VREDNOTENJE KOEFICIENTA PREPUSTNOSTI ZA NAPOVEDOVANJE NABREKALNIH LASTNOSTI ZBITIH EKSPANZIVNIH ZEMLJIN

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Ključne besede

nabrekalne lastnosti, gradacija, prepustnost, stopnja primarnega nabrekanja

Izvleček

Nabrekanje ekspanzivnih zemljin je zelo pomembna lastnost v geotehniki, saj lahko povzroča visoko škodo na gradbenih objektih. Za projektiranje zadostno varnih in ekonomičnih inženirskih projektov morajo biti nabrekalne lastnosti dobro znane.

Neposredna določitev nabrekalnih lastnosti zahteva veliko časa in finančnih sredstev ter vključuje resen eksperimentalni napor. Druga možnost je, da se uporabi ena od tehnik za posredno ocenjevanje, ki so bile razvite s pomočjo empiričnih modelov regresije, le te so na voljo v literaturi ter pogosto uporabljene v praksi. Te empirične tehnike ocenjevanja so bile na splošno podane kot funkcija lastnosti zemljine, te so: konsistenčne meje, gostota, vlažnost, količina in vrsta glinene frakcije ter kationska izmenjalna kapaciteta.

Članek opisuje odvisnost odstotka nabrekanja (S%) in tlaka nabrekanja (σ_{sp}) dobljenega iz preizkusa prostega nabrekanja (FS) in preizkusa nabrekanja pri konstantnem volumnu (CVS) ter primarnega časa nabrekanja (PST). V pričujoči študiji predstavlja primarni čas nabrekanja, novo karakteristiko nabrekanja, v katerem skoraj 90 % nabrekanja nastopi kot deformacija, koeficient prepustnosti (k) pa je nadzorovan s spreminjanjem granulometrije zbitih nabrekljivih zemljin. Poleg tega sta bila stopnja primarnega nabrekanja (C_{ps}), ki predstavlja naklon krivulje odstotka nabrekanja (S%) v odvisnosti od logaritma časa v območju primarnega nabrekanja, in razmerje (C_{ps}/k) uporabljena za analiziranje njunih zvez z nabrekalnimi lastnostmi.

S pomočjo empirične metode te študije je mogoče, dodatno ali skupaj s konvencionalnimi parametri, posredno oceniti odstotek nabrekanja (S%), tlak nabrekanja (σ_{sp}) in primarni čas nabrekanja (PST) v odvisnosti od k, C_{ps} in C_{ps}/k. Korelacijski koeficienti regresijske analize kažejo na trdne odnose med nabrekalnimi lastnostmi in indeksi predlaganimi v tej študiji, ter potrjujejo, da se te empirične enačbe lahko varno uporabljajo za napoved v inženirski praksi.

ASSESSMENTS OF THE HYDRAULIC CONDUCTIVITY FOR PREDICTING THE SWELLING CHARACTERISTICS OF COMPACTED EXPANSIVE SOILS

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Keywords

swelling characteristics, gradation, hydraulic conductivity, rate of primary swelling

Abstract

The swelling behaviour of expansive soils is significant in geotechnical engineering since it causes severe damage to civil structures. The swelling characteristics need to be well known for satisfactorily safe and economic engineering designs. A direct determination of the swelling characteristics requires considerable time and money, involving serious experimental effort. Alternatively, several indirect estimation techniques developed using empirical regression models available in literature are widely used in practice. These empirical estimation techniques have generally been assessed as a function of the soil properties, i.e., consistency limits, density, moisture content, clay fraction and type, and cation-exchange capacity.

This paper describes the dependence of the percentage swell (S%) and the swell pressure (σ_{sp}) obtained from a free-swell (FS) test and a constant-volume swell (CVS) test, and the primary swell time (PST), in which almost 90% of the swelling occurs as strain, which is considered as a new swelling characteristic in this study, on the hydraulic conductivity (k) controlled by a change in the gradation of compacted expansive soils. In addition, the rate of primary swelling (C_{ps}), which is the primary swelling phase's slope of the curve of percentage swell vs. log time, and the ratio of (C_{ps}/k) were used to analyse their relationships with the swelling characteristics.

This study provides the empirical methods that can be utilized to obtain indirect estimations of the percentage swell (S%), swell pressure (σ_{sp}) and primary swell time (PST) depending on k, C_{ps} and C_{ps}/k, in addition to, or with, the conventional parameters. The correlation coefficients of the regression analysis, having high performance, and indicating strong relationships between the swelling characteristics and the indices proposed in this study, state that these empirical prediction equations can be used safely in engineering practice.

1 INTRODUCTION

In many regions around the world, expansive soils are problematic for civil engineering projects such as low-rise buildings, embankments, airports, irrigation structures, roads and pavements, etc., some of which cannot be easily repaired. Such constructions over expansive soils having volume-change potential can suffer from considerable damage, irrespective of the project type, unless the swelling behaviour is taken into account. It has been recognized in geotechnical engineering that the swelling and shrinkage of expansive soils depending on moisture changing can result in significant distress, and therefore in serious damage to the structures on such soils [1, 2, 3]. A number of swelling-soil problems and damage in buildings caused by such ground movements have been well documented in the literature [e.g., 1, 2, 4, 5, 6, 7, 8, 9, 10, 11].

Numerous techniques, i.e., oedometer methods, methylene blue test, and empirical (indirect) methods developed to estimate the swell potentials of expansive soils are available [e.g., 11, 12, 13, 14, 15, 16, 17, 18, 19]. Empirical methods, used widely in geotechnical engineering, are generally needed in preliminary site investigations and in the case of the presence of a number of check points on the project area. Empirical methods for estimating the swelling characteristics are related to the soils' physical/chemical properties of the Atterberg limits (i.e., liquid limit, (LL), plastic limit (PL)), dry density, linear shrinkage (LS) and plasticity index (PI), clay type and content, coefficient of linear extensibility, cation exchange capacity, initial degree of saturation and exchangeable bases [e.g.,13, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33]. So far the investigations aimed at developing the swelling-prediction models have been based on relationships between the swelling potential (i.e., the percentage swell, *S*%), and/or the swell pressure and the soil properties mentioned above, assumed as a function of the swelling. In addition to these, Dananaj et al. [34] in their study, which only four data points of compacted different bentonites were used and correlated, reported an exponential dependence and a negative logarithmic relationship between the hydraulic conductivity (coefficient of permeability, *k*) and the percentage swell (swelling potential).

This study primarily focuses on the relationships between the swelling characteristics and the hydraulic conductivity controlled by the granulometric change of the clay soils. In this context, a method using two expansive clays with various percentages of uniform quartz sand was selected as a case study to generate a better understanding of the swelling behaviour of compacted fine-grained soils with different granulometries. The influence of the hydraulic conductivity (*k*) related to the content of uniform quartz sand in two different types of compacted clay-sand mixtures on the swelling characteristics, which were obtained from swelling tests using a conventional odeometer test device, was firstly investigated. In addition, the effects of granulometric change controlled by the increase in the sand ratio on the swelling characteristics of the percentage swell, swell pressure obtained from both the free swell test and the constant-volume swell test, and the primary swell time as a new term was also assessed in terms of graphical and statistical methods. By considering that *hydraulic conductivity, the rate of primary swelling* and the indices of *the rate of primary swelling-to-hydraulic conductivity* are functions of swelling, correlations between these variables and the swelling characteristics were made. Thus, the empirical prediction formulas for the swelling characteristic were derived using simple and multi-regression analysis.

2 MATERIAL

For the laboratory investigation of the changes in the swelling characteristics developed by clay-sand mixtures

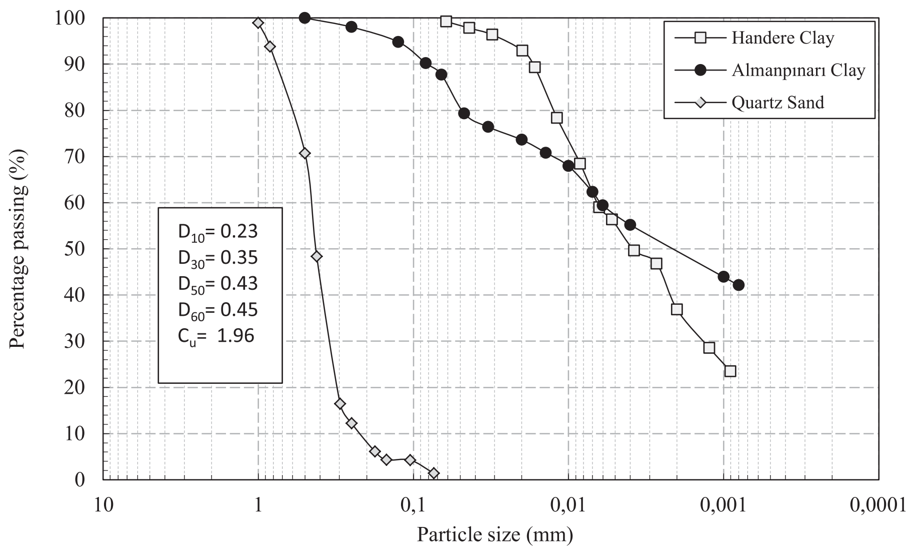


Figure 1. Particle size distributions for the sand and soils used during the experimental study.

with various granulometry techniques, two different clays, i.e., Handere Clay and Almanpınarı Clay, and a uniform quartz sand were used.

Specific gravity analysis, particle size analysis and Atterberg limit tests were performed to classify the clays and the quartz sand in accordance with the Unified Soil Classification System (USCS). The tests were performed on all the used samples according to the test procedures outlined in ASTM D 854-10 [35], ASTM D 422-63 [36], ASTM D 4318-10 [37] and ASTM D 427-98 [38], respectively. The characteristics of all the materials are summarized in Tables 1 and 2.

2.1 Clays

Two clay soils named Handere Clay and Almanpınarı Clay were used in this investigation. Handere Clay was derived from claystone layers of the Handere formation (Pliocene), north of the Adana region (Turkey), while Almanpınarı clay was derived from the clay formation in limestone layers aged U. Cretaceous, south of the Osmaniye region (Turkey). The depths of sampling were 0.5–1.0 m. Handere Clay contains mainly smectite, known to be expansive, and lesser amounts of illite and chlorite [39]. It has a liquid limit, LL=54; a plastic limit, PL=24; and a specific gravity, G_s=2.65. Almanpınarı Clay predominantly illite [40] known as moderate expansive has a liquid limit, LL=37; a plastic limit, PL=17; and a specific gravity, G_s=2.67.

Table 1. Index Properties, Classifications and compaction parameters of the tested soils.

Soil Name		Almanpınarı clay	Handere clay	Quartz Sand
LL (%)		37	54	
PL (%)		17	24	
PI (%)		20	30	
SL (%) (Shrinkage Limit)		9	13	
R (Shrinkage ratio)		1.99	1.95	
L_S (%) (Linear shrinkage)		9	14	
Specific gravity, G_s		2.67	2.74	2.63
Fines content (%)		92	99	
Sand size 4.75-0.075mm (%)		12	1	100
Silt size 0.075-0.002 mm (%)		33	62	
Clay size (%)<0.002mm		55	37	
Activity		0.42	0.5	
Initial void ratio (e_0)		0.589	0.662	
Classification	USCS	CI	CH	SP
	Group Name	Inorganic clays of medium plasticity	Inorganic clays of high plasticity	Poorly graded sand
Standard Proctor compaction	MDD (kg/m^3)	1683	1621	
	OMC (%)	19.4	19.3	

2.2 Sand

A commercially available quartz sand named Hebilli, derived from Mersin province (south of Turkey) was used in soil-sand mixtures. Grain size analyses (by sieving) of the sand are also shown in Fig. 1. It is a uniform, yellowish quartz sand (with a SiO_2 content of 99.47%) and classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). Grain-size data of the sand indicate a mean diameter D_{50}=0.43 mm, a coefficient of uniformity C_u=1.96, a coefficient of curvature C_c=1.18 and an effective diameter D_{10}=0.23 mm (Table 1).

3 SAMPLE PREPARATION

The sample-preparation technique was the same for all the specimens. The specimen preparation for the tests was performed at room temperature. Sand–clay mixtures were prepared on a dry-weight basis by using oven-dried (at 60 °C) sand and clay. The required amount of sand and clay were weighed, and mixed carefully in a dry state, until a homogeneous mixture was obtained.

For each of the two clays mentioned above, six artificial soil specimens were prepared by adding 0, 10, 20, 30, 40 and 50% of ,the uniform quartz sand by weight, in dry conditions, taking account of their natural grain content of sand size. In this way mentioned above, using two types of clay and one type uniform sand, two sets of artificial soil samples consisting of different clay-sand ratios were prepared. Following the oven drying, the sand-clay mixtures were compacted using a Proctor mould at values of optimum moisture content (OMC) and maximum dry density (MDD) obtained from the compaction curves.

Compacted soil samples in the swelling tests were used in order to provide homogeneity and eliminate the macro and micro cracks. In addition to that, the compacted specimens were preferred to provide the uniformity of the factors such as moisture content (w), void ratio (e) and natural density (Υ_n) on swelling, as well. Therefore, Standard Proctor compaction tests according to *ASTM D 698-07698-07* [41] were performed on each mixture to determine the compaction curves. The maximum dry densities and the optimum moisture contents of these artificial soils were achieved by applying an energy level of 600 kN-m/m^3, equal to the standard compactive effort recommended *by ASTM D 698-07698-07* [41].

The compaction curves of each mixture were displayed in Fig. 2 and 3. All the mixtures had bell-shaped compaction curves. From Fig. 2 and Table 2, it is clear that the values of MDD and OMC range between 1683–1881 kg/m^3 and 19.4–12 % for the mixtures of Almanpınarı Clay-Quartz Sand, respectively. On the other hand, as seen in Fig. 3 and Table 2, the values of MDD and OMC for the mixtures of Handere Clay-Quartz Sand are 1621–1791 kg/m^3 and 19.0–13.2 %, respectively.

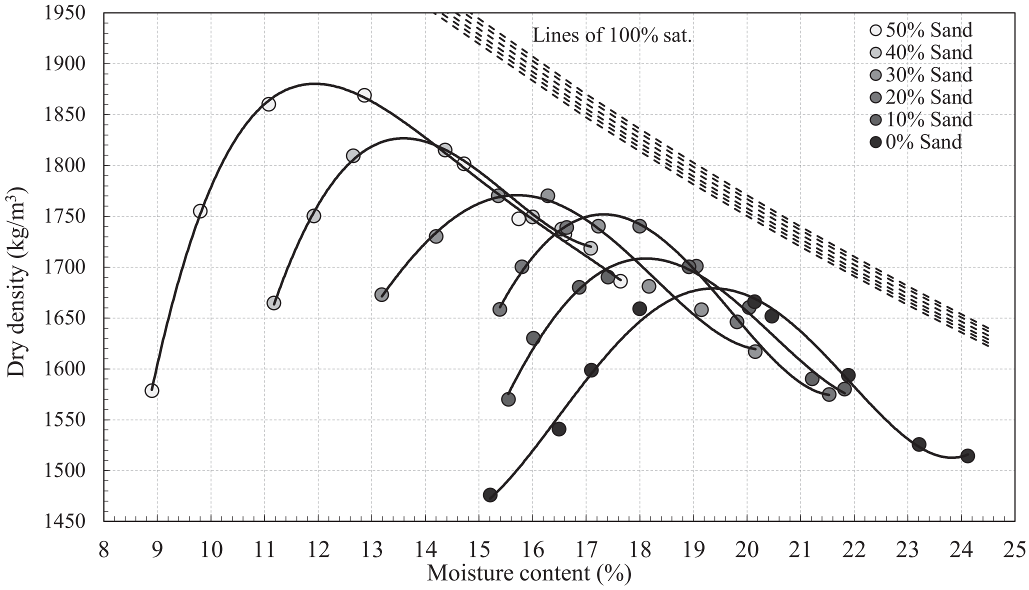


Figure 2. Graph of Standard Proctor compaction curves of Almanpınarı Clay and its mixtures with sand.

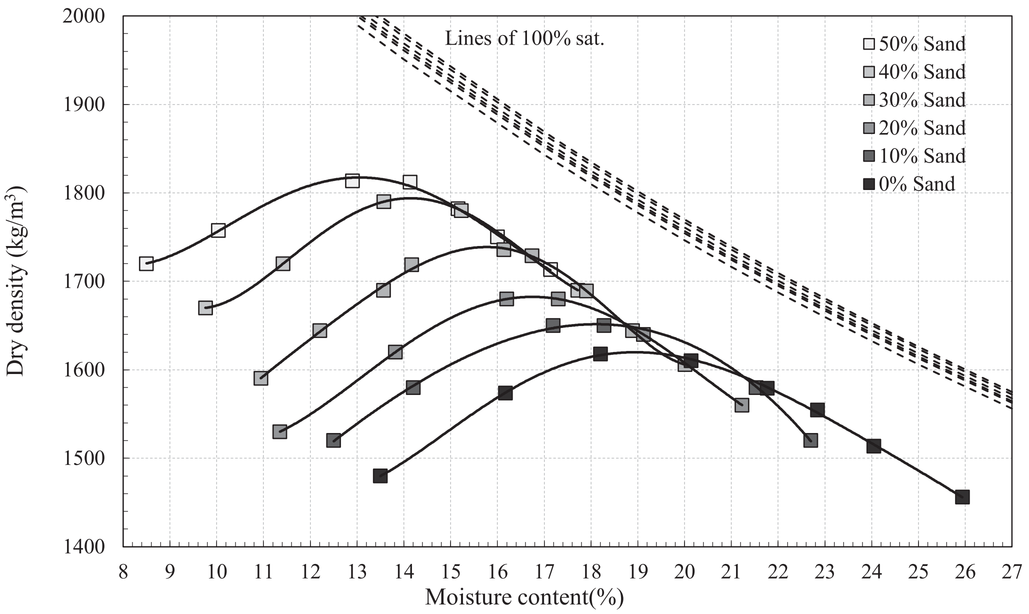


Figure 3. Graph of Standard Proctor compaction curves of Handere Clay and its mixtures with sand.

Table 2. Compaction parameters (Optimum moisture content [OMC], Maximum dry density [MDD], initial void ratio (e_0) and saturation degree [*s*(%)]) of soil-sand mixtures.

Clay Name	Almanpınarı Clay				Handere Clay			
Sand content (%)	MDD (kg/m^3)	OMC (%)	e_0	*s*(%)	MDD (kg/m^3)	OMC (%)	e_0	*s*(%)
50	1881	12.0	0.426	74.9	1791	13.2	0.499	71.0
40	1825	13.6	0.479	76.5	1787	14.2	0.513	74.8
30	1774	15.8	0.527	81.1	1754	15.8	0.545	78.6
20	1754	17.4	0.551	85.8	1683	16.8	0.617	74.2
10	1713	18.2	0.594	83.6	1652	18.1	0.653	75.6
0	1683	19.4	0.629	84.5	1621	19.0	0.690	75.5

After compaction, the soil was immediately extruded from the mould using a hydraulic jack. The side friction causing damage to the soil sample during the intrusion and extrusion was minimized by lightly lubricating the inner surface of the mould. After sampling, all the samples were covered with a stretch film and aluminium folio and stored in a wet room for one week to guarantee good moisture equilibration and homogeneity.

4 METHOD

Both the free-swell (FS) tests (constant stress tests) and the constant-volume swell (CVS) tests on the clay-sand mixtures were performed to measure the swelling deformation (percentage swell, *S*%) and the swell pressure. All the swelling tests were conducted in the conventional oedometer test device. The FS tests and CVS tests in accordance with *ASTM D4546-96: method A and C* [42] were carried out on two different fine-grained, compacted soil sets containing various proportions of quartz sand, i.e., from 0 to 50%.

All the artificial soils were tested in a standard fixed ring, 50 mm diameter and 20 mm height. However, a ring thinner than usual was used to reduce possible distribution. On the other hand, the side friction between the ring and the soil specimen, causing damage to the soil specimen during the intrusion, was minimized by lightly lubricating the inner surface of the ring with grease. Afterwards, the ring was intruded into the compacted soil-sand mixture using a hydraulic jack. The deformation caused by swelling or consolidation during the wetting is only in the vertical direction. The tests were performed with distilled water in order to avoid the possible effects of ion exchange.

In order to determine the percentage swell and the swell pressure (provided from FS tests) of the compacted pure clays and clay–sand mixtures, free-swell (FS) tests were performed. The sample in the ring was placed between two porous stones, loaded with a seating pressure (σ_{se}) of 1.0 kPa, and oedometer cell was fully inundated with distilled water. After the specimen was allowed to swell, readings of the dial gauge were periodically recorded for up to 18 days (Fig. 4). The percentage swell (*S*%) was then calculated as an increase in the length in relation to the initial thickness of the specimen. The deformation was considered to be finished when the variation in the indicator on the displacement transducer was less than 0.01 mm after an interval of 24 hours. After completion of the swell, the pressure maintained in the vertical direction (by conducting *ASTM D 2435* [43]) and necessary to achieve the initial void ratio/height of the specimen was calculated as the swell pressure (σ_{sp}).

The constant-volume swell (CVS) tests, another method to determine the swell pressure, were also conducted on all the specimens. In the CVS tests the vertical pressure increment was applied constantly to keep the volume of the specimen unchanged/or to prevent swelling. The vertical stress, which was provided to fully complete the swell or needed to prevent the swell, was considered as the swell pressure (σ_{sp}) of the specimen at a certain dry density.

The results of FS and CVS tests on the pure clays and the mixtures having various sand contents and the effect of the sand content on swell percentage and pressure of the soils were given in Table 3 and Fig. 5 and 6, respectively.

In order to compare the hydraulic conductivity (k) and the swelling characteristics, finally, the permeability tests were conducted on the compacted artificial soil specimens with the same properties as those used in the swell tests. For this purpose, falling-head permeability tests in accordance with *ASTM D 5856–95* [44] were performed. Each test was repeated three times and used the average values of these three tests results.

Correlations, and simple and multi-regression analysis, were carried out to identify the related variables effecting the swelling phenomena. The individual variables (parameters) focused on in this study, such as the content of quartz sand, the hydraulic conductivity and the rate of primary swelling, were compared to obtain correlations, and calculated estimates of the swelling characteristics of the percentage swell, swell pressure and the primary swell time, and the statistical relationships. The correlation coefficients of the relationships between the various properties and the experimentally obtained measurements (values) were used to derive prediction formulas for the swelling characteristics, and to analyse the confidence of those correlative functions.

5 EXPERIMENTAL RESULTS AND ANALYSIS

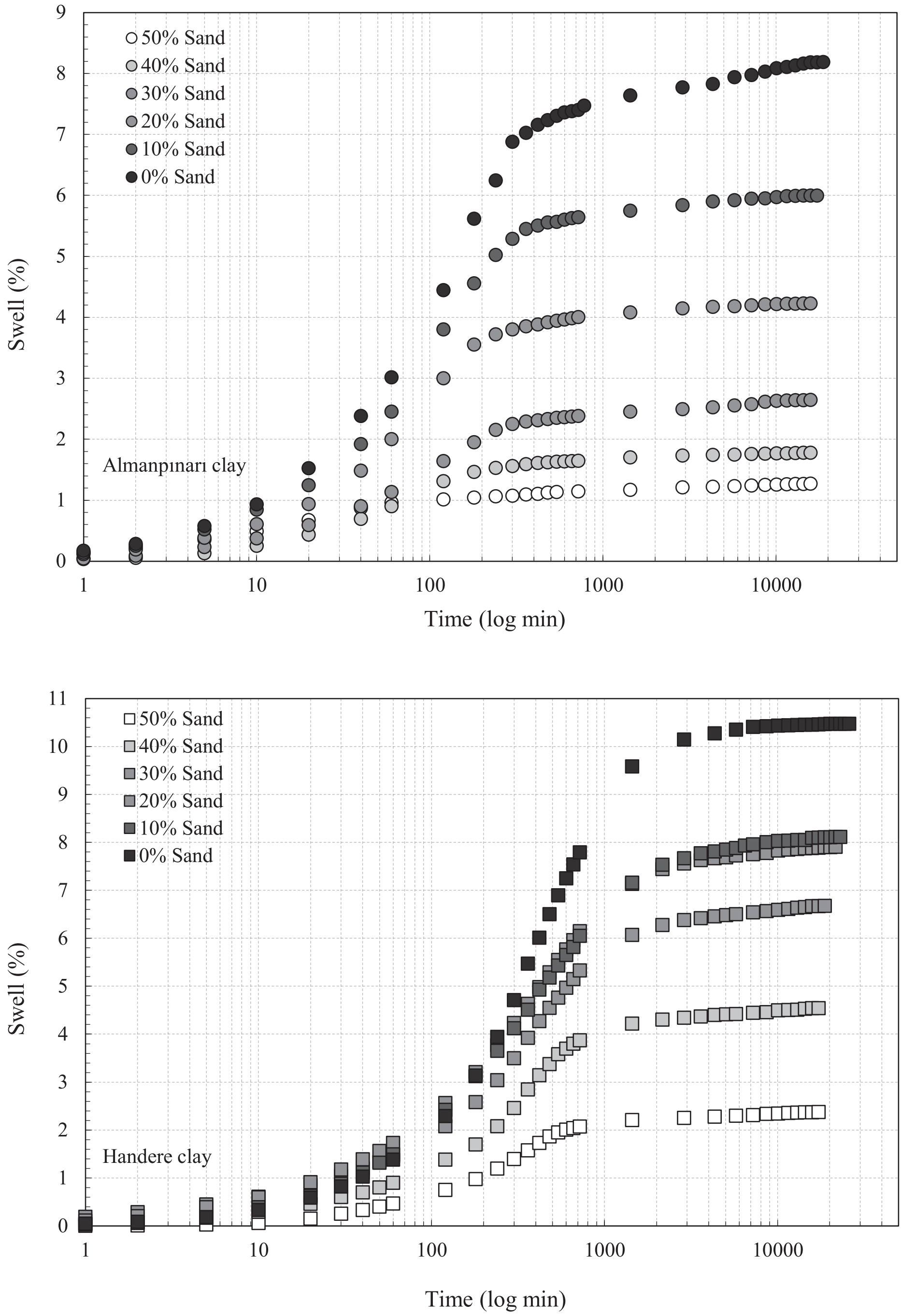
The swelling characteristics and the initial hydraulic conductivity (*k*) corresponding to the clay specimens having various sand contents are summarized in Table 3 for two clay types. Fig. 4a-b shows the log time vs. percentage swell for six different gradations of two different soil sets. The percentage swell (*S*%) is described as the ratio of the quantity of swell to the initial thickness of the soil specimen represented as a percentage. As can be seen in Fig. 4a-b, the enhancement in *S*% is relatively fast during the initial phases, and it gradually approaches the ultimate grade. Even after a period of 13–18 days, there was a gradual and slow increase in *S*%. On the other hand, the time to reach the ultimate swell level is a maximum for the specimens of pure clay for both clay types.

Yule and Ritchie [45] and Gray and Allbrook [46] reported there to be no relationship between clay percentage and soil swelling, and Karuiki and var der Meer [28] stated there were poor correlations among them. ElKholy [47] reported that the increasing coarse fraction in clay decreases exponentially both the percentage swell and the swell pressure. On the other hand, Rao et al. [48], Gürtuğ et al. [49] and Mishra et al. [50] stated there was a linear decrease for similar situations, whereas Cui et al. [51] suggested that with the increase in sand content of bentonite-sand mixtures, the percentage swell shows a sigmoid decrease, and the swelling pressure obtained from the CVS tests decrease exponentially. It is clear that there is no consensus on this subject in the literature, which is summarized partly above.

Fig. 5 presents the relationships between percentage swell (*S*%) and sand content for the clays. The figure indicates that the increase in sand content decreases almost linearly *S*%. The results about the effects of coarse particle content in clay soils on *S*% exhibit similarities to those found by Gürtuğ et al. [49] and Mishra et al. [50]. The addition of quartz sand up to 10% leads to an

Table 3. Percentage swell (*S*%), swell pressure (obtained from FS and CVS tests) hydraulic conductivity (*k*), completion time of primary swelling (*PST*), and rate of primary swelling (C_{ps}) at different sand contents of the clay soils studied.

Sand Content (%)	Percent Swell, *S*%	Swell Pressure [for FS tests] σ_{sp} (kPa)	Swell Pressure [for CVS tests] σ_{sp} (kPa)	Hydraulic conductivity, *k* (cm/sec)	Primary swell Time, *PST* (min)	Rate of primary swelling, C_{ps} (*S*%/min)
Almanpınarı clay						
0	8.2	764.9	192.2	3.66E-08	360	0.0195
10	6.0	684.9	163.9	5.71E-08	320	0.0175
20	4.2	412.9	144.1	5.69E-08	248	0.0148
30	2.6	258.4	122.5	9.28E-08	288	0.0068
40	1.8	170.6	86.6	1.57E-07	210	0.0078
50	1.2	121.6	62.5	1.70E-07	173	0.0051
Handere clay						
0	10.5	1026.8	454.4	1.44E-08	1490	0.0107
10	8.1	779.6	224.3	2.04E-08	1450	0.0075
20	7.9	774.5	169.2	2.06E-08	1350	0.0074
30	6.7	653.9	169.4	2.61E-08	1040	0.0068
40	4.5	445.2	107.3	4.26E-08	675	0.0059
50	2.4	233.3	48.2	5.37E-08	640	0.0030



(a)

(b)

Figure 4. (a). Log time vs. percentage swell relationship for Almanpınarı clay and its mixtures with the quartz sand (b). Handere clay and its mixtures with the quartz sand.

approximately 14 and 16% reduction in *S*% for Handere and Almanpınarı clays, respectively (Fig. 5). Despite the fact that the clays tested in this study have distinct swelling characteristics (Table 3), an increase of the sand content creates very close or almost same effect on *S*% for them. Fig. 6 shows the swell pressure (σ_{sp}) values obtained from both the FS and CVS tests vs. sand content for Handere and Almanpınarı clays. The results indicate that there are strong negative correlations between the sand content and σ_{sp}.

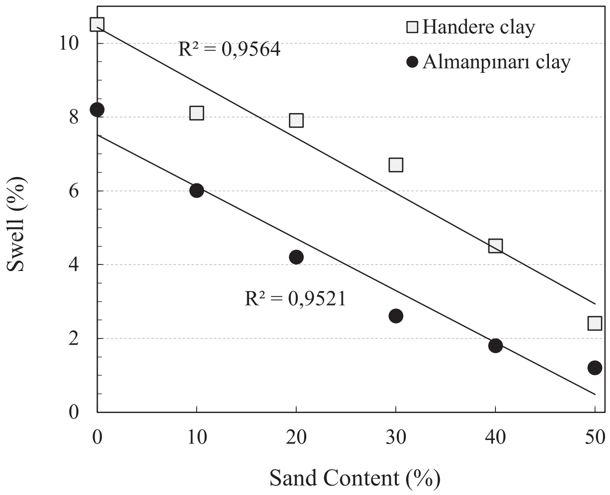


Figure 5. Sand content vs. percentage swell.

The correlation coefficient in the statistics was classified as strong, medium and weak for R≥0.8, 0.8<R<0.2 and R≤0.2, respectively [52]. As expected, compared to σ_{sp} and sand content of clay it appears that σ_{sp} decreases linearly as the sand content increases. An increase in the sand content of 10% leads to a decrease in σ_{sp} obtained from the FS test of average 159 and 129 kPa (or 24 and 30.1%) for Handere clay, and from CVS test of average 81 and 26 kPa (33.4 and 19.8%) for Handere clay and Almapınarı clay, respectively. Consequently, although the relations between the sand content and *S*% for the clays tested in this study are quite similar, the relations between sand content and σ_{sp} are unique, i.e., they depend on the clay type.

Based on the test results, σ_{sp} values obtained from the FS tests are greater than those obtained from the CVS

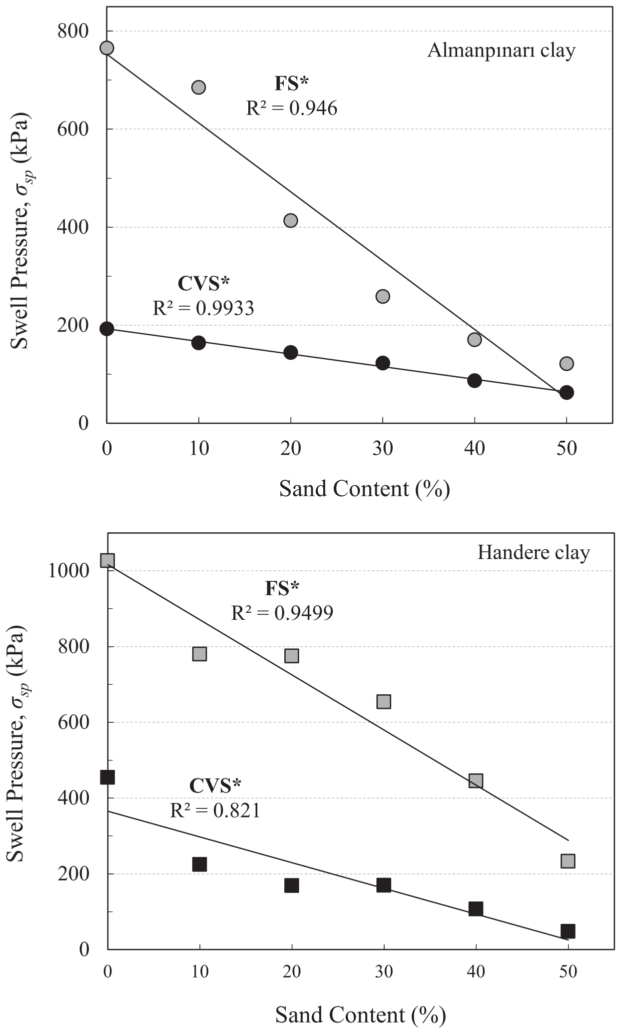


Figure 6. Effect of uniform quartz sand content on the swell pressure obtained from free-swell (FS*) and constant-volume swell (CVS*) tests for the specimens used in this study.

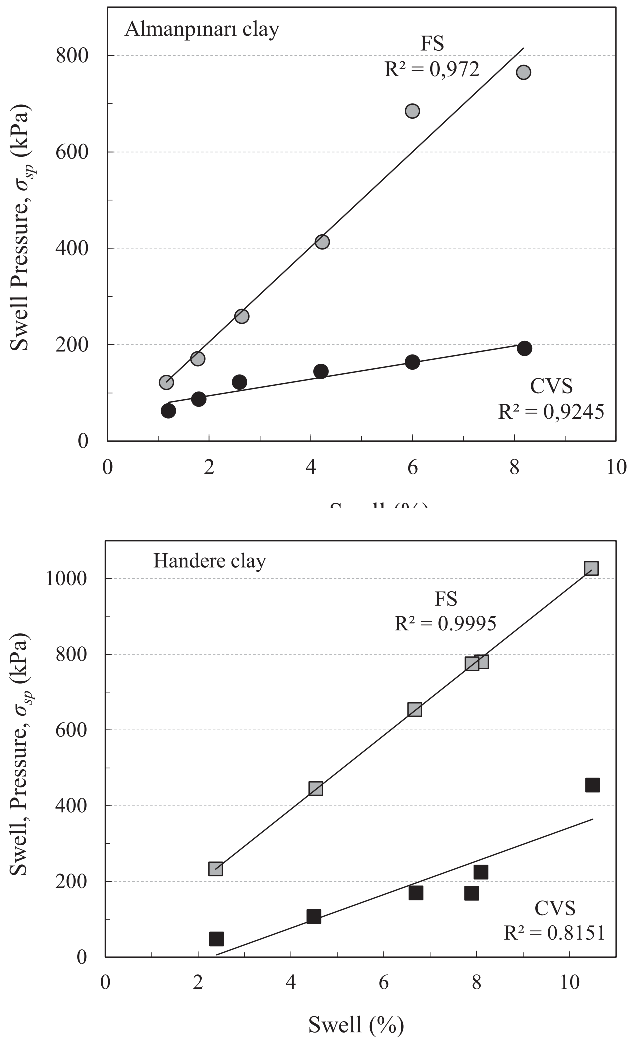


Figure 7. Percentage swell vs. swell pressure obtained from FS and CVS tests.

tests. The difference in the amount of σ_{sp} values between FS and CVS tests reduces with the quartz sand addition. However, considering the reducing as a ratio of σ_{sp} from FS test to σ_{sp} from CVS test [$\sigma_{sp(\mathrm{FS})}/\sigma_{sp(\mathrm{CVS})}$], when the sand content increases from 0 to %50, the reducing ratio ranges from 2.3 to 4.8 for Handere clay, whereas it is from 4.0 to 1.9 for Almanpınarı clay. This indicates that the difference between σ_{sp} obtained from FS and CVS test, and the change in that ratio mentioned above most probably is due to the clay type and its mineralogy.

Fig. 7 submits S% vs. σ_{sp} from the results obtained on the two clays with the six different sand contents (gradations). Linear-regression lines were fitted to all the data. Due to the linear-regression analysis, statistically quite meaningful relations were obtained between S% and σ_{sp} (for both FS and CVS). Quite similar attenuation relationships emerged between S% and σ_{sp}. Regardless of the clay type and the sand content, distinctive relationships from both the FS and CVS tests for the two clays were obtained between S% and σ_{sp} (Fig. 8). As seen in Fig. 8-a, an almost perfect linear relationship of the results obtained especially from the FS tests occurred. The results of the regression equations and the correlation coefficients for S% and σ_{sp}, which were derived from all the soils tested in this study, are listed in Table 4, as Eq. 1-2, and shown in Fig. 8a-b.

Table 4. Simple regression analysis results.

Regression equation	Correlation (judgment coefficient)	Equation Number
$\sigma_{sp(FS)}$=96.94S%+9.42	R=0.994	(1)
$\sigma_{sp(CVS)}$=30.12S%+1.14	R=0.852	(2)
PST=8E-05$k^{-0.926}$	R=0.919	(3)
S%=1E-05[C_{PS}/k]+1.89	R=0.943	(4)
$\sigma_{sp(FS)}$=0.0013[C_{PS}/k]+194.06	R=0.934	(5)
$\sigma_{sp(CVS)}$=0.0004[C_{PS}/k]+43.31	R=0.919	(6)

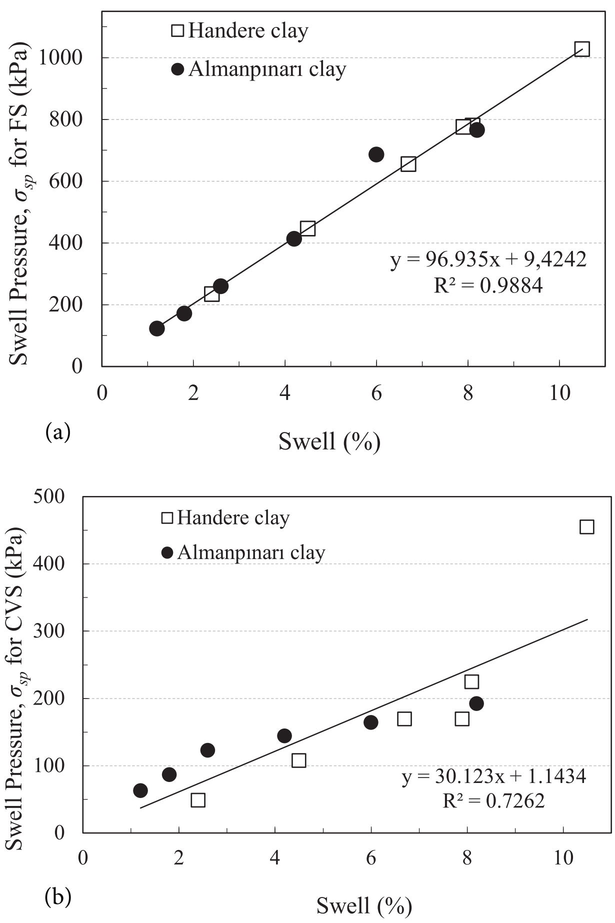


Figure 8. (a). Swell pressure obtained from FS test vs. swell percentage relationship, (b). Swell pressure obtained from CVS test vs. swell percentage relationship.

The main phases that can be expressed as the initial swelling or inter-void swelling [51], the primary swelling, and the secondary swelling are seen in the graph of S% vs. log time (Fig. 4). The S-shaped curve in this graph consists of three distinct slopes defined by the phases mentioned above. It is clear that the parameters of the swelling time and S% of the primary swelling as a function of swelling process can also be determined clearly. Sridharan and Gürtuğ [53] pointed out the similarity between the S-shaped curves of the S% vs. log time and the strain-log time for the consolidation process, indicating a diffusion process founded and those S-shaped curves expressed by Feda [53], and thus proposed an equation of $C_{\alpha s}=\Delta(\delta H_c/H)\ /\ \Delta\log_{10}t$ based on this resemblance, where $\Delta(\delta H_c/H)$ is the ratio of the secondary swelling, δH_c to the thickness of the sample, H during the time period of t1 to t2.

The primary swelling has an almost linear curve in the S% vs. log time plot, and is also similar to the linear portion of the strain-log time curve representing the primary consolidation (compression). Consequently, based on the similar analogical comparison, the *rate of primary swelling* (C_{ps}) can be defined as the slope of the curve of S% vs. log time, and formulated as

$$C_{ps}=\frac{\Delta S}{\Delta\log t} \qquad (7)$$

where ΔS, ($S2$-$S1$) is the magnitude of change in S% during the time period of $t1$ to $t2$.
$\Delta\log t=\log t2-\log t1$

An examination of Fig. 4 a-b shows that the shape of S% vs. log time is typically similar to an S for all the specimens tested in this study. From Fig. 4 a-b it is clear that the slope of the curve in the initial and primary portions increases as the sand content of the soil decreases (or the clay fraction increases). This increment is quite particular, especially in the primary swelling portion, even though there are some exceptions in the phase of the initial swelling. It is clear that the completion time of the primary swelling or the primary swelling time (*PST*), which can be determined by means of the graphical method seen in Fig. 9, decreases with increasing of sand content. Fig. 10 indicates that there is an apparent negative linear relationship, which is unique for each clay type, between the primary swelling time and the sand content.

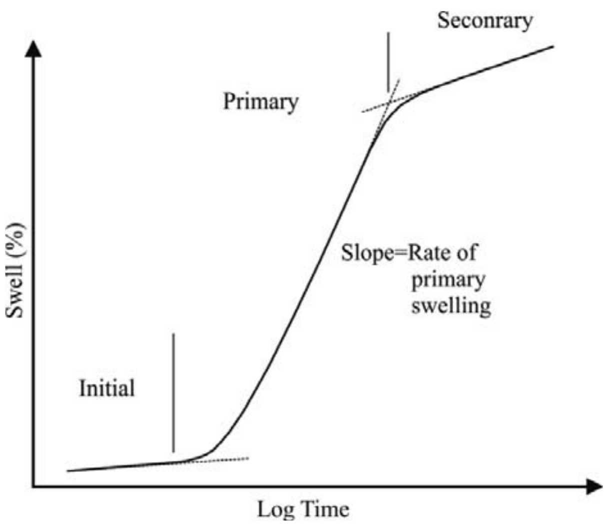


Figure 9. Schematic diagram showing the separation of the initial, primary, and secondary swellings [42, 51 and 53].

Compared to the rate of primary swelling (C_{ps}), considered as a parameter relating to the swelling behaviour, corresponding to S% and σ_{sp}, it is clear that C_{ps} increases linearly as both S% swell and σ_{sp} (obtained from both FS and CVS tests) increase, having strong correlation coefficients (Fig 11 and 12). Although it is clear that S% and σ_{sp} are closely related to C_{ps}, each relation is unique for the two clay types. It is clear from Fig. 11 and 12 that the relationships between C_{ps} and S%, and the σ_{sp} shows significant positive correlations between these parameters. The relationships between C_{ps} and the primary swell time (*PST*), almost 90% of swelling, as strain occurs in this phase, exhibits particular positive correlations between the two parameters depending on the clay type (Fig. 13), i.e., the steeper slope of the curve S% vs. log time, the longer time that the primary swelling occurs during the swelling. These strong correlations clearly indicate that C_{ps} is a function of the swelling and can be used in a prediction of the swelling characteristics (of S%, σ_{sp} and *PST*).

To check the effect of the hydraulic conductivity (k) on the swelling characteristics of S%, σ_{sp}, and *PST*, a series of comparisons was performed on the measurements obtained for the two clay specimens containing various sand-content ratios. It was reported that k and the void ratio of the soil-bentonite mixtures increase during swelling process [50 and 55]. Therefore, the initial k values were used in the correlations. Fig. 14 presents the relationship between k and the sand content in the two different clays used in this study. As expected, the figure shows that k increasingly varied with the sand content in the clay as well. A further increase in the sand content from 0 to %50 increased k only from 1.44×10^{-8} to 5.37×10^{-8} cm/sec and from 3.66×10^{-8} to 1.70×10^{-7} cm/

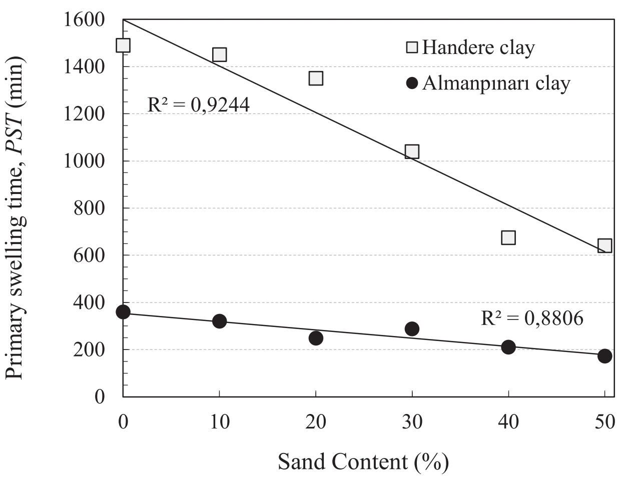


Figure 10. Effect of uniform quartz sand content on the primary swelling time, *PST*.

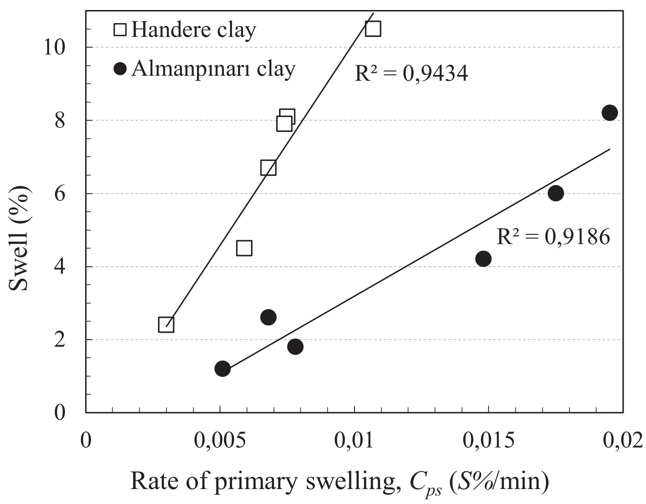


Figure 11. Relationship between the percentage swell and the rate of primary swelling.

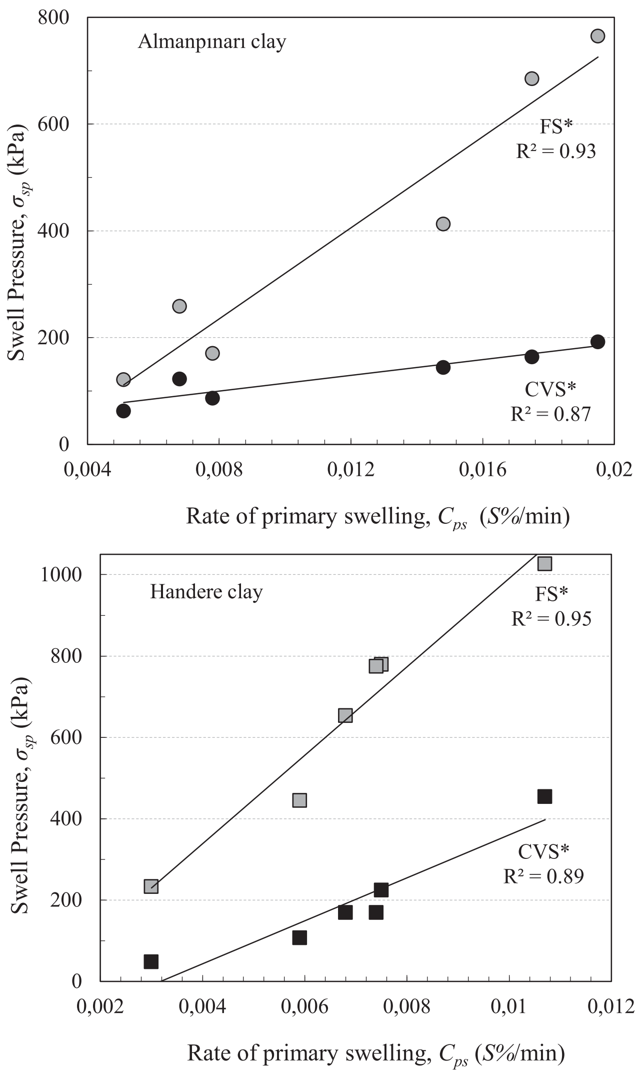


Figure 12. Relationship between the swell pressure and the rate of primary swelling (FS is the data obtained from the free-swell test, and CVS from the constant-volume swell test).

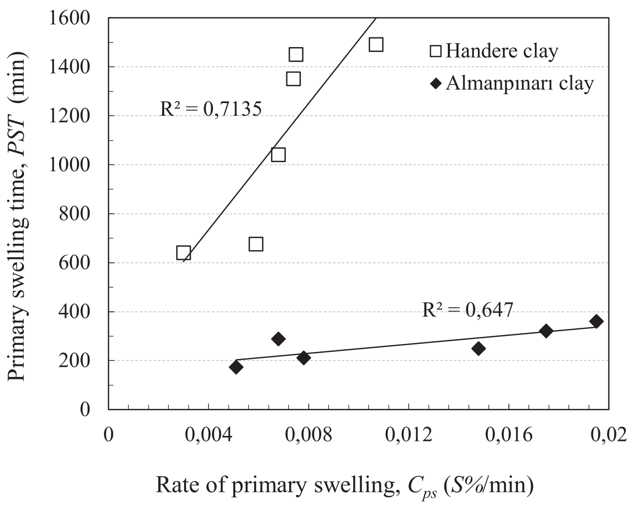


Figure 13. Relationship between the primary swelling time, *PST* and the rate of primary swelling, C_{ps}.

sec for the mixtures of Handere clay and Almanpınarı clay, respectively. The data from Fig. 14 and Table 3 show that the increase in *k* with the addition of quartz sand was much more for the Almanpınarı clay than that for the Handere clay, while the initial (for 100% clay) *k* values of these two different clays were relatively close to each other.

The hydraulic conductivity (*k*) of the mixtures was plotted in Fig. 15 and 16 as a function of *S*% and σ_{sp}, respectively. The results shown in Fig. 15 and 16 show that both *S*% and σ_{sp} (kPa) have an exponential decrease with an increase in *k*. The comparison of *k* corresponding to the values of *S*% and σ_{sp} indicates that there are negative relationships between *k* and both *S*% and σ_{sp}. The relationship between *k* and *S*% is seen in Fig. 15. The figure shows that the position and slope of the respective curves change in particular. The curve of Almanpınarı clay with higher *k* tends to locate upwards and has a greater slope than that of the Handere clay. The decrease in *k* with an increase in *S*% was quite steep

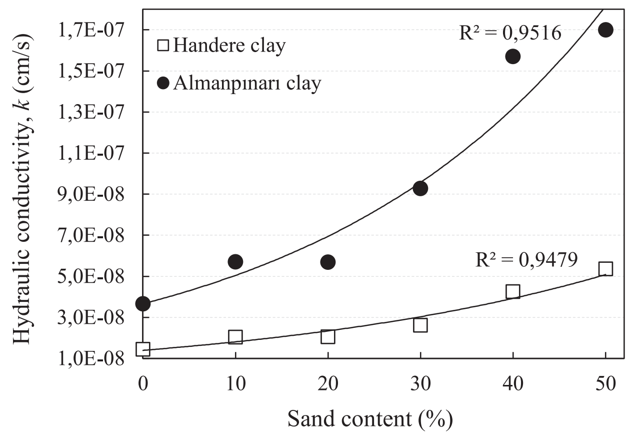


Figure 14. Hydraulic conductivity, *k* vs. sand content.

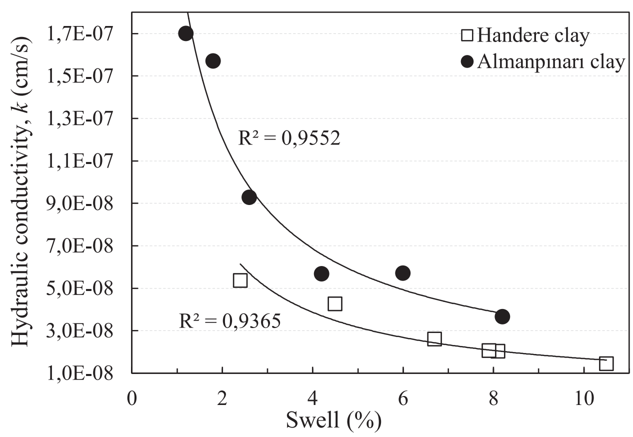


Figure 15. Hydraulic conductivity, *k* vs. percentage swell.

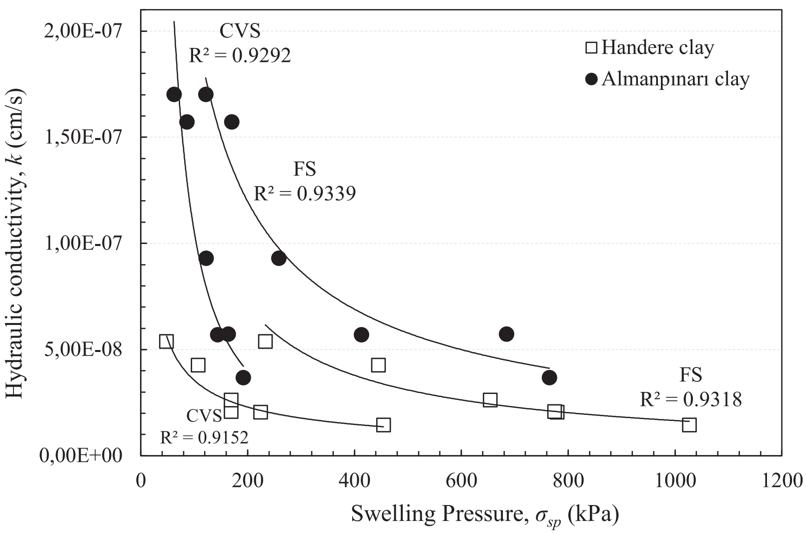


Figure 16. Hydraulic conductivity (k) vs. swell pressure.

in the beginning where k decreased from 1.7×10^{-7} to 5.69×10^{-8}cm/sec with an increase in S% from 1.2 to 4.2%, and remained nearly constant afterwards for the Almanpınarı clay, while this variation was relatively less for the Handere clay than that of the Almanpınarı clay.

A similar status to that mentioned above can be seen between k and σ_{sp} obtained from both FS and CVS tests (Fig. 16). Consequently, it is clear that k has a significant negative influence on the swelling behaviour of a clay depending on the changing gradation, and can be evaluated as a function of the swelling properties of S% and σ_{sp}. The reduction in S% and σ_{sp} due to the increase in k can be explained in terms of the decrease in the amount of clay leading to swelling phenomena, while the sand particles (non-swelling material) increase, resulting in the increase in k.

Consequently, the data from Fig. 15 and 16 show that there is no clear relationship between k and the corresponding swelling parameters for these two different types of clay. On the other hand, an assessment of a particular clay type and its mixtures with sand indicates that a clay sample with higher k depending on gradation possess a smaller S% and σ_{sp}.

The hydraulic conductivity (k) followed a similar trend (hyperbolic, i.e., exponential) with the primary swelling time (PST) as well. Irrespective of the clay type and the sand content, a unique relationship having a strong negative correlation coefficient (R=0.919) for all the specimens was obtained between PST and k (Fig. 17). Similar to Fig. 14-16, the k for the clay-sand mixtures exhibited a steep decline from 1.70×10^{-7} to 2.61×10^{-8} cm/sec with an increase in PST from 173 to 1040 min, and much less change for a further increase in PST. With an increase in k, the interaction volume increases and the clay particle becomes free to move at higher water contents, resulting in an increase in the interparticle distance as a function of time and consequently the PST reduces. Based on this PST is an exponential function of k, and on the simple regression analysis, it can be defined as

$$PST = 8E\text{-}05k^{-0.926} \quad (R=0.919) \qquad (3)$$

where PST is primary swelling time; and k is the hydraulic conductivity.

In order to show the relationship between the values experimentally measured and predicted, the PST predicted by Eq. (3) is compared with the measured values from the tests, as shown in Fig. 18. The figure shows that the predicted values are very close to the measured values. The cross-correlation between the predicted and measured data indicated a strong coefficient of correlation (R=0.8862), and that the measured PST is 1.1177 times the predicted PST.

An examination of Fig. 19 shows that the rate of primary swelling (C_{ps}) decreases with the increment of the k depending upon the type of clay. The figure also shows that the position and slope of the respective curves differ significantly. The curve of Handere clay with lower k tends to locate downwards and gives a lesser slope. Therefore, it can be assumed that k is of a function of C_{ps} as well, and this inverse proportion between them is unique for each soil type.

Taking into account that the hydraulic conductivity (k) and the rate of primary swelling (C_{ps}) are functions of

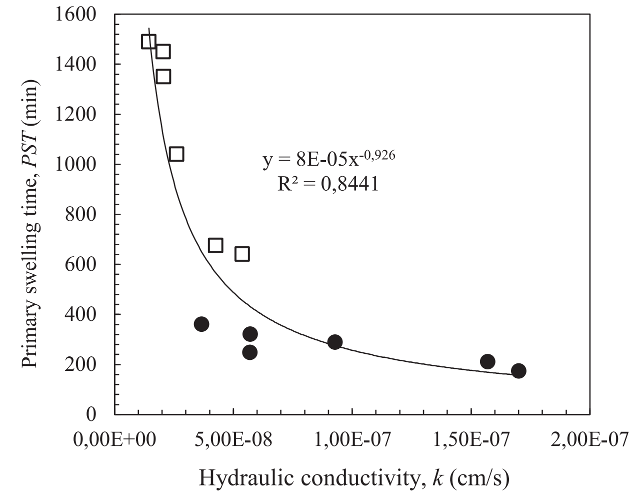


Figure 17. Hydraulic conductivity, *k* vs. primary swelling time, *PST* relationship for all the mixtures tested.

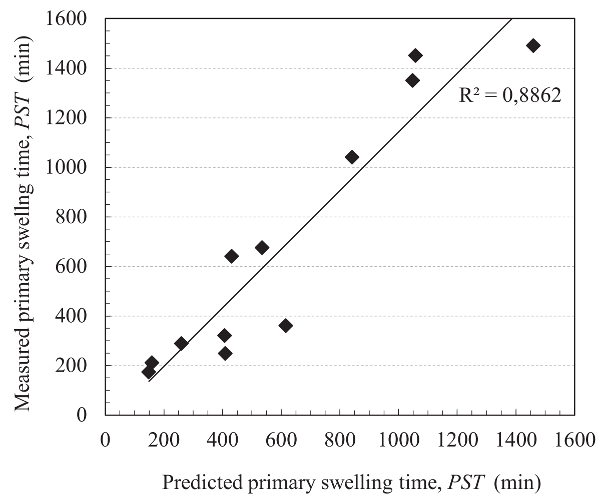


Figure 18. Measured primary swelling time, *PST* vs. predicted primary swelling time for all the test results.

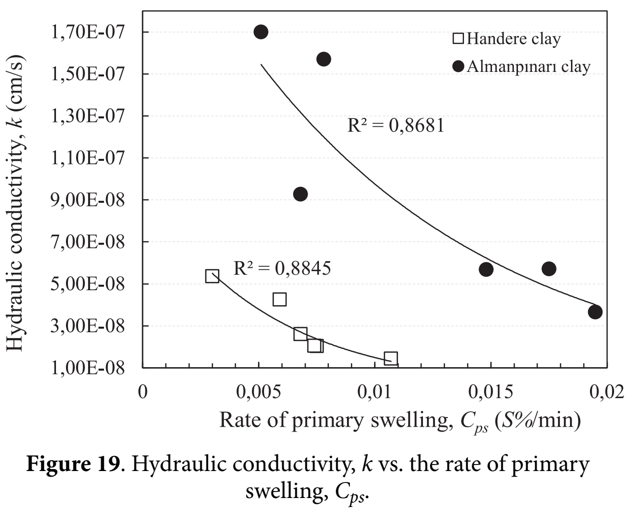


Figure 19. Hydraulic conductivity, *k* vs. the rate of primary swelling, C_{ps}.

the swelling process, and related to each other, the ratio of $[C_{ps}/k]$ as an indices (where C_{ps} normalized by k) in the estimate models that were focused to find the main swelling characteristics of $S\%$ and σ_{sp} was used to obtain the general linear prediction equations. Thus, the indices of $[C_{ps}/k]$ was assessed to determine $S\%$ and σ_{sp} obtained for both FS and CVS tests, as a function of them (Fig. 20, 21 and 22, Eq. 4-6). The graphs seen in Fig. 20-22, offering to evaluate multi (more than two) parameters depending on soil type, indicate that the value of this index can be assessed as a variable to predict the main swelling characteristics of $S\%$ and σ_{sp}. The data indicate that a straight line could fit the indices of $[C_{ps}/k]$ against $S\%$ and σ_{sp} (kPa). The slope of the straight lines for each function has a downward trend with the ratio of $[C_{ps}/\mathrm{k}]$ from 3.00×10^4 to 7.43×10^5, which means that the index would increase $S\%$ and σ_{sp}. Based on a graphical correlation method and the simple regression analysis, $S\%$ and σ_{sp} can be defined as

$$S\%=1E\text{-}05[C_{ps}/k]+1.89 \qquad (R=0.943) \qquad (4)$$

$$\sigma_{sp(FS)}=0.0013[C_{ps}/k]+194.06 \qquad (R=0.934) \qquad (5)$$

$$\sigma_{sp(CVS)}=0.0004[C_{ps}/k]+43.311 \qquad (R=0.919) \qquad (6)$$

where $S\%$ is the percentage swell; $\sigma_{sp(FS)}$ is the swell pressure for the FS test; $\sigma_{sp(CVS)}$ is the swell pressure for the CVS test; C_{ps} is the rate of primary swelling ($S\%$/min); k is hydraulic conductivity (cm/sec).

Eq. (1-6) indicated that the simple correlations between the main swelling characteristics and the factors controlling them were especially evaluated in this study for the clay-sand mixtures. Whereas independent variables (controlling factors) are correlated one another in the simple correlation (or regression), multiple regression analysis is more advantageous than the simple regression analysis in order to determine the dependent major variables that can account for the variation in the dependent variables of $S\%$, σ_{sp} and *PST*. Even though strong correla-

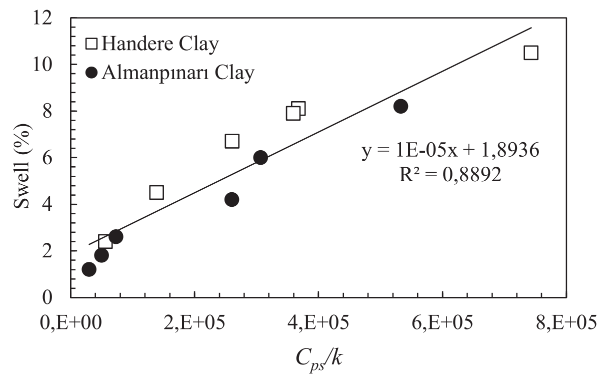


Figure 20. Relationship between the percentage swell and the ratio of the primary swelling rate to the hydraulic conductivity.

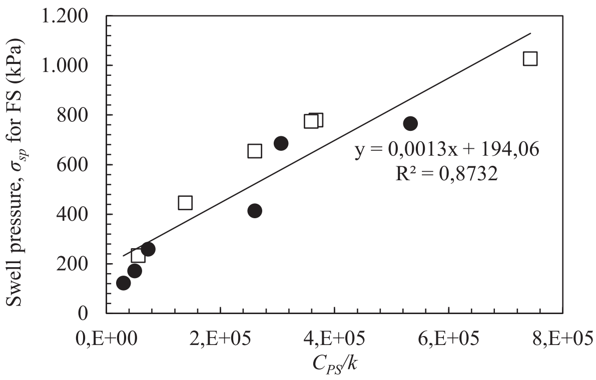


Figure 21. Relationship between the ratio of the primary swelling rate to the hydraulic conductivity and the swell pressure obtained from the FS test.

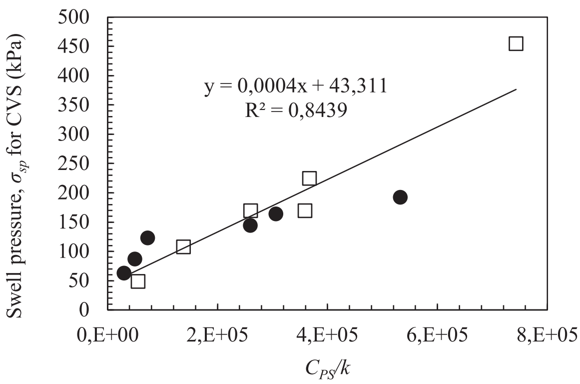


Figure 22. Relationship between the ratio of the primary swelling rate to the hydraulic conductivity and the swell pressure obtained from the CVS test.

tions among the controlling factors taken into account, in this investigation they were provided for Eqs. (1-6) and the related graphs, the multiple regression analysis were also conducted using two or three independent variables such as k, C_{ps} and the measured σ_{sp}. The multiple regression equations and their correlation coefficients are listed in Table 5. All the equations derived using the multiple regression analysis had strong correlations, ranging from 0.833 to 0.883. These data also indicate that the proposed regression relation expressions can quantifiably describe the relationship between the swelling characteristics of S%, σ_{sp} and PST, and the swelling parameters of k and C_{ps} , proposed firstly in this study.

6 DISCUSSION

The test results indicate that the increase in amount of sand in the clay decreases linearly the percentage swell (S%) and the swell pressures (σ_{sp}) obtained from both FS and CVS tests. The reduction of S% with sand addition is almost the same as the percentage for each clay type, and it can be suggested as a general expression that an increase in sand content of 10% leads to an almost 15% decrease in S%. However, the negative relationship between the sand content and σ_{sp} is linear, and it varies according to clay type. In addition to that, the difference between $\sigma_{sp(FS)}$ and $\sigma_{sp(CVS)}$ at the same sand content displays the differences depending on the clay type.

An examination of the relationship between S% and σ_{sp} indicates that, irrespective of the clay type and the sand content, there are strong positive linear correlations between them, especially for the swell pressure (σ_{sp}) values obtained from the FS tests (Fig. 8 and Table 4). Eqs. (1 and 2) derived from the correlations mentioned above can provide reliable predictions for the swell pressures of both $\sigma_{sp(FS)}$ and $\sigma_{sp(CVS)}$ using S% determined experimentally.

In this study, it is suggested that the primary swell time (PST) is a main swelling characteristic, such as S% and σ_{sp}, since approximately 90% of the swelling takes place in the primary swelling phase, and the completion time of this process could be important and critical for light engineering structures, i.e., motorways, railways, pipelines, and energy and water transmission lines, for which backfill applications are needed. In addition to PST, the rate of primary swelling (C_{ps}), the primary swelling phase's slope of the curve of S% vs. log time, is firstly used to predict the swelling characteristics as a parameter of the swelling process. An examination of the results indicates that C_{ps} vs. the swelling characteristics can be taken as linearly related, and C_{ps} can be confidently used in prediction formulas for swelling characteristics (Fig. 11-13 and Table 4-5).

Based on the correlations of k vs. the swelling characteristics (Fig. 15-16), it is shown that there are negative exponential relationships between k and S%, and σ_{sp} depending on the clay type. With an increase in k up

Table 5. Multiple regression analysis results.

Regression equation	Correlation (judgment) coefficient	Equation Number
$S\%=6.739-44035373.278k+143.416C_{ps}$	R=0.857	(8)
$\sigma_{sp(FS)}=644.403-4237790362.192k+15642.539C_{ps}$	R=0.862	(9)
$\sigma_{sp(CVS)}=0.457\sigma_{sp(FS)}+866084896.466k-2827.656C_{ps}-106.12$	R=0.883	(10)
$PST=1595.385-(8080928775.177)k-(43036.038C_{ps})$	R=0.833	(11)

to 2.06×10^{-8} and 5.69×10^{-8} corresponding to the sand content of 20% for Handere clay and Almanpınarı clay, respectively, the swelling characteristics of the percentage swell and the swell pressures decrease dramatically. As can be seen in Fig. 17, a similar relationship and curve using all the data was obtained for k vs PST, which showed a steep decrease from 1.70×10^{-7} to 2.61×10^{-8} cm/sec with an increase in PST from 173 to 1040 min (from about 3 to 24 hours), and much less change for a further increase in PST. Thus, regardless of the clay type and fraction it is clear that k is directly a function of PST, and Eq. 3 derived from this strong correlation can provide a good estimation of PST using k (Fig. 17). The examination of k vs C_{ps} seen in Fig. 19 indicates that similar trends and negative exponential relationships exist, and k has a direct effect on C_{ps} depending on the clay type.

In order to provide general linear functions as prediction equations including, multi parameters, and without the variable of the clay type effect, the ratio of $[C_{ps}/k]$ as an indices was correlated to the main swelling characteristics of S% and σ_{sp}. Eqs. (4-6) having strong positive correlation coefficients ranging from 0.919 to 0.943 state that S% and σ_{sp} can be estimated rather closely to the experimental values by means of the indices of $[C_{ps}/k]$.

As can be seen in Table 5, the effect of k and C_{ps} on the swelling characteristics of S%, $\sigma_{sp(FS)}$, $\sigma_{sp(CVS)}$ and PST were analysed, and prediction equations with strong correlation coefficients ranging from 0.833 to 0.862 were obtained by means of multiple regression analysis method. The multiple regression analyses also indicate that k and C_{ps} are the parameters that directly affect the swelling, and can confidently be evaluated functions of swelling. Although the prediction equations of 8-11 (Table 5) derived from the multiple regression analyses have strong correlations, Eqs. (1-6) provided by simple regression analyses will most probably give more realistic results since they have stronger correlation coefficients, varying from 0.852 to 0.994 (Table 4) than those of Eqs. (8-11). Besides comparing the correlation coefficient, since k is a direct function of PST, the Eqs. (3) providing a prediction of PST will be more meaningful than Eqs. (11) as well.

Although the literature contains a number of empirical models for prediction of the swelling parameters, the relationships and predictive equations derived in this study are mainly about the effect of varying hydraulic conductivity, which depends on granulometric change, on the swelling behaviour of an expansive soil. Therefore, the predictive equations in the literature are not comparable to the equations proposed in this study.

Reliable swelling prediction equations (formulas) can contribute in terms of time and economy in engineering applications, such as road, railway and airport constructions on areas consisting of expansive soils that include a large number of checkpoints necessary for many costly and time-consuming test process. Utilizing more than one prediction method in drawing conclusions as to the swelling of an expansive soil is quite essential [25]. In this context, the results and examinations in this study introduce the fact that k and C_{ps} are also the parameters directly affecting the swelling behaviour of expansive soils depending on changing the gradation, and can be safely used in prediction formulas for swelling characteristics.

It should be pointed out that the above results and predictive equations were obtained using only two different high and moderate expansive clays, and limited to a range of uniform quartz sand content up to 50%. Although strong statistical relationships between k and C_{ps} , and swelling were obtained, further research is necessary to check the validity of these results and the derived equations for other soil types having different physic-mechanical properties.

7 CONCLUSIONS

Numerous series of laboratory tests were performed to investigate the effect of a change of uniform quartz sand content and of hydraulic conductivity caused by varying gradation on the swelling of compacted clay specimens. In order to realize such an objective comparative survey, two different clay soils were prepared for free-swelling tests and constant-volume swelling tests, and tested under similar conditions in accordance with the same technical standards. From the data and observations presented in this paper the following conclusions can be drawn:

1. The increase in the content of uniform quartz sand decreases almost linearly the percentage swell (S%). Regardless of the clay type, the addition of quartz sand by 10% leads to an average 15% reduction in the swelling percentage. The swell pressures that are obtained from both the free-swell tests and the constant-volume swell tests decreases linearly as the sand content increases as well; however, the amount of decrease is controlled by the clay type.
2. Based on correlations between the percentage swell and the swell pressures, irrespective of the clay type and the sand content, there are strong negative linear relationships between them. Prediction equations derived from these correlations can provide reliable predictions for swell pressures obtained from both the free-swell and constant-volume swelling tests using the values of the percentage swell (S%) determined experimentally.

3. The rate of primary swelling (C_{ps}), which is the primary swelling phase's slope of the curve of percentage swell vs. log time, corresponding to the swelling characteristics is discussed. The correlations indicate that the rate of primary swelling as a parameter of the swelling process can be safely used in the prediction of swelling characteristics such as the percentage swell, the swell pressure and the primary swelling time, in which almost 90% of swelling as strain occurs.
4. According to the correlations between the hydraulic conductivity (k) and the swelling characteristics controlled by a change in the gradation of a clay, both percentage swell and the swell pressures decrease exponentially with an increase of the hydraulic conductivity. On the other hand, the primary swelling time (*PST*), irrespective of the clay type, decreases as the hydraulic conductivity increases. Therefore, the primary swelling time can be reliably predicted using the correlation equations.
5. Based on the index that is the ratio of $[C_{ps}/k]$ propounded to use multi parameters of swelling process, and to eliminate the effect of the clay type on swelling, considerable meaningful relationships having strong correlations between $[C_{ps}/k]$ and the swelling characteristics have emerged. The prediction equations derived using the ratio of $[C_{ps}/k]$ as an index can predict the swelling characteristics.

As an overall conclusion, this paper demonstrates that granulometric changing and hydraulic conductivity have an important influence on the swelling behaviour of cohesive soils. The relationships and formulas derived in this study are only valid for the varying gradation of a clay soil by adding uniform quartz sand up to 50%. In addition, the prediction formulas suggested in this study for compacted clay soils with various sand contents and hydraulic conductivities can be used safely in engineering practice.

REFERENCES

[1] Chen, F.H. 1988. Foundations on Expansive Soils. Elsevier Science Publishers, Amsterdam. The Netherlands.

[2] Basma, A.A. 1991. Estimating uplift of foundations due to expansion: a case history. Geotech. Eng. 22, 217–231.

[3] Nelson, D., Miller, D.J. 1992. Expansive Soils Problems and practice in Foundation and Pavement Engineering. John Wiley and Sons, NY. (ISBN: 978-0-471-18114-9)

[4] Ruwaih, I.A. 1987. Experiences with expansive soils in Saudi Arabia. Proceedings of the 6th International Conference on Expansive Soils. New Delhi, India, 317–322.

[5] Bell, F.G., Jermy, C.A. 1994. Building on clay soils which undergo volume changes. Architectural Sci. Rev. 37, 35–43. DOI:10.1080/00038628.1994.9697327

[6] Bell, F.G., Maud, R.R. 1995. Expansive clays and construction, especially of low-rise structures: a viewpoint from Natal, South Africa. Env. Eng. Geosci. I (1), 41–59. DOI:10.2113/gseegeosci.I.1.41

[7] Al-Homoud, A.S., Al-Suleiman, T.I. 1997. Loss in serviceability of pavements due to expansive clay subgrades. Env Eng Geosci. III (1), 277–294. DOI: 10.2113/gseegeosci.III.2.277

[8] Popa, A. 1997. Shrinkage-swelling phenomena effects on building. Proceedings of the International Symposium on Engineering geology and the Environment, Athens, Greece, 327–329.

[9] Derriche, Z., Iguechtal, L. 2000. Damage due to swelling soils in the region of In-Amenas: Algeria. Proceedings of GeoEng 2000, An International Conference on Geotechnical and Geological Engineering, Melbourne, Australia (on CD).

[10] Al-Shamrani, M.A., Dhowian, A.W. 2003. Experimental study of lateral restraint effects on the potential heave of expansive soils. Eng Geology. 69, 63–81. DOI:10.1016/S0013-7952(02)00248-X

[11] Erguler, Z.A., Ulusay, R. 2003. Engineering characteristics and environmental impacts of the expansive Ankara clay, and swelling maps for SW and central parts of the Ankara (Turkey) metropolitan area. Env. Geology 44, 8, 979-992. DOI:10.1007/s00254-003-0841-y

[12] Seed, H.B., Woodwart, R.J., Lundgren, R. 1962. Prediction of swelling potential for compacted clays. J. Soil Mech. Found. Div., ASCE, 88(4), 107-131.

[13] Komornik, A., David, D. 1969. Prediction of swelling pressure of clays. ASCE Proc. SM. FE. Div., 95 SM1, 209-225.

[14] Snethen, D.R. 1984. Evaluation of expedient methods for identification and classification of potentially expansive soils. Proceedings, 5th International Conference on Expansive Soils, Adelaide, 22–26.

[15] Sridharan, A., Rao, A.S., Sivapullaiah, P.V. 1986. Swelling pressure of clays. Geotech. Testing J., ASTM 9, 1, 24– 33. DOI: 10.1520/GTJ10608J

[16] Puppala, A., Punthutaecha, K., Vanapalli, S. 2006. Soil-water characteristic curves of stabilized expansive soils. J. Geotech. Geoenv. Eng. 132, 6, 736–751. DOI: 10.1061/(ASCE)1090-0241(2006)132:6(736

[17] Çokça, E. 2002. Relationship between methylene blue value, initial soil suction and swell percent of expansive soils. Turkish J. Eng. Environ. Sci. 26, 521-530.

[18] Chiappone, A., Marello, S., Scavia, C., Setti, M. 2004. Clay mineral characterization through the methylene blue test: comparison with other experimental techniques and applications of the method. Can. Geotech. J. 41, 1168-1178. DOI: 10.1139/t04-060

[19] Türköz, M., Tosun, H. 2011. The use of methylene blue test for predicting swell parameters of natural clay soils. Sci. Res. Ess. 6, 8, 1780-1792. DOI: 10.5897/SRE10.629

[20] Ranganatham, B.V., Satyanarayana, B. 1969. A rational method of predicting swelling potential, for compacted expansive clays. Proc. 6th Int.Conf. SM and FE, Canada 1, 92-96.

[21] Vijayvergiya, V.N., Ghazzaly, O.I. 1973. Prediction of

swelling potential of natural clays. Proceedings, 3rd Int. Research. and Eng. Conf. on Expansive Clays, 227–234.

[22] Nayak, N.V., Christensen, R.W. 1971. Swelling characteristics of compacted expansive soils. Clay and Clay Min. 19, 251-261.

[23] O'Neil, M.W., Ghazzally, O.I. 1977. Swell potential related to building performance. Journal of the Geotechnical Engineering Division, ASCE 103 (GT12), 1363–1379.

[24] Johnson, L.D., Snethen, D.R. 1978. Prediction of potential heave of swelling soils. Geotech. Testing J. 1, 117–124. DOI: 10.1520/GTJ10382J

[25] Kariuki, P.C., van der Meer, F. 2004. A unified swelling potential index for expansive soils. Eng. Geology 72, 1-8. DOI: 10.1016/S0013-7952(03)00159-5

[26] Weston, D.J. 1980. Expansive Roadbed Treatment for Southern Africa. Proceedings, 4th International Conference on Expansive Soils, 1, 339–360.

[27] Snethen, D.R. 1980. Characterization of expansive soils using soil suction data. Proceedings of the 4th International Conference on Expansive Soils, Boulder, Colorado, 18–23.

[28] Mowafy, M.Y., Bauer, G.E. 1985. Prediction of swelling pressure and factors affecting the swell behaviour of an expansive soil. Transport Res. Rec. 1032, 23-28.

[29] Rao, K.M., Babu, G.G., Rani, C.S. 2006. Influence of coarse fraction on swelling characteristics. E. J. Geotech. Eng. 11A, 0627.

[30] Erzin, Y., Erol, O. 2004. Correlations for quick prediction of swelling pressure. E. J. Geotech. Eng., 9F, 0476.

[31] Kariuki, P.C., van der Meer, F. 2003. Issues of effectiveness in empirical methods for describing swelling soils. International Journal of App. Earth Observation and Geoinformation 4, 231–241. DOI: 10.1016/S0303-2434(03)00005-9

[32] Yılmaz, I. 2006. Indirect estimation of the swelling percent and a new classification of soils depending on liquid limit and cation exchange capacity. Eng. Geology 85, 295–301. DOI:10.1016/j.enggeo.2006.02.005

[33] Rao, S.M., Ravi, K. 2015. Influence of initial degree of saturation on swell pressures of compacted Barmer bentonite specimens. Annals of Nuclear Energy 80, 303–311. DOI:10.1016/j.anucene.2015.02.019

[34] Dananaj, I., Frankovska, J., Janotka, I. 2005. The influence of smectite content on microstructure and geotechnical properties of calcium and sodium bentonites. App. Clay Sci. 28, 223-232. DOI: 10.1016/j.clay.2004.02.006

[35] ASTM D 854-10, 2010. Standard test methods for specific gravity of soil solids by water pycnometer. ASTM International, West Conshohocken, PA.

[36] ASTM D 422-63, 2007. Standard test method for particle-size analysis of soils. ASTM International, West Conshohocken, PA.

[37] ASTM D 4318-10, 2010. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. West Conshohocken, PA.

[38] ASTM D 427–98, 2007. Standard Test method for shrinkage factors of soils by the mercury method. ASTM International, West Conshohocken, PA.

[39] Erdoğan, Y. 2015. Physicochemical Properties of Handere Clays and Their Use as a Building Material. Journal of Chemistry, ID:374245, 1-6. DOI: 10.1155/2015/374245

[40] Mirdallı, N., Halefoğlu, Y.Z., Sakarya, N. 2006. The investigation on the possible use of Almanpınarı red clay as a stain ceramics. J. Soc. Sci. Inst. Cukurova Uni. 15, 1, 229-234.

[41] ASTM D 698-07, 2012. Standard test methods for laboratory compaction characteristics of soil using standard effort (12,400 ft-lbf/ft3 (600 kN-m/m^3)). West Conshohocken, PA.

[42] ASTM D 4546, 1996. Standard test methods for one-dimensional swell or settlement potential of cohesive soils. ASTM International, West Conshohocken, PA.

[43] ASTM D2435, 2011. Standard test methods for one-dimensional consolidation properties of soils using incremental loading. ASTM International, West Conshohocken, PA.

[44] ASTM D 5856–95, 2002. Standard test method for measurement of hydraulic conductivity of porous material using a rigid-wall, compaction-mold permeameter. West Conshohocken, PA.

[45] Yule, D.F., Ritchie, J.T. 1980. Soil shrinkage relationships of Texas vertisols: 1 small cores. Soil Sci. Soc. Am. J. 44, 1285–1291. DOI:10.2136/sssaj1980.03615995004400060031x

[46] Gray, C.W., Allbrook, R. 2002. Relationships between shrinkage indices and soil properties in some New Zealand soils. Geoderma, 108, 3–4, 287–299. DOI:0.1016/S0016-7061(02)00136-2

[47] ElKholy, S.M. 2008. Improving the Characteristics of Expansive Soil Using Coarse-grained Soil. J. Eng. and Comp. Sci., Qassim Uni. 1, 71-81.

[48] Rao, M. 1988. A Proper Parameter for correlation of swell potential and swell index for remould expansive clays. M. Tech. Dissertation Submitted Dept. Civ. Eng., J.N.T.Uni. coll. Eng., Kakinada, India.

[49] Gürtuğ, Y., Banu, S., İklizler, M., Aytekin, M., Vekli, M. 2010. Prediction of swelling pressure of expansive soil stabilized with sand. Proceedings, 13th National Conference of Soil Mech. and Found. Eng. İstanbul Culture Uni. 793-802.

[50] Misra, A.K., Ohtsubo, M., Li, L., Higashi, T. 2011. Controlling factors of the swelling of various bentonites and their correlations with the hyraulic conductivity of soil-bentonite mixtures. App. Clay Sci. 52, 78-84. DOI:10.1016/j.clay.2011.01.033

[51] Cui, S-L., Zhang, H-Y., Zhang, M. 2012. Swelling characteristics of compacted GMZ bentonite-sand mixtures as a buffer/backfill material in China. Eng. Geology 141-142, 65-73. DOI:10.1016/j.enggeo.2012.05.004

[52] Smith, G.N. 1986. Probability and Statistic in Civil Engineering. Collins, London, 244.

[53] Sridharan, A., Gürtug, Y. 2004. Swelling behavior of compacted fine-grained soils. Eng. Geology 72, 9–18. DOI: 10.1016/S0013-7952(03)00161-3

[54] Feda, J. 1991. Creep of Soils. Elsevier, Amsterdam, 269.

[55] Komine, H. 2010. Predicting hydraulic conductivity of sand–bentonite mixture backfill before and after swelling deformation for underground disposal of radioactive wastes. Eng. Geo. 114, 123–134. DOI: 10.1016/j.enggeo.2010.04.009