Effects of Cyclic Test in Decreasing Damages to Structures and Roads on Gypsum Soils

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ABSTRACT

Fine gypsum soils, when saturated and loaded, because of their high porosity, have large settlements. Compaction of the soil and removal of the load causes the soil to swell. These properties of gypsum soils cause many problems for structures built on them. For instance unsymmetrical settlement, uneven ground floor and cracks in façade are some of the problems. Likewise in road engineering, swelling of this type of soil located under the asphalt after absorbing water is one of it most important problem.

So realizing and identifying the behavior of gypsum soils and effort in finding solutions for decreasing the amount of settlement and swelling are the main objectives of this study. The soil samples were from the City of Mashhad, which is the second largest city in Iran. These soils naturally contain high amount gypsum and hence have a special behavior. In this study, samples with different amount of gypsum were gathered and classified to seven sample groups. Preliminary tests done showed that the increase in the amount gypsum causes the soil plasticity index and unit weight to decrease, which in turn increases settlement. In order to investigate the influence of degree of compaction, all samples were compacted with different unit weight and the swelling potential and swelling pressure were measured after saturation.

The results show that with increasing unit weight and amount of gypsum, the soil swelling potential increases. Cycles of wetting and drying and also cycles of loading and unloading were performed to investigate their influence on the gypsum soil.

Key Words: Load & unload cycles, Gypsum soil, Settlement, Swelling potential, Wetting & drying cycles.

Introduction

Swelling soils are among the problematic soils with their specific physical and mechanical properties. Such soils are always accompanied by structural problems in urban areas, problems that mostly plague engineers and contractors of the housing and road making sectors. When dried, swelling soils decrease in volume, but when saturated, they swell and increase in volume.

The swelling of the soil occurs as a result of formation of a water membrane around its elements. Calcium sulfate absorbs water and converts into gyps or water calcium sulfate ($CaSo_4$, $2H_2O$) and during this process its volume increases up to 60%. The main cause of swelling in most swelling soils is the presence of special minerals and clay, while the reason behind swelling of some fine soils is the presence of gypsum [2]. Due to the presence of plenty of gypsum particles, this type of soil is usually porous and has a low unit weight, in such a way that sometimes they have been Observed with their natural specific weight, which is 1.3 gram/cm^3 [1][3].

Fig. 1 *Damages to flooring due to the swelling of gypsum soils*

Though swelling soils cause major damages to buildings in many places [4], the porosity of gypsum soils may also be a cause of large settlements.

Settlement or swelling depend on various factors such as clay soil content and its mineral type, moisture content, relative density, soil structure, and the amount and ways of applying loads [5]. Gypsum soils have a high gypsum content and therefore low unit weight; unless improved they will cause the building to settle, and if they are compress or in case lime is added during compression, they will swell [1] [3].

Although the use of lime is a good way to improve most types of soils, if the chemical reactions result in formation of minerals such as Ettringite and Thaumasite due to the high water absorption capacity of these minerals, the soil will swell severely [1] [6].During the last decade buildings erected on the southwest of Mashhad city has faced soil settlement or swelling. These two contradictory phenomena, the main cause of which was not known, inflicted serious damages on building. Figure 1 clearly shows how the swelling of lower layers has caused the flooring to heave. In order to study the mechanical behavior of the soils of this region, samples were first taken from various locations and determined their gypsum content and unit weights. Then the samples were categorized based on these two parameters and underwent complementary tests so that their mechanical features, swelling potential, swelling pressure, and effect of wetting-drying and loading-unloading cycles on each of the seven chosen samples were known.

Table 1 Chemical Analysis of Chosen Samples

Sample	pH	$CaSo_{4\%}$	$So_{3\%}$
S1	7.74	0.5	0.55
S2	7.32	13.7	8.3
S3	7.11	15.4	12.9
S4	7.23	17.6	13.1
S5	7.51	21.0	13.3
S6	7.47	22.1	13.6
S7	7.49	23.4	13.9

1. Physical and Mechanical Features of Gypsum Soils

In order to examine the properties of gypsum soils in the southwestern region of Mashhad city - second big city in Iran, in which presence of gypsum in the soil has inflicted damages to buildings, the region was divided into seven zones. Forty soil samples were taken from various locations which are supposed to have little to large amounts of gypsum and had caused settlement or swelling in that region.

The samples were first granulated (ASTM C33) and once their Atterberg were determined (ASTM D4318) their properties were compared. As some samples were similar in terms of granulation, Atterberg limits, and gypsum contents, the samples were divided into seven types and one sample was chosen from each type (totally seven samples). Table 1 shows the chemical properties of these seven samples and Figure 2 shows their granulation. As seen in Table 1 the gypsum content of S1 sample was too little and ranged between 13% and 24% for other samples. The samples have been named in order of their gypsum content.

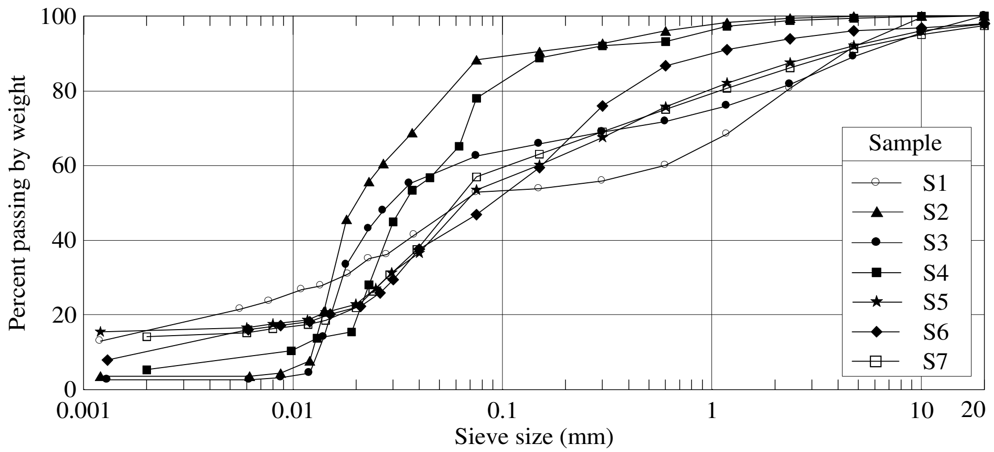


Fig. 2 *Granulation of the Seven Samples*

Table 2 Geotechnical and Mechanical properties of Chosen Samples

Sample	Unit Weight (gr/cm^3)		Specific Density	Atterberg Limits			MDD[a] (g/cm^3)	OMC[b]	USCS[c]
	Natural	Dried		LL (%)	PL (%)	PI (%)			
S1	1.50	1.43	2.71	36.0	23.0	13.0	1.61	10.1	CL
S2	1.49	1.40	2.61	24.2	13.6	10.6	1.62	9.0	CL
S3	1.58	1.38	2.70	25.0	17.3	7.7	1.64	9.6	CL
S4	1.49	1.37	2.71	27.0	23.4	3.6	1.64	9.7	ML
S5	1.46	1.37	2.73	23.8	23.8	0.0	1.66	11.2	ML
S6	1.40	1.33	2.59	22.9	----	----	1.68	14.6	SM
S7	1.36	1.31	2.77	19.5	18.8	0.7	1.69	12.9	ML

MDD[a] = Maximum Dry Density
OMC[b] = Optimum Moisture Content
USCS[c] = Unified Soil Categorization System

Also the geotechnical features including plasticity features and categorization of the seven samples have been summarized in Table 2. Given the gypsum content of the samples (Table 1) and their other specifications (Table 2), the following conclusions can be made:

- Most gypsum soils of the region are fine and had textures of tiny clay or silt particles.
- The gypsum content has no remarkable effect on the specific density of the soil.
- The soils of the region are mostly porous and that reduces the gypsum content and natural unit weight; in other words, the more the gypsum content the less the natural unit weight. The high porosity of the soils of the region appears to be the main cause of settlement in most buildings.
- As the gypsum content increases the optimum moisture and the maximum dry unit weight increase and the plasticity index decreases. The main reason for this is the absorption of the water content of the soil by the gypsum, which in turn indicates the mineral structure of gypsum.

Figure 3 shows the unit weight and plasticity index (PI) along with gypsum percent. The first sample is not included in this figure because of its very low gypsum content. As seen in the picture, we can consider a linear relationship between the increase of gypsum content and the decrease of unit weight and plasticity index. Reduction of the natural unit weight of the soil along with the increase of gypsum content is due to the presence of gypsum and porosity of the soil. On the other hand, this diagram also indicates that the

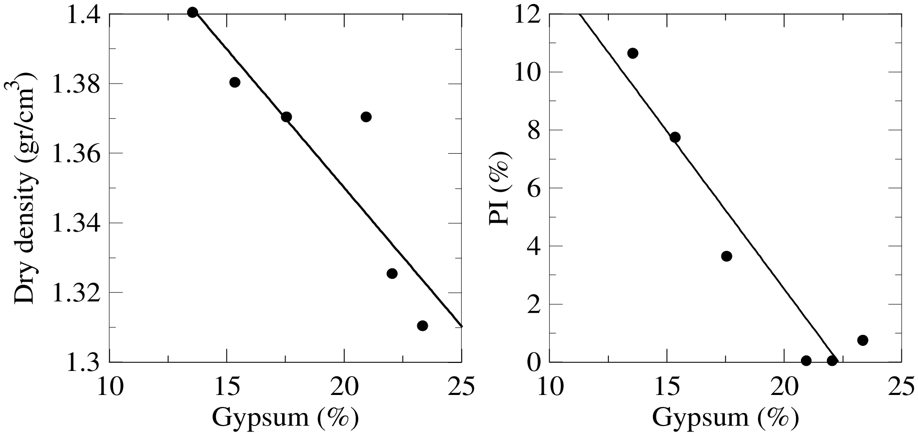


Fig. 3 *Changes of Unit Weight and Plasticity Index with the Gypsum Percent of Chosen Samples*

Increase of gypsum content has reduced the plasticity features of the soil, in such a way that high percentages of gypsum make the soil nearly non-plastic.

3. Settlement of Gypsum Soils

In order to study the settlement of the soils of this region and also to study the effect of compression as a mechanical improvement method, samples with natural moisture content and compressed samples with optimized moisture and maximum dry unit weight were tested by means of a specially made consolidation instrument.

After placing the samples in the instrument and adding water up to the saturation moisture level, the settlement was measured at the end of the consolidation process. The results of the test which are included in Table 3 show that the increase of gypsum content, which increases soil porosity, also causes an increase in the settlement. It is also observed that compression decreases settlement up to 30 percent and improves load bearing capacity of the soil. But given the swellings observed in the region it seem that though compressing the soil results in its settlement, yet presence of water and saturation of the soil may result in its swelling. This topic will be covered in the next section.

Table 3 Consolidated Settlement Rate of Chosen Samples (%)

Sample	Settlement of Natural Samples (%)	Settlement of Compressed Samples (%)
S1	6.0	4.2
S2	7.4	6.1
S3	7.5	6.1
S4	8.5	6.5
S5	17.9	12.3
S6	21.5	14.0
S7	19. 9	13.0

4. Swelling of Gypsum Soils

As pointed out earlier, swelling of the soils of this region was observed from years ago. The swelling potential may be discussed from two points of view:

1. Free swelling that demonstrates the height increase percent of the sample in proportion to its primary height, and may be calculated by using the consolidation instrument and applying a surcharge of 25 kPa to the sample.

2. Swelling pressure that is equal to the surcharge pressure that has to be applied to the sample in order to keep its height fixed. The swelling pressure too may be measured by the consolidation instrument [4].

In order to investigate the volumetric changes of the soil, be it settlement or swelling, a instrument similar to the consolidation instrument was made that was capable of measuring the swelling with or without applying surcharge pressure. Figures 4(a) and 4(b) show the said instrument and its accessories. The main feature of this instrument is its simplicity. It is easily produced in mass and

Fig. 4(a) *plan of instrument*

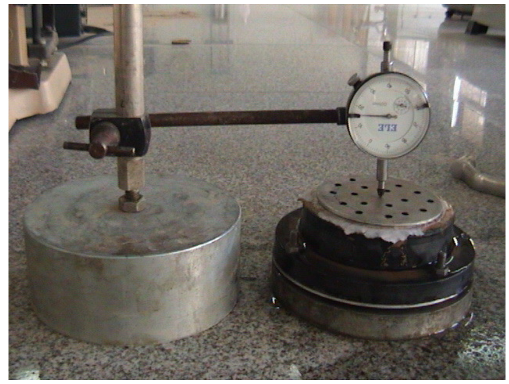


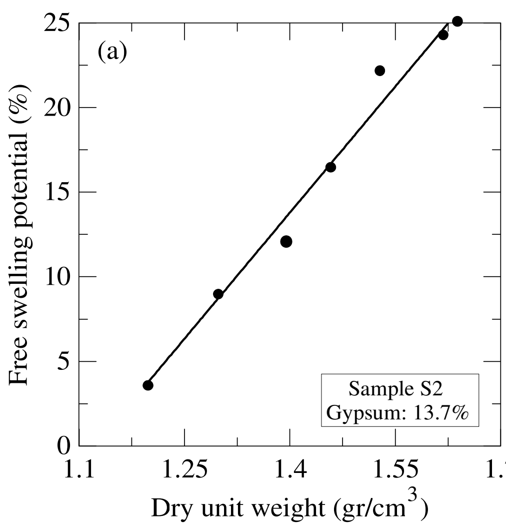
Fig. 4(b) *section of instrument*

Fig4. *Instrument made for Measuring the Swelling Rate*

Enables us to conduct various tests with different samples. To study the impact of compression on the swelling potential, S2 sample with a gypsum content of 13.7% was chosen and compressed in the said instrument with various moisture contents and changing unit weights ranging from 1.16 to 1.62 g/cm^3. Then the mould containing the sample was fully submerged in water so that the sample could slowly saturate and the compressed sample could swell due to saturation. Figures 5(a) and 5(b) present the free swelling of this sample with different unit weights (without applying overhead pressure). Also in this image the swelling changes during the course of time are demonstrated for this very sample with a unit weight of 1.62 g/cm^3. The following conclusions are made according to this diagram:

- The main cause of soil swelling in this region is presence of gypsum. Compression of the soil even in lower unit weights will cause swelling if the soil is saturated.
- With the rise of the unit weight, the swelling rate reduces. Therefore, while compression may decrease settlement, it may bring about swelling in case of saturation.
- Maximum swelling occurs at the very early hours of saturation. The time needed for the swelling to stop is about 70 hours after saturation.

For a more accurate investigation of the impacts of compression on the swelling of the region soils, numerous samples were taken from the soils with gypsum contents above 10% (samples S2 to S7) and then compressed with optimized moisture but varying unit weights ranging from 1.15 to 1.65 g/cm^3. The samples were then placed into the instrument and saturated and their free swelling was measured.



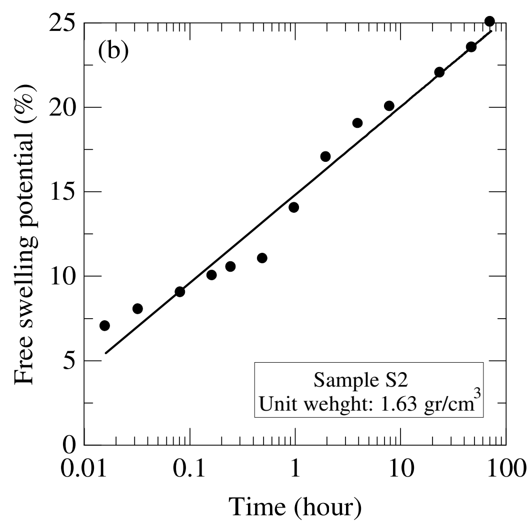


Fig. 5 (a) *Changes in the Free Swelling of S2 Sample with Unit Weight*
5(b) *Swelling Changes per Time for Sample S2 with a Gypsum Content of 13.7% and with maximum dry unit weight*

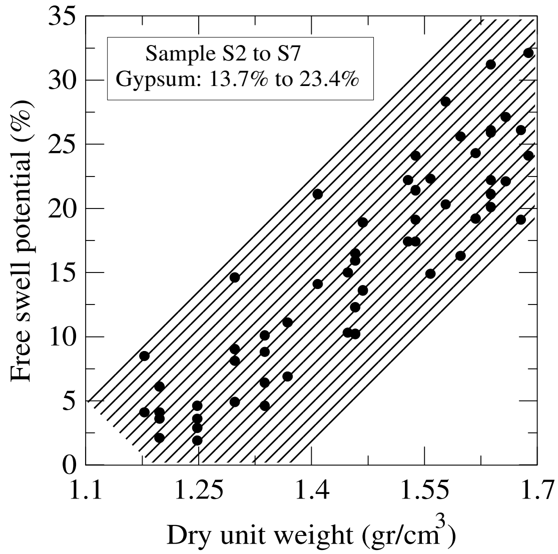


Fig. 6 *Free Swelling of all Samples Containing Gypsum which are Compressed with Different Unit Weights*

Figure 6 presents the results of these tests for soils with different gypsum content and unit weights. The image clearly demonstrates the effect of compression on swelling; in other words, higher compression results in larger swelling. Therefore, while compression causes settlement, saturation of the soil will be followed by swelling.

In order to determine the swelling pressure, the samples were compressed with optimum moisture and maximum dry unit weight inside the instrument mould, and after saturation their heights were kept fixed by applying surcharge pressure. While Figure 4 demonstrates the method for measuring the swelling by this instrument, Figure 7 shows how to apply stress to the mould containing the sample. As seen in the image, for a uniform distribution of stress, a pipe has been passed through the opening, the diameters of which are equal. The amount of stress applied is controlled by unit weights.

Fig. 7 *How to apply Stress to Measure Swelling Pressure by using the Instrument shown in Figure 4*

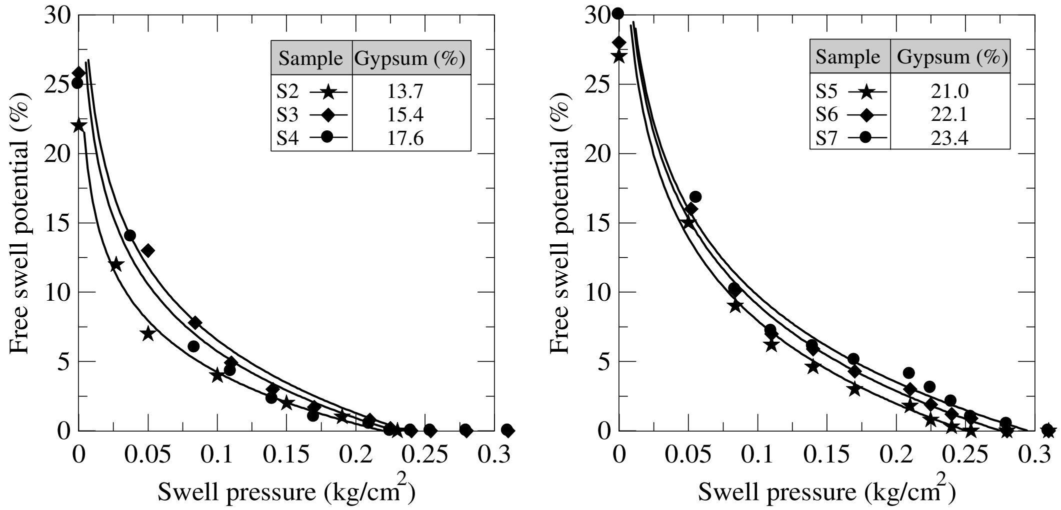


Fig. 8 *Swelling Pressure for all Samples with High Gypsum Content*

Table 4 *a* and *b* Ratios for Samples being Tested

Sample	Gypsum Percent	*a*	*b*
S2	13.7	-5.37	-8.13
S3	15.4	-7.60	-10.94
S4	17.6	-6.95	-10.27
S5	21.0	-8.64	-11.94
S6	22.1	-8.97	-11.57
S7	23.4	-9.02	-11.00

Figure 8 presents the swelling pressure for all samples containing various gypsum contents.

The swelling pressure is nearly independent of the gypsum content of the samples, though a rise is observed in the swelling pressure with the increase of gypsum content. Obviously, this pressure is enough for inflicting serious damages to light structures. Figure 1 shows an instance of such damages on the flooring of the structure. Given the test results shown in Figure 8, the relationship between the swelling pressure and swelling percent may be modeled in the following manner:

$$S = a.In\ P+b \qquad (1)$$

In this equation (1), S is the swelling percentage, P is the swelling pressure (kg/cm^2), and a and b are fixed ratios which may be determined inside the laboratory. The values of a and b ratios for samples being tested have been included in Table 4.

By taking the average values of a and b ratios, Equation (1) may be written as Equation (2):

$$S = -\ (7.75\ In\ P+10.6) \qquad (2)$$

4. The Effect of Wetting-Drying Cycles on Swelling

In order to study the effects of wetting-drying on the swelling rate, the sample was first saturated and the final free swelling was measured after it became constant (in a time span of 70 hours). Afterwards, the sample was placed inside the heating chamber with low temperature so that its moisture could decrease slowly and the decline of its swelling reached a fixed amount. This cycle was continued until the sample reached a fixed volume. Figure 9(a) show the effects of consecutive wetting-drying cycles on S2 sample. As seen in the picture, with the increase of the consecutive wetting-drying cycle the swelling increases and reaches a fixed amount after 5 consecutive cycles. In other words, consecutive wetting-drying cycles not only do not decrease swelling, they rather increase it. Therefore, they will not be useful as a soil improvement method.

To examine the effects of gypsum content on the wetting-drying cycles the same test was repeated for all samples with different gypsum contents, and their swelling percentage in saturated and dried conditions were recorded in the last cycle (after which there was no significant change in the swelling). In Figure 9(b) changes in the swelling percentage has been shown along with the gypsum content of the samples undergoing the wetting-drying cycles test. As can be seen, as the gypsum content increases the rising trend of swelling in gypsum soils increases in a linear manner.

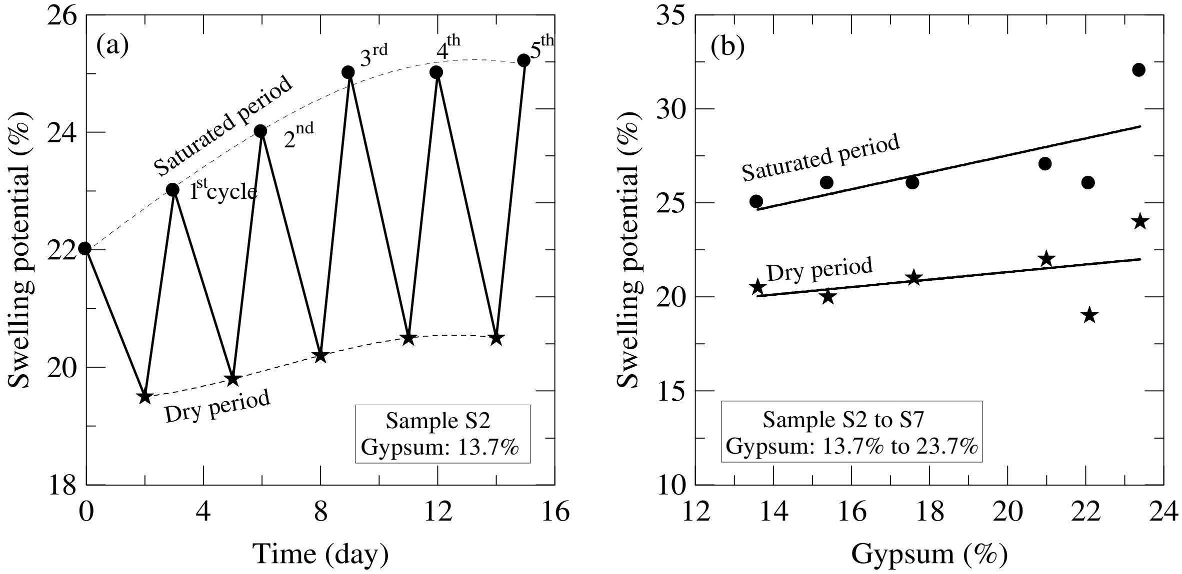


Fig. 9(a) *Effect of Consecutive Wetting-Drying Cycles on Swelling Potential*
9(b) *Maximum Swelling percentage after cycles in dry and saturated case for all samples*

Indeed, the effect of wetting-drying cycles may be taken for the changes of seasons or seasonal rainfalls, which saturate the soil and cause damages to buildings. Similar results have been reflected in the studies conducted by other researchers.

5. The Effect of Loading-Unloading Cycles on Swelling

One of the soil improvement methods is preloading [8]. In order to study the effects of loading and unloading on swelling changes, the samples were first saturated and given sufficient time to reach final swelling; afterwards, the swelling was reduced by gradual application of overhead load. The increasing of the overhead load continued until the swelling was totally eliminated and the sample height returned to is initial form. Then the surcharge loads were omitted and the sample was allowed to swell again. After some time during which swelling reached its maximum, the surcharge load was again applied gradually until the swelling was totally eliminated. These loading and unloading cycles were repeated until the swelling reached a fixed rate in two consecutive cycles.

Figure 7 presents how the surcharge load was applied by means of a circular plate that was connected to an upper plate by means of a pipe. Figure 10 demonstrates the results of this series of tests, which included applying the pressure necessary for eliminating the swelling in S2 sample and the number of cycles needed to reach a fixed volume for the other samples.

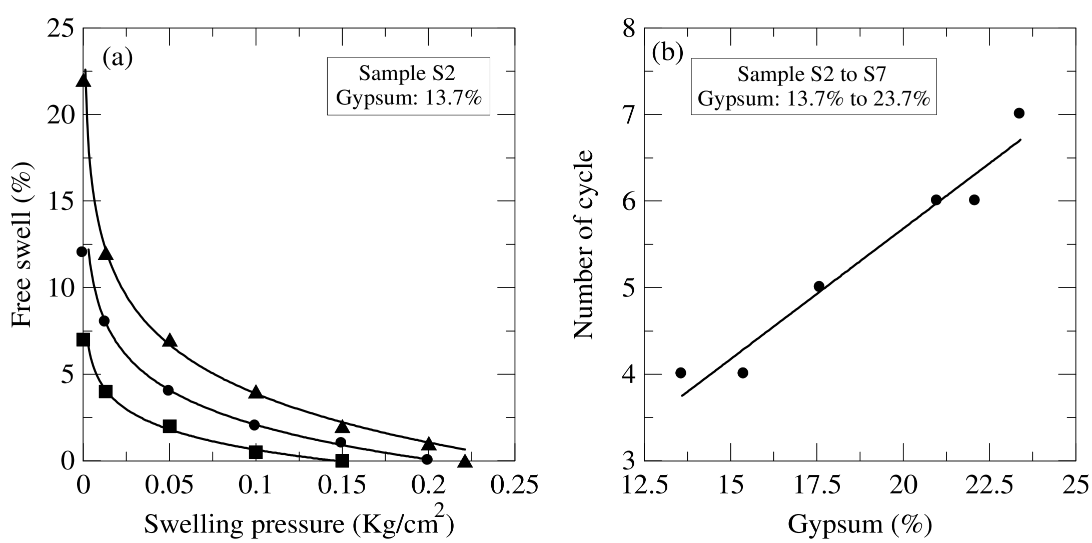


Fig. 10(a) *Effect of Consecutive Loading-Unloading Cycles on Swelling Potential for S2*
10(b) *Maximum number of loading-unloading cycles needed for reaching a fixed swelling rate for all samples*

Table 5 Effect of loading-unloading cycles on swelling potential of each Chosen Samples

Sample	Free swelling potential before cyclic tests (%)	Free swelling potential after cyclic tests (%)
S1	0.25	0.0
S2	23.0	6.5
S3	23.0	8.5
S4	24.0	8.5
S5	24.0	9.0
S6	25.0	9.0
S7	28.0	12.0

Figure 10(a) shows the swelling pressure changes in percent of swelling in the first three cycles of loading and unloading. As can be observed, after only three cycles the swelling reduces more than 70%. Of course it is obvious that by increasing the number of loading-unloading cycles the swelling is reduced, but it is never eliminated. The reason for this may be the compression of the soil due to loading and unloading actions. The above test was done on other samples with different gypsum contents, the results of which are included in Figure 10(b). This figure shows the maximum number of loading-unloading cycles needed for reaching a fixed swelling rate. As seen, the number of loading-unloading cycles required to attain a fixed swelling rate increases with the rise of the gypsum content.

Table 5 shows the free swelling potential before and after the loading-unloading cycles for all samples. As you can see remarkable decrease of swelling percentage is a result of applying these cycles

6. Conclusion

Soils naturally containing gypsum have special mechanical behaviors which depend on various factors such as gypsum content, natural unit weight, moisture content, and type of soil. Many urban areas have such type of soil which not only cause damages to structures, but also introduce damages to environment as well [9]. Tests conducted on such soils have yielded the following results:

- Gypsum soils are generally fine and have a texture of tiny clay or silt particles. Presence of gypsum causes porosity and reduction of natural unit weight that in turn causes settlement in many buildings.
- As the gypsum content increases the porosity of the soil also increases, which seems compaction to be a good solution for reduction of settlement and increasing the load-bearing capacity of the soil. On the other hand, the test results indicate that the compressed samples will swell if saturated. The swelling pressure which is about 0.3 kg/cm^2 for samples with high gypsum content, serves as the main cause of damages to light structures.
- The changes of swelling pressure are similar to the swelling potential of gypsum samples, and follow a special trend.
- Not only the effect of wetting-drying cycles that somehow models the weather changes in various seasons does not reduce the swelling, but also increases it 10 to 15%. Therefore, it is not reliable as an improvement method.
- Loading-unloading cycles result in a remarkable reduction, even up to %80 in the swelling and hence may be taken as a good method of mechanical improvement. The number of cycles required to reach a fixed volume is about 3 to 5.

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September 4, 2008

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To: All Authors

Dear Jafar,

I am happy to inform you that the Sixth International Conference on Case Histories in Geotechnical Engineering and Symposium in Honor of Professor James K. Mitchell went very well. We had 318 participants from 43 countries.

We take this opportunity to thank you for your contribution, which makes our publication of high quality.

We will look forward to receiving you for our Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics and Symposium in Honor of Professor I.M. Idriss in San Diego, California, May 23-29, 2010, as shown below. Please mark your calendar. If you have any questions, please feel free to ask me.

Best regards and love,

Shamsher Prakash
Conference Chairman