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# Modification-Stabilization of Clayey Silt Soil Using Small Amounts of Cement

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## Abstract

This paper presents the effects of using a small percentage of cement to stabilize clayey silt with a low organic content. Cement was added at percentages of 1, 2, 4 and 7% by dry weight. The physical and mechanical properties of the treated and untreated soil were evaluated by laboratory tests including tests of consistency limits, unconfined compressive strength, soil density, solidification and pH values. These tests have been conducted after 7, 14, 28, 60 and 90 days of curing time. Workability is defined as how easily the soil can be control or to handle physically. Results showed that the engineering properties of the clayey silt were improved. The soil exhibited better workability directly after treatment, and the workability increased with time. Soil density increased, while water content decreased, with increasing cement content and longer curing time. The pH value was immediately raised to 12 after adding 7% cement content, and then it gradually decreased as curing time increased. An increase of unconfined compressive strength and stiffness was observed, while strain at failure decreased. A gradual change in failure mode from ductile behavior to brittle failure was observed. The findings are useful when there is a need for modification and stabilization of clayey silt in order to increase the possibilities for different use which will reduce transportation and excavation.

**Keywords:** Stabilization, small amounts, cement, secant modulus, workability, solidification, pH value.

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# 1 Introduction

Ground improvement is widely used to modify and improve the engineering properties of soft soils, i.e. soils with low shear strength, stiffness and workability [1]. Cement is the most commonly used agent since the modern application of soil stabilization [2].

Numerous studies have been conducted on cement stabilization in a broad range of soils treated with high cement content (>10 % of soil dry weight). The most desirable outcomes of cement treatment are stronger and stiffer soil showing reduced plasticity and enhanced soil strength [3-13].

Generally, soil–cement reactions (hydration and pozzolanic reactions) improve the engineering properties of treated soil by producing primary and secondary cementitious materials [14]. A hydration reaction occurs rapidly and produces three types of primary cementitious materials; calcium-silicate hydrate (CSH) in the forms ($C_2SHx$, $C_3S_2Hx$), calcium-aluminate-hydrate CAH in the forms ($C_3AHx$, $C_4AHx$) and hydrated lime $Ca(OH)_2$ is deposited as a third cementitious product. Here, C, S, A, H are the abbreviations for calcium (CaO), silicate ($SiO_2$), aluminate ($Al_2O_3$) and water ($H_2O$) respectively. Secondary cementitious materials are produced by the pozzolanic reaction between hydrated lime and alumina and silica from clay minerals and provide additional cementitious products of CSH and CAH [15-17].

Several factors control the amounts of cement needed for stabilization such as, soil type, water content, organic content and targeted soil properties [18, 19]. In most of the reported studies, only high cement amounts were used.

In contrast, some recent studies have been conducted on the benefits of using a smaller percentage of cement (less than 10%) to decrease the environmental impact of stabilized soils and the costs, in addition to improve the strength, stiffness and workability of the treated soil [20-23]. Therefor there is the need to study the behavior of treated soil with smaller cement content (e.g., less than 7%).

This study presents an extensive experimental program to examine the effects of using a small amount of cement to modify and improve the engineering properties of low organic clayey silt. Tests of consistency limits, unconfined compressive strength, and pH tests were conducted on the treated soil with varied cement contents and curing periods to investigate the improvement in strength, stiffness and workability of the soil after treatment.

# 2 Experimental Programs

A series of unconfined compression (UCS), consistency limits, and pH tests were conducted on untreated and stabilized slight organic clayey silt with varied cement content and curing periods. Unconfined compression tests (UCS) were performed to investigate the enhancement of soil strength before and after treatment. Workable soil is a term refers to the soil which can easily be handled and compacted homogeneously. Consistency limits tests were conducted to investigate the improvement in soil workability directly after treatment, and over time, by measuring the reduction in the plasticity index.

Finally, pH tests were conducted to investigate the effects of small amounts of cement on the alkalinity of the soil immediately after treatment and over time, which can give an indication on the progress of the of soil-cement reactions. The solidification of the treated soil was investigated by measuring the reduction in water content directly after one hour of treatment and over time. In addition, density, strains at failure, stiffness and stress-strain behavior of treated soil were measured and evaluated at different cement percentages and curing times. Table 1 summarizes the main testing program.

Table 1: Testing program used.

| **Testing program** | **Cement content %** | **Curing time (days)** | **Number of samples per cement content** | | | | | **Compaction method** |
|---|---|---|---|---|---|---|---|---|
| | | | **0%** | **1%** | **2%** | **4%** | **7%** | |
| Consistency limits | **0**<br>**1**<br>**2**<br>**4**<br>**7** | 0 3 7 14 28 60 90 | 1 | 7 | 7 | 7 | 7 | hand compaction by light hammer |
| Soil pH | | 0 7 14 28 60 90 | 1 | 7 | 7 | 7 | 7 | N/A |
| Unconfined compression test (UCS) | | 7 14 28 60 90 | 11 | 7 | 10 | 11 | 11 | Compacted in five layers. Proctor hammer with 25 blows per layer |

N/A : Not applicable.

## 2.1 Soil and Cement

The soil under investigation originated from Gothenburg, Sweden. Untreated soil was classified by tests of particle size distribution, consistency limits, loss of ignition, chemical composition, compaction characteristics, pH and specific gravity. The physical and mechanical properties are listed in Table 2. The chemical composition of the untreated soil is presented in Table 3. The particle size distribution of the untreated soil is shown in Figure1. The untreated soil mainly consists of silt (55%), fine sand (29%) and clay (16%). It is classified as lean clay (CL) according to the Unified Classification System ASTM D 2487 [24] and as clayey silt soil (Cl Si) according to the Swedish standard [25]. Organic content, assessed by ignition test according to ASTM D2974 [26], was 4%, thus to be classified as having a low organic content [27-29]. Portland cement (FINJA concrete from Finja AB Sweden) was used as a binder in May 2016.

Table 2: Engineering properties of tested soils.

| Parameters | Values |
|---|---|
| **Particle-size distribution (%)** | |
| Sand (%) (1-0.63mm) | 29 |
| Silt (%) (0.063 – 0.002 mm) | 55 |
| Clay (%) ( < 0.002 mm) | 16 |
| **Consistency limits (%)** | |
| Liquid limit (%)* | 37 |
| Plasticity limit (%) | 19.5 |
| Plasticity index (%) | 17.5 |
| **Proctor test** | |
| Optimum moisture content (%) | 12 |
| Maximum dry unit weight (γd max), t/m3 | 1.97 |
| pH | 5 |
| Natural Water Content (%) | 30 |
| Specific Gravity Gs | 2.69 |
| Loss of Ignition % | 4 |

* Determined by the fall cone test

Table 3: Chemical composition of untreated soils.

| Oxides % | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | Mg O | Ca O | $K_2O$ | $Na_2O$ | Mn O | $P_2O_5$ | Ti $O_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Values | 65.7 | 12.3 | 3.42 | 1.31 | 2.4 | 2.84 | 0.0556 | 0.159 | 0.159 | 0.55 |

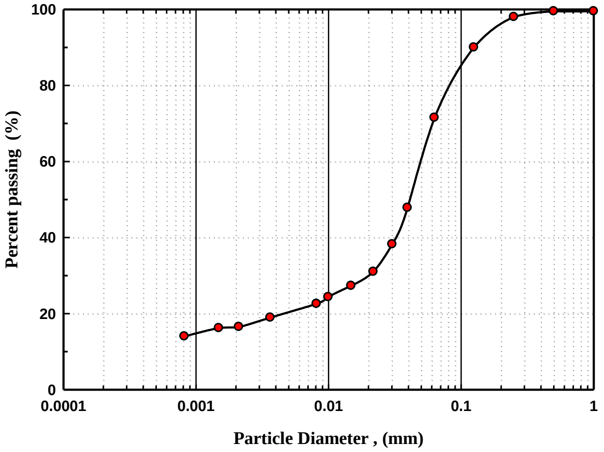


Figure 1: Particle size distribution of untreated soil

## 2.2 Specimen Preparation and Testing methodology

Specimens for unconfined compressive tests were prepared following a standard procedure of crumbling the untreated soil with its initial water content (30 %) followed by adding the cement as a dried material at ratios of 1, 2, 4 and 7% by soil dry mass and mixing for ten minutes using a laboratory mixing machine. The mixtures were filled into cylindrical plastic tubes (170 x 50 mm) by hand. The specimen was compacted in five layers with 25 blows per layer by using a Proctor hammer and standard procedure. The height of the specimen was 100 mm. The tubes were covered with a plastic cover and sealed with rubber lids at both ends to prevent access to water. The curing periods were set at 7, 14, 28, 60 and 90 days before testing. For curing, the specimens were placed inside a glass container partially filled with water (Figure 2) and stored in controlled room temperature at 20°C. After curing, the specimens were removed from the tubes by using a mechanical jack and tested using unconfined compression tests (UCS). Testing rate was 1 mm/minute until failure occurred. The specimen height-to-diameter ratio was 2. Before testing, the specimen was cut and smoothed to obtain parallel end surfaces. The end plates were lubricated to reduce friction. Water content and densities were determined in connection to the unconfined compression tests. All specimens for unconfined compressive tests were prepared during a period of one hour after mixing the untreated soil with the binder.

Specimens for consistency limit tests were prepared and cured identical to the unconfined compression specimens with using a light hammer for compaction instead of Proctor hammer to remove air bubbles. Before testing and after curing, the specimen was removed from its tube.

Liquid limit and plastic limit tests were conducted according to Swedish standards SS 027120 1990 and SS 027121 1990 [30, 31]. The fall cone method was used to determine the liquid limit. The average of four tests represents the liquid limit, while the plastic limit is based upon the average of five tests.

pH tests were conducted on air dried and grinded material from the UCS specimens. pH tests were carried out using a HI 208 pH meter with built in magnetic stirrer. The procedure was used for both the treated and untreated soils according to ASTM D4972 [32]. The average of three pH tests represents the soil pH value. A ratio of liquid to solid of 1 was used to mix the soil and distilled water. The mixture was poured into a glass container and mixed thoroughly using a magnetic stirrer for 2 minutes. The soil-water mixture was left for one hour for retention and the mixing process was repeated every 10 minutes before the pH value was measured.

Figure 2: Laboratory mixer and curing specimens aimed for UCS and consistency limits tests

# 3 Results and Discussion

## 3.1 Consistency Limits (Atterberg limits)

One of the main objectives of cement treatment is to accelerate the construction work by improving workability of the soil [13]. Workability has shown to increase with reducing the plasticity index [22, 33, 34]. The immediate effect (after one hour of mixing) on the consistency limits is presented graphically in Figure 3. It can be seen that both the liquid limit (LL) and plastic limit (PL) increase due to the adding of cement (from 1 to 4 %). The liquid limit remains almost constant at further increased cement content 4 and 7 %, and drops slightly at higher cement content (10 and 15%). The plastic limit slightly increased between 4 to 15% in addition to the large increase at lower cement contents. Consequently, the plasticity index (PI) slightly increased at small cement content and then decreased as the cement content increased. Therefore, treated soil exhibits better workability with increasing cement content within a short time (one hour) after treatment due to flocculation and agglomeration from the hydration reaction.

The observation of an immediate increase in the liquid limit in the low plasticity soil (LL<40%) was due to flocculation and agglomeration caused by the hydration reaction. In comparison to previous studies, [35] reported similar trends for lime treated black cotton clay with low clay content (19%). This black cotton clay showed an immediate increase in liquid limit because of a low cation exchange capacity, which leads to larger double layer. Another possible reason for the raised liquid limit, suggested by [36, 37], is related to the presence of entrapped water within the intra-aggregate pores after flocculation and agglomeration. In contrast, increasing the amount of cement produces an increase in cementitious products, and this has an effect that leads to decreasing liquid limits. A similar trend in the immediate increase in liquid limits has been found by other researches [22, 38, 39].

The long-term effects on consistency limits of the treated soil (Figure 4) were found to be an increase in plastic limits and decrease in liquid limits with time. Due to the different trends between liquid and plastic limits, the plasticity index was found to decrease with time. The decrease became larger in relation to the increase in cement content, as shown in Figure 4. A similar trend of a decreasing plasticity index over time was found by [2, 37, 39, 40]. Thus, an improvement in soil workability can be achieved after a relatively long period after treatment even with very low cement content.

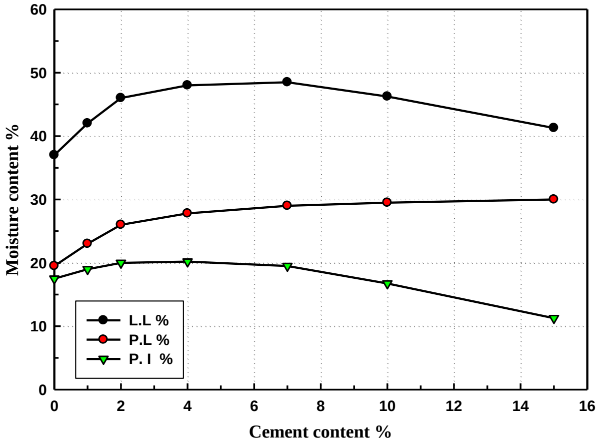


Figure 5: Immediate change in consistency limits versus cement content

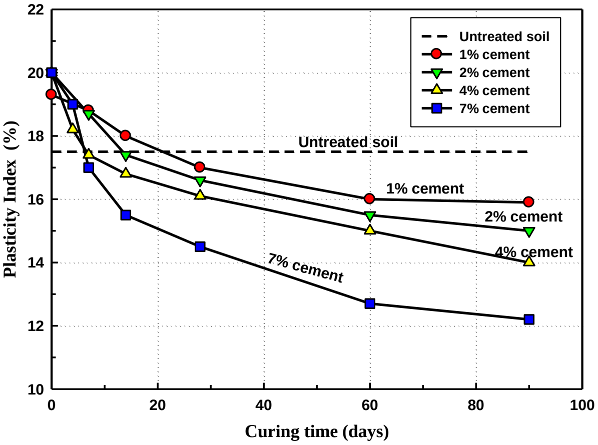


Figure 6: Effect of curing time and cement content on Plasticity index

### 3.2 Water content and density

Solidification is defined as an immediate reduction in the soil water content after treatment with a cementitious binder as a result from the hydration reaction of cement [41]. The water content in the soil-cement mixture comes from the untreated soil. Results show an immediate reduction (after one hour of mixing) in water content of treated soil from its initial value due to adding small amounts of cement as shown in Figure 5. The reduction in water content (solidification) is mainly related to the hydration reaction between the cement and water. Moreover, solidification increases significantly with increase of cement content.

The effects of curing time and cement content on the water content are presented in Figure 6. From Figure 6, it can be seen that further decreases in water content (increasing drying rate) occur during the first 28 days, with almost no further reduction for the longer curing periods. This is valid for all samples tested. The reduction in water content over time was mainly related to the hydration and pozzolanic reactions as the specimens were cured in a sealed condition. For specimens having 4% cement content an increase in water content after 60 and 90 days, as shown in Figure 6 could be observed. This is due to small leaks in the covers of the specimens, which led to absorption of moisture from the surroundings at long curing period.

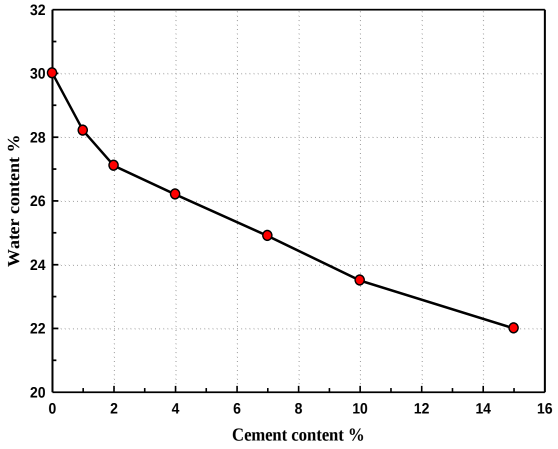


Figure 5: Immediate reduction in water content versus cement content

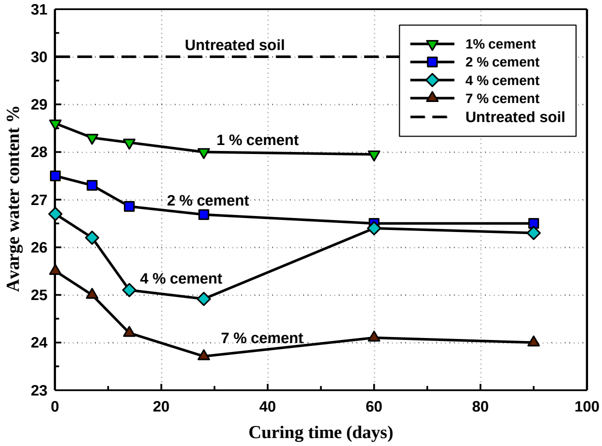


Figure 6: Effect of curing time and cement content on water content

One of the main outcomes of cement treatment is the reduction of water content as it has dominant effects on strength and durability. Generally, the reduction in water content mainly depends on cement content, curing time and initial water content of the untreated soil, which has been in this case about 30 %.

In Figure 7 the effect of cement content on specimen density is depicted. It is seen that soil density increases with increasing cement content. Increase in density is related to deposition of CSH and CAH gel, which are produced during the hydration and pozzolanic reactions. These substances fill the pore voids.

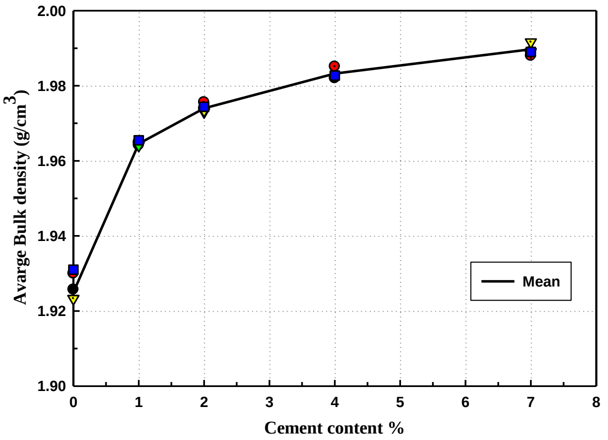


Figure 7: Effect of cement content on specimen density

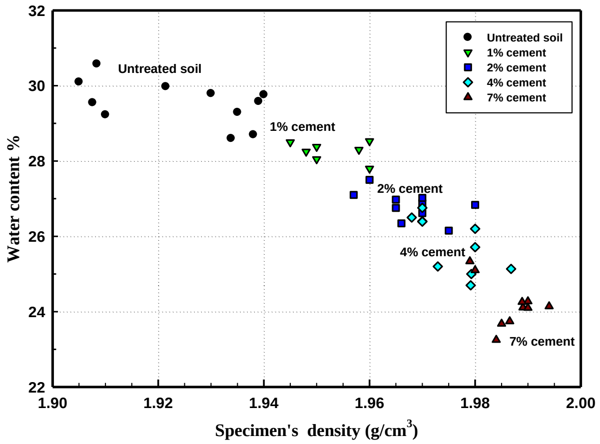


Figure 8: Water content versus specimen density and cement content for all curing

The hydration and pozzolanic reactions of cement reduce the water content of treated soil and produce a large amount of solids that increase the density of the soil. As density is related to soil strength the observation reflect an increase in soil strength. In Figure 8 it is shown the general specimen density were in the range between 1.92 for untreated soil to 1.99 g/cm$^3$ for a cement content of 7%. The reductions in soil water content were in the range of 30 to 24 % for all samples. Similar observations in increasing density and reducing water content for various cement contents is reported earlier [3,9,22,37,40,42,43].

### 3.3 pH value

Figure 9 shows the immediate effects (after one hour) on pH value after mixing with cement. The soil pH value rose to 12 as the cement content was increased up to 7%. Beyond that, the pH is slightly increased to 13 at 15% cement content. The increase in pH was related to an increase in calcium ion concentration (Ca+2) on the particle surfaces as a result from the hydration reaction [21, 37]

The variation in pH with curing time is presented in Figure 10. Regardless of the cement content, the pH gradually decreases with increasing curing times. Pozzolanic reactions have the effect of decreasing pH over time as the reactions produce more CSH or CAH gel. The decrease in pH is due to the comsumption of (OH-). Similar trend for decreasing pH with time is reported by [44, 45]

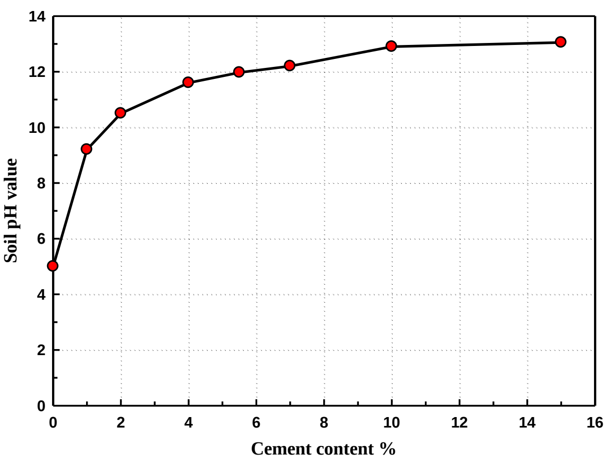


Figure 9: Immediate rise in pH value versus cement content

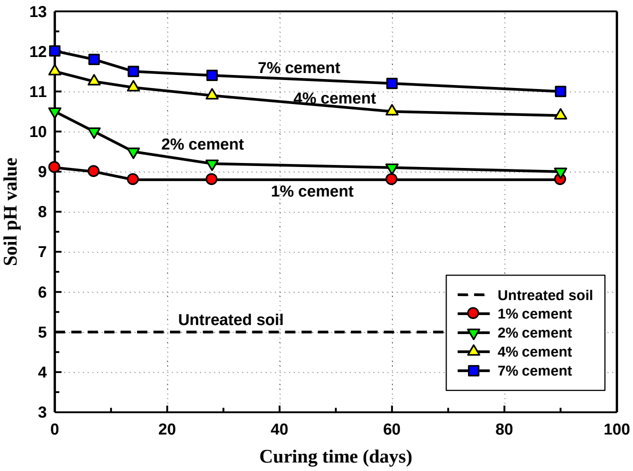


Figure 10: Soil pH value versus curing time

### 3.4 Unconfined compressive strength (UCS)

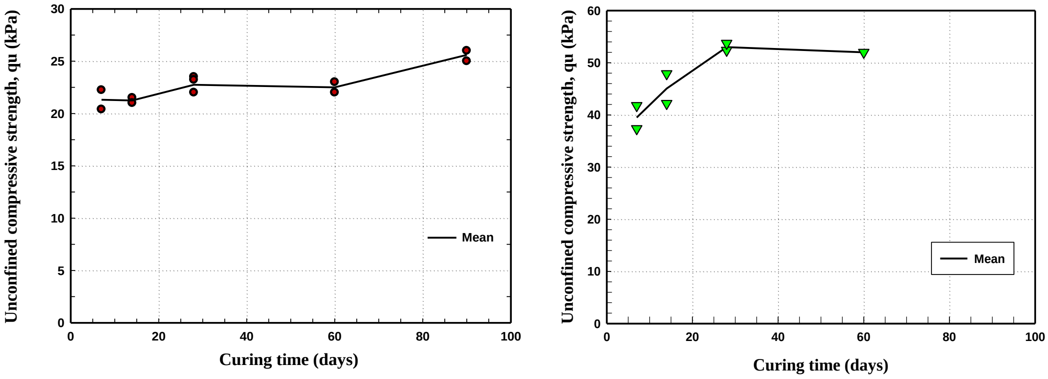
Unconfined compressive strength tests were conducted on untreated and treated soil, prepared in a similar way. For the untreated soil, unconfined compression strength ($q_u$) slightly increased with curing time, as shown in Figure 11 A. This was related to small variation in natural water content. Figures 11 B, C, D and E show the effect on soil strength when cement was added. As expected, the strength increased with increasing cement content and curing time. This is explained by the production of new cementing compounds (primary and secondary) such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) gels from the hydration and pozzolanic reactions. At low cement content (1 and 2%), soil strength improved during the first 28 days of curing time, but after this there was no further improvement i.e. after 60 and 90 days (see Figures. 11 B and C, respectively). An increase in soil strength is related to the production of primary cementing materials as a result of the hydration reaction, which binds soil particles together and hardens over time. Additionally, the pH value can explain the lack of increase in soil strength after 28 days. For the 90 days curing time, it was found that the pH of the treated soil were 8,8 and 9 for 1 and 2% cement content respectively, see Figure10. As stated [45-48], a pH value higher than 10 is sufficient to dissolve silicates and aluminate and to produce additional cementing compounds from the pozzolanic reaction. For this reason, a longer curing time has no additional effect on strength as the pH is below 10.

On the other hand, during the first 28 days of curing time, soil strength increased when increasing cement content from 2% to 4%. Soil strength was reduced for longer curing periods, as shown Figure 11 D. The reduction in soil strength is explained by an increase in water content for long curing periods as discussed earlier and shown in Figure 6. A similar trend of reduced soil strength under saturation conditions has been observed [3, 8, 22].

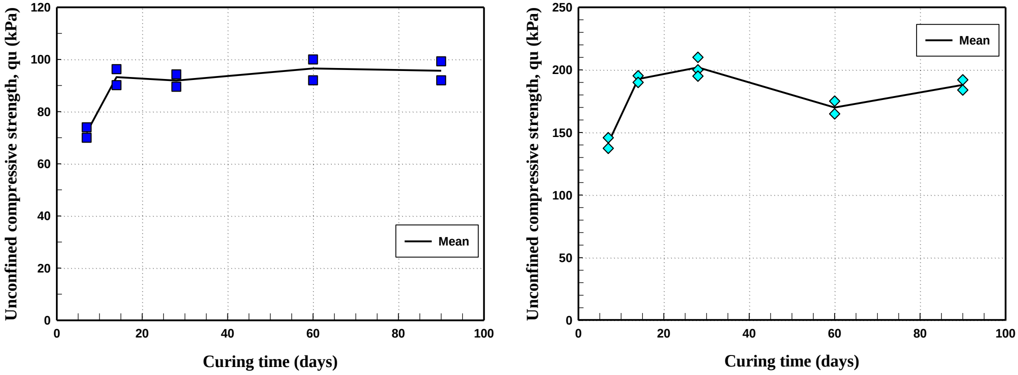
A similar trend of strength development when the cement content is increased from 4% to 7% during the first 28 days was observed. Strength gradually increases for longer curing time, as shown in Figure 11 E. This is related to the production of more CSH and CAH during the pozzolanic reactions at relatively high amounts of cement (7%), in combination with high pH values, as shown in Figure 10.

In order to explain the improvement in soil strength after several treatments, the enhancement can be defined as the ratio between the strength of treated specimens to the strength of the untreated soil. Based on this, adding 1, 2, 4, 7% of cement improves the soil strength to about 2, 4, 9 and 27 times respectively after 28 days curing time.

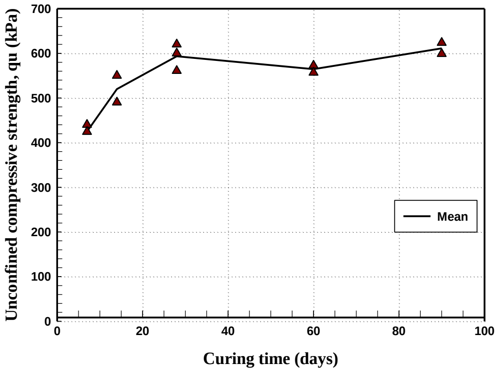
Strength of the treated soil increases with cement content and curing time due to hydration and pozzolanic reactions. The gain in soil strength is noticed for the shorter curing time (28 days) and becomes gradual for longer curing periods. The trend is consistent with other studies on different soils [5, 10, 11, 49].



**(A) Untreated soil** **(B) 1 % cement content**



**(C) 2 % cement content** **(D) 4 % cement content**

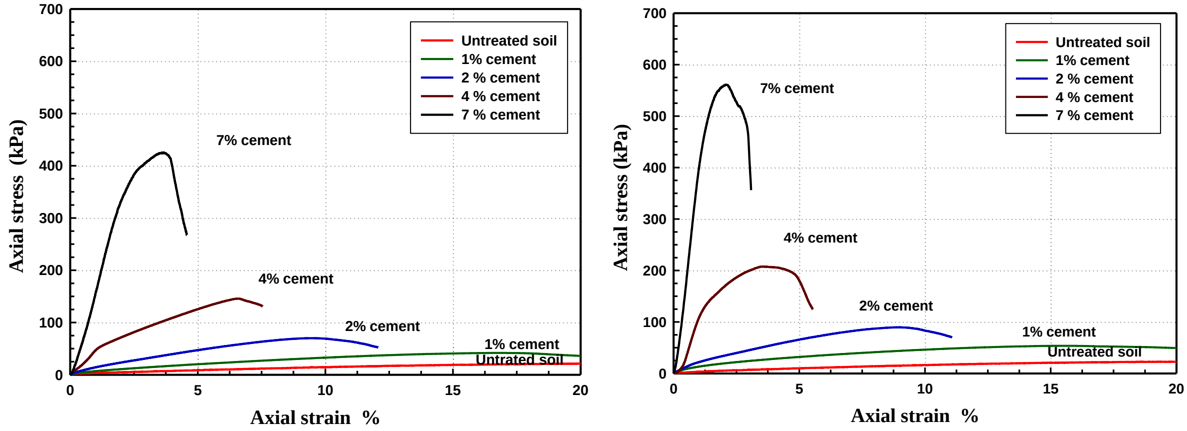


**(E) 7 % cement content**

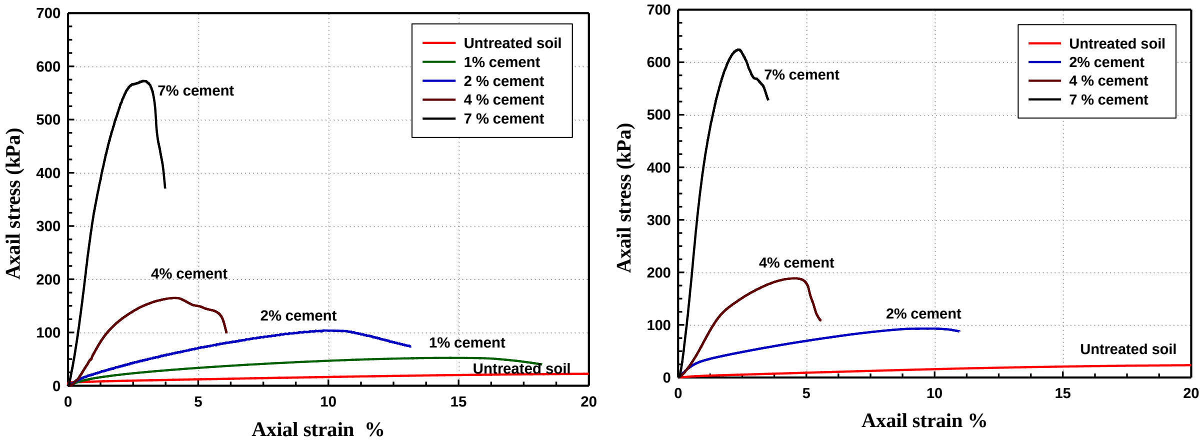
Figure 11: UCS versus curing time for different cement content for all tests.

## 3.5 Stress-strain curves

Figure 12 show typical stress-strain behaviors for untreated and treated soils for different cement content and curing times. In Figure 12 it is shown that the untreated soil has a low peak stress of 23 kPa combined with a large failure strain (24%). In contrast, after several cement treatments from 1 to 7 %, even for very low cement content, as content of cement increases the peak strength also increases. Moreover, failure strain corresponding to the peak stress decreases with an increase in the cement. Significant changes in the stress-strain behavior occurs during the first curing period (less than 28 days) with no further changes for longer curing times. Additionally, for 28 days curing time, the treated specimens with high cement content (7%) exhibit a more brittle failure than for lower cement content, where a more ductile behavior is observed, (Figure 12 B). The failure mode thus gradually changes from plastic failure to brittle failure as cement content increases. It can also be observed, that it is the cement content that has the major effects on the stress-strain curves, rather than curing times. These findings are in line with what has been observed by other [10, 11, 22, 37, 50]



(A) 7 dyas curing time (B) 28 dyas curing time



(C) 60 dyas curing time (D) 90 dyas curing time

Figure 12: Stress–strain relationship for treated and untreated soils versus cement and curing time.

### 3.6 Strain at failure

The addition of cement significantly reduced axial strain at failure from 24% for the untreated soil to about 15, 10, 5 and 3% for 1, 2, 4 and 7% cement content respectively, see Figure 13. Failure strain slightly decreases as curing time increased for the first 28 days curing time. Axial strains at failure versus unconfined compressive strengths are presented in Figure 14 for all samples and curing times. As content of cement increases, strength increases and strain at failure decreases (see Figure 14) but the variations in measured UCS increased. From Figure 14, a scattered pattern in measured failure strain was observed at low strengths (22 kPa for untreated soil). Moreover, a significant reduction in strain at failure was observed regarding different cement treatments from 1 to 4%, which led to increased soil strength of up to 200 kPa (see Figure 14). However, further increasing in cement content to 7%, increase the soil strength of up to 600 kPa with less significant on decreasing failure strain. A similar trend has been observed in previous studies for higher cement contents [11, 40, 49].

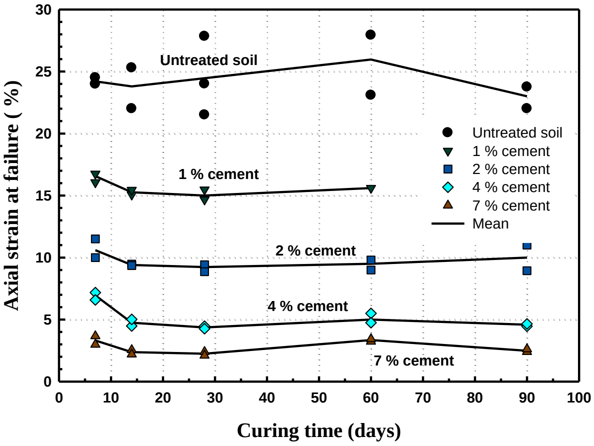


Figure 13: Strain at failure versus curing time and cement content for all tests

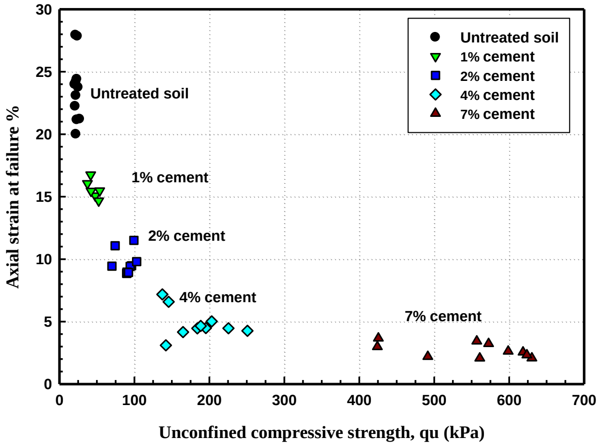
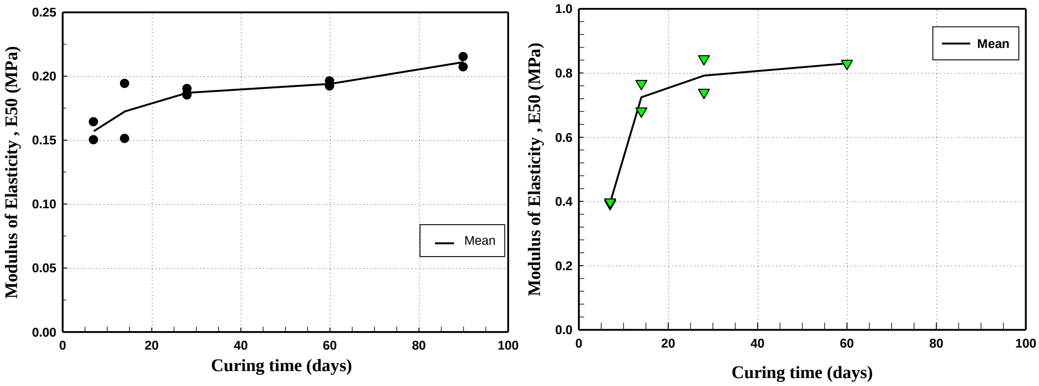


Figure 14: Strain at failure versus UCS strength

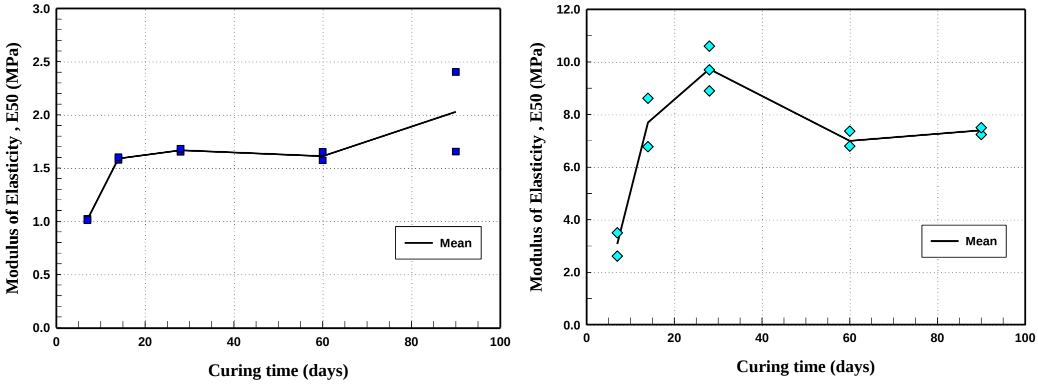
### 3.7 Stiffness of treated soil

The effects of different cement contents and curing times on the stiffness are shown in Figure 15. The stiffness is defined by a secant modulus of elasticity ($E_{50}$) of tested specimens. It was evaluated from stress–strain curve as a ratio of half of the maximum unconfined compressive strength to corresponding strain. Figure 15 shows that the stiffness of the treated soil increases with an increase in cement content and curing time. This can be related to the production of primary and secondary cementitious materials as a result of the hydration and pozzolanic reactions. Higher cement contents produce more cementing components and vice versa. As discussed earlier, the production and deposition of cementing materials leads to an infill of the pore space, resulting in a denser structure. Consequently, soil stiffness increased with increasing curing times and cement content. The trend is consistent with previous studies [10, 11, 22].

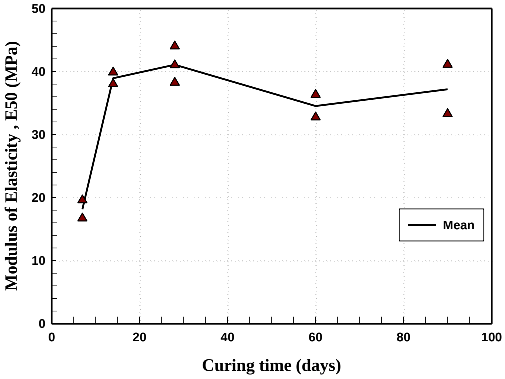
Increase in soil stiffness can be illustrated by the ratio between the stiffness of the treated samples to the stiffness of the untreated soil samples. Based on this, adding 1, 2, 4 and 7% cement content improves the soil stiffness approximately 4, 9, 45 and 180 times respectively when compared to untreated soil after 28 days curing time.



**(A) Untreated Soil** **(B) 1 % cement content**



**(C) 2 % cement content** **(D) 4 % cement content**



**(E) 7 % cement content**

Figure 15: Modulus of elasticity versus curing time and cement content for all tests.

The relationship between unconfined compression strength and the modulus of elasticity, $E_{50}$, is shown in Figure 16. A significant increase in soil stiffness was observed with increase in soil strength. Based on the results shown in Figure 16, the soil stiffness can be taken between $E_{50}=16\ q_u$ and $E_{50}=85\ q_u$. Table 4 presents the upper and lower ranges of soil stiffness, $E_{50}$, and $q_u$ for both the untreated and treated soil.

Table 4: Upper and lower range of soil stiffness times qu after 28 days

| **Cement content** | **$E_{50}$= A × $q_u$ Lower range** | **$E_{50}$= B ×$q_u$ Upper range** |
|---|---|---|
| Untreated soil | 6 | 10 |
| 1% | 14 | 18 |
| 2% | 15 | 20 |
| 4% | 35 | 54 |
| 7% | 50 | 85 |

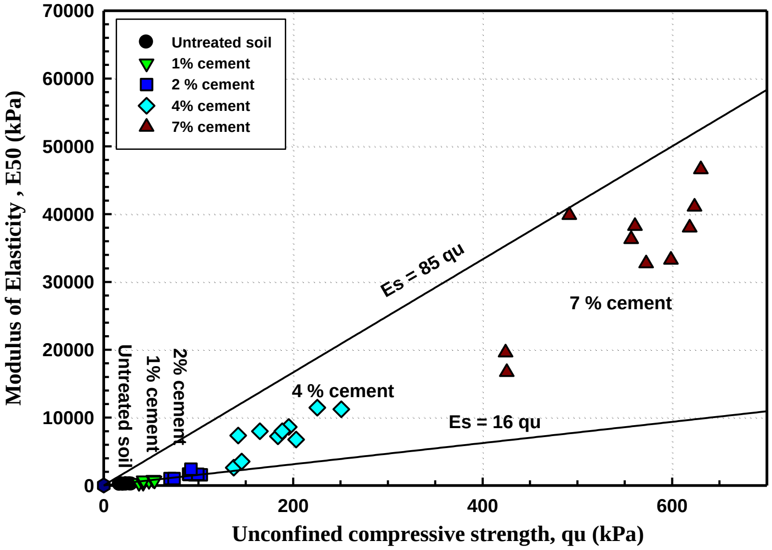


Figure 16: Modulus of elasticity versus UCS strength for different cement contents and length of curing periods.

In comparison to previous studies of cement treated soils, [11] have shown a correlation of stiffness, ($E_{50}$ to $q_u$), ranging from 100 to 326 for different soil types (silt, silty clay and laterite) with 7 and 13% cement content. [51] found the modulus of elasticity, $E_{50}$ , ranged between 53 $q_u$ to 92 $q_u$ based on laboratory tests in Sweden on a stabilized clay soil with 200 kg/m$^3$ (18- 24 %) of cement and lime. [47] refers to a modulus of elasticity, $E_{50}$, ranging between100 $q_u$ to 200 $q_u$

for different clay types treated with 3 - 37 % cement content in Finland . [52] found the stiffness, $E_{50}$, of stabilized Bangkok clay with cement content from 5 to 20% ranged between 115 $q_u$ and 150 $q_u$.

## 4 Conclusion

In this study, the modification and improvement of clayey silt soil treated with low cement content (≤7%) is investigated. The following conclusions can be drawn from the present study.

1- Adding 1, 2, 4 and 7 % cement content improves unconfined compressive strength to about 1, 3, 7 and 23 times, while soil stiffness is increased by 3, 7, 36 and 180 times respectively when compared to untreated soil during the first 28 days. A gradual increase in soil strength and stiffness is observed for the longer curing periods when higher cement content (7%) is used.

2- Adding small percentages of cement has the immediate effects of increasing the plasticity index followed by a decrease at higher cement content. The plasticity index significantly decreases over time, even for very low cement content. Treated soil shows better workability with increasing cement content directly after mixing and over time, even for very low cement content due to the reduction in the plasticity index.

3- Treated soil with small percentages of cement has the initial effect of increasing the solidification of soil after treatment, and it has moderate effects over time until 28 days.

4- Axial strain at failure decreases with an increase in cement content and time, leading to a gradual change in failure mode from plastic to brittle failure when compared to untreated soil.

5- pH in connection with other variables provides useful assessment information to describe soil cement reaction. pH value lower than 9 is not sufficient to initialize the pozzolanic reaction leading to not gaining more soil strength for the long curing period.

The findings confirm that using smaller percentages of binder still has a significant effect on the behavior of the clay used in this study. Further investigations will focus on other binders as the reduction in cement content will contribute significantly to the environmental balance and to saving money for construction.

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