Studia Geotechnica et Mechanica, 2022; 44(3): 198–210

Original Study

Open Access

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Effect of Time History on Long-Term Deformation of Gypseous Soils

https://doi.org/10.2478/sgem-2022-0011
received February 18, 2021; accepted May 8, 2022.

Abstract: The time-dependent behavior of three gypseous soils was investigated. The soils had gypsum content of 66%, 44%, and 14.8%. The mineralogical and chemical properties of the soils were determined. Two series of tests were performed. In the first, collapsibility characteristics were investigated for a long period (60 days) by conducting single and double oedometer tests. In the second series, the effect of relative density on collapse with time was investigated. The samples were compacted to 40%, 50%, and 60% relative density and then tested. The results of collapse tests showed that the relationship between the strain and logarithm of effective stress has two vertical lines. The first one represents the collapse settlement taking place within 24 h, while the second one represents the long-term collapse. The collapse potential (CP) in both single and double oedometer tests increases when the gypsum content increases from 14.8% to 66% and when the initial void ratio increases.

The CP–logarithm of time relationship for soaked samples prepared at different relative densities under 800 kPa indicated that the CP increased with time for the soil sample compacted at 60% relative density and the increase was higher than those compacted at 40% and 50% relative density. The curves started with a straight line and then a concave downward curve was observed with a high strain. For samples compacted at 40% and 50% relative densities, the curves were interrupted by little soil collapses, while the third curve exhibited smooth relation following the collapse.

Keywords: Gypseous soil; creep; collapse; time history; relative density.

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1 Introduction

Gypseous soils are problematic from both engineering and agricultural points of view. Many problems had been noticed when structures were constructed on gypseous (gypsiferous) soils in the last four decades. These problems are related to collapsing of the soil, increasing leakage of water through the soil, softening of the soil, and sulfate attack of concrete. All these problems are related to the continuous and slow dissolution of gypsum by water seeping through gypsum-containing soil.

The presence of gypsum in soil affects its engineering properties and behavior to a degree, which is greatly dependent on the amount of gypsum present in the soil. Gypseous soil in Iraq constitutes 7.3%–10% of the total world gypseous area and it forms about 20% of the area of Iraq.

Gypseous soils are found in arid and semi-arid regions on gypseous rocks and sediments of different origins. There are different origins and different definitions of gypseous soils as given below:

1. Alphen and Romero (1971) reported that gypseous soils are those containing more than 2% gypsum by weight.
2. Barazanji (1973) distinguished five classes of gypseous soils according to their gypsum contents as shown in Table 1.
3. Saaed and Khorshid (1989) defined gypseous soil as the soil that contains more than 6% gypsum.
4. Nashat (1990) considered soils as gypseous when they contained 3% or more of gypsum by weight.
5. Boyadgiev and Verheye (1996) noticed that gypsum content over 15% tends to give unstable structure to soil.

Gypseous soils offer a relatively rapid settlement due to the addition of water because the loose particle structure is cemented together with soluble minerals and/or with small quantities of clay. Water infiltration into such soils can break down the inter-particles cementation, resulting in collapse of the soil structure. Predicting the collapse potential (CP) is important in the design of many engineering structures.

Table 1: Classification of gypseous soil (after Barazanji, 1973).

Gypsum content (%)	Classification
0.0–0.3	Non-gypsiferous
0.3–3.0	Very slightly gypsiferous
3.0–10	Slightly gypsiferous
10–25	Moderately gypsiferous
25–50	Highly gypsiferous

Jennings and Knight (1957) suggested the double oedometer test (DOT) to predict collapse settlement for foundation design purposes. In this method, two identical specimens are loaded in two oedometers. The first specimen is tested at the natural water content till the end of the test following the standard procedure. The other is initially soaked and then loaded following the same procedure. The difference between the compression curves quantifies the amount of deformation that would occur at any stress level. Knight (1963) suggested a laboratory test to calculate the collapsibility of soil, named the single collapse or the collapse test (CT). The method is similar to the standard oedometer test except that it requires placing a soil specimen with the natural water content in a consolidometer, applying a predetermined vertical stress to the specimen (200 kPa), and then inundating the specimen with distilled water at the same load maintained for 24 h to induce CP in the soil specimen. The test is then continued with the specified pressure. The CP is defined as

$$CP = \Delta H/H_o = \Delta e/(1 + e_o) \quad (1)$$

where: ΔH: change in specimen height upon wetting, H_o: initial height of the specimen, Δe: change in void ratio upon wetting, and e_o: initial void ratio.

Houston et al. (1988) stated that these soils exist at a relatively low density and with a low moisture content and they possess high apparent strength but are susceptible to large reduction in void ratio (collapse) upon wetting. The reduction in void ratio (volume) can occur at fairly low levels of stresses that are close or equivalent to overburden soil pressure. In contrast to consolidation where the reduction in void ratio is a result of the time-dependent expulsion of pore water, the settlement in these soils is more or less immediate and coincides with intake of moisture. Thus, gypseous soil takes the collapsibility characteristics.

Many attempts were made by several researchers to treat and improve the properties of gypseous soils in order to decrease the dissolution of gypsum and the CP of these soils.

Taha et al. (2007) studied the effectiveness of liquid asphalt in the enhancement of gypseous soils properties. This enhancement takes place by reducing the effect of water on gypsum particles and increasing the strength parameters. The work included two types of treatment – firstly, by the mixing technique and the second type is by the grouting technique. The test results showed that the maximum unconfined compressive strength and the shear strength of soil increased to an optimum value and then decreased with increasing liquid asphalt. The study concluded that the mixing technique was better than the injection technique, because the mixing technique covers the particles with a film of asphalt, while the injection technique fills the voids of soil with asphalt.

Fattah et al. (2008) reported that the results of DOT showed that the relationship between CP and the logarithm of time for samples loaded to 800 kPa for 60 days consisted of three distinct segments. The first segment was represented by a concave downward curve in which the compressibility gradually increased. The second segment was a straight line with a higher increase in the strain. The third segment, which refers to creep collapse, depended on the gypsum content. Gypseous soil with low gypsum content (14.8%) exhibited significant decrease (from 5.21% at 24 h to 7.16% at 60 days) in CP with time.

Fattah et al. (2012) tried to investigate the effect of dynamic compaction process on the behavior of gypseous soils. Extensive laboratory tests were carried out to study the geotechnical properties and the behavior of three gypseous soils of different gypsum contents: 60.5%, 41.1%, and 27%. The tests included compaction characteristics, compressibility, and collapsibility tests for samples tested before and after treatment by dynamic compaction process under different number of blows, falling weights, and heights of falling of the weights. Three weights were used to compact the samples, that is, 2, 3, and 5 kg. The number of blows was varied between 20 and 40, while three heights of the drop were tried: 35, 50, and 65 cm. The results showed that the best improvement in compressibility was achieved when the sample was compacted by 20 blows; above this number, a negligible decrease in the compression index was obtained. As the gypsum content increases, the dynamic compaction has a greater effect on improvement of compressibility of the soil, while as the height of the drop increases, the compression index decreases.

Poterasu (2013) presented the results of experimental investigations on passive earth pressure acting on walls retaining dry and wet collapsible soils. Laboratory tests were carried out on a prototype setup that was developed to simulate the movement of a retaining wall toward the collapsible backfill, meaning the passive pressure state. The experiments were conducted on collapsible soil with various CPs to study the effect of this variation effect on the results. The results of the experimental investigation were used to validate the results of the numerical model developed in this investigation. The numerical model was used to generate results for a wide range of parameters, which are believed to govern this complex soil.

Fattah et al. (2013) carried out tests on four types of gypseous soils that had different properties and various gypsum contents. The samples were grouted with acrylate liquid. The treated samples showed that acrylate liquid reduces the compressibility of the gypseous soil by more than 60%–70%. This was attributed to the acrylate liquid film coating the gypsum particles and so isolating them from being subjected to the effect of water. The treated gypseous samples exhibited a low CP, where acrylate liquid reduced the collapsibility of the gypseous soil by more than 50%–60%. The acrylate liquid affects the shear strength parameters of the gypseous soil by increasing the cohesion and decreasing the angle of internal friction.

Aldaood et al. (2013) studied the effect of long-term soaking and leaching on the stability properties of fine-grained soil with and without gypsum content, in relation to changes in the mechanical properties and permeability. The soil samples were stabilized with 3% lime and cured for 28 days at 20°C. The cured samples were subjected to soaking for different periods that extended to 180 days. Results showed that long-term soaking has a strong effect on the unconfined compressive strength, wave velocity, and volume change of the stabilized soil samples. These properties are degraded when compared with the initial properties of the unsoaked samples. Moreover, the results indicated that an increase in gypsum content has significant effects on the stability properties of soil samples.

Fattah et al. (2014a, b) presented the results of tests carried out on four types of gypseous soil with different properties and various gypsum contents. The testing was conducted on undisturbed samples to evaluate the compressibility of the gypseous soil under different conditions. The samples were grouted with acrylate liquid. For unsoaked samples, it was observed that the cohesion increased and the angle of internal friction relatively decreased. Acrylate liquid affects the shear strength parameters of the gypseous soil by increasing the cohesion and decreasing the angle of internal friction. For the untreated soil, most compression took place during the first cycle of loading, and then the rate of deformation increment decreased slightly to become nearly constant in the later two cycles. For a 6-h soaking period, 15%–60% of the settlement ratio of untreated soils occurred during the first minute, whilst while for the treated soils, only 2%–15% occurred during the first minute. Most compression occurred during the first cycle of loading, and then the rate of deformation decreased slightly to become nearly constant in the other two cycles.

Al-Obaidi and Mohammed (2017) examined field data of 84 boreholes form 10 chosen sites in Iraq. The soils for these sites were granular gypseous with the gypsum content ranging from 8% to 51%. Based on the standard penetration test (SPT), the N values for each chosen site were corrected for the field procedures and overburden pressure effects by exploiting Novo SPT program to get (N1)60 or NCor. values, where these values were used later by this program for allowable bearing capacity calculations. To study the properties and illustrate the behavior of these gypseous soils, the Statistical Package for the Social Sciences (SPSS) and the Curve Expert programs were used to perform statistical analysis for the data of the chosen sites.

The major purpose of this paper is to investigate the time-dependent behavior of gypseous soils. An attempt will be made to investigate the creep characteristics under the effect of different conditions of relative density and stress history.

2 Structure of Gypseous Soil

Soil particles in gypseous soils are weakly aggregated, as the cohesive forces attracting single soil particles are very weak. Gypsum particles have no cation exchange capacity. Erosion of gypseous soils can be very serious because of poor aggregation.

2.1 Solubility of Gypsum

Gypsum is soluble, relative to most other rocks. It dissolves in water into calcium ions and sulfate ions. Its solubility in water is about 2.0 g/l, but it varies due to the presence of certain types of salts such as NaCl and $MgCl_2$, which increase its solubility, and calcium bicarbonate, which reduces it (Barzanji, 1973).

Kemper et al. (1975) studied the dissolution rate of gypsum in flowing water. It was shown that the dissolution coefficient may be dependent on some factors including the flow rate and the surface area, and increases more rapidly than the surface area at a given flow rate as the fragments become smaller and finally the fragment size decreases if the particle size increases at a given flow rate.

2.2 Experimental Work

Undisturbed soil samples were taken from three locations of Al-Tar region in Al-Najaf city in Iraq. It lies in a high area about 10 km to the west of Al-Najaf city. Water can be found in this region at about 4 m below the ground surface. So, the samples are generally partially saturated. The sand of this area is white tends to pink. It is washed in seawater, which then goes to the seabed.

2.3 Classification Tests

The specific gravity of the soil was determined according to the British Standards (B.S. 1377: 1990 test No. 6 B). Kerosene was used instead of water to prevent gypsum from being dissolved in water. The liquid limit test was carried out according to the British Standards (B.S. 1377: 1990 test No. 2, A) using the cone penetrometer method, while the plastic limit test was performed according to B.S. 1377: 1990 test No. 3. Grain size was determined by sieve analysis, which was conducted in accordance with the procedure described by Bowles (1978), but kerosene was used instead of water.

Minimum density test was performed according to B.S. 1377: 1990, to get a lower density possible to be achieved by slow pouring of the pre-weighed dry soil in air through a graduated cylinder. Then, the maximum void ratio can be calculated, from which the relative density can be estimated.

Maximum density test was performed according to the procedure described by Bowles (1978). In this test, three trials of maximum density were performed by placing the oven-dried soil in the standard mold in five layers, confining the layers with a round steel block of at least 12 kg with rapping the mold sharply 25 times using a rubber mallet. The largest density obtained was used.

The results of dry unit weight, as expected, showed that an increase in gypsum content causes a decrease in dry unit weight, because the specific gravity of gypsum crystals, which is approximately equal to 2.32, is lower than that of soil particles (about 2.6). As a result, the specific gravity decreases with increase in gypsum content. Similar results were found by Seleam (1988) and Nashat (1990).

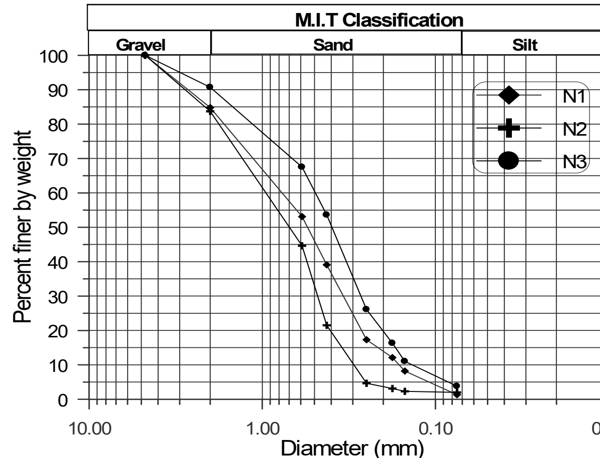


Figure 1: Grain size distribution.

The grain size distribution curves of the soil samples are shown in Figure 1. From these results, the soil specimens can be classified according to the Unified Soil Classification System and MIT (Massachusetts Institute of Technology) as poorly graded sand (SP) for soils N1 and N2 and as well-graded sand (SW) for soil N3.

The physical properties of the three soils are summarized in Table 2. In this table, N1, N2, and N3 refer to the three samples.

2.4 Chemical Tests

The total soluble salts, SO_3%, and gypsum content were determined according to the British Standards (B.S. 1377: 1990). Table 3 shows the results of some chemical and composition tests conducted on the samples.

The results of x-ray diffraction tests indicated that gypsum and quartz are the dominant non-clay minerals, while montmorillonite, palygorskite, illite, and chlorite dominate the clay mineral components.

2.5 Oedometer and Creep Tests

Three series of compression tests were performed in accordance with ASTM D 2435, 2002, that is, the load increment ratio (LIR = 1) and load increment duration (LID = 1 day). To conduct the tests, fixed-type consolidometer cells and loading frame with specimens of 75 and 50 mm diameter and 19 mm height were used. A series of DOT and CT were performed according to ASTM D5333, 2003. In both tests, the samples were prepared at the values of initial water content listed in Table 4.

Table 2: Summary of physical test results.

Soil property	Type of soil		
	N1	N2	N3
Specific gravity, G_s	2.44	2.56	2.69
Initial void ratio, e_o	1.017	0.619	0.480
Field dry unit weight, γ_d field (kN/m^3)	12.1	15.5	17.3
Maximum dry unit weight, γ_{dmax} (kN/m^3)	13.13	16.40	19.00
Minimum dry unit weight, γ_{dmin} (kN/m^3)	9.98	12.00	10.87
Relative density, D_r %	73	84	86
Gravel %	15.0	16.0	9.0
Sand %	83.8	82.0	87.0
Fines %	1.2	2.0	4.0
D_{10} (mm)	0.170	0.300	0.042
D_{30} (mm)	0.35	0.48	0.27
D_{60} (mm)	0.75	0.95	0.60
Coefficient of curvature, C_c	0.96	0.79	2.89
Coefficient of uniformity, C_u	4.41	3.17	14.28
Soil classification according to USCS	SP	SP	SW

SP: poorly graded sand; SW: well-graded sand; USCS: Unified Soil Classification System.

Table 3: Chemical test results.

Type of soil	TSS, %	SO_3, %	Gypsum content, c %
N1	9	30.6	66
N2	7.3	20.5	44
N3	6	6.9	14.8

TSS: total soluble salts

1) Collapse Test

The results of CTs, shown in Figure 2, are drawn as the vertical strain (ε) versus logarithm of effective stress (log σ'_v). Two vertical lines are noticed in these figures. The first line refers to the settlement that occurs suddenly when water is added to the soil sample under 200 kPa pressure.

The loading period for the first line is 24 h. The change in strain upon flooding in water points out that the soil is collapsible. The bonds start losing strength with the increase in water content and at a critical degree of saturation, the soil structure collapses (Jennings and Knight, 1957 and Barden et al., 1973). A summary of data is given in Table 4.

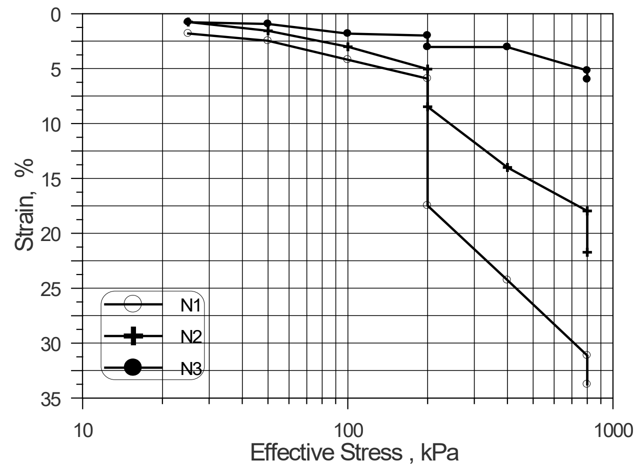


Figure 2: Results of collapse test for the three samples.

It can be noticed in Figure 2 that the CP increases with increase of gypsum content and the initial void ratio. The second line represents the additional settlement caused by creep that occurs under 800 kPa for 60 days.

In Figure 3, the vertical strain is plotted versus time in a logarithm scale for the second line of the three samples. The curve is linear during the entire creep period for sample N3. For samples N1 and N2, a change from the initial linear behavior to another with higher rate of strain is observed and a sudden soil collapse is noticed within the creep stage. This may be explained by high heterogeneity of soil with the existence of gypsum crystals in these samples.

Al-Aithawi (1990) found similar results through the analysis of axial strain versus log time for gypseous soils. A linear behavior was found at 100 and 200 kPa stress intensity. This linearity step was followed by the collapse occurrence.

2) Double Oedometer Test

Figure 4 shows the variation of strain with the logarithm of vertical effective stress obtained from the DOT. The compressibility of the soil is low when loaded under unsaturated condition. The loading of the unsaturated soil is the same as the loading of the saturated one from 25 to 800 kPa. From Table 4, it can be seen that the CPs for samples N2 and N3 obtained from DOTs are greater than those obtained from CT at a stress level of 200 kPa, while for sample N1, the CP obtained from DOT was smaller than that obtained from CT. This may be caused by sample preparation, in addition to high gypsum content which may prevent more dissolution of gypsum.

Table 4: The CP values.

Soil property			N1 c = 66%	N2 c = 44%	N3 c = 14.8%
e_o			1.017	0.619	0.480
γ_d (kN/m^3)			12.1	15.5	17.3
Initial water content, w_o %			8.3	4.8	3.6
D_r %			73	84	86
CP %	200 kPa	CT	11.57	3.42	1.04
		DOT	8.93	4.72	5.21
	800 kPa	CT	---	---	---
		DOT	18.33	14.63	7.16

CP: collapse potential; CT: collapse test; DOT: double oedometer test

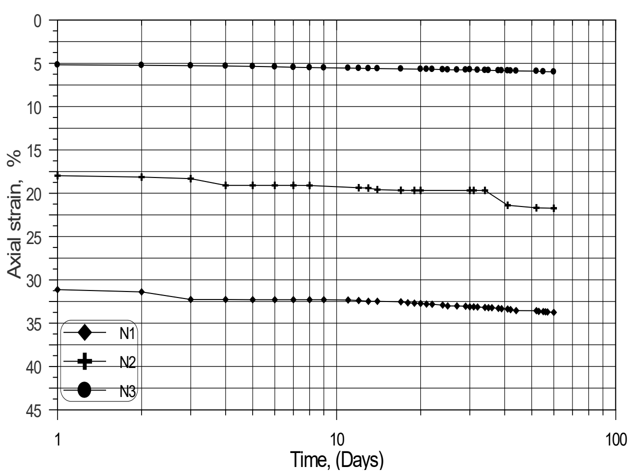
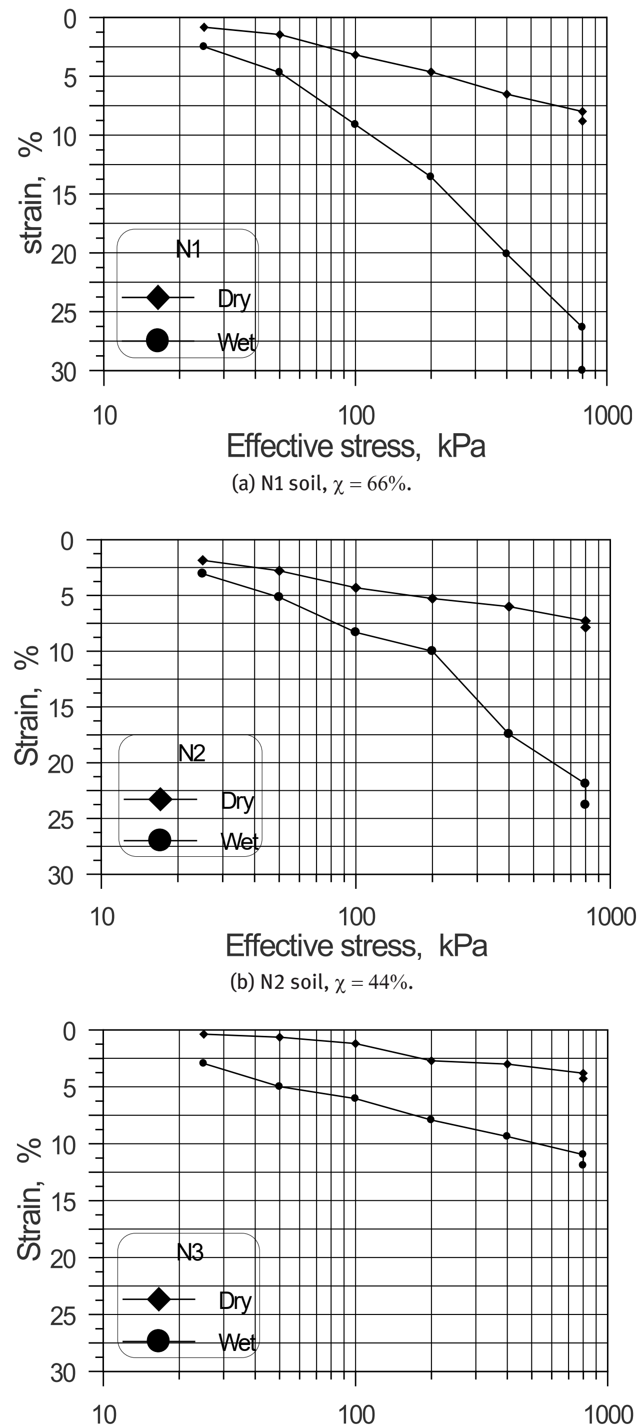


Figure 3: Variation of strain with the logarithm of time (creep).

In DOTs, it is difficult to set both specimens at the same initial void ratio. In addition, the friction that develops between the oedometer ring and soil specimen under equal external stress will be different in dry and wet specimens, resulting in a difference in "true" compressive stresses applied to dry and wet specimens. We may then expect the CP obtained from DOTs to be higher than that obtained from CT; this is what was found for samples N2 and N3 at a stress of 200 kPa.

The relationship between the CP and the logarithm of time from the DOT at 800 kPa for 60 days is plotted in Figure 5. The percent of CP versus log time curves for the N1 and N2 samples consists of three distinct segments. The first segment is represented by a concave downward curve. In this stage, the compressibility gradually increases.

The second segment is generally a straight line with a higher increase in strain. In the third segment, the rate of strain increases again to form approximately another straight line opposite to the CP axis for the sample N1 and parallel to the time axis for the sample N2, where the rate of strain remains constant after day 37 till the end of the test. The curve of sample N3 differs from the curves of N1



(a) N1 soil, $\chi = 66\%$.

(b) N2 soil, $\chi = 44\%$.

(c) N3 soil, $\chi = 14.8\%$.

Figure 4: Results of double oedometer test on semi-log scale.

and N2 samples. This curve consists of two segments: the first is a straight line where the strain increases rapidly and the other is a concave upward curve where the strain decreases. This expansion may be attributed to the presence of montmorillonite clay mineral, since gypsum is not expansive.

The results are compatible with the findings of Dudley (1970) who showed that the collapse in fine sand (with 14% montmorillonite) increased with the increase of initial water content until it reached values higher than 10%; the collapse then became less at the same stress level and dry unit weight. Sand deformation response is directly related to the parent minerals (Lambrechts and Leonards, 1978). Hossain (2001) found that the swelling pressure decreases with increasing gypsum content for Al-Qatif clay.

In Table 3, it is noted that the fine fraction (Si + Cl) in all soils was below 4%, and in Figure 5c, it is found that the result was due to the presence of montmorillonite, which may result in some type of swelling that is opposite to collapse.

The effect of gypsum content on CP for a long term under 800 kPa is well illustrated by Figure 6. The relation obtained indicates that the creep values increase as the gypsum content increases. This may be ascribed to the continuous dissolution of gypsum.

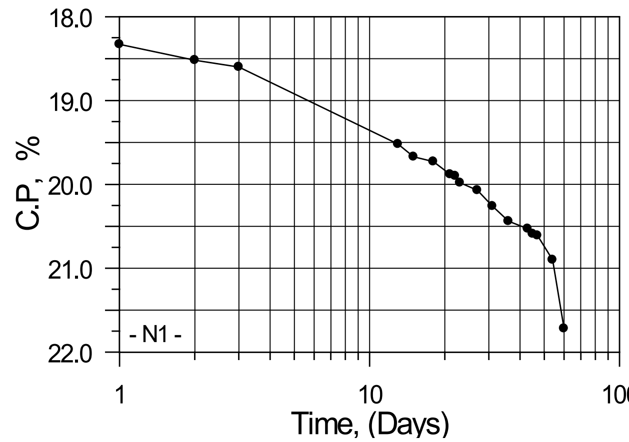
As shown in Figure 7, the CP increases with increasing stress for the three samples. When the stresses are low (below 100 kPa), this effect is not apparent.

The collapse may be caused by the breakdown of the interparticle bonds under high loads. It can be seen that for N1 sample, where the gypsum content is 66%, the same rate of increase of CP takes place at all stress levels. On the other hand, for samples N2 and N3, a continuous increase in CP rate occurs when the stress level increases.

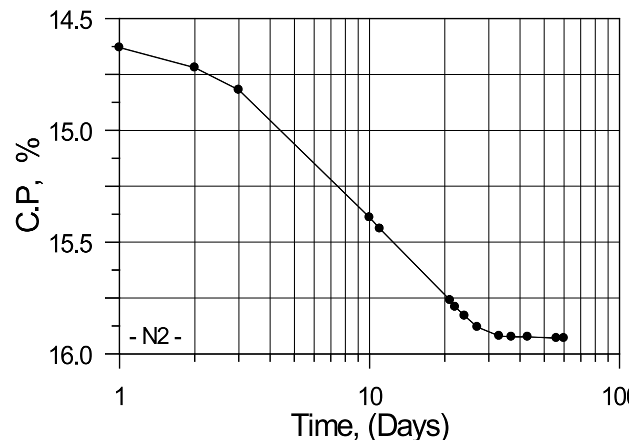
2.6 Effect of Relative Density

In this part of the experimental program, two identical specimens with relative densities 40%, 50%, and 60% for the N1 soil were tested independently: one with the natural moisture content, while the other was soaked in water from the beginning. The soil specimens were statically compacted in the oedometer ring to a dry unit weight that maintained the desired relative density. The results of double oedometer test are summarized in Table 5.

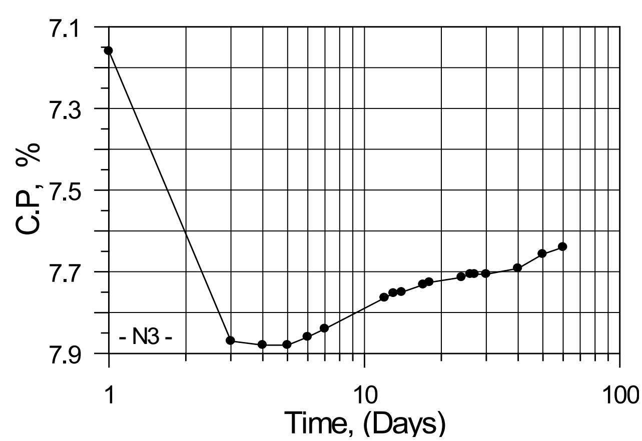
It can be observed that the effect of relative density on collapse strain at 200 kPa is not clear. The effect of relative density is evident at 800 kPa. The strain increases with the increase of relative density from 40% to 60%.



(a) N1 soil, $\chi = 66\%$.



(b) N2 soil, $\chi = 44\%$.



(c) N3 soil, $\chi = 14.8\%$.

Figure 5: Variation of collapse potential with time in double oedometer test.

Once the sand became unsaturated, the rate of increase in strength decreased, and in fact, the strength decreased when the suction was increased beyond some limiting value.

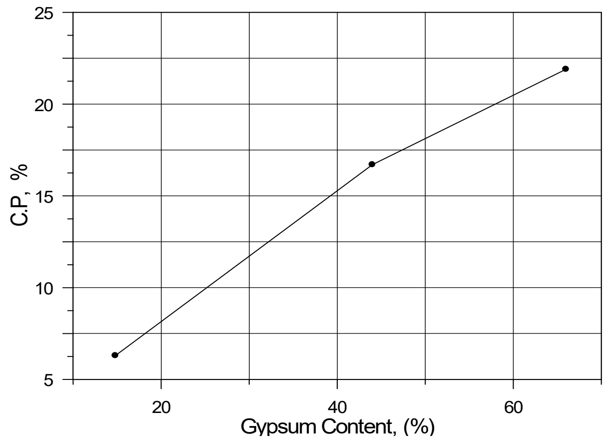


Figure 6: Effect of gypsum content on the long-term collapse potential (under 800 kPa for 60 days).

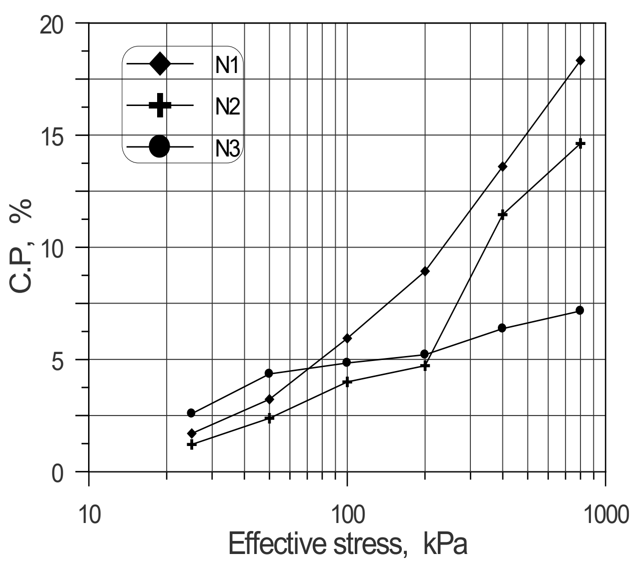


Figure 7: Effect of gypsum content on the collapse potential under different stresses.

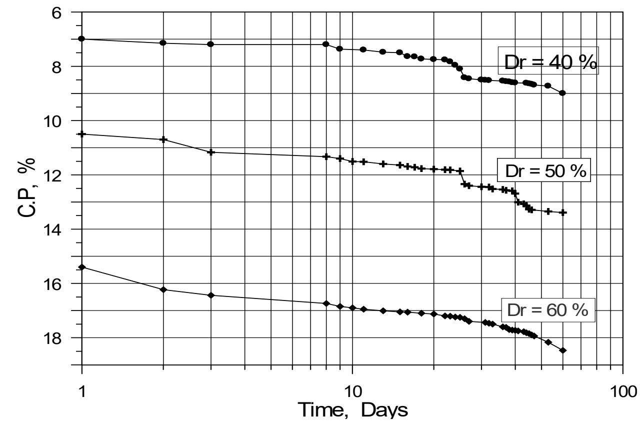


Figure 8: Collapse potential -log time relationships at different relative densities, (N1 soaked soil).

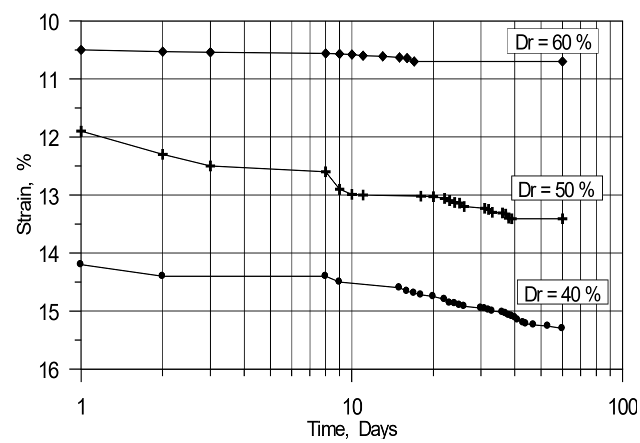


Figure 9: Effect of relative density on creep for dry samples (N1 soil).

Table 5: Effect of relative density on the collapse potential of N1 soil.

σ_v, kPa	D_r = 40%		D_r = 50%		D_r = 60%	
	CP 1 day	CP 60 days	CP 1 day	CP 60 days	CP 1 day	CP 60 days
200	1.87	---	7.47	---	6.42	---
800	7	9	10.5	13.39	15.4	18.47

Figure 8 shows the CP–logarithm of time relationship for soaked samples prepared at the three relative densities under 800 kPa. The curves indicate that the CP increases with time for the soil sample compacted at a relative density 60%, and the increase is higher than in those compacted at 40% and 50%. The curves start with a straight line then a curve concave downward at a high strain is observed. For the samples compacted at 40% and 50% relative densities, the curves are interrupted by little soil collapses, while the third curve exhibits a smooth relation following the collapse.

Figure 9 shows the variation of strain with time for dry N1 soil at different relative densities. It can be noticed that the strain decreases more when the dry soil is compacted at higher relative density.

A decrease of about 43% was noticed when the relative density changed from 40% to 60% at long times, while the inverse behavior was noticed for soaked samples, as illustrated in Figure 10. The strain increases when the wet soil is compacted at a higher relative density. This behavior can be attributed to the apparent cohesion initiated in saturated samples. This cohesion is greater in

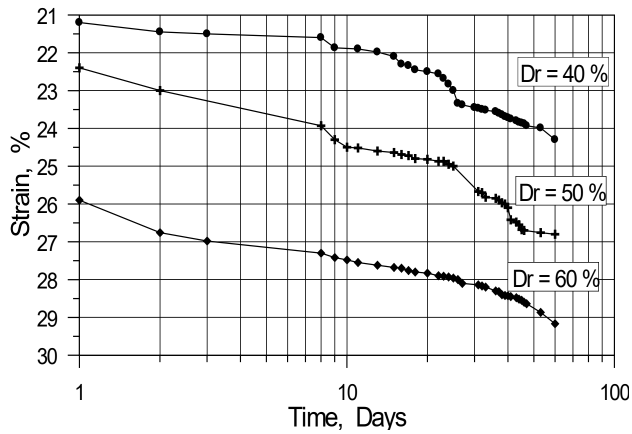


Figure 10: Effect of relative density on creep for soaked samples (N1 soil).

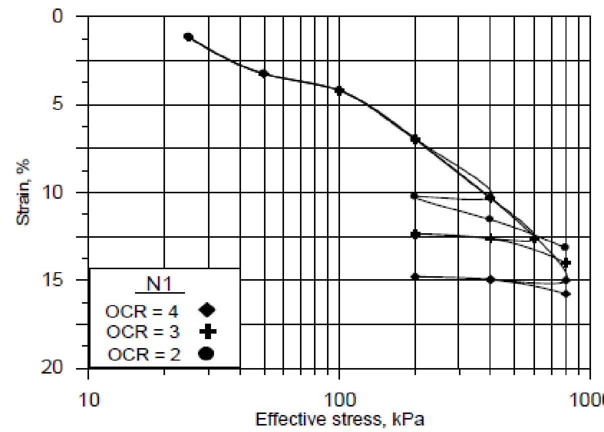


Figure 11: Strain versus effective stress for the N1 sample. OCR: overconsolidation ratio.

loose samples than in medium samples, which leads to lower strain in loose samples.

2.7 Effect of Stress History

To investigate the effect of stress history on creep, soil testing was carried out on three samples: one of the samples was loaded to 800 kPa, the other sample was loaded to 600 kPa, while the third one was loaded to 400 kPa. The three samples were then unloaded to 200 kPa, and thereafter reloaded again to 800 kPa. At this stage of reloading where the stress level was kept at 800 kPa, the samples were left for 60 days under the same load.

Figures 11–13 show the strain–logarithm effective stress relations for the soil samples N1, N2, and N3, respectively. The values of compression index C_c and swelling (rebound) index C_r for the three samples are given in Table 6.

Figures 14–16 show the strain–logarithm of time relations for the three soils. The relations indicate two stages: a period of primary compression followed by a period of secondary compression. A comparison between stages of creep shows that the secondary compression (creep) takes place after about 10 days for all specimens.

The relationship between the overconsolidation ratio (OCR) and the creep strain for the three soils is shown in Figure 17. When the gypsum content is small (N3, χ =14.8%), the creep strain increases when the OCR increases from 2 to 4, while soil N2 shows a little decrease in creep strain when the OCR increases from 2 to 3, and then increases with OCR. The preloading of gypseous soil may cause breakdown of the particle structure, which leads to increase in creep strain. This may be the case of soil N2. In soil N1, the creep strain increases when the OCR

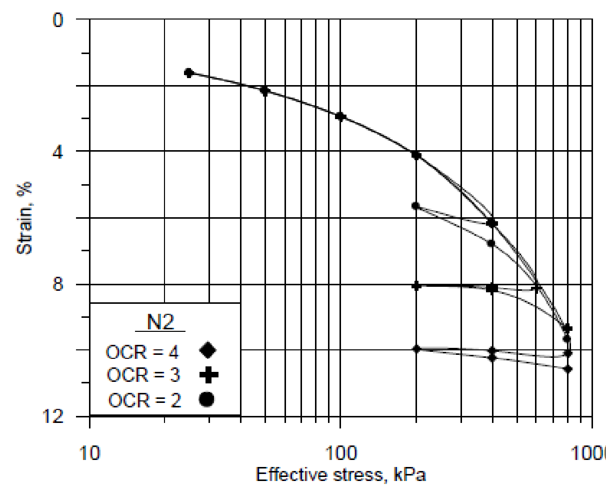


Figure 12: Strain versus effective stress for the N2 sample. OCR: overconsolidation ratio.

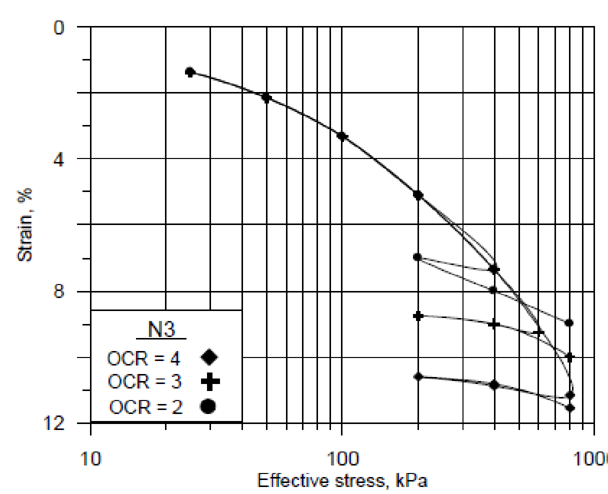


Figure 13: Strain versus effective stress for the N3 sample. OCR: overconsolidation ratio.

Table 6: The compression and swelling indices.

OCR	Type of soil					
	N1 c = 66%		N2 c = 44%		N3 c = 14.8%	
	C_c	C_r	C_c	C_r	C_c	C_r
4	0.124	0.004	0.109	0.01	0.162	0.009
3		0.0014		0.002		0.016
2		0.0019		0.017		0.012

C_c: compression index; C_r: swelling (rebound) index; OCR: overconsolidation ratio

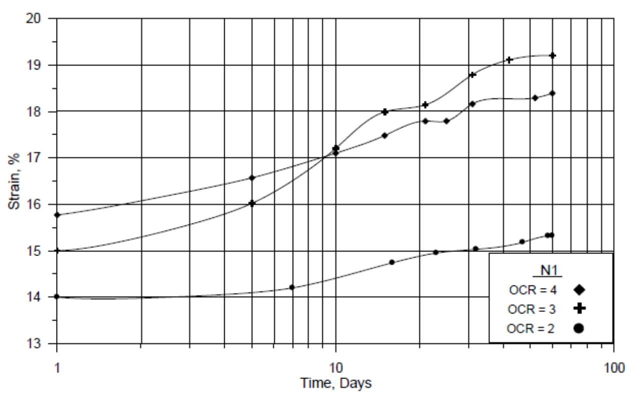


Figure 14: Variation of strain with time for the N1 soil. OCR: overconsolidation ratio.

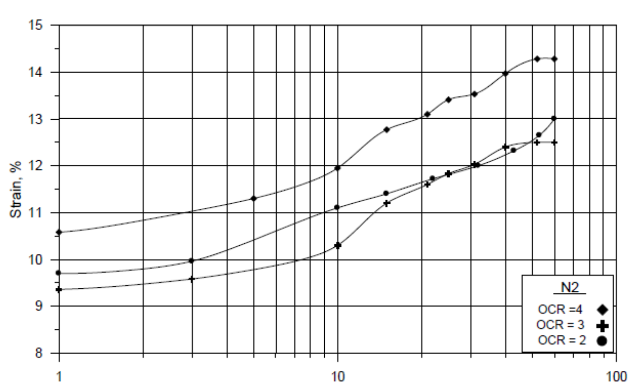


Figure 15: Variation of strain with time for the N2 soil. OCR: overconsolidation ratio.

increases from 2 to 3, and then decreases. Also, it can be noticed that the creep strain increases with increase in gypsum content for the same OCR.

The strain rates versus time at log–log scale for the three soils are plotted in Figures 18–20. The three samples exhibit higher values of the initial strain rate. These values

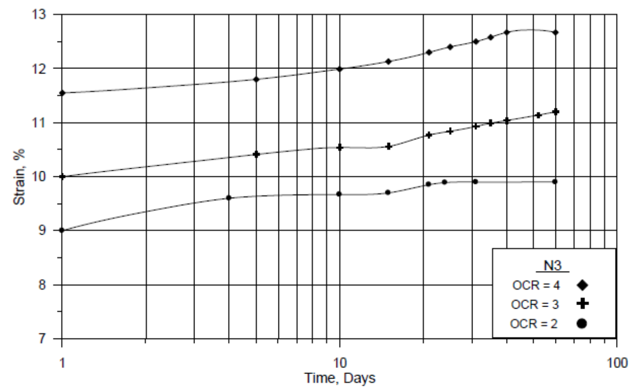


Figure 16: Variation of strain with time for the N3 soil. OCR: overconsolidation ratio.

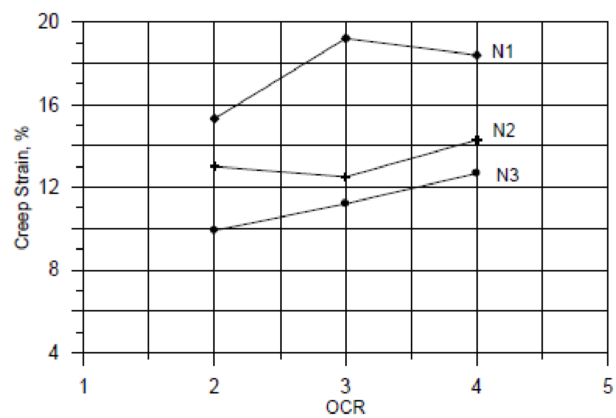


Figure 17: Effect of OCR on the creep strain for the three soils. OCR: overconsolidation ratio

show a steady decrease of strain rate with time, caused by decrease in dissolution of gypsum leading to equilibrium at later times under the sustained loads.

2.8 Mathematical Models of Results

In this section, the results obtained from the laboratory for geotechnical properties tests which relate the collapse potential are grouped as statistical data (observations) to build a mathematical model. The computer package Statistica is used to represent a relationship between the CP of the three soils with gypsum content (χ), relative density (D_r), and time (t).

The computer package presents the results of experimental data as a mathematical model of the CP of the three soils with gypsum content (χ), relative density (D_r), and time (t). Accordingly, the statistical model for the CP is derived to be:

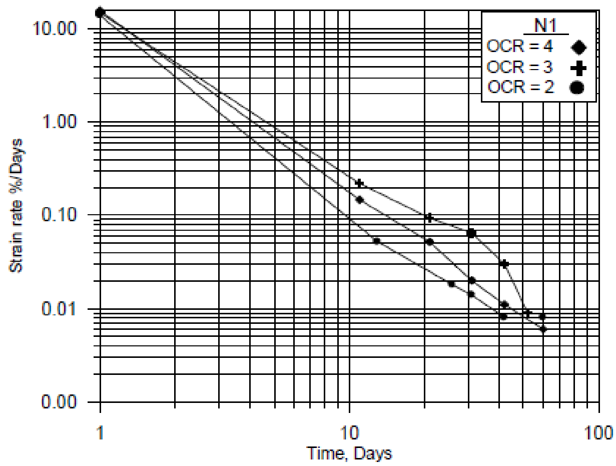


Figure 18: Variation of strain rate with time for the N1 soil at different overconsolidation ratios.

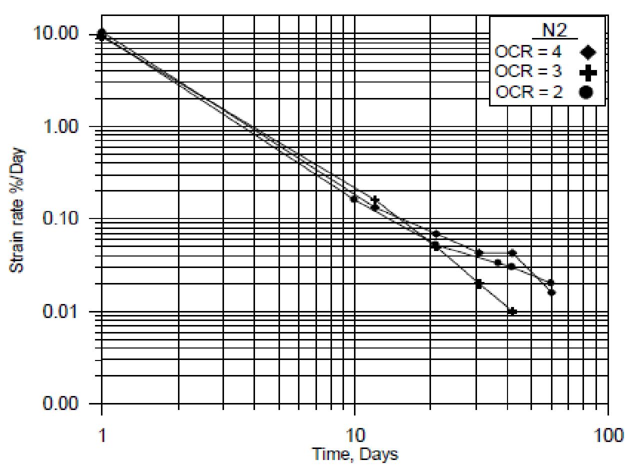


Figure 19: Variation of strain rate with time for the N2 soil at different overconsolidation ratios.

$$\text{C.P.} = \chi\,(70.482\ D_r + 0.0522\ t - 22.771) \quad (2)$$

The coefficient of determination (R^2) for this relation was found to be 96.7%.

For soil N1 only, the following relation could be obtained, in which the CP is a function of gypsum content, relative density, and the applied stress (σ'_v):

$$\text{C.P.} = \chi\,(49.053\ D_r + 0.0144\ \sigma'_v - 19.4524) \quad (3)$$

The coefficient of determination (R^2) for this relation was found to be 94.2%. A comparison between the measured and predicted values of CP is shown in Figure 21 for equation (2) and in Figure 22 for equation (3).

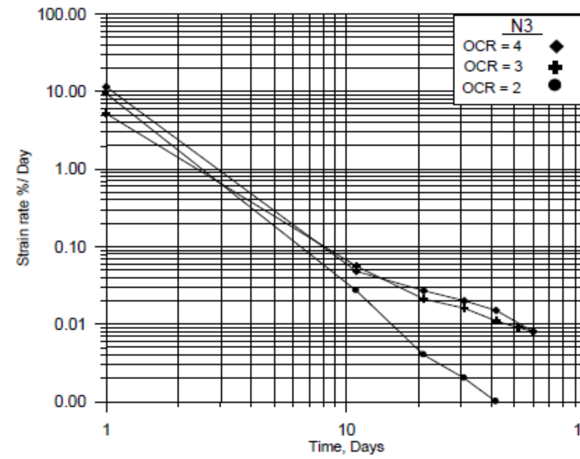


Figure 20: Variation of strain rate with time for the N3 soil at different overconsolidation ratio s.

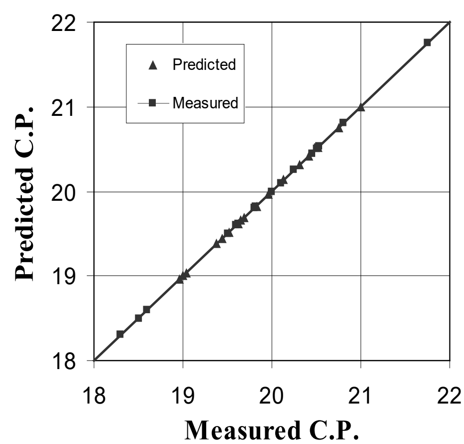


Figure 21: Comparison between the measured and predicted collapse potential in the three soils using equation (2).

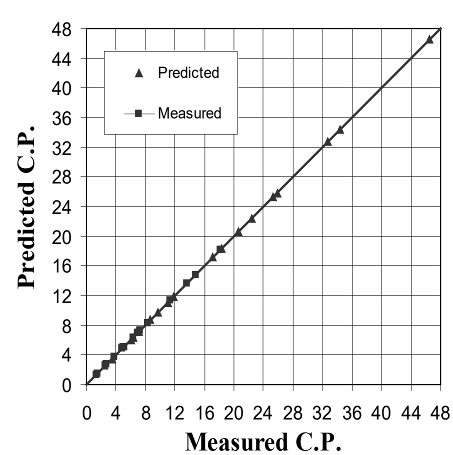


Figure 22: Comparison between the measured and predicted collapse potential in soil N1 using equation (3).

3 Conclusions

From the results and analysis of the tests presented in this paper on samples of gypseous soil having percentages of gypsum of 66%, 44%, and 14.8%, the following conclusions could be drawn:

1. The results of collapse tests showed that the relationship between the vertical strain and logarithm of effective stress has two vertical lines. The first one represents the collapse settlement taking place within 24 hours, while the second one represents the long-term collapse.
2. The secondary compression (creep) for the three soils was found to start after about 10 days of loading.
3. The collapse potential in both single and double oedometer tests increases significantly when the gypsum content increases from 14.8% to 66% and when the initial void ratio increases.
4. The relations of collapse potential–logarithm of time for soaked samples prepared at different relative densities under 800 kPa indicate that the CP increases with time for the soil sample compacted at 60% relative density and the increase is higher than those compacted at 40% and 50% relative density.
5. When the gypsum content is small (14.8%), the creep strain increases when the OCR increases from 2 to 4. The axial strain rates versus time expressed by log–log plot showed a steady decrease of strain rate with time, followed by a decrease of dissolution of gypsum leading to equilibrium at later times under sustained loads.

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