STRENGTH DEVELOPMENT AND SHEARING BEHAVIOR OF CEMENT STABILIZED GYTTJA

Daniel F. Holdt-Olesen[1], Nicolas F. Holdt-Olesen[1], Christoffer O. Jensen[1], Kenny K. Sorensen[1], and Michael R. Lodahl[2]

KEYWORDS

Cement stabilization, organic soils, gyttja, shearing behavior, triaxial testing

ABSTRACT

This paper examines the shearing behavior of cement stabilized soil and the effect of curing time, curing temperature, and cement content on the strength and stiffness development through a series of triaxial tests. The soil used is a marine, postglacial, soft, organic, clayey, silty gyttja, extracted from Aarhus University's soft soil test site situated in Randers Harbor, Denmark. A total of 34 unconsolidated undrained (UU) triaxial tests were performed where cement contents of 75 and 150 kg/m^3, curing temperatures of 8 and 22 °C, and curing times from 1 to 56 days were examined. Furthermore, a total of 9 isotropically consolidated undrained (CIU) triaxial tests were performed on specimens with a cement content of 150 kg/m^3 that were cured for 7, 14, and 28 days and sheared after isotropic compression to effective stresses of 30, 60, and 90 kPa.

The results from the UU tests show that the undrained shear strength and the stiffness of the cement stabilized gyttja generally increases with the cement content and the curing time and that the relationship between the undrained shear strength and the curing time is described well by a logarithmic expression. Analysis of the maturity of the specimens using an equivalent 20 °C curing time indicates that specimens would reach the same strength as maturity develops. In the CIU triaxial tests, the stress path reaches the tension cut-off without failing, indicating a tensile strength in the material. The cement stabilized gyttja obtains effective friction angles in the range of 30-33° with an effective cohesion that increases with the curing time. The observed tendencies from the performed laboratory tests match well with findings from the existing literature.

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[1] Department of Civil and Architectural Engineering, Aarhus University

[2] COWI A/S, Transport Infrastructure, DK North

1. INTRODUCTION

Dealing with soft organic soil deposits is a significant challenge when planning large infrastructure projects such as roads, railways, and port facilities. The soft soil is traditionally excavated and replaced with transported materials. This process results in large CO_2-emissions and requires large amounts of sand and gravel materials which are becoming scarce resources [1].

One method to minimize the CO_2-emissions and material consumption when encountering soft soils deposits for large infrastructure projects is the use of cement stabilization. Cement stabilization of soft soils such as gyttja is a soil stabilization technique that eliminates the need for removal and replacement of soft soils with transported materials. Instead, the existing soft soil can be improved on site by adding cement and thereby increasing the strength and stiffness of the soil. Upon the addition of cement, chemical reactions occur between the cement and the water present in the soil forming cementitious products such as calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H) that bind the soil particles together [2]. The technique of cement stabilization is common practice in Sweden, Norway, and Finland but is rarely used in Denmark, where only a handful of projects in the last couple of years have used cement stabilization [3].

This study aims to investigate the shearing behavior of cement stabilized gyttja through a series of triaxial tests where the effect of curing time, curing temperature, and cement content is examined. Cement contents of 75 and 150 kg/m^3 are investigated, and the specimens have been cured at either 8 °C or 22 °C. The curing times investigated for the triaxial tests are 1, 3, 7, 14, 28, and 56 days.

2. TESTING MATERIAL AND SPECIMEN PREPARATION

The soil used for the experimental tests in this project is a marine, postglacial, soft, organic, clayey, silty gyttja, which has been extracted at a depth of 2 m from Aarhus University's soft soil test site situated at Randers Harbor, Denmark (UTM32E89 X: 565577 (m) Y: 6257802 (m)). The soil has a grey and slightly green color and contains numerous shells and shell fragments. Table 1 shows the determined classification parameters for the natural gyttja.

Table 1. Soil classification parameters - natural gyttja

Soil classification parameters			
Unit weight [kN/m^3]	15 [4]	Organic content [%]	7.7
Water content [%]	106 - 119	Undrained shear strength [kPa]	21 [4]
Plastic limit [%]	45	Clay fraction [%]	38.3
Liquid limit [%]	102	Silt fraction [%]	57.5
Plasticity index [%]	57	Sand and gravel fraction [%]	4.2

The natural water content was generally just above the liquid limit, and the liquid limit has been determined in accordance with DS/EN ISO 17892-12:2018 using the fall cone method, while the plastic limit is determined as the water content where a thread of 3 mm in diameter starts to crumble. The organic content has been determined based on the loss on ignition, and the particle size distribution is determined by a hydrometer analysis combined with dry sieving.

Cylindrical specimens with the dimensions 100 × 50 mm (H/D=2) were used for the triaxial tests performed in this study. The preparation procedure of the specimens is inspired by the guidelines in Helle et al. [5]. All specimens were prepared at the natural moisture content of the gyttja.

The natural gyttja was homogenized and remolded by stirring it in a mixer for 2 × 30 seconds. The cement was added as dry powder, and the mixing procedure of 2 × 30 seconds was then repeated. The cement used in this project is called FUTURECEM cement from Aalborg Portland A/S, which is a type of Portland cement produced with a reduced clinker content, which means that the CO_2-emissions in the manufacturing process can be reduced up to 30 %. Cement contents of 75 and 150 kg/m^3 were used in this study. After the mixing of the gyttja and the cement, the stabilized soil was manually compacted into acrylic cylindrical molds using a wooden muddler. The soil was compacted in 6 layers of approximately the same height, and each layer was scored to ensure bonding between the layers.

The quality and the uniformity of the compaction was monitored by comparing the weight of the compacted specimens. A maximum deviation of 2.1 % in weight was measured for specimens with a cement content of 75 kg/m^3, while a maximum deviation of 4.0 % was measured for specimens with a cement content of 150 kg/m^3. The small deviations in the weight of the compacted soil indicate that the chosen compaction method ensured consistent and satisfying results.

During curing, the specimens were placed individually inside two closed plastic bags with a damp cloth on top of the sealed specimen to ensure a relative humidity of 100 %. The specimens were cured at either room temperature corresponding to approximately 22 °C or at 8 °C in the refrigerator. The gyttja used for the specimens that were cured at 8 °C had been stored in a refrigerator for a minimum of 24 hours prior to mixing.

3. EXPERIMENTAL PROGRAM AND TEST METHODS

A series of 34 unconsolidated undrained (UU) triaxial tests were performed to analyze the influence of the curing time, curing temperature, and cement content on the strength and stiffness development for the cement stabilized gyttja. Due to the partially saturated nature of the cement stabilized specimens, all of the UU tests were performed at a confining cell pressure of 100 kPa.

Additionally, a total of 9 isotropically consolidated undrained (CIU) triaxial tests were performed to determine the effective strength parameters and investigate the shearing behavior of the cement stabilized gyttja in more detail at low to intermediate stress levels of 30, 60, and 90 kPa. Full saturation of the specimens was ensured by applying a high back pressure of 760 kPa for 24 hours prior to testing resulting in B-values in the range of 0.88-0.96. For specimens that did not obtain a B-value exceeding 0.95, the B-value for three cell pressure increments did not show any significant increase and the specimens were therefore assumed to be fully saturated. Table 2 shows the experimental program for the performed triaxial tests.

Table 2. Experimental program for UU and CIU triaxial tests (*duplicates have been performed)

UU tests	**Curing times in days**					
	1	3	7	14	28	56
8 °C – 75 kg/m^3	X*	X	X	X	X*	X*
8 °C – 150 kg/m^3	X	X	X	X	X*	X*
22 °C – 75 kg/m^3	X	X	X	X	X	X*
22 °C – 150 kg/m^3	X*	X*	X	X	X*	X*
CIU tests						
22 °C – 150 kg/m^3 (30 kPa)	-	-	X	X	X	-
22 °C – 150 kg/m^3 (60 kPa)	-	-	X	X	X	-
22 °C – 150 kg/m^3 (90 kPa)	-	-	X	X	X	-

4. RESULTS AND ANALYSIS OF THE UU TRIAXIAL TESTS

To analyze the development in undrained shear strength of the tested specimens, the undrained shear strength is plotted against the curing time. The data is fitted with the following logarithmic expression proposed by Mitchell [6] to better visualize the tendencies.

$$c_u = c_u(d_0) + K \cdot \log\left(\frac{d}{d_0}\right) \tag{4.1}$$

Where $c_u(d_0)$ is the undrained shear strength at the curing time of d_0 days, and K is an empirical factor. The factor K has been determined as the value that provides the best fit for the test data and the factor is found to be affected by both the curing temperature and cement content. A reference curing time of $d_0 = 28$ days is used. Figure 1 shows that the logarithmic expression provides a reasonable fit for the four test series except at low curing times and for the two specimens cured for 56 days at 8 °C. These two specimens obtain a significantly larger strength than expected. This could be explained by an error in the sample preparation procedure, where the soil used for specimens cured at 8 °C for 56 days was not precooled to 8 °C. From Figure 1 it is evident that the addition of cement to the gyttja ensures a significant increase in the undrained shear strength compared to the natural gyttja. The figure also shows that the undrained shear strength increases with an increase in the curing time and an increase in the cement content. This is explained by new cementitious materials being formed with time from the hydration and pozzolanic reactions, and a higher cement content results in the production of more C-S-H gel, which binds the soil particles together and increases the strength.

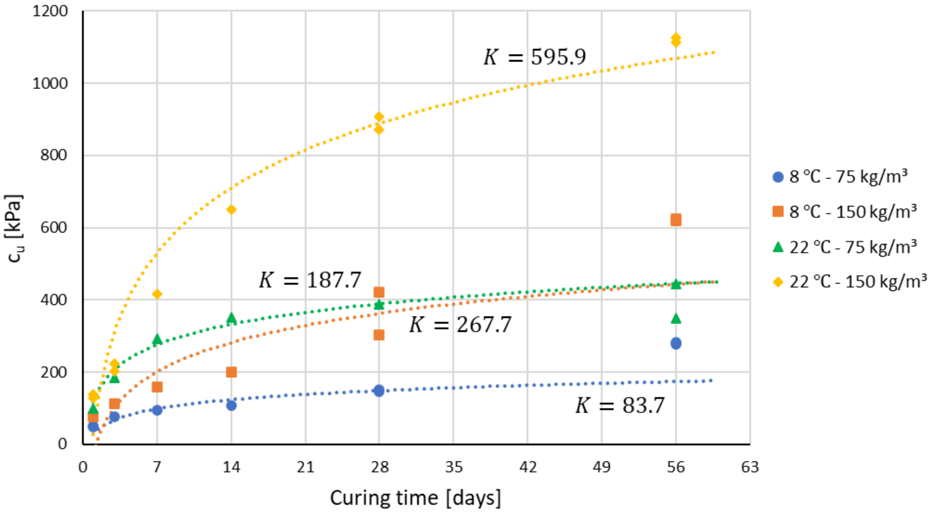

Figure 1. Undrained shear strength vs. curing time - UU triaxial tests

From the slope of the fitted curves, it is evident that the largest increase in the undrained shear strength takes place at the beginning of the curing period up to about 7 days of curing. After 7 days of curing, the slope of the curves gradually decreases. However, the slopes of the fitted curves for the four test series never reach zero and are always positive, indicating that the chemical reactions were still taking place even after 56 days of curing. Figure 1 also shows that specimens cured at 22 °C generally obtain a notably higher undrained shear strength than specimens cured at 8 °C. The curing temperature affects the rate of the chemical processes taking place as a higher temperature will speed up the chemical processes, resulting in a faster rate of strength increase with time [7]. Based on the ratios of K-values, the results indicate that the influence of curing temperature is independent of cement content, and that the influence of cement content is independent of curing temperature.

Maturity of tested specimens

In concrete technology, the maturity is measured as the equivalent curing time at 20 °C. A similar expression for the equivalent 20 °C curing time of cement stabilized soil, t_{eq}, is proposed by Åhnberg and Holm [8] and modified by Vervoorn and Barros [9].

$$t_{eq} = \frac{\left(20 + K_t(T_c - 20)\right)^4}{\left(20 + K_t\left(T_{ref} - 20\right)\right)^4} \cdot t_c \tag{4.2}$$

Where K_t is an empirical factor not to be confused with the factor K from equation (4.1), where a value of 0.5 provides the best fit for Swedish soil types [8]. T_c is the actual curing temperature in °C, T_{ref} is the reference temperature of 20 °C, and t_c is the actual curing time in days. The factor K_t was found to be influenced by the cement content. For the cement content of 75 kg/m^3, $K_t = 0.7$ was found to be suitable, while $K_t = 0.5$ was found to provide a good fit for the higher cement content of 150 kg/m^3. The expression originally proposed by Åhnberg [10] and modified by Helle et al. [11] in equation (4.3) is used to describe the development in undrained shear strength as a function of the equivalent 20 °C curing time.

$$c_u = 0.3 \cdot \ln\left(t_{eq}\right) \cdot c_{u.28} \tag{4.3}$$

Where $c_{u.28}$ is taken as the undrained shear strength after 28 days of curing for the curing temperature of 22 °C in this study. The undrained shear strength is plotted against t_{eq} and fitted with equation (4.3) in Figure 2.

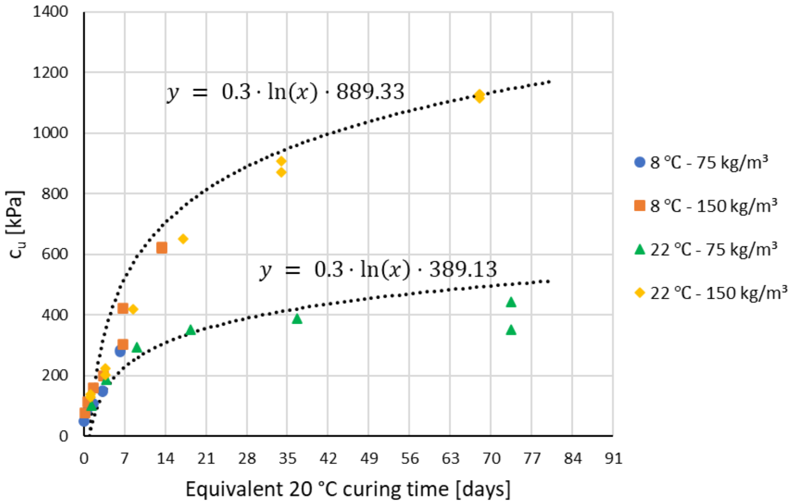

Figure 2. Undrained shear strength vs. equivalent 20 °C curing time - UU tests

Figure 2 shows that the development in undrained shear strength against the equivalent 20 °C curing time follows the logarithmic expression from equation (4.3) quite well. The graph also indicates that the reason for why specimens cured at 8 °C have not reached the same strength as specimens cured at 22 °C is the different level of maturity reached due to the chemical reactions taking place being retarded at lower curing temperatures. However, the results suggest that specimens cured at 8 °C would reach the same strength and maturity as specimens cured at 22 °C for extended curing times.

The development in undrained shear strength for the performed UU tests, excluding the two outliers cured for 56 days at 8 °C, is now normalized with respect to the 28-day strength and compared with similar studies found in the literature. Tanderup [12] has investigated the undrained shear strength of FUTURECEM cement stabilized Aalborg gyttja with a cement content of 150 kg/m^3 and cured at 20 °C using CIU triaxial tests. Åhnberg [10] has investigated the unconfined compressive strength of cement stabilized Holma gyttja and Löftabro clay with a cement content of 100 kg/m^3 and specimens cured at 8 °C. The cement type used by Åhnberg [10] is a type of Portland cement commonly used in Sweden. Figure 3 shows the comparison of the normalized strength with results found in the literature.

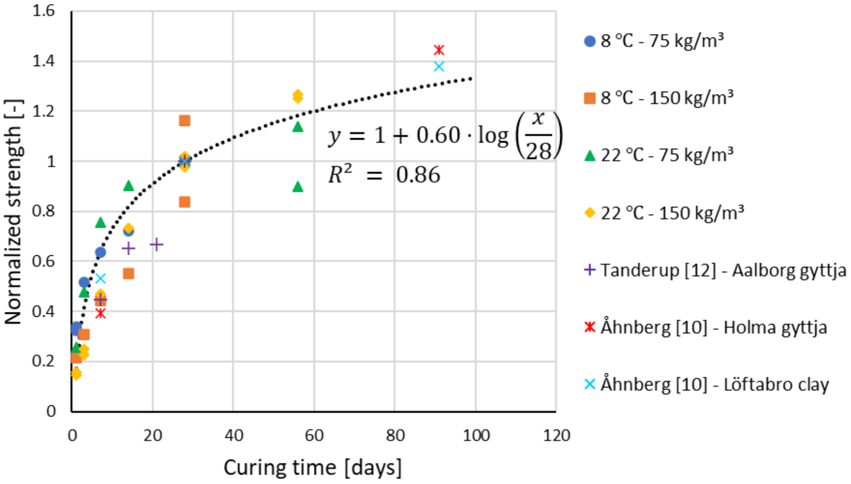

Figure 3. Normalized 28-day strength vs. curing time - comparison with the literature

The figure shows that when normalizing the strength of cement stabilized soil with the 28-day strength, the strength development follows the same trend relatively well regardless of cement content, soil type, curing temperature, and test type.

Secant modulus

The same overall trends observed in the development of the undrained shear strength are also observed for the secant modulus, E_{50}, which is determined as the slope between the origin and the point on the deviator stress vs. axial strain curve, where 50 % of the maximum deviator stress is mobilized. In Figure 4, the secant modulus is plotted against the undrained shear strength and fitted with a linear regression passing through the origin. Figure 4 shows a good proportional correlation between the secant modulus and the undrained shear strength independent of curing temperature and cement content with a slight tendency of increasing E_{50}/c_u ratio at higher values of the undrained shear strength. This correlation applies to the tested gyttja and cannot necessarily be expanded to other soil and test types.

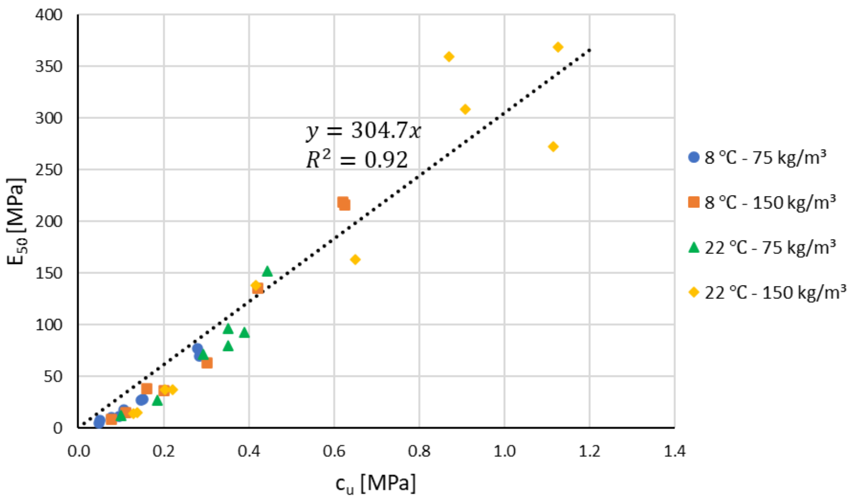

Figure 4. Secant modulus vs. undrained shear strength - UU triaxial tests

5. RESULTS AND ANALYSIS OF THE CIU TRIAXIAL TESTS

For all the performed CIU triaxial tests, a rather interesting stress-strain behavior is observed that was not present in the UU triaxial tests. After reaching an initial peak in the deviator stress at around 1-1.3 % axial strain for the performed tests, the deviator stress decreases shortly, whereafter it increases again and is relatively constant until the end of the test. A cement content of 150 kg/m^3 has been used for the CIU triaxial tests. Figure 5 shows the deviator stress and excess pore water pressure plotted against the axial strain for the specimen that has been cured for 14 days and sheared after isotropic compression to an effective stress of 60 kPa.

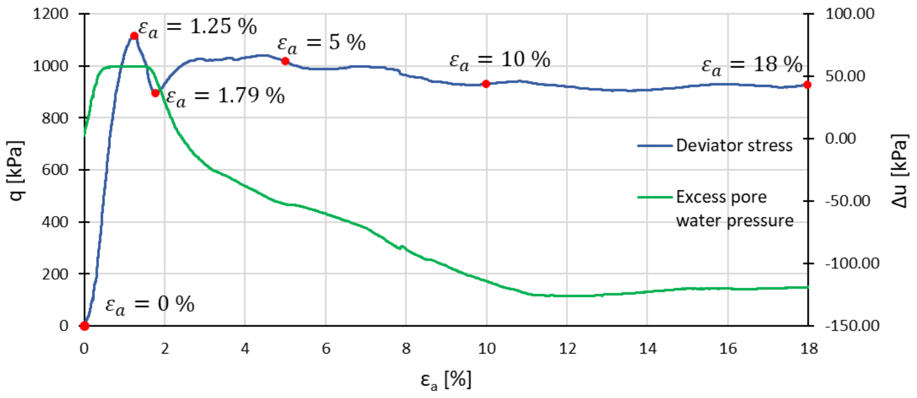

Figure 5. Deviator stress and excess pore water pressure vs. axial strain - 14 days of curing, isotropically consolidated to 60 kPa in effective stress, and a cement content of 150 kg/m^3 - CIU triaxial test

Initially, a buildup of excess pore water pressure is observed followed by a plateau around the peak deviator stress where there is no change in Δu. After the peak, a negative excess pore water pressure is developed indicating a tendency to dilate. To analyze the failure mode, still images are pictured in Figure 6 for axial strains corresponding to the axial strains highlighted in Figure 5.

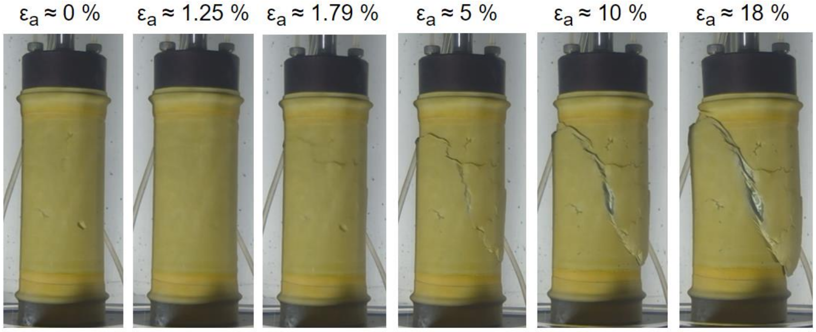

Figure 6. Stills from shearing phase - 14 days of curing, isotropically consolidated to 60 kPa in effective stress, and a cement content of 150 kg/m^3 - CIU triaxial test

Figure 6 shows no visible failure mechanism at 1.25 % axial strain corresponding to the peak deviatoric stress. At 1.79 % axial strain, the first signs of a visible failure mechanism are observed. This failure mechanism develops into a single shear plane at larger strains. As proposed by Lee et al. [13], the mobilized strength and stiffness of the specimen up until the peak is governed by cementitious materials that bond the soil particles together. After the peak, a gradual breakdown of the internal structure will then take place where the cementitious bonds between the soil particles are broken down. When a clearly defined shear plane is formed, the shearing of the specimen is governed by the friction between the two slipping halves of the specimen as opposed to the cementitious bonds.

Effective strength parameters

The effective strength parameters are determined by plotting the stress paths for specimens at the same curing time together. A straight line is then fitted to the data. Figure 7 below shows the stress paths for the three tests cured for 28 days and the fitted straight line. As the stress path prior to peak failure state has a slope of approximately 3, which corresponds to an effective friction angle of 90° and zero effective cohesion, it can be concluded that the tension cut-off has been reached. According to Åhnberg [10], it is likely for specimens consolidated at a low confining stress to reach the tension cut-off.

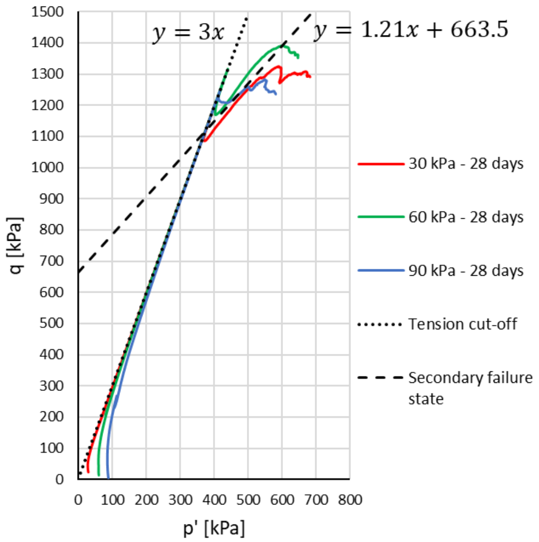

Figure 7. Deviator stress vs. effective mean stress - 28 days of curing, and a cement content of 150 kg/m^3 - CIU triaxial tests

Table 3 shows the effective strength parameters determined for the secondary failure state at large strains past the initial peak.

Table 3. Effective strength parameters - cement stabilized gyttja (150 kg/m^3)

Curing times [days]	$\phi'_{secondary}$ [°]	$c'_{secondary}$ $[kPa]$
7	31.9	117
14	33.2	221
28	30.2	319

For the secondary failure state, the effective cohesion increases with the curing time, but the friction angle does not change much and does not seem to be affected by the curing time. This indicates proportionality between the undrained shear strength and the effective cohesion. Significantly higher undrained shear strengths are observed in the UU triaxial tests compared to the CIU triaxial tests. The likely reason for this could be suction induced by unsaturated conditions in the UU triaxial tests.

6. DISCUSSION: LABORATORY VS. IN-SITU

The strength development of cement stabilized soil is largely influenced by the mixing procedure and the homogeneity obtained for the stabilized soil. Generally, the strength increases with homogenization, as the cement and the cementitious gels produced in the hydration are more evenly distributed in the soil [14]. Cement stabilized specimens mixed in the laboratory are usually more homogenous than what is achievable in the field [15]. This results in the strengths obtained in the laboratory being higher than what is normally obtained in the field. When comparing laboratory mixing with mixing in the field, it is important to keep in mind that the homogeneity achieved in the field can vary a lot depending on the soil type, the equipment used, and the overall in-situ mixing procedure [3]. Even for laboratory testing, the strength obtained can vary based on the exact mixing, compaction, and curing procedure [5]. For these reasons, it would be necessary to compare the tests on laboratory specimens with tests on in-situ mixed soil to predict the in-situ strength and stiffness. The curing temperature of cement stabilized columns in the field will also vary depending on the air temperature, depth below ground level, and the heat generated from the chemical reactions. When cement stabilizing in-situ, a significant increase in the temperature is observed for cement stabilized columns, which increases the rate of the chemical reactions. For cement stabilized specimens prepared in the laboratory, however, the effect of heat generation is negligible [10].

7. CONCLUSION

The results from the performed triaxial tests show that cement stabilized specimens with a cement content of 150 kg/m^3 obtain a significantly higher undrained shear strength and stiffness than specimens with a cement content of 75 kg/m^3. For both cement contents, the shear strength increases with an increase in the curing time and the correlation is described well by the logarithmic relationship proposed by Mitchell [6]. Compared to the natural gyttja, a significant increase in the undrained shear strength is observed for both cement contents. Furthermore, it is observed that specimens cured at 22 °C obtain higher shear strengths than specimens cured at 8 °C. An investigation of maturity using the equivalent 20 °C curing time indicates that specimens cured at 8 °C will reach the same shear strength as specimens cured at 22 °C as they mature. The low temperature retards the chemical reactions and makes them occur at a slower rate. The tendencies found for the strength and stiffness development match well with the findings from existing literature. Stress paths from the CIU triaxial tests indicate that the initial peak failure line corresponds to the tension cut-off. The fact that the specimens do not fail when reaching the tension cut-off indicates that the material has a tensile strength due to the cementitious bonds. The secondary failure state shows effective friction angles of 30-33° that do not change significantly with the curing time, and an effective cohesion that increases with the curing time similar to results from the literature [10], [6].

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