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Kamil Kayabalı
kayabali@ankara.edu.tr

Özgür Yaldız
ozguryaldiz_04290326@hotmail.com

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ESTIMATION OF SWELLING PRESSURE USING SIMPLE SOIL INDICES

Kamil KAYABALI[a*] and Özgür YALDIZ[a]

[a] *Ankara Üniversitesi Mühendislik Fakültesi Jeoloji Mühendisliği Bölümü, Tandoğan, Ankara 06100*

Keywords:
Expansive soils, swell pressure, free swell, Atterberg limits, water content, dry density

ABSTRACT

In arid to semiarid regions, damage from expansive soils to light structures in the long term may be as costly as damage by major natural hazards. Swell characteristics, including swell pressure, of expansive soils have been the subject of numerous studies. Studies examining this property employ almost exclusively the conventional oedometer apparatus, which indirectly measures swell pressure. The results of such studies are often speculative. This investigation covers 1000 swell tests on 124 soil samples, using constant swell and free swell tests. Identical specimens at different initial water contents and dry densities were constituted through static compaction for each soil sample. Atterberg limits were incorporated into regression analyses along with the water content and dry density data. The resulting empirical relationship reasonably predicts the swell pressure. The correlation between the data from constant volume and free swell tests was even more conclusive. Comparing the empirical form obtained from this investigation and the previously published two equations reveals that the other relationships dramatically underestimated the swell pressure, which was attributed to the use of indirect methods.

1. Introduction

Expansive soils may exhibit severe volume changes upon wetting and drying. Light structures such as pavement, canals, and utility lines are susceptible to damage because of the heave in underlying expansive soils. Large uplift forces from heave may even damage structural members of a building when the pressure exerted by the building on a soil foundation is smaller than the swelling pressure. Expansive soils exist in many parts of the world. As such, the cost of damage from heave alone accounts for more than any other foundation problem, reaching billions of dollars annually in some countries (Nelson and Miller, 1992; Siemens and Blatz, 2009).

Swelling potential is influenced by many factors such as clay mineral composition, amount of nonclay material present, density, size and orientation of clay particles, void ratio, cementation, size and thickness of the clay body, macrostructure, and depth below ground surface. Amongst those, the most significant factor appears to be the clay-mineral composition (Komornik and David, 1969).

The swelling pressure of expansive soils has been the subject of many investigations, and various methods have been proposed to assess the problem. The one-dimensional consolidation test is the most commonly used technique to quantitatively evaluate swelling pressure. Investigations to determine swelling pressure usually related the swelling behavior to certain physical properties such as initial moisture content, consistency limits, dry density, and clay content (Komornik and David, 1969; Nayak and Christiensen, 1971; Vijayvergiya and Ghazzaly, 1973; Attom and Barakat, 2000; Rao et al., 2004, to mention a few).

* *Corresponding author: Kamil KAYABALI, kayabali@ankara.edu.tr*

Basma et al. (1995) introduced two techniques termed the restrained swell test and the double oedometer swell test. They carried out a series of swell tests by employing four methods, including the most commonly used zero swell and swell consolidation tests. They concluded that the restrained swell test is best suited to determine swelling.

Shuai (1996) provided an excellent review of the testing procedures used to measure swelling pressure in expansive soils. Shuai gathered all available methods under two categories: the constant load oedometer test and the constant volume oedometer test. The first category listed the free swell, double oedometer, loaded swell oedometer tests, the direct model method, and the Chinese method, whereas the second category listed the constant volume oedometer, the Sullivan and McClelland, and strain controlled tests. Between the two methods, Shuai recommended the constant volume method because it does not involve volume change, while recognizing a key a limitation in the sampling disturbance is not accounted for.

Kayabalı and Demir (2011) utilized a simple and robust swell pressure measurement apparatus to conduct a series of swell tests on twelve statically compacted, high plasticity clay soils by employing the four methods cited by Basma et al. (1995), terming those as indirect tests, and their own constant volume test, which they termed as the direct method. They compared the results of indirect swell tests to those of the direct method, concluding that (1) the restrained test underestimates swelling pressure; (2) the swell-consolidation and zero swell tests significantly overestimate swelling pressure; (3) the results of the double oedometer test shows no correlation with the direct method; and (4) the correlation between the swell pressure from the direct method and the free swell test is considerably high and should be further investigated using a broader database. They also argued that the direct method may slightly underestimate the true swelling pressure, owing to the stiffness of the load cell of the measuring unit.

Many investigators proposed that the swelling pressure can be estimated using simple soil parameters. Nevertheless, the methods to determine the swelling pressure in almost all of those studies were the various versions of the one-dimensional consolidometer. Kayabalı and Demir (2011) pointed out that some of those indirect methods require more than one soil specimen for any soil sample and that all specimens be identical. In addition, those methods either significantly overestimate or underestimate the swelling pressure.

The scope of this investigation is to relate the swelling pressure to simple soil indices, specifically to the initial moisture content, dry density, and Atterberg limits, using the constant volume method. An empirical relationship between the free swell and swelling pressure is also developed by employing a much wider database.

2. Materials

This investigation uses 124 soil samples of different levels of plasticity, which were collected from different parts of Ankara, as bulk specimens. They were first oven-dried then pulverized to pass through a #40 sieve (some of the soil samples were sieved through both #40 and #200 meshes as part of another broader project). Their plasticity characteristics and USCS (Unified Soil Classification System; ASTM, 2000) classes are presented in table 1. The major tool employed for the investigation consists of a frame unit equipped with a load cell and a digital display (Figure 1).

3. Methods

Identical soil specimens were created from each of the 124 samples through static compaction. Swelling pressure testing was carried out in two phases. The first phase included only four soil samples (numbered 201–204 in table 1) subjected to extensive swelling pressure tests. During this part, two groups of specimens were considered. The first group consisted of soil specimens wetted at around 25% water content and was statically compressed in a cylindrical container of 50.5 mm in diameter until the applied load reached 1 kN, 2 kN, 3 kN, 4 kN, 5 kN, 6 kN, 7 kN, 8 kN, 9 kN, and 10 kN. This way, ten soil specimens of different initial dry densities were prepared. Each loading level included preparing three soil specimens of each kind of soil. The statically compacted soil specimens were then transferred into a consolidation ring of 20 mm in height and 50 mm in diameter, and the protruding part of the soil was carefully trimmed. The three soil specimens were placed in the constant volume swelling pressure test devices, as shown in figure 1. A slight seating load was applied to the statically compacted test specimen to eliminate the possible clearance between the rod attached to the digital load cell and the consolidation cell before initiating the inundation, and the seating

Figure 1- Constant volume swell test apparatus.

load (usually on the order of 10–20 N) was recorded. The specimen was then inundated, and the swelling pressure at the end of one day was recorded. The second group consisted of statically compacted specimens with water contents ranging from 20% to 30% with 1% increments. Those specimens were compressed until the load cell recorded a force of 10 kN, an arbitrarily determined value. Three specimens were prepared for each of four soil samples, as in the case of the first group. A similar procedure was followed to emplace the statically compacted specimens into the constant volume swelling pressure test devices (three of which were employed simultaneously). Likewise, a small seating load was applied prior to inundation, and after 24 hours the swelling pressure was recorded through the digital display of the testing unit. The initial load was deducted from the final reading, and the remaining amount was divided by the area of the test specimen, resulting in the swelling pressure.

The second phase of testing included measuring the swelling pressure and free swell of 120 samples. A sufficient amount of dry mass of each soil was mixed with a water content slightly higher than 25% (so that the yielding water content was nearly 25%) and was subjected to static compaction. Each mixture was loaded until the force display showed 10 kN. The transfer and trimming of the statically compacted soil were similar to those in the first phase. This time, however, six specimens from each of the 120 soil samples were prepared. Three were subjected to the swelling pressure test under constant volume conditions, and the remaining three specimens were reserved for the free swell test. One-dimensional consolidation test cells were employed for the free swell tests. The consolidation ring containing a specimen was emplaced into the consolidation cell. An initial seating pressure of 7 kPa was applied prior to inundation. The amount of free swell was recorded through the dial gauge at the end of one day, and the percent swell was computed by dividing the amount of free swell by the initial height of the specimen.

4. Experiments, Results and Discussion

Numerous investigations can be found in the literature that relate swell characteristics to initial water content and dry density. For example, the swell pressure versus water content shown in figure 2 (after Kayabalı and Demir, 2011) was based on tests on 40 artificially prepared specimens, which illustrates that there is almost a linear relationship between the initial water content and the swell pressure. Clearly, as the water content increases, the swell pressure decreases.

The relationship between dry density and swell pressure is such that as the dry density increases, the swell pressure increases. To demonstrate and emphasize the importance of this fact, a series of swell tests were executed on the samples numbered 201–204. The results are displayed in figure 3. Ten

Table 1- Plasticity and USCS classes of soils material used for is this investigation.

No.	LL	PL	USCS
1	66.3	29.3	CH
2	57.1	24.4	CH
3	62.0	30.0	CH
4	54.5	25.6	CH
5	69.8	32.9	CH
6	71.4	31.8	CH
7	79.0	33.9	CH
8	57.8	29.6	CH
9	73.9	33.3	CH
10	75.0	33.1	CH
11	49.3	29.8	ML
12	57.4	24.3	CH
13	69.2	26.6	CH
14	71.0	40.3	MH
15	66.3	39.1	MH
16	60.6	41.3	MH
17	57.0	29.9	CH
18	53.7	33.4	MH
19	52.6	30.5	MH
20	53.1	25.0	CH
21	50.3	24.8	CH
22	61.0	29.9	CH
23	56.3	28.8	CH
24	42.9	26.2	ML
25	65.2	27.2	CH
26	48.5	28.6	ML
27	74.4	29.6	CH
28	57.4	25.3	CH
29	65.2	33.8	MH
30	53.3	25.4	CH
31	54.6	30.9	MH
32	58.5	24.2	CH
33	69.0	29.2	CH
34	54.6	21.9	CH
35	57.4	29.2	CH
36	47.8	25.5	CL
37	77.1	26.5	CH
38	68.2	31.2	CH
39	62.7	24.0	CH
40	47.7	25.0	CL
41	67.3	37.1	MH
42	68.6	27.3	CH

No.	LL	PL	USCS
43	57.9	37.0	MH
44	55.3	25.0	CH
45	54.0	29.8	MH
46	49.8	26.1	CL
47	57.4	28.5	CH
48	54.6	30.1	MH
49	59.5	30.3	CH
50	55.9	24.2	CH
51	75.5	35.6	MH
52	66.7	31.6	CH
53	70.8	35.8	MH
54	63.7	31.5	CH
55	78.6	36.5	MH
56	78.1	38.6	MH
57	90.3	35.2	CH
58	71.1	35.7	MH
59	77.6	35.3	CH
60	83.9	35.0	CH
61	59.4	39.0	MH
62	81.0	26.5	CH
63	87.2	34.0	CH
64	84.5	41.4	MH
65	72.2	40.2	MH
66	64.3	40.5	MH
67	65.0	35.0	MH
68	55.1	36.3	MH
69	58.9	30.8	MH
70	64.3	27.3	CH
71	61.5	30.1	CH
72	64.9	30.2	CH
73	71.4	31.2	CH
74	55.6	33.7	MH
75	67.8	27.6	CH
76	53.8	33.3	MH
77	75.9	32.0	CH
78	65.0	30.5	CH
79	67.9	40.0	MH
80	55.9	27.8	CH
81	61.5	34.0	MH
82	70.2	29.4	CH
83	71.8	30.2	CH
84	51.9	25.2	CH

No.	LL	PL	USCS
85	62.2	27.8	CH
86	46.4	28.1	ML
87	78.4	29.1	CH
88	61.4	35.9	MH
89	62.8	29.9	CH
90	54.4	31.3	MH
91	70.2	43.8	MH
92	68.0	30.8	CH
93	64.1	36.6	MH
94	61.9	32.0	MH
95	65.1	30.7	CH
96	52.6	32.3	MH
97	60.7	30.5	CH
98	60.2	33.2	MH
99	62.2	35.3	MH
100	61.7	30.3	CH
101	52.6	33.9	MH
102	53.0	32.7	MH
103	56.7	32.5	MH
104	58.0	25.6	CH
105	54.7	30.4	MH
106	55.2	31.2	MH
107	57.0	29.9	CH
108	53.0	30.0	MH
109	56.3	31.0	MH
110	55.4	30.8	MH
111	66.2	39.6	MH
112	59.5	36.3	MH
113	65.1	30.8	CH
114	67.6	30.2	CH
115	63.8	31.8	CH
116	61.6	32.6	MH
117	67.7	31.4	CH
118	60.5	30.4	CH
119	64.6	32.9	MH
120	63.4	30.7	CH
201	90.3	35.2	CH
202	72.2	40.2	MH
203	88.0	29.7	CH
204	66.4	35.5	MH

experiments were conducted on each soil sample to evaluate the relationship between the swell pressure and dry density. Those experiments were conducted on artificially prepared soils with an approximate water content of 25%. It should be noted that an exact value of 25% cannot be achieved due to some evaporation during mixing of dry soil with a water content of more than 25%. Likewise, ten experiments were performed on the same samples to confirm the effect of the initial water content on swell pressure. This time the artificial specimens were prepared at nearly constant dry densities. Because it is difficult to set the dry density at the desired level, compaction was considered to be the controlling agent for the dry density. Accordingly, all specimens serving this purpose were compressed, up to 10 kN. Figure 3 shows that the swell pressure increases as the dry density increases. One of the graphs in figure 3 that shows swell pressure versus initial water content appears to violate our first interpretation of swell pressure linearly decreasing with the increasing initial water content (soil sample 202). A possible explanation for this would be that below a certain level of water content, the static compaction test for that specific soil sample may yield lower dry density values than tests illustrating the normal swell pressure versus initial water content behavior.

As the initial water content appears to be the most crucial parameter affecting the swell pressure, at what level of initial water content should experiments be conducted? Considering that the plastic limit would be an appropriate value, a series of swell pressure tests were performed. The results are displayed in figure 4 for 40 samples selected from the first 120 samples in table 1. figure 4 reveals two facts. First, there is not a meaningful relationship between plastic limit and swell pressure. Second, the yielding swell pressures are relatively low, suggesting that the water contents corresponding to plastic limits are high enough to be considered in swell pressure tests. Initial water contents therefore need to be somewhat lower than plastic limits. Considering that the majority of the plastic limits in the 120 samples were above 25, an initial water content of 25% was set as the key value for swell pressure tests. Using a single value would also help in comparing experiment results.

To establish an empirical relationship between easily defineable simple soil indices such as water content, dry density, Atterberg limits, and swell pressure, a series of swell pressure tests were carried out on 120 soil samples, whose consistency limits were well defined, using the apparatus shown in figure 1. Three swell pressure tests were executed on each soil sample. For these tests, three identical specimens, prepared with a 25% water content with the ultimate compression load of 10 kN, were set in three constant volume apparatus. The average swell pressures for 120 soil samples are given in table 2. It should be noted that all numbers in the table correspond to the average value obtained from the three tests.

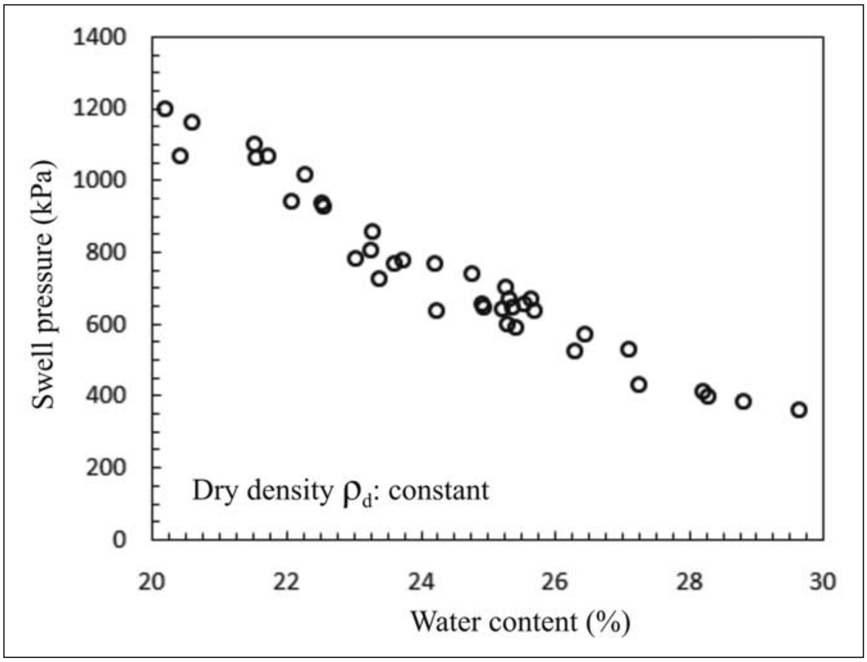

Figure 2- Relationship between the swell pressure and the initial water content (after Kayabalı and Demir, 2011).

A number of regression analyses were performed among the initial water content, dry density, liquid limit, plastic limit, and plasticity index using DATAFIT software (2008). The regression analyses were carried out interchangeably among those parameters to match the best coefficient for the correlation. Six hundred values were incorporated into the regression analyses. Of which, 360 constituted 120 soil samples, each having three specimens; the remaining 240 constituted the soils numbered 201 through 204 in table 1, each of which comprising 60 experiments (10 experiments for swell pressure versus water content with three repetitions for each soil sample, yielding 30 values and 10 experiments for swell pressure versus dry density, yielding another 30 values). The best relationship is obtained by including the initial water content, dry density, liquid limit, and plastic limit. The equation relating those four parameters to the swell pressure is as follows:

$$SP = -30.8w_i + 1025\rho_d + 6.35LL + 42.4PL - 2208 \quad (1)$$

where SP is the swell pressure in kPa. The regression coefficient (R^2) for this correlation is 0.724. Figure 5 compares the measured swell pressures for 600 experiments with the predicted swell pressures using Eqn. (1). The newly established empirical relationship appears to slightly underestimate swell pressures at ranges over 600 kPa, a reasonably meaningful threshold value below which a great majority of fine grained soils may be covered.

Including only initial water content and dry density in regression analyses to obtain swell pressure results in a poor correlation, with a regression coefficient of 0.08. This shows that, while the initial water content and dry density are two crucial factors affecting the swell pressure, they cannot be utilized without considering plasticity data. For this reason, the authors chose not to include such a figure in the text. It should be emphasized that, while figure 3 implies that the swelling pressure shows reasonably good relationships with water content and dry density, a regression analysis excluding plasticity characteristics does not yield a universally acceptable empirical relationship to predict the swelling pressure.

The literature review conducted prior to this investigation unveiled many previous studies that focused on the swell characteristics of expansive soils, including the empirical relationships. Few of such studies (Komornik and David, 1969; Vijayvergiya and Ghazzaly, 1973; Erzin and Erol, 2004) focused on relationships. For a comparison, studies by Komornik and David (1969) and Erzin and Erol (2004) were considered. Erzin and Erol (2004) related the initial water content (w_i in percent), dry density (ρ_d in g/cm^3), and plasticity index (PI) to swell pressure (SP in kgf/cm^2) in the following equation:

$$\log(SP) = -4.812 + 0.01405PI + 2.394\rho_d - 0.0163\, w_i. \quad (2)$$

Figure 6 shows a comparison between the measured swell pressures in this investigation and the predicted swell pressures using Eqns. (1) and (2). Astonishingly, the empirical relationship proposed by Erzin and Erol (2004) yields unusually low swell pressures. While the relationship by Erzin and Erol (2004) results in acceptable and consistent values when employing their own data, it dramatically underestimates the swell pressure using the data of this investigation. A possible reason for such a discrepancy is that their data is restricted to small number of tests and is dominated by high plasticity index values. The degree of underestimation by Eqn. (2) is about 50 times than that of Eqn. (1). The plasticity index of soil samples employed in this study ranges from 17 to 58. Thus, the similar setback may be of concern for the empirical relationship proposed in this investigation, particularly at higher ranges of the plasticity index, and such a situation requires further investigation.

Komornik and David (1969) related the swell pressure (SP in kgf/cm^2) to the initial water content (w_i in percent), dry density (ρ_d in kg/m^3), and liquid limit in the following form:

$$\log(SP) = -2.1 + 0.021LL + 0.00067\rho_d - 0.027\, w_i. \quad (3)$$

A comparison between the measured swell pressures in this investigation and the predicted swell pressures using Eqns. (1) and (3) is presented in figure 7. The empirical form by Komornik and David (1969) yields swell pressures with somewhat higher values than that by Erzin and Erol (2004); however, the degree of underprediction is still dramatic. That is, the degree of underprediction by Komornik and David's (1969) approach is about 10 times when compared to those obtained using Eqn. (1).

Swell pressures were also evaluated in correlation with free swell. Regarding free swell tests, three specimens were prepared for testing. The specimens were set in a conventional one-dimensional

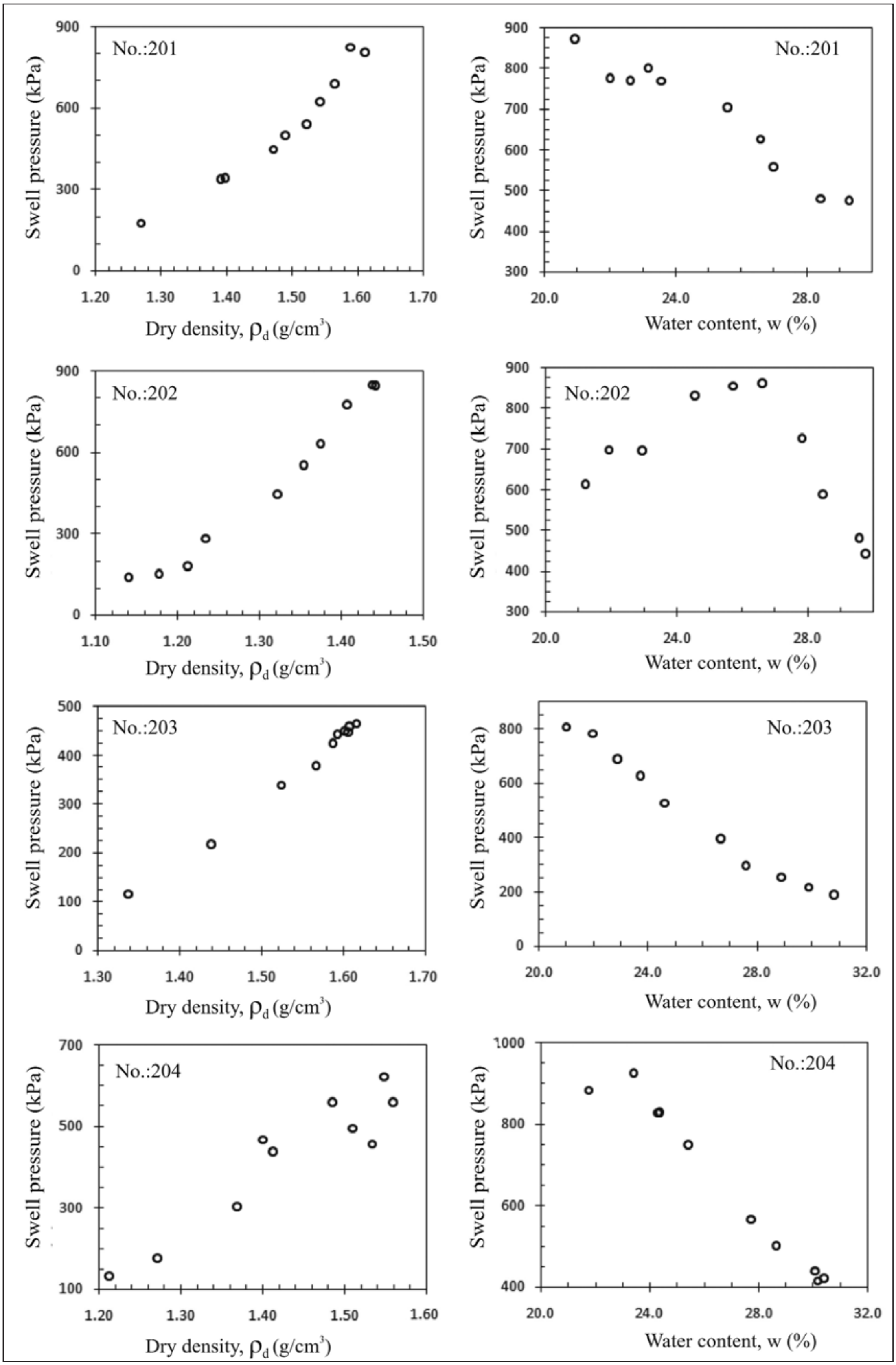

Figure 3- Swell pressure versus dry density (the left column), and swell pressure versus initial water content (the right column) graphs for soil samples 201–204.

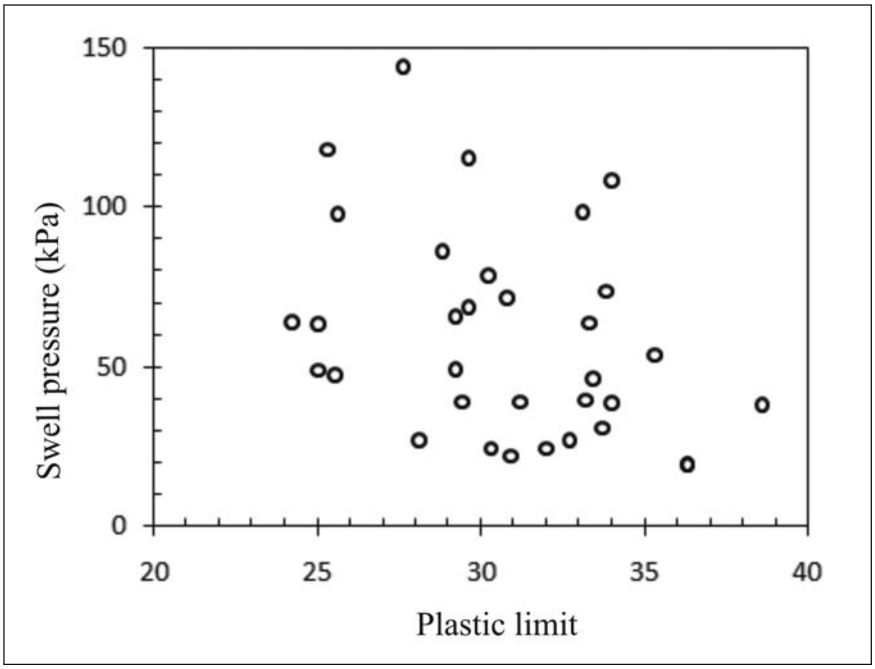

Figure 4- Relationship between swell pressure and plastic limit for 40 soil samples.

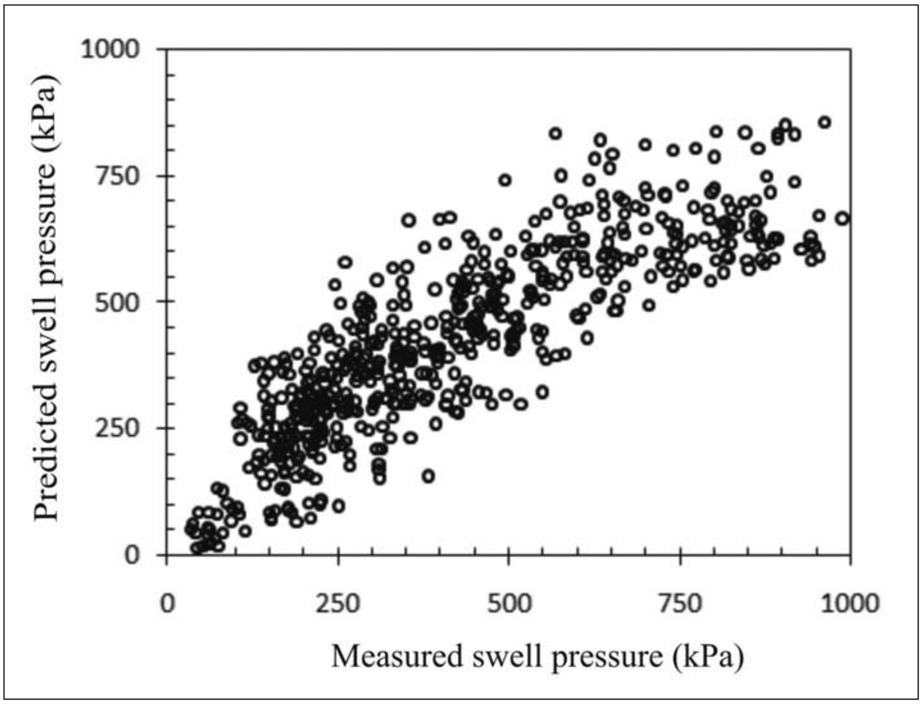

Figure 5- Predicted swell pressure versus measured swell pressure for 600 pairs of data.

Table 2- The initial water content (w_i), dry density (ρ_d), swell pressure (SP) and free swell (FS) values for 120 soil samples. Each number in the table represent the average of the results obtained from three specimens per soil sample.

No.	w_i (%)	ρ_d (g/cm^3)	SP (kPa)	FS (%)	No.	w_i (%)	ρ_d (g/cm^3)	SP (kPa)	FS (%)	No.	w_i (%)	ρ_d (g/cm^3)	SP (kPa)	FS (%)
1	25.2	1.61	351	9.1	41	26.3	1.47	507	12.8	81	24.9	1.57	405	6.3
2	25.4	1.61	184	5.5	42	26.3	1.57	246	8.1	82	24.8	1.59	341	8.9
3	25.5	1.59	344	8.4	43	26.4	1.53	290	6.4	83	24.9	1.60	477	9.6
4	25.4	1.60	160	4.2	44	26.1	1.57	46	2.6	84	25.8	1.60	83	3.1
5	24.8	1.59	673	13.3	45	26.1	1.55	170	5.2	85	25.9	1.59	326	9.6
6	25.2	1.60	551	10.8	46	25.4	1.58	60	2.7	86	26.0	1.58	227	7.5
7	25.3	1.60	682	15.4	47	25.7	1.59	125	5.5	87	25.8	1.61	335	11.1
8	25.5	1.59	261	7.8	48	26.1	1.59	162	5.4	88	25.5	1.49	256	7.4
9	25.7	1.60	569	12.3	49	25.4	1.59	200	6.8	89	25.7	1.60	230	7.9
10	25.3	1.62	497	10.8	50	25.7	1.56	76	2.9	90	25.6	1.56	206	6.0
11	25.5	1.55	245	7.3	51	25.3	1.59	604	13.8	91	27.1	1.41	676	14.8
12	25.4	1.61	74	4.3	52	25.3	1.60	332	8.8	92	25.7	1.59	330	9.3
13	26.0	1.58	158	7.3	53	24.6	1.58	598	9.8	93	25.0	1.56	448	8.3
14	26.3	1.45	853	19.1	54	25.2	1.60	325	6.8	94	25.7	1.59	175	6.8
15	26.1	1.47	711	15.8	55	26.2	1.56	744	15.6	95	25.6	1.58	383	7.1
16	25.7	1.42	626	15.2	56	25.9	1.57	607	11.9	96	25.6	1.59	204	5.8
17	25.6	1.60	155	6.0	57	25.7	1.54	931	22.6	97	25.6	1.59	221	5.8
18	25.7	1.52	316	6.6	58	27.3	1.54	405	9.2	98	25.6	1.58	313	7.9
19	25.5	1.55	224	3.6	59	26.6	1.59	529	12.6	99	25.6	1.57	425	7.9
20	25.6	1.60	258	4.0	60	27.1	1.58	635	13.4	100	26.0	1.59	196	7.9
21	25.6	1.55	58	2.5	61	25.0	1.58	389	8.5	101	25.8	1.55	232	5.6
22	26.4	1.58	317	9.2	62	26.7	1.59	219	10.0	102	26.2	1.55	168	4.6
23	25.8	1.59	295	9.3	63	27.2	1.56	454	12.0	103	26.0	1.57	264	7.6
24	25.4	1.56	47	1.8	64	25.3	1.39	841	20.4	104	24.7	1.58	160	5.8
25	25.0	1.62	218	8.1	65	26.6	1.44	849	18.1	105	26.1	1.58	171	5.9
26	25.4	1.56	80	2.5	66	25.5	1.45	799	18.9	106	26.1	1.57	215	7.0
27	25.4	1.63	249	9.1	67	25.8	1.62	293	7.6	107	26.2	1.59	165	5.6
28	25.7	1.60	133	5.1	68	25.5	1.48	411	9.1	108	25.8	1.58	154	5.3
29	26.1	1.58	319	10.0	69	25.1	1.58	520	10.0	109	25.6	1.57	227	5.9
30	25.7	1.62	51	3.3	70	25.2	1.55	454	9.4	110	25.7	1.59	205	6.2
31	25.6	1.56	116	4.7	71	25.6	1.57	220	7.2	111	26.2	1.49	613	12.8
32	25.9	1.61	39	2.3	72	26.0	1.60	359	9.1	112	26.0	1.56	291	7.6
33	25.9	1.60	243	9.4	73	26.0	1.59	407	10.8	113	26.2	1.57	314	8.2
34	25.8	1.62	64	4.0	74	25.4	1.58	285	6.0	114	25.8	1.58	298	9.6
35	25.6	1.60	220	8.5	75	28.3	1.53	205	7.4	115	25.2	1.60	306	8.6
36	25.8	1.61	64	3.1	76	25.6	1.57	246	5.6	116	25.4	1.59	294	7.6
37	25.8	1.61	314	6.5	77	25.6	1.63	249	7.7	117	25.7	1.60	275	8.3
38	25.6	1.58	137	4.9	78	25.4	1.60	244	7.9	118	24.9	1.60	212	6.2
39	25.6	1.60	131	5.6	79	25.3	1.60	544	9.6	119	25.4	1.60	318	8.8
40	25.2	1.59	52	2.3	80	25.1	1.61	176	6.1	120	25.1	1.61	275	8.7

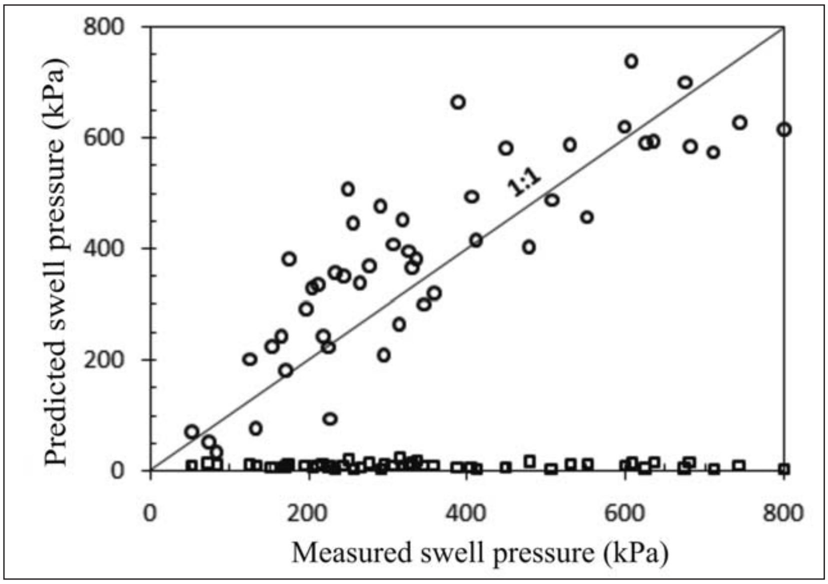

Figure 6- Comparison between the predicted swell pressures using the proposed relationship and the measured swell pressures (circles) and the swell pressures computed using the relationship by Erzin and Erol (2004) (squares).

consolidation testing apparatus (or oedometer). The amount of heave (the change in the height of a specimen, ΔL) measured at the end of 24 hours was recorded. The free swell (in percent) was determined as the heave divided by the original height of the specimen, L. The average values of three specimens per soil sample are presented in table 2. figure 8 shows two comparisons between the swell pressures obtained from the constant volume swell pressure test and the free swell test. First, 360 swell pressures were compared with 360 free swells for 120 samples. The regression coefficient for this correlation is 0.822, and the relationship obtained is as follows:

$$SP = 46.04FS - 63.43. \qquad (4)$$

Second, the average swell pressure and the average free swell of three specimens per soil sample are compared for 120 soils. The quality of correlation with this comparison is slightly better than the previous one ($R^2 = 0.888$). The empirical relationship for this correlation is:

$$SP = 48.09FS - 76.01 \qquad (5)$$

The constant volume swell pressure and free swell tests were all conducted over a 24-hour period. This length of time is selected only for the sake of convenience. At this point, one might raise a question regarding if this length of time is long enough for a soil specimen to undergo full swelling. To address such a likely criticism, a series of additional tests were executed. Three soil specimens representing the lowest, moderate, and highest swell pressures were subjected to swell pressure and free swell tests, and the amount of swell was monitored. Figure 9 illustrates the swell behavior with respect to elapsed time and reveals that, if not completely, almost all swelling takes place in a 24-hour period, which justifies our selection of time length for all swell tests.

5. Conclusions

Based on a comprehensive investigation comprising 1000 experiments that employ the constant volume and the free swell tests, the following conclusions were reached:

1. While the initial water content and dry density significantly affect the outcoming swell pressure, they cannot be used alone to predict swell pressure accurately.

2. Including Atterberg limits in regression analyses with the initial water content and dry density resulted in an empirical relationship with a reasonably good regression coefficient of 0.724. The empirical form of

$$SP = -30.8w_i + 1025\rho_d + 6.35LL + 42.4PL - 2208$$

is proposed to estimate the swell pressure for soils with the plasticity index up to about 60.

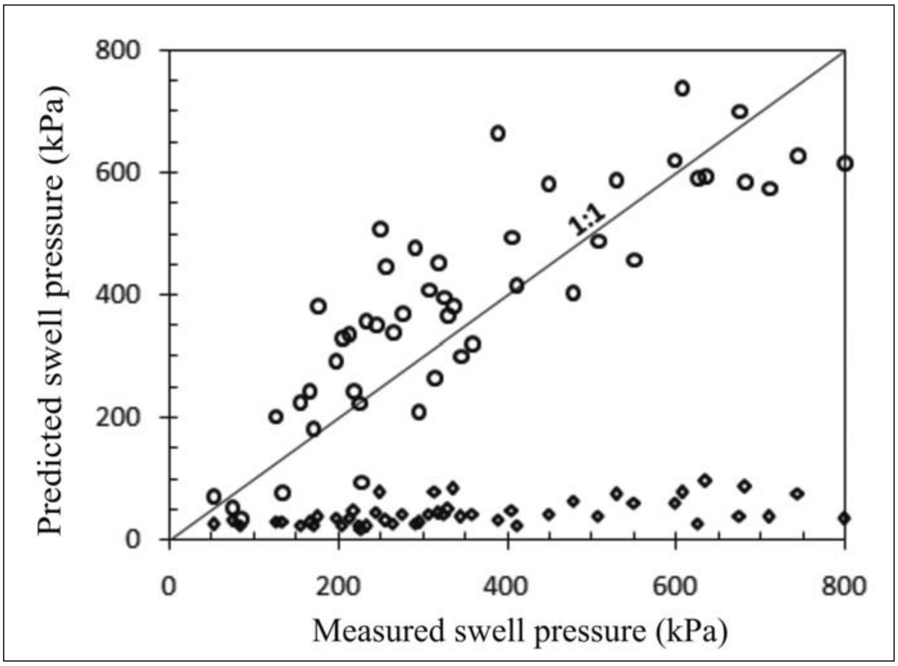

Figure 7- Comparison between the predicted swell pressures using the proposed relationship and the measured swell pressures (circles) and the swell pressures computed using the relationship by Komornik and David (1969) (squares).

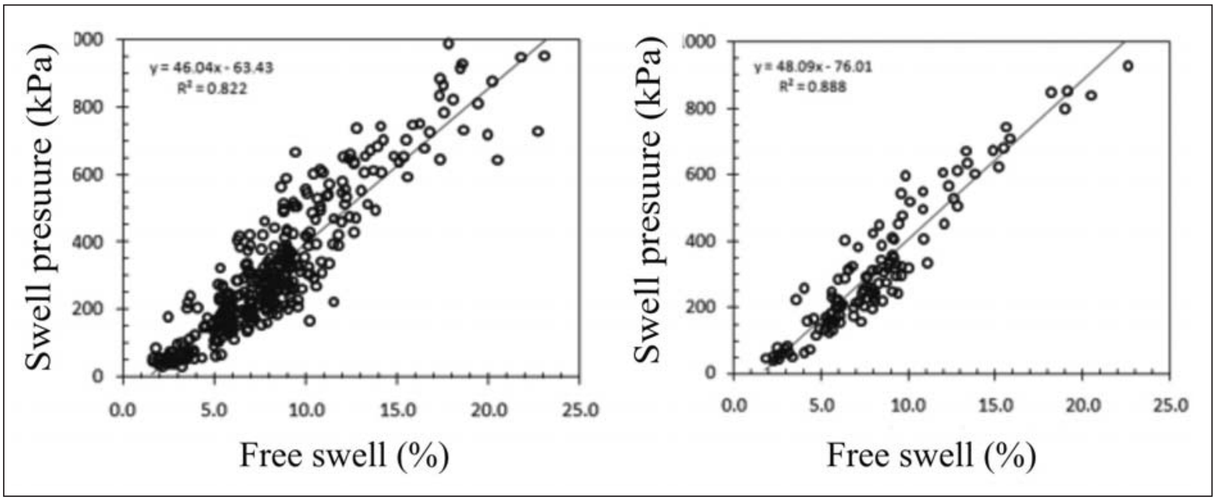

Figure 8- Comparisons between the swell pressures from the constant volume and free swell tests for 360 data pairs (left) and the average swell pressures and average free swells for 120 soil samples (right).

3. Comparing a large body of data from constant volume swell tests and free swell tests also unveils a remarkably good relationship in the following form ($R^2 = 0.888$):

$$SP = 48.1FS - 76.$$

4. Initial water content, dry density, and Atterberg limits are basic soil indices easily obtainable from all undisturbed samples. Swell pressure can be computed empirically by using those parameters without requiring further tests. Disturbed samples do not allow for determining the dry density. By making reasonable assumptions for dry density, index values obtained using disturbed soils may also provide an idea about the swell potential.

5. The free swell test is also a simple test that can be conducted almost in all laboratories. It can be used to confirm the accuracy of swell pressure obtained using the simple soil indices.

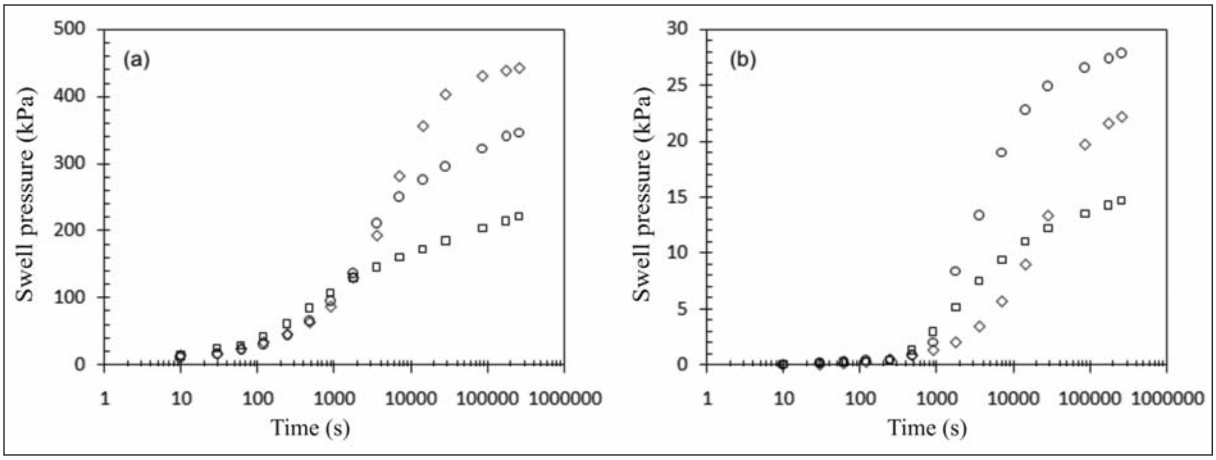

Figure 9- Swell pressure behavior (a) and free swell behavior (b) with respect to time for three selected soils.

6. The empirical relationships to determine swell pressure established in this investigation covers a plasticity index range of about 20–60. These relationships should be used cautiously for higher ranges, however. Further study is suggested to cover a higher range of the plasticity index.

7. Comparing the results of this investigation and those of two previous studies reveals that the other two relationships that also utilize the basic soil indices yield swell pressures up to 50 times smaller than those found using the empirical relationship proposed in the present study. Such a dramatic discrepancy can be attributed to several reasons. One reason is the use of the oedometer method. Kayabali and Demir (2011) showed that the swell pressures obtained from oedometer methods are highly speculative. Other reasons may include the limited amount of data, the specific range of soil plasticity, and the like.

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