefore a pocket penetrometer was used. However, it reached maximum capacity, indicating a strength above 2000 kPa. The tests displayed a significant difference in results, depending on where in the Shelby tubes the test was carried out, indicating the stabilization is not homogeneous on a scale of centimeters. The laboratory vane results on specimens 5, 7 and 8 is in coherence with results of the UCS tests prepared in the laboratory and tested after 28 days.

Table 4. Results from laboratory vane and pocket penetrometer tests on specimens stabilized in-situ.

| Specimen no. | Depth [m] | Undrained shear strength [kPa] |
|--------------|-----------|--------------------------------|
| 5            | 3.90      | 50                             |
| 7            | 4.00      | 92                             |
| 8            | 2.50      | 75                             |
| 9            | 2.80      | >2000                          |

It was clear both from the undrained shear strength and from visual inspection of the in-situ stabilized samples that there was a large scatter in the results depending on how much cement was locally present. This is also seen in Figure 11, where a photo of an in-situ stabilized sample is shown. The left hand side appears have high cement content, whereas the right hand side displays no calcareous parts, with a collapsed end and larger voids.

![Figure 11. Photo of in-situ stabilized sample prior to laboratory testing.](image)

The samples taken from the in-situ stabilized soil have comparable relation between the undrained shear strength and bulk density, as the specimens prepared in the laboratory. This is seen in Figure 12. Specimens UCS(b) and CU(c) are taken from the same Shelby tube and shows the same bulk density. The CU(c) test had a $c_u = 40$ kPa, and the corresponding UCS(b) a $c_u = 23$ kPa.
Figure 12. Undrained shear strength and bulk density of all UCS tests on laboratory-stabilized samples plotted with the results from the five in-situ stabilized specimens (a, b, c, d and e).

4. In-situ tests
The strength of the soil in the test fields were determined using the Swedish field vane method [2] and the Danish vane test [3].

The Swedish vane tests was conducted with vane sizes of 200 mm and 500 mm, where the vane is pushed into the soil at a fixed velocity and the force is measured. The set-up is shown in Figure 13.

In the Danish field vane test, the vane is pushed in to the bottom of a cleaned borehole and then turned at a fixed rotational velocity. The set-up is shown in Figure 14. Two vane sizes, V5 and V7.5 were used for these boreholes, corresponding to a vane size (diameter, height) of (50, 100) mm and (75, 150) mm, respectively.
Examples of results from the Swedish vane tests are showed in Figure 15 and Figure 16 with different cement content and curing time. The expected strength based on Swedish experience is shown. There is a good correlation with the expected strength.

**Figure 13.** Field vane test equipment according to the Swedish method.

**Figure 14.** Field vane test equipment according to the Danish method.

**Figure 15.** Swedish vane test of a soil stabilized with 84 kg/m$^3$ and a curing time of 7 days.

**Figure 16.** Swedish vane tests of a soil stabilized with 125 kg/m$^3$ and a curing time of 34 days.
Results from the Danish field vane tests are shown in Figure 17, Figure 18 and Figure 19 for curing times of 7, 28 and 90 days respectively. The size of the Danish field vane is small compared to the scale of the in situ cement stabilization. This results in large scatter in the undrained shear strength from the Danish field vane tests.

As observed in the laboratory tests on specimens stabilized in situ, there is a variation in undrained shear strength on a small scale. This results in large scatter when the measurements are conducted on small samples as done by the Danish field vane. However, due to the large size of the Swedish field vane, it measures an average of the soil resulting in less scatter of the undrained shear strength.

5. Conclusion
The homogenised specimens from the laboratory tests showed good correlation between the undrained shear strength, curing time, cement content and bulk density. The undrained shear strength of the specimens stabilized in situ showed similar correlation for the individual tests. However, there was large variation between the tests on specimens taken next to each other, indicating large variation in the achieved degree of cementation on a small scale.

The Swedish field vane tests similarly showed good correlation between undrained shear strength, curing time and cement content. Due to the large size of the Swedish vane, the variation in strength was significantly less than observed using the Danish field vane.

The laboratory and field measurements showed that it was possible to improve the undrained shear strength of Gyttja at Jyllinge Nordmark. However, the scale of measurement should be considered, as the large variation in the results was seen on the small samples compared to the scale of the in situ cement stabilization.

References
[1] Helen Åhberg et.al, 1995. Cement och kalk för djupstabilisering av jord, rapport no 48. Swedish Geotechnical Institute, SGI
[2] SGF Rapport 2:2000, Appendix B, Beskrivning av kontrollmetoder för kalk- och kalkcementpelare i fält.
[3] DGF Bulletin 14, Felthåndbogen. Referenceblad 1. Referenceblad for vingeforsøg.