Swell and compressibility characteristics of expansive clays in north Cyprus

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Abstract. Expansive clays in semi-arid regions are known as problematic soils especially for low weight civil structures. Volume change is a critical issue, therefore determining expansive clays and quantifying their expandability, retraction and strength is a major step to be considered in geotechnical engineering. This research provides a study on the behaviour of expansive clays done under different geotechnical laboratory experiments on four different types of expansive clays brought from various areas in Northern Cyprus, aiming to prepare a soil-properties map in these regions. Fundamental assessments were performed for determining soil index properties. Swell and consolidation behaviours were determined using one-dimensional oedometer apparatus. The results showed that the rate of the expansiveness of the bentonitic clay samples were the highest for the predicted ultimate swell with expandability index categorized as very high. Also, these samples showed the largest compressibility in the consolidation test results. The results obtained were used to construct a relationship between compression and plasticity Index.

1. Introduction
Expansive clays are high swelling soils, they are very reactive due to their high plasticity. Clays with high plasticity are composed of fine-grained particles which are prone to a huge volume change whenever water content differs. According to [15], clays with a plasticity index larger than 35 percent are highly plastic. Clay moisture content decreases and increases depending on the environmental conditions surrounding it resulting in shrinkage and swell, this change in moisture is regarded as the main reason for the change in volume. Also, the mineralogy, soil structure, specific surface and stress history all contribute to the volume change [20]. The factors that mainly affect the soil volumetric change potentials are clay mineral type, the ratio of voids and moisture content of a certain soil [8], [13], [17], [19]. Expansive clays moisture content changes when wetted or dried which leads to void ratio and volume change of the soil.

Expansive soils behavior was also studied by other researchers like [12], [18], [21], [22], [26]. Clays with swell potentials are found in semi-arid regions of tropical and climate temperature zones worldwide [9]. Considerable infrastructure damages had been reported caused by high plastic clays due to their shrink and swell behavior. It is a challenging issue for engineers to design substructures on expansive clays, in order to bypass that, the volume change, swell and shrinkage, characteristics of expansive clays must be considered before engineering structures are built. Determining type of clays and evaluating their swell potential before construction can assist in reducing future possible damages.
The geology and climate of Cyprus made expansive clay formations in some parts of the Island [25]. The majority of swelling clays in Cyprus occur in a geological unit of Neogene. The greatest amount of damages caused by swelling clays are contained in stratigraphic sequence ranging in age from Miocene to Quaternary. Therefore, the island’s geological and geotechnical evolution contributed to the swelling clay formations. The geological location of Cyprus is at the triple junction of Africa, Eurasia and Arabian plates. Through the complex tectonical and sedimentary process, the triple junction intersection zone occurred. Complex geotectonic activities were found in Cyprus during Late Cenozoic [10]. In this work volume change and mechanical behavior of four typical expansive clay samples of Cyprus is studied. The obtained information could be used as the basic step for engineers and researchers in stabilizing and foundation design works in this area.

2. Experimental work

2.1. Materials

Cyprus is covered with marly and clayey formations bearing montmorillonite clays to bentonitic group of clays. Kythrea formation, Mamonia complex, Nicosia formation, Alluvial soils and Bentonitic clays are the most common soils of Cyprus. Clay deposits consisting of bentonite are mostly found at Lefke (Lefka) and Yiğitler (Arsos) [7]. Swelling clay formations are mostly found at Nicosia, Famagusta, Kyrenia, Kalecik, Çamlıbel and Değirmenlık figure 1.

![Figure 1: Swelling clay settlements in Cyprus](image)

The laboratory work was planned to understand the properties related to expansive clay mechanical behaviour. Four natural expansive soil samples were taken from different sites, which are located in the South of Taskent village (sample T1), North of Haspolat village (sample T2 and T3) and South of Yiğitler village (sample T4) within and around Nicosia, North Cyprus. Theses clays are widely known for their expansiveness and are responsible for the large amount of damage to civil structures resulting from swelling and shrinkage cycles. Different laboratory experiments were applied for obtaining the characteristics of the clays in accordance to [1, 2, 3, 4, 5, 6]. The physical properties of sample T1, T2, T3 and T4 are presented in Table 1.

After determining the basic physical properties, free-swell and consolidation tests were carried out on the obtained soil samples compacted at their optimum moisture content (OMC) and maximum dry density (MDD). The maximum dry density and optimum water content of all samples were measured by standard Proctor compaction test [4]; the obtained results are represented in Table 2.
Table 1. Physical properties of obtained soils

| Samples Name | T1  | T2  | T3  | T4  |
|--------------|-----|-----|-----|-----|
| Silt Content (%) | 52  | 40  | 32.5| 25  |
| Clay Content (%)  | 48  | 60  | 67.5| 75  |
| Liquid Limit (%)   | 64  | 72  | 115 | 132 |
| Plastic Limit (%)  | 33  | 28  | 32  | 40  |
| Plasticity Index (%) | 31  | 44  | 83  | 92  |
| Specific Gravity (Gs) | 2.55| 2.56| 2.55| 2.48|
| USCS classification | CH  | CH  | CH  | CH  |

The main purpose of doing the free swell test is to obtain the maximum ultimate swell value of the obtained compacted soil samples. Also, the consolidation test was performed for finding the properties of compression for all samples at an applied pressure ranging between 6.9-3530 kPa.

Table 2. Compaction test results of investigated samples

| Sample Name | Maximum dry density (g/cm$^3$) | Optimum water content (%) |
|-------------|---------------------------------|---------------------------|
| T1          | 1.60                            | 21.5                      |
| T2          | 1.62                            | 22.0                      |
| T3          | 1.67                            | 19.0                      |
| T4          | 1.30                            | 39.4                      |

Consolidation and free swell tests were carried out in a one-dimensional oedometer apparatus. The soil samples were compacted into a metal ring of 20 mm height and an inner diameter of 50 mm. The height of the compacted soils was kept at 14 mm in order to allow free swell in the remaining 6 mm of the consolidation ring.

3. Results and discussions

Full swell is to be achieved before knowing the maximum ultimate swell; therefore, the samples were left to swell until no further change in samples height was seen. The response of free swell in percent swell ($\Delta H/H_o \times 100$) versus time in minutes for the obtained samples is shown below in figure 2, where the percent swell is represented as axial strain (%) and time in logarithmic (min). The overall swell of each sample consists of three stages which are the initial swell stage, primary swell stage and secondary swell stage. The initial stage starts and ends in the first few minutes, while the main part of the whole swell is the primary stage and finally the secondary stage which is the part that builds up progressively from the primary stage taking the most time before completion [25].

Also, Figure 4 represents the results of all four samples as it shows their overall swelling behavior from the start to maximum swell measured. It is clear that T1 has the lowest swelling potentials with a primary swell of 3.45%, whilst T2 and T3 exhibited a higher swell with a primary swell of 9.53% and 7.49% respectively. The highest swell was for T4 with a primary swell of 17.4% which makes it the most expansive among all samples. The potential expansion of the soils is classified by their Expansion Index (EI), calculated by equation (1) shown in Table 3 [1].

$$EI = \frac{\Delta H}{H_o} \times 1000$$

(1)
Where

\( EI = \) Expansion index
\( \Delta H = Final\ dial\ reading\ (mm) - Initial\ dial\ reading\ (mm) \)

**Table 3.** Samples classification of potential expansion according to their EI [1]

| Samples | Expansion Index, EI | Potential Expansion |
|---------|---------------------|---------------------|
| T1      | 38                  | Low                 |
| T2      | 113                 | High                |
| T3      | 133                 | Very High           |
| T4      | 189                 | Very High           |

The curves shown in Figure 2 flows in three trends; initial escalation in axial strain with time then a leap indicated by a curve ending up with a linear line and finally a slight increase indicated by a horizontal or inclined finishing. The initial, primary and secondary time were extracted by applying the tangent-intersection method. In this method, the S-shaped axial strain-time curve is composed of two non-linear parts at the secondary (upper phase) and initial (lower phase) swelling stages, in addition to that a part which is linearly inclined at the primary (middle phase) swelling stage [23]. The initial and primary swell time for all sample are shown in Table 4.

**Figure 2.** Percent swell of sample T1, T2, T3 and T4 versus logarithmic time

The mechanism of different swelling phases is due to surface hydration of particles during the initial swell caused by the non-swelling fractions within the voids; primary swelling occurs when voids cannot bear any more water causing it to develop faster whereas secondary swelling occurs due to swelling of active minerals [11].

**Table 4.** Swelling time of sample T1, T2, T3 and T4

| Samples | Initial swelling time (min) | Primary swelling time (min) |
|---------|-----------------------------|------------------------------|
| T1      | 90                          | 5200                         |
| T2      | 18.5                        | 1440                         |
| T3      | 7.8                         | 91                           |
| T4      | 8                           | 1500                         |
The value of ultimate swell cannot be reached in the laboratories using the normal practical methods because by theory an infinite time is required to get to the ultimate swell. Through the straight lines fitted in figure 3 which shows the time/swell versus time, the ultimate swell can be predicted using equation 2 as proposed by [24]. The values obtained from plotted graphs and equations are presented in Table 5 including the highest $R^2$ of the straight line.

\[ u_{max} = \lim_{t \to \infty} \left( \frac{1}{\frac{1}{x} + y} \right) = \frac{1}{y} \]  

(2)

Where

$U_{max}$ = Ultimate swell  
$X$ = represents the ordinates of a line  
$Y$ = represents the slope of a line.

t = time

![Graphs of Sample T1, T2, T3, and T4](image)

**Figure 3.** The relationship of time/swell vs time of samples T1, T2, T3 and T4

**Table 5.** Ultimate swell values prediction and swell properties of tested samples

| Samples | Initial swell (%) | Primary swell (%) | Max swell measured (%) | Hyperbolic constant, y | Hyperbolic constant, x | Ultimate swell (%) | $R^2$ |
|---------|------------------|------------------|------------------------|------------------------|------------------------|-------------------|------|
| T1      | 0.5              | 3.45             | 3.79                   | 25.9310                | 13451                  | 3.85              | 0.9979|
| T2      | 1.6              | 9.53             | 11.39                  | 8.7341                 | 1589.6                 | 11.44             | 0.9994|
| T3      | 2.2              | 7.49             | 13.66                  | 7.3013                 | 1681.3                 | 13.69             | 0.9970|
| T4      | 1.4              | 17.4             | 19.20                  | 5.1665                 | 668.1                  | 19.36             | 0.9996|
The compression index \( (C_c) \) obtained from the test results illustrated in figure 6 which represents void ratio versus logarithmic pressure (kPa) clearly shows that all the samples have decreased in volume well enough, that describes their mechanical behaviour as highly prone to volume change making it undesired for construction. The test results are expressed as consolidation parameters which are compression index \( C_c \) responsible for compressibility indication of soils, rebound index \( C_r \) known as swell index after unloading and pre-consolidation pressure (kPa). The pre-consolidation pressure is the pressure where a rapid fall in stiffness of soil occurs and is shown by a concave curve which indicates the maximum effective past pressure \([14]\). The consolidation parameters obtained from the investigated sample results are all tabulated in Table 6. All the samples show a curve which is concaved before reaching the point where virgin compression line is extended. Also, as the pressure exceeds the pre-consolidation pressure, a continuous decrease in compressibility is observed with the increase in effective stress.

The main difference between all four clays is that T1 showed the least compression index \( C_c \) whereas T2 and T3 are almost at the average and higher than T1 and finally T4 showing the highest compression index \( C_c \) among all the samples.

![Figure 4. Tested samples consolidation results](image)

**Table 6. Consolidation parameter**

| Samples     | T1  | T2  | T3  | T4  |
|-------------|-----|-----|-----|-----|
| Swell (%)   | 3.79| 11.39| 13.66| 19.20|
| Compression Index \( C_c \) | 0.166| 0.199| 0.282| 0.399|
| Pre-consolidation P (kPa) | 146| 115| 110| 102|
| Rebound Index \( C_r \) | 0.086| 0.042| 0.080| 0.170|

A correlation was made between the compression index \( C_c \) and plasticity Index (PI) in order to understand the physical and mechanical behaviour of the obtained clays. An important element in civil engineering is the behaviour of soil. Soil properties such as strength, compressibility and plasticity have a great influence on the design during construction. Since index properties such as moisture content and Atterberg limits are basic in soils tests, it will be a wise step to use them for understanding clays behavior \([16]\). Figure 7 shows the correlation between the plasticity index and the compression index. It was observed that the compression index increased with increasing plasticity index, the compressibility index of soil could be predicted from the relation as, \( C_c = 0.0033PI + 0.0551 \), by \( R^2 \) of 0.8825. The ability of a material to undergo a large amount of deformation is termed as its plasticity; clay soil exerts this property at a large degree especially with an increasing liquid limit. That explains why soils having a high liquid limit, contains high compression index.
4. Conclusions
The results obtained from the hydrometer test showed that all the obtained samples were composed of silts and clays which makes them highly prone to expansion when wet.

- The liquid limit and plasticity index obtained during the Atterberg test showed that all the samples were above 50% LL and 25% PI. Therefore, their volume change was categorized as high to very high [15]. Also, the clays were all beyond the A-line and were categorized as clay with high plasticity (CH) according to Unified Soil Classification System.

- The maximum dry density obtained for sample T1, T2, T3 and T4 were 1.60, 1.62, 1.67, 1.30 g/cm$^3$ respectively with optimum moisture contents of 21, 22, 19, 39 % respectively.

- The one-dimensional oedometer swell test showed that T4 had the maximum ultimate swell 19.36%, T2 and T3 had a close maximum ultimate swell value of 11.44 and 13.69% respectively, while T1 had the lowest with an ultimate maximum swell value of 3.85% and therefore all of the samples are considered as highly expansive.

- The consolidation test showed that T1 had the highest pre-consolidation pressure, T2 and T3 had a close pre-consolidation pressure while T4 showed the lowest pre-consolidation pressure. The correlation between the compression index and plasticity index showed that the compression index increases with increasing plasticity index in a linear manner.

References
[1] American Society for Testing and Materials. (2011). *Standard test method for Expansion index of soils* (D4829-11). ASTM International.

[2] American Society for Testing and Materials. (2010). *Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils* (D4318). ASTM International. https://doi.org/10.1520/D4318-10E01

[3] American Society for Testing and Materials. (2011b). *Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading* (D2435/D2435M). ASTM International. https://doi.org/10.1520/D2435

[4] American Society for Testing and Materials. (2012). *Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft$^3$ (600 kN-m/m$^3$)) (D698).* ASTM International. https://doi.org/10.1520/D0698-12E01

[5] American Society for Testing and Materials. (2014a). *Test Methods for One-Dimensional Swell or Collapse of Soils* (D4546). ASTM International.
[6] American Society for Testing and Materials. (2014b). *Test Methods for Specific Gravity of Soil Solids by Water Pycnometer* (D854). ASTM International.

[7] Atalar, C., & Kilic, R. (2006). Geotechnical properties of Cyprus clays. *International Association for Engineering Geology and the Environment, Formerly International Association for Engineering Geology*, (419), 9.

[8] Bell, F. G. (2000). *Engineering Properties of Soils and Rocks* (3rd ed.). Oxford: Butterworth-Heinemann Ltd.

[9] Chen, F. H. (1988). *Foundations on Expansive Soils* (2nd edition). Amsterdam; New York: New York, NY, U.S.A: Elsevier Science.

[10] Constantinou, G., Petrides, G., Kyrou, K., & Chrysostomou, C. (2002). *Swelling Clays: Continuous Threat to the Built Environment of Cyprus* (ETEK). Nicosia, Cyprus: ETEK-Cyprus Scientific and Technical Chamber.

[11] Elsharief, A. M., & Sufian, M. (2018). Time rate of swelling of compacted highly plastic clay soil from Sudan. *MATEC Web of Conferences*, 149, 02032. https://doi.org/10.1051/matecconf/201814902032

[12] Estabragh, A. R., Parsaei, B., & Javadi, A. A. (2015). Laboratory investigation of the effect of cyclic wetting and drying on the behaviour of an expansive soil. *Soils and Foundations*, 55(2), 304–314. https://doi.org/10.1016/j.sandf.2015.02.007

[13] Ferber, V., Auriol, J.-C., Cui, Y.-J., & Magnan, J.-P. (2009). On the swelling potential of compacted high plasticity clays. *Engineering Geology*, 104(3–4), 200–210. https://doi.org/10.1016/j.enggeo.2008.10.008

[14] Ho, M.-H., Chan, C.-M., & Bakar, I. (2010). One Dimensional Compressibility Characteristics of Clay Stabilised with Cement-Rubber Chips, 1(2), 14.

[15] Holtz, R. D., & Kovacs, W. D. (2010). *An Introduction to Geotechnical Engineering* (2 edition). Upper Saddle River, NJ: Pearson.

[16] Jain, V. K., & Dixit, M. (2015). Correlation of Plasticity Index and Compression Index of Soil. *International Journal of Innovations in Engineering and Technology*, 5(3), 8.

[17] Jones, D. Earl, & Jones, K. A. (1987). Treating Expansive Soils. *Civil Engineering—ASCE*, 57(8), 62–65.

[18] Jotisanaka, A., Coop, M., & Ridley, A. (2009). The mechanical behaviour of an unsaturated compacted silty clay. *Géotechnique*, 59(5), 415–428.

[19] Mitchell, A. R., & van Gennuchten, M. T. (1992). Shrinkage of Bare and Cultivated Soil. *Soil Science Society of America Journal*, 56(4), 1036–1042.

[20] Pusch, R., & Yong, R. N. (2006). *Microstructure of Smectite Clays and Engineering Performance*. CRC Press. https://doi.org/10.1201/9781482265675

[21] Sharma, R. S. (1998). *Mechanical behaviour of unsaturated highly expansive clays*. University of Oxford, Oxford-England.

[22] Sivakumar, V., Tan, W. C., Murray, E. J., & McKinley, J. D. (2006). Wetting, drying and compression characteristics of compacted clay. *Géotechnique*, 56(1), 57–62. https://doi.org/10.1680/geot.2006.56.1.57

[23] Soltani, A., Taheri, A., Khatibi, M., & Estabragh, A. R. (2017). Swelling Potential of a Stabilized Expansive Soil: A Comparative Experimental Study. *Geotechnical and Geological Engineering*, 33(4), 1717–1744. https://doi.org/10.1007/s10706-017-0204-1

[24] Komine, H. and Ogata, N. (1994). Experimental study on Swelling Characteristics of Compacted bentonite. Canadian Geotechnical Journal, 31, 478-490.

[25] Sridharan, A., & Gurtug, Y. (2004). Swelling behaviour of compacted fine-grained soils. *Engineering Geology*, 72(1–2), 9–18.

[26] Wheeler, S. J., Sharma, R. S., & Buisson, M. S. R. (2003). Coupling of hydraulic hysteresis and stress–strain behaviour in unsaturated soils. *Géotechnique*, 53(1), 41–54. https://doi.org/10.1680/geot.2003.53.1.41