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Research Article

Comparison of Swelling Pressures Determined by Two Different Methods

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ABSTRACT

Expansive soils are a problem affecting many parts of the world. The fact that the expenses incurred due to the damage caused by swelling soils are quite high shows that this problem cannot be ignored. In this study, swelling pressures of compacted clays are determined using two different test methods, one of which is an oedometer test equipment. Three different clay samples were used in the tests. Free and constant-volume swell tests are conducted on compacted samples prepared at various water contents and dry densities. Free swell pressure and constant-volume swell pressure tests are performed on samples with identical initial conditions using oedometer testing equipment. These tests are repeated more than two times. Regression analysis was conducted on the free and constant-volume swell pressures based on the obtained data. Then, the swelling pressures calculated using the empirical equation are compared with test results and literature data.

Keywords: *Clay soil, Free swelling pressure, Constant volume swelling pressure.*

İki Farklı Yöntemle Belirlenen Şişme Basınçlarının Karşılaştırılması

ÖZ

Şişen zeminler dünyanın birçok bölgesini etkileyen bir sorundur. Şişen zeminlerin neden olduğu hasarlar nedeniyle oluşan masrafların oldukça yüksek olması bu sorunun göz ardı edilemeyeceğini göstermektedir. Bu çalışmada, sıkıştırılmış killerin şişme basınçları ödometre test cihazı kullanılarak iki farklı deney yöntemi ile belirlenmiştir. Üç farklı kil numunesi ile deneyler yapılmıştır. Farklı su muhtevalarında ve farklı kuru birim hacim ağırlıklarda hazırlanan sıkıştırılmış numunelerde serbest şişme deneyleri ve sabit hacimli şişme deneyleri yapılmıştır. Başlangıç koşulları aynı olan numuneler üzerinde ödometre test cihazı ile serbest şişme basıncı ve sabit hacimli şişme basıncı deneyleri yapılmıştır. Bu deneyler her numune için en az iki kez yapılmıştır. Elde edilen verilerden serbest şişme basıncı ve sabit hacimli şişme basıncı için regresyon analizi yapılmıştır. Daha sonra, ampirik denklemden bulunan şişme basıncı değerleri hem deney sonuçları hem de literatür verileri ile karşılaştırılmıştır.

Anahtar Kelimeler: *Kil zemin, Serbest şişme basıncı, Sabit hacimli şişme basıncı.*

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I. INTRODUCTION

Clayey soils can increase in volume by absorbing water or may exhibit excessive pressure when this volume increase is restricted, characteristics known as swelling behavior in soils. When examining the swelling properties of clay, the aim is to determine the swelling pressure and percentage. The ratio of the volume increase of a soil sample in its natural state or compressed in the laboratory until it becomes saturated with water under a certain load, to its initial volume, is called swelling potential. The pressure that prevents volume changes in swelling soil is called swelling pressure. There are many methods for determining swelling characteristics. These methods can be considered in three groups [1]: 1) Mineralogical methods: X-ray diffraction, differential thermal analysis, dye adsorption, chemical analysis, and electron microscope method, 2) Indirect methods: clay consistency limits properties, PVC method, activity method, suction pressure method, and empirical relations. Since these methods reflect the soil characteristics of certain geographical regions, it is not independently recommended for usage, 3) Direct measurement: The measurement is the most accurate method for determining the clay's swelling percentage and pressure. The most commonly used direct measurement technique is the one-dimensional consolidation method in ASTM D4546 [2]. Three methods have been proposed for direct measurement. The first method is the swell-consolidation method (CS) or swell-load method. In this test, the stress on vertical direction is subjected to the specimen and wetted under that vertical stress while the specimen is laterally confined. The second method is the constant volume (CV) or zero-swell method. The vertical stress of this second method is subjected to the specimen and the vertical strain that is confined during wetting. The last method is the swell overburden method (SO). In this test, many specimens (three or more specimens) are loaded to the different initial applied vertical loads around estimated swelling pressure, and water is added to monitor the swell until the primary swell completes or is compressed to reach equilibrium positions [2].

The swelling mechanism in soils with swelling potential is quite complex. Swelling occurs due to changes in internal forces within the clay-water system, which disrupts the balance of internal stresses. Clay grains generally have negative electrical charges on their surfaces and positive electrical charges on their edges. Negative charges are balanced by cations in the groundwater held by electrical forces on the surfaces of the clay plates. The intergranular electrical field is a function of both the electrical charges and the electrochemistry of the groundwater. Van Der Waals surface forces and adsorption forces between clay crystals and water molecules are affected by intergranular forces. This change in the electrical field between grains occurs as swelling or shrinkage. Factors affecting the swelling behavior of soil can be grouped into three main groups [1]: 1) Soil properties affected by the basic structure of the internal force field (Plasticity, dry unit volume weight, clay mineralogy, groundwater chemistry, soil absorption capacity, soil structure and fabric, initial water content, etc.), 2) Environmental factors affected by changes in the internal force system (Change of water content, groundwater chemistry, dry unit volume weight, etc.), 3) Stress state in the soil.

The swelling pressure of the soil can be determined using different test techniques in the one-dimensional oedometer test system. Changes in test techniques include the condition of the sample (undisturbed, disturbed), surcharge load (1 kPa, 7 kPa, 30 kPa or geological load on the field), water content (natural, optimum), and stress state (dead load, constant volume, etc.). The three oedometer procedures produce different swelling pressure measurements. The swelling pressure from the SC test leads to the greatest measurement, the intermediate value results in the constant volume (CV) test, and the smallest value results from the swell overburden (SO) test. The loading conditions, side friction effect, and wetting process are the factors causing different swelling pressure values [3]. When the swelling pressures obtained in the swelling tests performed by applying free swelling, constant volume swelling, and geological load are listed from largest to smallest, the following order emerges; free swelling pressure, constant volume swelling pressure, and swelling pressure found by applying geological load. It has been stated that these differences are due to differences in loading and wetting conditions in the test methods [3]. It has been implied that the swelling test with geological load applied is more suitable for field conditions, while the constant volume and free swelling tests are not fully appropriate for field conditions [4]. It was found that the swelling pressures obtained from the triaxial pressure test were better suited to field conditions compared to those obtained from the oedometer test [5, 6, 7].

Tisot and Aboushook [8] stated that the swelling pressure obtained from free swelling experiments was three times higher than that obtained from constant volume swelling experiments. Al-Shamrani and Dhowian [9] compared the swelling pressures obtained from free and constant-volume swelling experiments on clays compacted under the same conditions indicating that the free swelling pressure was 1.4 times greater than the constant-volume swelling pressure. Liang et al. [10] first introduced the recently developed suction-controlled swelling pressure device to measure the swelling pressure of expanding soil in a wide suction range. The development of swelling pressure was closely related to the water retention characteristics. At high suction, the swelling pressure stems mainly from interlayer hydration; at low suction, however, the swelling pressure was controlled by the development of double layers, accompanied by the collapse of some macropores. The nuclear magnetic resonance (NMR) technique was introduced to determine the specific amount of adsorbed and capillary water contents, shedding new insights into the swelling behavior of compacted expansive soil during the wetting process under confined conditions. The reason that the compacted expansive soils show nonmonotonic swelling behavior can be attributed to the fact that the compacted expansive soils include pores of different types and sizes, such as the intra-aggregate pores and the inter-aggregate pores [11].

Microlevel properties such as mineralogical and chemical compositions greatly control the macro behavior of expansive soils. In the study, 46 different samples of expansive-type soil were collected from various locations across India. The mineralogical and chemical contents of the soil samples were analyzed to investigate their combined impact on swelling property. The results are unique and significant for field engineers, as they can predict swelling behavior based on measured chemical and mineral parameters [12]. Taherdangkoo et al. [13] present a dataset comprising maximum swelling pressure values from 759 compacted soil samples, compiled from 16 articles published between 1994 and 2022. The dataset is classified into two main groups: 463 samples of natural clays and 296 samples of bentonite and bentonite mixtures, providing data on various types of soils and their properties. Different swelling test methods, including zero swelling, swell consolidation, restrained swell, double oedometer, free swelling, constant volume oedometer, UPC isochoric cell, isochoric oedometer, and consolidometer, were employed to measure the maximum swelling pressure. The comprehensive nature of the dataset enhances its applicability for geotechnical projects. The dataset is a vital resource for understanding the intricate interactions between soil properties and swelling behavior, which enhances advancements in soil mechanics and geotechnical engineering.

Numerous studies indicate that swelling pressure can be estimated using various soil properties. In a study, the swelling stress of soils collected from 15 locations in 5 sites across South Africa has been predicted by using the artificial neural network (ANN), genetic programming (GP), and evolutionary polynomial regression (EPR)-based intelligent techniques [14]. Neuronet models relating the potential expansiveness to some geotechnical properties are derived to overcome the need to perform lengthy swelling pressure determination experiments [15]. In another study, different independent scenarios of explanatory features' combinations that influence soil behavior in swelling were investigated. Preliminary results indicated Bayesian linear regression (BLR) as possessing the highest amount of deviation from the predictor variable (the actual swell-strain) [16]. The activity, water content, dry unit weight, liquid limit, plastic limit, plasticity index, and clay content were considered as the input parameters of the models as they are commonly measured during the experimental testing of soil behavior. The results show that the feed-forward neural network trained with the Levenberg–Marquardt algorithm is the most accurate model for the prediction task. The model performance is satisfactory, showing an acceptable agreement with experimental data. The developed model showed substantial improvements over previous empirical and semi-empirical correlations in determining the swelling potentials of both natural and artificial soils [17].

In this study, the constant-volume swelling pressures and free swelling pressures of compacted clays were compared under the same initial conditions. Correlations between free swelling pressure and constant volume swelling pressure have been made and an empirical relationship has been proposed. The free swelling pressure values obtained from the experiments were compared with the calculated free swelling pressure values obtained from the empirical relationship. The proposed empirical relationship was compared using experimental data from the literature obtained under identical experimental conditions. It is shown that the proposed relationship can be used to pre-estimate the free swell pressure.

II. MATERIAL AND METHOD

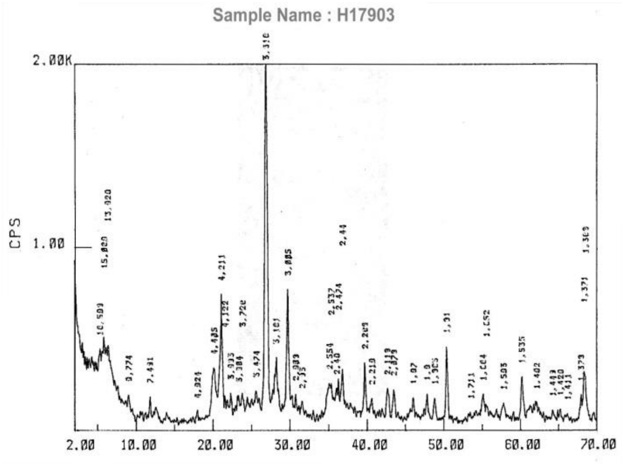
A. DEFINITION OF SAMPLES

Experiments were conducted on disturbed clay samples with high plasticity taken from various regions in the study. Sample 1 was taken from Istanbul-Türkiye, and samples 2 and 3 were taken from Antalya-Türkiye. Soil classes were determined using sieve analysis and consistency limit tests on the samples according to the Unified Soil Classification System. Optimum water contents and maximum dry unit volume weights were determined by performing standard compaction tests. The results obtained from the experiments are given in Table 1.

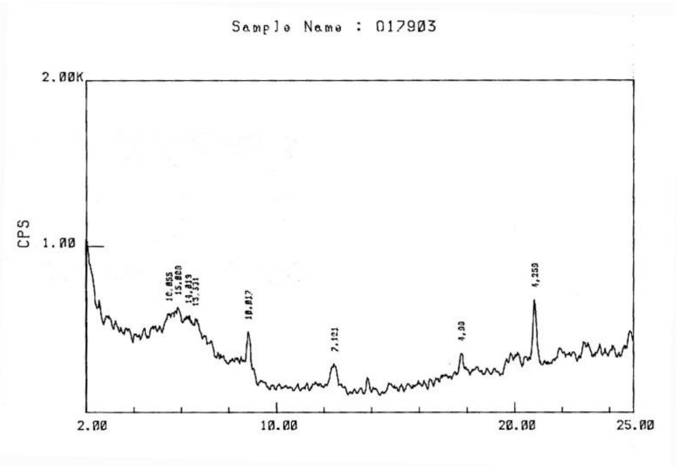
Table 1. *Properties of the samples used in the experiments [18]*

Properties	Sample 1	Sample 2	Sample 3
Liquid limit (%)	75	73	66
Plastic limit (%)	21	26	28
Plastisity index (%)	54	47	38
Grain unit volume weight (kN/m^3)	27.4	27.7	28.1
Max. dry unit volume weight (kN/m^3)	16.1	16.0	15.2
Optimum water content (%)	23	23	27
Gravel (%)	1	1	0
Sand (%)	6	3	2
Silt + Clay (%)	93	96	98
Soil Class	CH	CH	CH

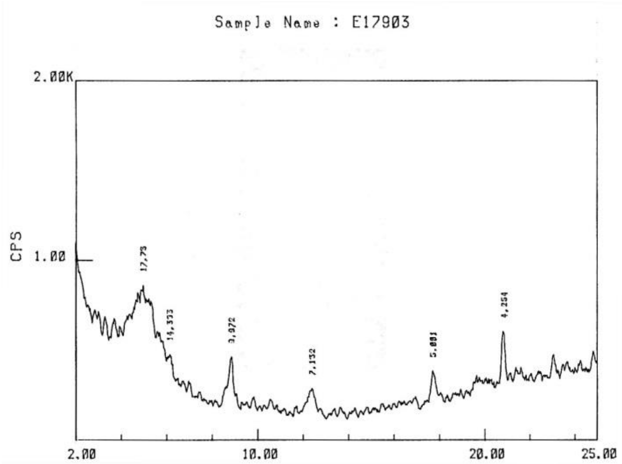
Since the mineralogy of the soil samples influences swelling behavior, it was determined. The X-ray diffraction method is widely used to determine the mineralogy of the clay samples. XRD analyses were conducted on both the clay portion and the entire sample. XRD analyses were performed separately on the oriented and unoriented samples where the clays were air-dried, swollen with ethylene glycol, and heated at 550 °C. The resulting diffraction curves are given in Figures 1-3. The X-ray analyses were carried out in two parts: whole rock analysis and clay size analysis. In whole rock analyses, smectite, chlorite, quartz, feldspar, calcite, and illite minerals are present in the samples. Besides, only the clay part of the samples was separated and clay fraction analyses were performed on it. The clay sample was saturated with ethylene glycol to determine the clay mineral type, followed by an X-ray analysis. Samples subjected to ethylene glycol treatment were heat treated at 550ºC and X-ray images were taken. The minerals obtained from the analyses were determined in order of abundance and are given in the third section.



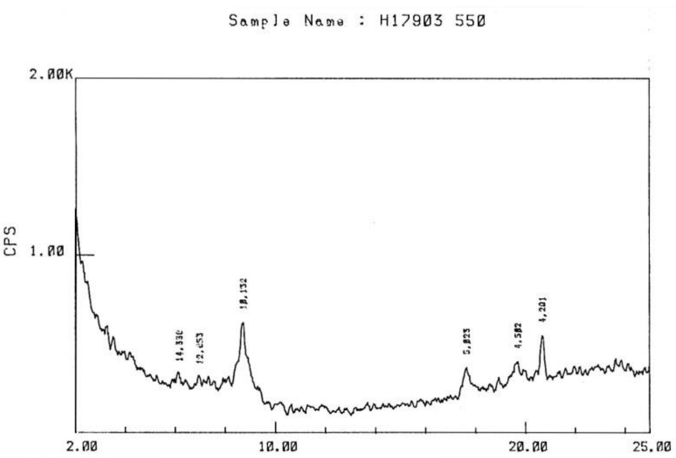
a) Whole rock analysis



b) Orientation

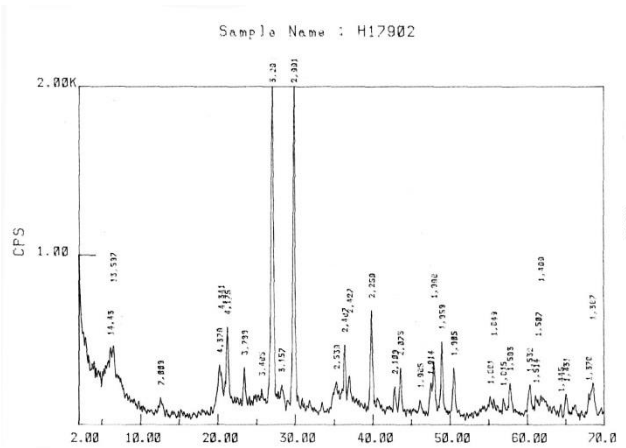


c) Analysis with ethylene glycol

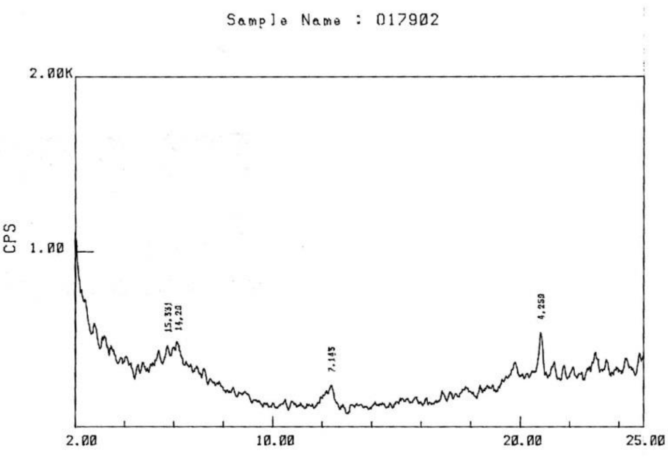


d) Analysis subjected to heat at 550 ^{o}/1 hour

Figure 1. *X-ray diffraction curves of sample 1 [18]*

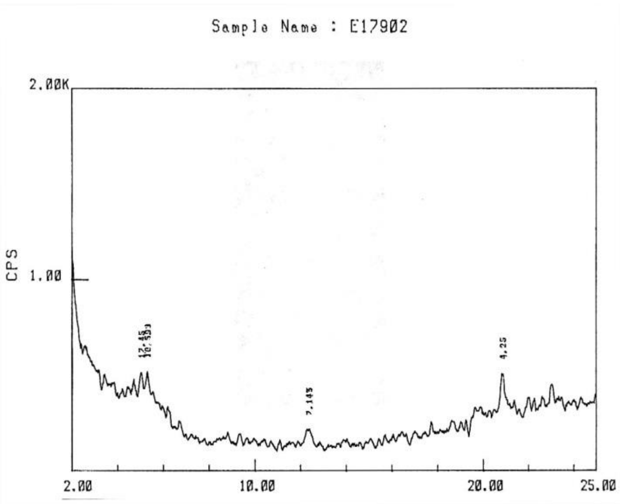


a) Whole rock analysis

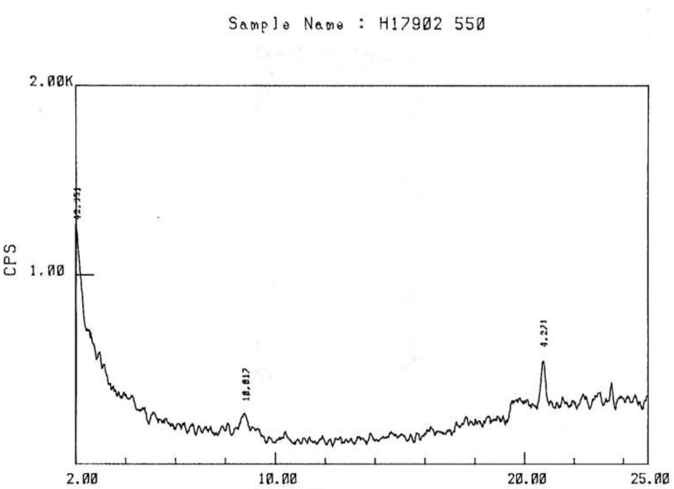


b) Orientation

Figure 2. *X-ray diffraction curves of sample 2 [18]*

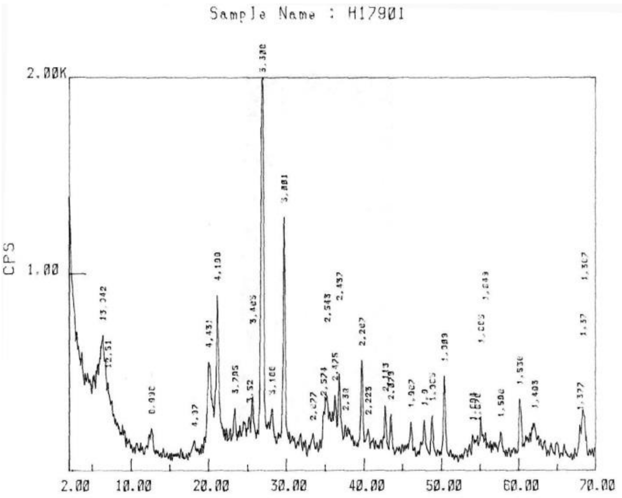


c) Analysis with ethylene glycol

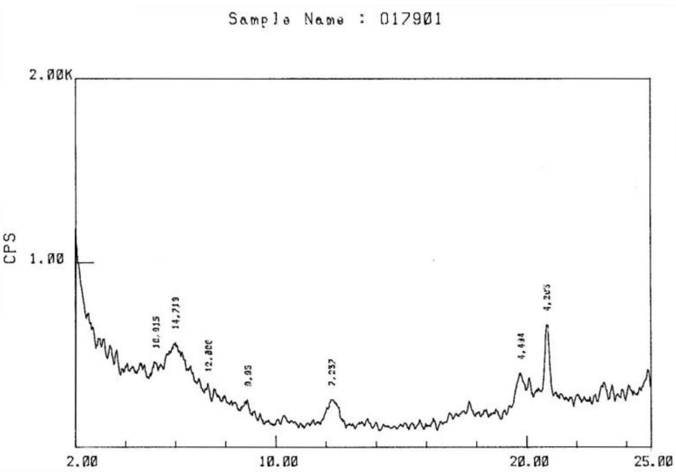


d) Analysis subjected to heat at 550 ^{o}/1 hour

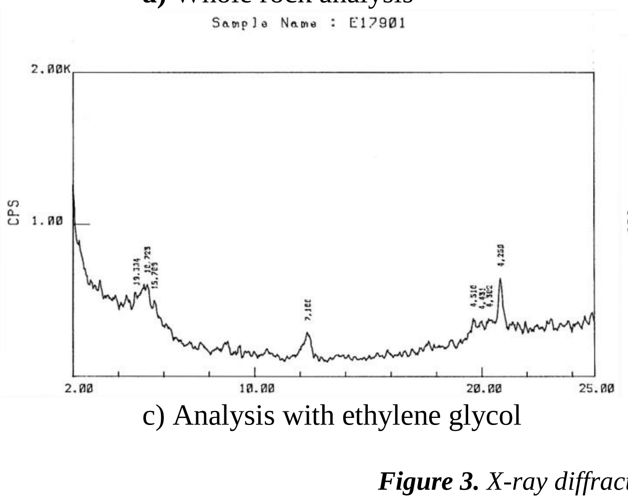
Figure 2 (cont). *X-ray diffraction curves of sample 2 [18]*



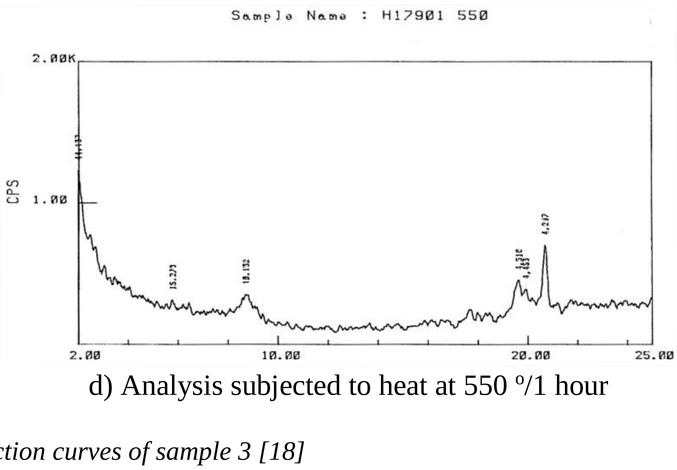
a) Whole rock analysis



b) Orientation



c) Analysis with ethylene glycol



d) Analysis subjected to heat at 550 ^{o}/1 hour

Figure 3. *X-ray diffraction curves of sample 3 [18]*

A. 1. Determination of Swelling Pressures by Oedometer Method

The free swelling method specified as Method A and the constant volume swelling method specified as Method C, which is among the ASTM D4546 [2] test methods, are selected to determine the swelling pressures. Samples under the No.40 sieve were prepared by mixing at different predetermined initial water contents (15%, 20%, 25%, 30%, 35%, 40%) to be on the dry and wet side of the optimum water content. The optimum water content of the samples was used to determine these initial water contents. Distilled water was used in every stage of the experiments performed on the samples.

Samples prepared at different water contents were compacted with standard compaction at different dry unit volume weights (11.5 kN/m^3, 13.0 kN/m^3, 14.0 kN/m^3, 15.0 kN/m^3, 16.0 kN/m^3, 17.0 kN/m^3). An oedometer ring was immersed in these prepared samples and the sample was placed in the ring. Experiments were primarily carried out on samples prepared at the same dry unit volume weight and different initial water contents. Then, it was carried out for samples prepared at the same water content and different dry unit volume weights. During compaction, care was taken to maintain consistent water content and achieve homogeneous compaction.

The soil samples placed in the oedometer cell were allowed to absorb water via capillary under a surcharge load of 1 kPa. The swelling amount of the soil samples allowed to swell in this way was determined from the vertical deformation meter. After waiting until the final swelling of the soil samples was completed, that is, after the value read on the deformation clock was fixed, the oedometer cell was filled with water and waited for 24 hours. At the end of this period, it was observed that the final swelling value of the sample did not change. After the swelling of the sample was completed, load was applied to the sample in small steps. At least 24 hours were waited at each load level. The pressure required to reset the total swelling amount was determined and thus the swelling pressure of the ground was determined. This pressure was taken as the pressure at which the hand of the clock measuring the vertical deformation returned to its starting point (zero). This pressure value was recorded as free swelling pressure.

In the second series of studies, the samples were prepared under the same initial conditions and allowed to absorb water via the capillary method, and this time they were subjected to a constant volume swelling test. In these experiments, continuous loading was applied to ensure that the deformation clock on the oedometer cell remained at zero while the sample was receiving water. The pressure applied to the sample was constantly increased to prevent swelling and the needle of the vertical deformation clock was kept constant at zero. Then, the cell was filled with water and the pressure value obtained after waiting 24 hours was recorded. The pressure at which inflation was inhibited is the constant volume inflation pressure. The results obtained from the experiments were correlated.

III. RESULTS AND DISCUSSION

This study aims to compare swelling pressures and investigate the relationship between them by using results from free swelling and constant volume swelling experiments conducted with three different soil samples. Firstly, the mineral structure of the samples was determined by X-ray analysis. The analyses identified the dominant clay minerals and others in the samples in order of their abundance. Accordingly, the minerals identified in the samples were:
Sample 1: smectite + chlorite, quartz, calcite, feldspar, illite.
Sample 2: smectite + chlorite, quartz, feldspar, calcite.
Sample 3: smectite + chlorite, calcite, illite, quartz.

The mineral structure of the samples used in the experiments suggests a high potential for swelling. The clay minerals that exhibit greater expansion belong to the 2:1 group of clay minerals, characterized by layers of tetrahedrons and octahedrons where cations and water molecules are held in the interlayer spaces. As can be seen in Table 2, the swelling clay exhibits greater interlayer spacing than non-swelling clay. Different clay minerals exhibit different swelling potentials due to changes in their structure and interlayer bonding. Smectites and vermiculites undergo significant volume changes when wet and dry [20]. Regarding swelling, clay type is a more important factor than clay percentage and the amount of smectite is also effective in the swelling potential measured in the laboratory [21].

Table 2. *Basal spacing of different types of clay minerals based on swelling potential [19]*

Clay Mineral	Type	Basal Spacing(A)	Swelling Potential
Kaolinite	1:1	7.2	Almost none
Montmorillonite	2:1	9.8-20	High
Vermiculite	2:1	10-15	High
Mica	2:1	10	Low
Chlorite	2:1:1	14	None

The results obtained from the swelling experiments are presented in Table 3. The table shows P_s the constant volume swelling pressure and P_s' the free swelling pressure. The results obtained from the swelling experiments are presented in Table 3. The table indicates that at a constant dry unit volume weight, swelling pressure decreases as the initial water content increases. The swelling pressure increases as the dry unit volume weight rises at a constant initial water content. At the same time, it can be seen that the free swelling pressure is higher than the constant-volume swelling pressure. The sample is subjected to a low surcharge pressure in the free swelling pressure tests. The low pressure applied facilitates the entry of the water into the clay having high swelling properties. In constant volume swelling pressure experiments, the applied pressure reduces water ingress.

Table 3. *Initial conditions and swelling pressure values of the samples [18]*

		Sample 1		Sample 2		Sample 3	
γ_k (kN/m^3)	w_o(%)	P_s (kPa)	P_s' (kPa)	P_s (kPa)	P_s' (kPa)	P_s (kPa)	P_s' (kPa)
11.5	15	126	208	79	163	42	86
	20	98	161	65	128	33	75
	25	86	157	50	103	24	52
	30	53	112	26	63	18	41
	35	33	69	19	48	10	22
	40	26	42	8	20	4	10
13.0	15	152	321	90	202	51	110
	20	135	260	80	187	43	96
	25	98	202	59	128	39	88
	30	63	130	38	92	22	71
	35	51	100	26	68	10	24
	40	32	48	12	32	6	15
14.0	15	281	509	120	340	68	203
	20	198	300	100	271	54	126
	25	132	281	71	152	42	98
	30	78	173	48	102	31	85
	35	61	103	26	58	15	48
	40	37	68	18	43	9	22
15.0	15	345	640	143	376	74	217
	20	296	410	112	250	65	183
	25	170	290	85	186	51	122
	30	94	145	56	122	40	94
16.0	15	405	680	171	398	82	250
	20	289	478	129	282	66	204
	25	186	292	98	210	49	132
17.0	15	483	848	189	482	88	260
	20	312	526	150	326	72	218

As an example of the swelling pressure values in Table 3, the relationship between constant volume swelling pressure and different water contents, when the dry unit weight is 13 kN/m^3, is given in Figure 4. The relationship between free swelling pressure and different water contents is presented in Figure 5. It is seen that swelling pressures decrease as water content increases at constant dry unit weight from Figures 4 and 5.

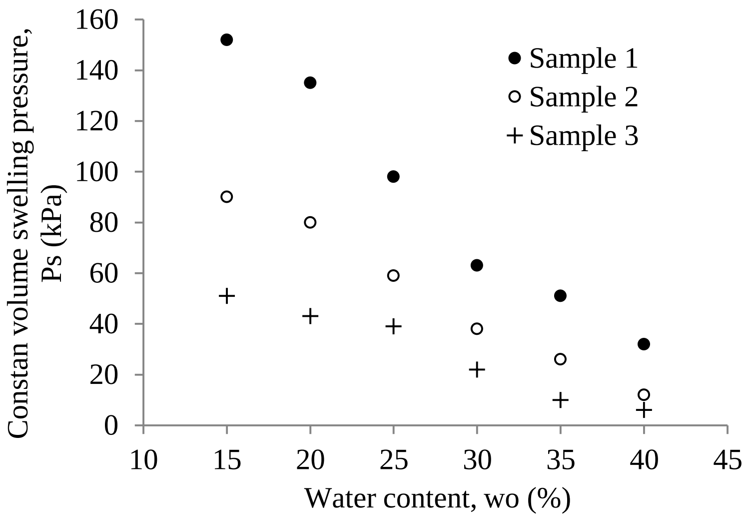


Figure 4. *Relation between water content and constant volume swelling pressure for* $\gamma_k = 13.0\ kN/m^3$

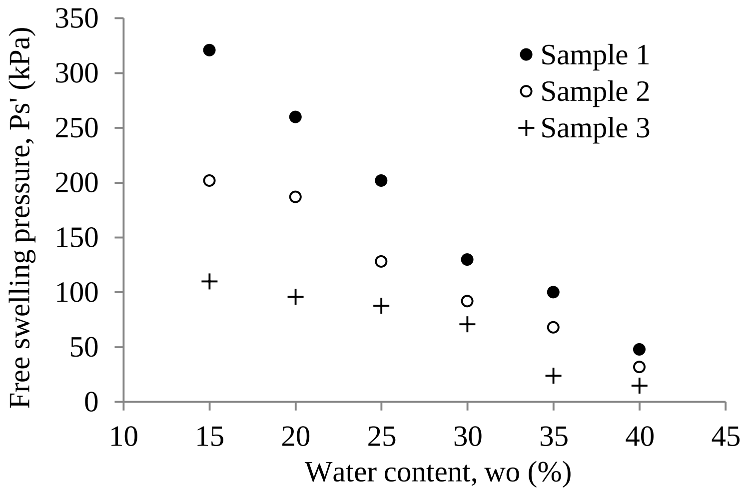


Figure 5. *Relation between water content and free swelling pressure for* $\gamma_k = 13.0\ kN/m^3$

The relationship between the free swelling pressures determined from swelling experiments in which volume change is not prevented and the swelling pressure values obtained from swelling experiments in which volume change is prevented is given in Figure 6. This relationship was obtained by comparing the constant-volume and free swelling pressures on samples prepared under the same initial conditions. It can be seen that free swelling pressures are higher than fixed volume swelling pressures. Equation (1) was obtained from the regression analysis between the results obtained from the two groups of swelling test results.

$$P'_{s,c} = 3.111 P_s^{0.9149} \quad (1)$$

In this relation, the term $P'_{s,c}$ is the free swelling pressure calculated according to Equation 1, and P_s (kPa) is the constant-volume swelling pressure. The coefficient of determination (R^2) for this relationship was 0.964.

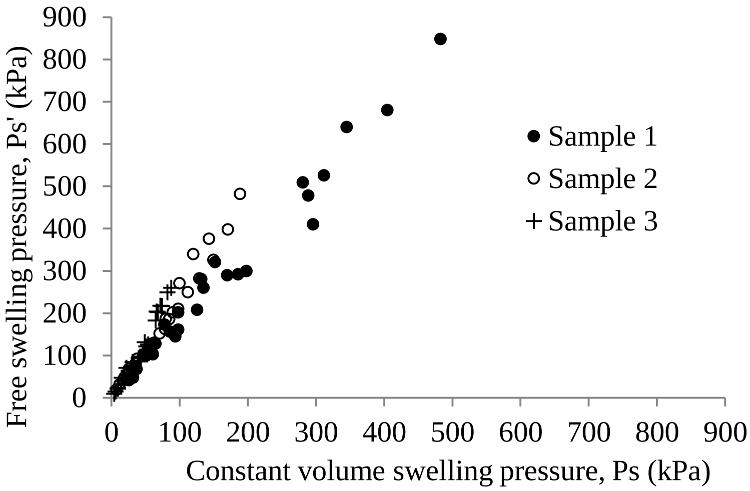


Figure 6. *Relationship between constant volume swelling pressure and free swelling pressure [18]*

The comparison of the free swelling pressure value determined with the help of this equation and the free swelling pressures obtained from the experiments can be seen in Figure 7. Based on the error calculations between the free swelling pressures from the experiments and those derived from Equation (1), the average error was -0.015, while the average absolute error was 0.132. It can be implied according to the error values that free swelling pressures can be estimated from the constant volume swelling pressure values using Equation (1) developed in this study.

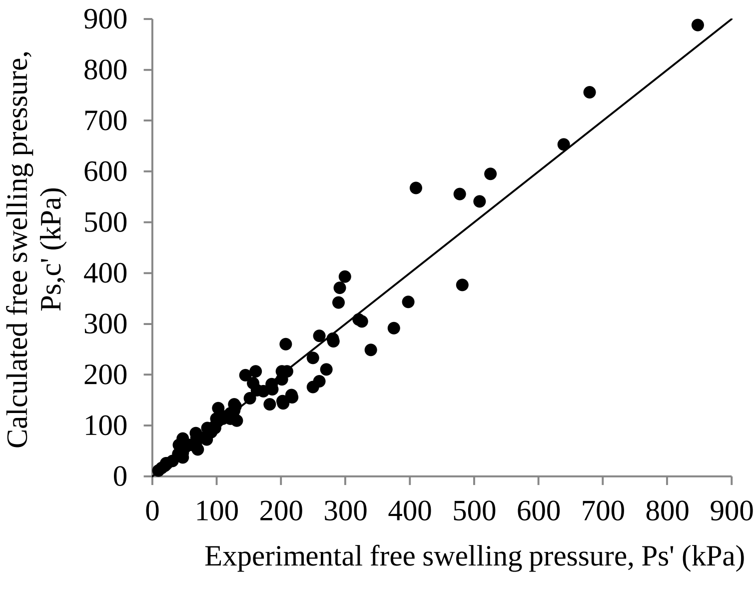


Figure 7. *Comparison of free swelling pressures obtained from experiments and Equation 1 [22]*

Free and constant volume swelling pressure test results in the literature were used to test the proposed relationship. Table 4 has been prepared for this purpose. When this table is examined, it is seen that the calculated free swelling pressure values are in good agreement with the experimental free swelling pressure values in the sources. It is stated that Equation 1 can be used as a preliminary idea to estimate the free swelling pressure. However, the importance of mineralogical structure, grain settlement, climatic conditions, external loads, and stress conditions in the field should not be forgotten.

Table 4. *Comparison of the values obtained from Equation (1) with literature data [22]*

Literature	P_s (kPa)	P_s' (kPa)	$P_{s,c}'$ (kPa)
Keskin [23]	50	125	112
Abduljauwad and Sulaimani [7]	560	3100	1017
	480	1390	883
	420	1340	781
	380	1200	713
Abduljauwad et al. [24]	800	3100	1409
	520	1820	950
Al- Muhaidib [3]	70	230	152
	18	60	44
Al-Shamrani and Dhowian [9]	960	1700	1665
	586	829	1060

IV. CONCLUSION

The swelling pressures of clays with high swelling potential containing smectite minerals were investigated in the study. This mineral increases its volume when in contact with water, significantly increasing the swelling pressure. Chlorite generally has a lower swelling capacity but can increase the swelling effect when present with smectite. All three samples contain smectite and chlorite, which are significant components of the swelling pressure. Quartz is a mineral with no swelling capacity and is present in all three samples. Calcite is a carbonate mineral that does not directly influence swelling potential. However, it can affect the compressibility properties of the soil and indirectly reduce the swelling pressure. Calcite is present in all three samples, suggesting that this mineral may help stabilize swelling. Illite is a clay mineral with a lower swelling capacity than smectite. In samples containing illite (Sample 1 and Sample 3), the swelling potential of smectite may be somewhat balanced. Feldspar minerals are generally chemically stable and do not contribute directly to the swelling pressure. Feldspar is present in samples 1 and 2. Swelling pressure test results performed on three different high-plasticity clay soil samples using two different methods with the help of an oedometer test set are included. Test samples were prepared with standard compaction at various initial water contents and different dry unit volume weights. The relationship between free swelling and constant volume swelling pressure was obtained. The constant-volume swelling test gives results in a shorter time. With the proposed equation, the free swelling pressure can be determined by knowing the constant volume swelling pressure in compressed soils. It is important to note that the correlation obtained was based on a limited dataset and that various factors significantly influence swelling.

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