Characterization of Unsaturated Shrink-Swell Soils Properties in Egypt

Fayek Hassona[1(✉)], Remon I. Abdelmalak[1], and Beshoy M. Hakeem[2]

[1] Civil Engineering Department, Faculty of Engineering, El-Minia University, El-Minia, Egypt
Fhassona@excite.com, remonisaac@gmail.com
[2] Civil Engineering Department, Higher Institute of Engineering and Technology, El-Minia, Egypt
civileng_beshoy@yahoo.com

Abstract. Expansive soils show high volumetric changes with changes in water content. When they imbibe water during wet season, they expand and upon evaporation thereof through dry season, they shrink. Because of this alternate swelling and shrinkage, structures founded on them are severally damaged. Potentially problematic shrink-swell soils can be found almost anywhere in the world especially in arid and semi-arid regions of the tropical and temperate climate. Due to the lack of experience pertinent to characterization and dealing with problematic shrink-swell soils in Egypt, many defects appear in some structures established in development projects. Density and severity of problems associated with the presence of shrink-swell soils differ from region to another. Many factors contribute to the problem such as: soil type, soil engineering properties, foundation type, nature of development project, and the extension of development zone…etc. In this research, extensive experimental work has been performed on sixty two (62) soil samples obtained from various sites all over Egypt. The investigation targeted to assess volumetric change and moisture diffusion characteristics as well as index properties of unsaturated clayey soils. Test results confirm that volumetric change and moisture diffusion characteristics for unsaturated soils can be reasonably related to conventional soil index properties. Based on the obtained comprehensive database of results, ten (10) equations expressing relationships among different engineering properties of unsaturated shrink-swell soils in Egypt are proposed and discussed.

Keywords: Expansive soil · Shrink-swell soil · Soil water characteristic curve · Swell potential · Bentonite · Montmorillonite · Volumetric change · Moisture diffusion · Unsaturated soils

1 Introduction

Expansive soils in many areas of the world impose a substantial threat to foundations especially for light buildings. Jahangir et al. (2011) reported that shrinkage-swelling of clayey soils is a natural hazard, which may significantly affect buildings by differential settlements. Dafalla et al. (2010) concluded that the distortion is normally observed in the light structures due to relative flexibility of the frames and substructure foundations.

L.R. Hoyos and J. McCartney (eds.), *Advances in Characterization and Analysis of Expansive Soils and Rocks*, Sustainable Civil Infrastructures,
DOI 10.1007/978-3-319-61931-6_2

This is not tolerated by the brick walls normally used to fill up the panels in concrete frame structures. Severe cracks can be shown when twist or movement takes place. Therefore the use of rigid design methodology approach is expected to give less flexible support and reduce the chances of cracks and damage.

Expansive soils attribute their characteristics to the presence of swelling clay minerals. As they get wet, the clay minerals absorb water molecules and expand. Conversely as they dry, they shrink and leave large voids or cracks in the soil. Soils with active clay minerals, such as montmorillonite, exhibit the most dangerous swelling and shrinking properties. According to Lajurkar et al. (2013), expansive soil exhibits very complex and undesirable characteristics when used as engineering material.

Briaud et al. (2003) proposed a new method to estimate the vertical movement of the ground surface for soil that swells and shrinks due to variations in water content. They estimated the change in water content and the depth of seasonal moisture changes from local databases or from existing techniques. The method was evaluated by comparing the predicted movement and the measured movement of four full-scale spread footings over a period of 2 years.

According to Sood (2005), footings of a structure founded on an unsaturated soil are subjected to stresses developed due to swelling or shrinking of the soil. This is due to the change in suction (negative pore water pressure) of the soil due to the variation in the water content. These movements can be predicted by using the diffusion equation which defines the movement of moisture through unsaturated soils. The equation for moisture diffusion in unsaturated soils is similar to the consolidation equation for saturated soils when suction is expressed in logarithmic scale unit (pF).

Suction is mainly measured in units of water pressure such as kPa. Typical suction range is from 1 kPa, for a very wet soil close to 100% degree of saturation, to a 10^6 kPa, for an oven dried soil sample. As the value of suction can be very high, it is usually expressed on a logarithmic scale. The commonly used pF scale, [U (pF) = $\log_{10} |u_w|$] provides another alternative unit to measure of suction where u_w is the total suction expressed in units of cm of water head.

Expansion of soils can directly be measured in the laboratory, by immersing a remolded soil sample and measuring its volume change through 24-hour free swell test, (Hammam and Abdel-Salam 2013). Israr et al. (2014) found that there exist unique relationships between the index properties and the swelling characteristics of swelling soils. The results showed that, the increasing Atterberg's limits such as plasticity index (P.I.) from 18% to 150% impart significant increases in the values of swell potential (SP) and swell pressure (P_{sw}) from 2.62% to 13.36% and 94.2 kPa to 928.6 kPa, respectively. Erzin and Erol (2007) Concluded that an increase in the bentonite content in the clay mixtures yielded an increase in the specific surface area (SSA) value, the cation exchange capacity (CEC) value, the liquid limit (L.L.) and the plasticity index (P.I.) values. Meanwhile, plastic limit (P.L.) value was nearly unaffected by increases in the bentonite content. These results indicate that the SSA, the CEC, the L.L. and the P.I. values of the clay mixtures are more sensitive to changes in clay mineralogy than the P.L. is. It was also observed that the L.L. values were controlled by the SSA and CEC values.

Zapata et al. (2000) defined the soil water characteristic curve (SWCC) as the relationship between soil suction and some measure of the water content, which can be measured or predicted based on soil index properties such as the grain size distribution (GSD) function. Estimation based on index properties is highly desirable due to its simplicity and low cost and would be the path of choice to the SWCC, provided the accuracy of the estimate were adequate. According to AL-Shihabi (2010), suction compressibility indices (γ_h) can be obtained by determination of the slope of Soil Water Characteristic Curve (SWCC).

The main objective of this paper is to assess soil engineering properties (mainly volumetric change and moisture diffusion characteristics) for expansive soils samples obtained from various sites in Egypt. The soil water characteristic curve (SWCC) was determined to investigate the water retention capacity of the soil. Geotechnical index properties were determined for preliminary soil assessment as well as find reliable correlations with key unsaturated soil parameters. Finally, a new proposed set of relationships were developed that may be treated as are liable tool to estimate the swelling and shrinking characteristics with carefully evaluated index properties in hand.

2 Laboratory Investigations

In this study, a comprehensive experimental scheme has been undertaken at Geotechnical Engineering Laboratory, Faculty of Engineering, and EL-Minia University, to investigate various factors controlling the swelling and shrinking characteristics of expansive soils. Extensive experimental work was carried out on sixty two (62) soil samples. The shrink-swell behavior of the soil was studied by obtaining the volumetric increase and decrease of soil samples during swelling and shrinking. The analysis of test results and observations made during the experiments have been reported herein. The interpretations facilitated the development of a set of simple empirical correlations between soil index properties and key swelling and shrinking parameters of expansive soils.

2.1 Natural Soil Samples

Natural soil samples were obtained from 12 sites located at different regions in Egypt such as: Fayoum (two sites), BeniSuif (three sites), El-max Elkebly (El-Wadi El-Gedid), Abo-Tartor (El-Kharga, El-Wadi EL-Gedid), El-Mokatam area, Zahra El-Maadi area, the 6th of October, and Qena (two sites), as illustrated in Fig. 1.

Only two samples were undisturbed (obtained from EL-Mokatam and Zahra EL-Maadi areas). The rest of the soil samples (taken from 10 sites) were dry and cracked and had to be remolded. Hence, four remolded samples from each site were prepared in oedometer cells using remolding pressures of 400, 800, 1200, and 1600 kPa. This ended up with forty two natural soil samples (40 remolded samples and two undisturbed). Figure 1 shows the scattering of the selected 12 sites for the collected soil samples.

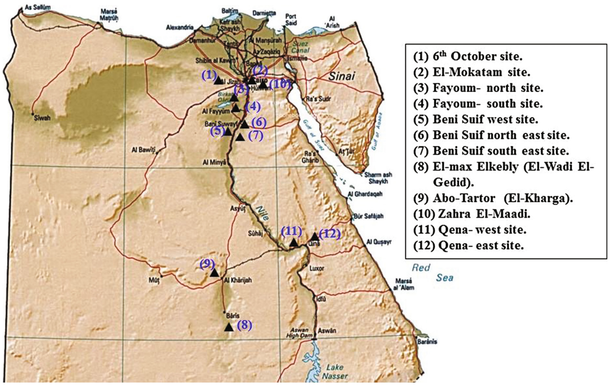

Fig. 1. Map of Egypt with locations of the samples sites.

2.2 Bentonite-Silty Clay Soil Mixtures

To widen the range of shrink-swell potentials of the tested samples, additional five bentonite-silty clay soil mixtures were used in the experimental program. In the same way, Lajurkar et al. (2013) considered five soil mixes with different Bentonite contents to develop characterizing parameters for soils with different shrink-swell capacity characteristics. Generally, increasing the number of tested samples enriches the obtained database of results and improve the reliability of the developed correlation equations expressing relationships among different shrink-swell parameters.

Bentonite is a family of clay minerals, produced by the weathering of volcanic ash, and is highly hygroscopic in nature. (OCMA DFCP.4) is a commercial bentonite, produced by Egyptian Gulf Chemical Company "EGCC", located at Sadat city – Industrial Zone 6 – Cairo, which has been used in the current research work. The laboratory investigation classified it as high plastic clay (CH), exhibiting liquid limit of 149.77%, plastic limit of 40.49%, and plasticity index of 109.28%. The bentonite was mixed with different proportions of non-swelling natural silty clay soil obtained from a site located at Damaris, EL-Minya city. The obtained five bentonite-silty clay soil mixtures will be denoted according to their bentonite contents for easy reference (i.e. 100 Bent., 80 Bent., 60 Bent., 40 Bent. and 20 Bent.). The five bentonite-silty clay soil mixtures were reconstituted using four different remolding pressures, similar to the remolded natural soil samples, resulting in a total of twenty soil mixture samples.

3 Testing Program

3.1 Soil Index Properties

Identification tests were performed in order to have a background data base for the soil properties. The conducted tests were:

- Atterberge limits: Liquid Limit (L.L.), Plastic Limit (P.L.), and Plasticity Index P.I., according to (ECP 202-2001).

- Dry unit weight (γ_{dry}), and specific gravity of soil solids (G_s), according to (ECP 202-2001).
- Free swell (F.S. %), and swelling potential (SP %), according to (ECP 201-2001).
- Swell limit (I_{sw}), shrink limit (I_{sh}), and shrink-swell index (I_{ss}) following Abdelmalak (2007) procedure.

3.2 Moisture Diffusion and Volume Change Properties

For the sixty two soil samples, coefficients of soil unsaturated diffusivity in shrink and swell cases as well as the suction compressibility indices were determined.

Coefficients of soil unsaturated diffusivity in shrink condition (α_{sh}) were determined using α-shrink test procedure developed by Abdelmalak (2007). However, coefficients of soil unsaturated diffusivity in swell condition (α_{sw}) were determined using 1-D time factors similar to commonly used in consolidation test, Das (2008). This is referred to the similarity between 1-D unsaturated diffusion equation when suction expressed in logarithmic units and 1-D consolidation equation, Abdelmalak (2007). In α-shrink test, a cylindrical soil specimen shrinks in both the vertical and horizontal directions (i.e. 2-D axisymmetric problem), which obliged Abdelmalak (2007) to develop time factors for 2-D axisymmetric diffusion problem. Meanwhile, in α-swell test, a cylindrical soil specimen is allowed to swell in the vertical direction only as the swelling in the horizontal direction is constrained by the oedometer ring (i.e. 1-D problem).

The Soil Water Characteristic curves (SWCC), expressed as gravimetric water content versus suction in pF unit, were determined following Sood (2005) and Bulut (2001). Slope of the straight line in the desaturation zone were determined, which equals to the suction compressibility index (γ_h).

Vapor equilibrium technique was implemented to determine SWCC by controlling the relative humidity in an air space above saturated salt solutions in a closed system. The tests were carried out in closed-lid desiccator for inducing suctions of 2.5, 3.5, 4.5 and 5.5 pF using saturated salt solutions of Na CL.

4 Results and Discussion

The liquid limit, plasticity index, as well as free swell of the soil samples increased with the increase of bentonite percentage for the bentonite-soil mixtures as indicated in Fig. 2.

Ten different regression equations were established among swelling characteristics and soil index properties, as illustrated in Table 1. For example, to develop reliable predictive equation for the soil suction compressibility index (γ_h), relationships between (γ_h) and many parameters and combinations of parameters (such as: α_{sh}, α_{sw}, SP, P.I./γ_{dry}, P.I., L.L./γ_{dry}, P.L./γ_{dry}) have been investigated. Various mathematical

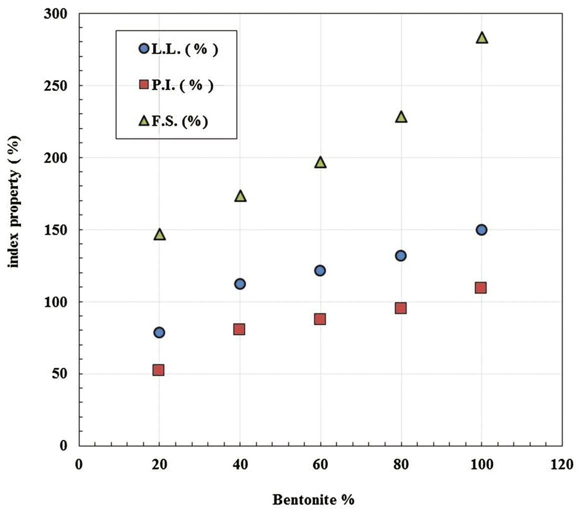

Fig. 2. Effect of Bentonite content in Bentonite-soil mixtures

Table 1. Swelling characteristics correlation equations based on soil index properties.

Equation no.	Equation	Regression statistics (R^2)
(1)	$\mathbf{I_{ss} = PI/(1.07 + 0.0011 \times PI)}$	0.96
(2)	$\mathbf{I_{ss} = 0.30 \times (F.S.) + 8.60}$	0.93
(3)	$\mathbf{I_{sw} = 3.13 \times (PI)^{0.7415}}$	0.93
(4)	$\mathbf{I_{sw} = 0.0004 \times (F.S.)^2 + 0.1909 \times (F.S.) + 27.30}$	0.93
(5)	$\boldsymbol{\gamma_h = 55.83 \, Ln \, (PI/\gamma_{dry}) - 158.63}$	0.83
(6)	$\boldsymbol{\alpha_{sh} = 0.026 \times (\gamma_h)^{-0.4973}}$	0.74
(7)	$\boldsymbol{\alpha_{sh} = 0.0023 \, Ln \, (\gamma_h/\gamma_{dry}) + 0.012}$	0.73
(8)	$\boldsymbol{\alpha_{sw} = 1.20 \times \alpha_{sh}}$	0.98
(9)	$\mathbf{SP = 32.40 \, Ln \, (PI) - 97.47}$	0.77
(10)	$\mathbf{SP = 36.91 \, Ln \, (I_{ss}) - 110.54}$	0.87

Table 2. R^2 values for different correlations between suction compressibility index and several combinations of soil – index parameters.

Curve fitting	α_{sh}	α_{sw}	SP	P.I./γ_{dry}	P.I.	L.L./γ_{dry}	P.L./γ_{dry}
Hyperbolic	0.57	0.51	0.04	0.51	0.50	0.53	0.51
Linear	0.65	0.65	0.49	0.79	0.79	0.80	0.74
2^{nd} degree polynomial	0.71	0.68	0.51	0.80	0.80	0.81	0.76
Logarithmic	0.72	0.70	0.35	**0.83**	0.79	0.78	0.75
Exponential	0.73	0.69	0.27	0.72	0.72	0.72	0.67

functions were employed to find the best curve fitting for each relationship such as: exponential, linear, 2nd degree polynomial, hyperbolic, and logarithmic. Table 2 presents resulting (R^2) values from curve fittings. Logarithmic curve fitting equation between (γ_h) and (P.I./γ_{dry}) was found to have the highest value ($R^2 = 0.83$), and hence chosen as the predictive model equation. In the same manner, the rest of equations, illustrated in Table 1, were developed.

The established relationships that estimate swelling characteristics based on carefully determined index properties will be presented and discussed in the following section.

4.1 Soil Shrink-Swell Index

Relationship between soil shrink-swell index and corresponding plasticity index for the 62 samples is presented in Fig. 3. The regression analysis revealed that hyperbolic curve fitting for the measurements has high coefficient of determination ($R^2 = 0.96$, refer to Eq. 1 in Table 1), which confirms the existence of strong correlation between shrink-swell index and plasticity index of soil.

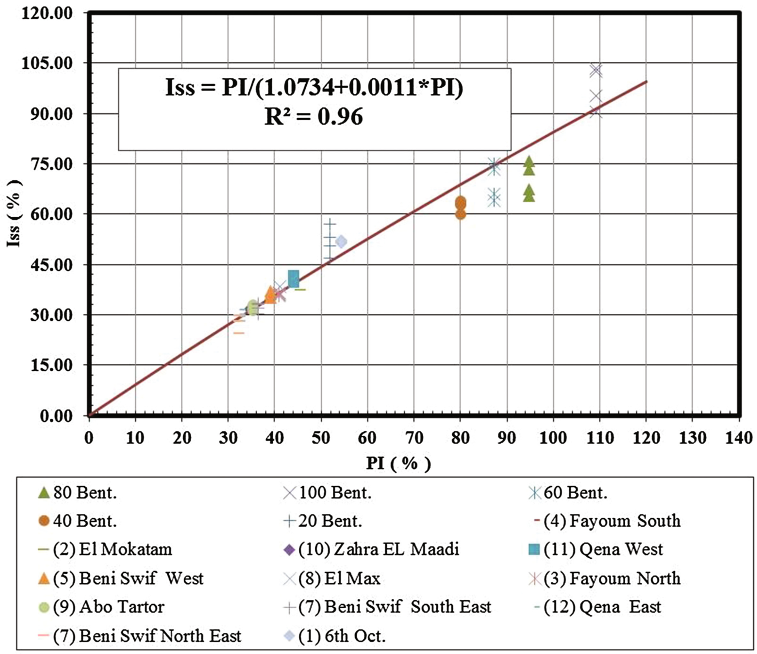

Fig. 3. Relationship between soil shrink-swell index and plasticity index.

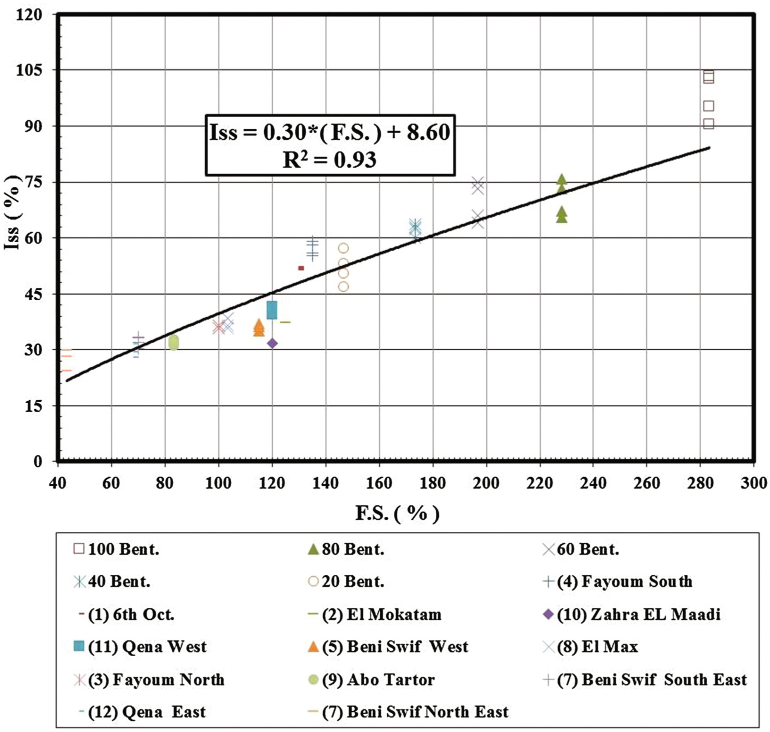

Fig. 4. Relationship between soil shrink-swell index and free swell.

Similarly, soil shrink-swell indices were plotted against free swell values, as shown in Fig. 4. The data indicate the existence of a linear relationship between soil shrink-swell index and free swell. The determined coefficient of determination value (R^2 = 0.93, refer to Eq. 2 in Table 1) was high indicating the strong correlation.

4.2 Soil Swell Limit

Exponential regression equation (Eq. 3 in Table 1) was found to be perfectly representing the relationship between soil swell limit and plasticity index. This regression analysis resulted in a high coefficient of determination (R^2 = 0.93, as shown in Fig. 5), which suggests the high degree of correlation between swell limit and plasticity index of soil.

The same level of correlation was found between the soil swell limit and free swell value, as illustrated in Fig. 6. A 2nd degree polynomial well represented the relationship

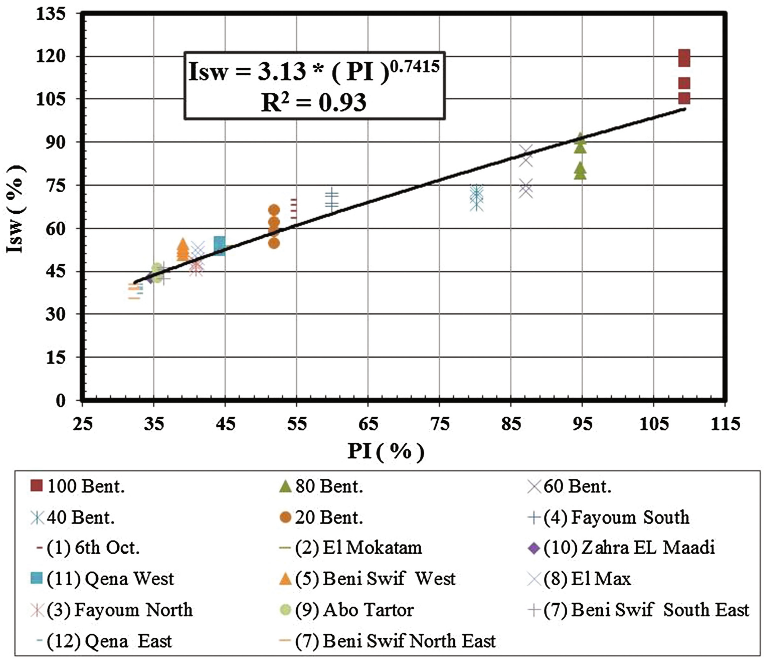

Fig. 5. Relationship between swell limit and plasticity index.

between soil swell limit and free swell with a high coefficient of determination (R^2 = 0.93, Eq. 4 in Table 1).

4.3 Suction Compressibility Index

Figure 7 demonstrates the relationship between measured soil suction compressibility indices and their corresponding determined ratios between plasticity index and dry unit weight. Logarithmic regression (Eq. 5 in Table 1) reflected the good correlation between suction compressibility of soil and the ratio of plasticity index to dry unit weight (R^2 = 0.83).

4.4 Soil Coefficients of Unsaturated Diffusivity

The soil coefficients of unsaturated diffusivity in shrink condition (α_{sh}) were plotted against suction compressibility index (γ_h), as shown in Fig. 8, and against the ratio of suction compressibility index to dry unit weight (γ_h/γ_{dry}), as shown in Fig. 9. The data indicated the existence of an exponential relationship between soil coefficients of unsaturated diffusivity (α_{sh}) and suction compressibility index (γ_h). The regression analysis revealed reasonable correlation (R^2 = 0.74, Eq. 6 in Table 1). Almost the same level of correlation (R^2 = 0.73, Eq. 7 in Table 1) was found between coefficients

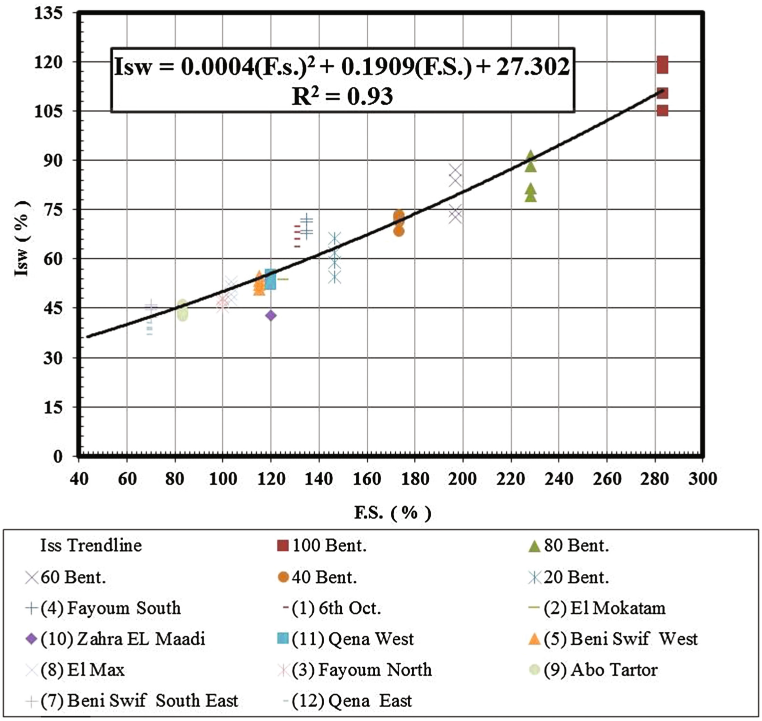

Fig. 6. Relationship between swell limit and free swell.

of unsaturated diffusivity in shrink condition (α_{sh}) and the ratio of suction compressibility index to dry unit weight (γ_h/γ_{dry}).

To investigate the correlation between soil coefficients of unsaturated diffusivities in shrink condition (α_{sh}) and in swell conditions (α_{sw}), Fig. 10. was presented. The linear regression analysis revealed very high degree of correlation between them with coefficient of determination of R^2 = 0.98, Eq. 8 in Table 1.

4.5 Soil Swell Potential

It is commonly recognized that soil swell potential correlates well with plasticity index for soils. However, better correlation was found to be soil swell potential and shrink-swell index, as shown in Figs. 11 and 12. The regression analysis indicated that R^2 = 0.77 (Eq. 9 in Table 1) for relationship between swell potential and plasticity index. Meanwhile, R^2 = 0.87 (Eq. 10 in Table 1) for relationship between swell potential and shrink-swell index.

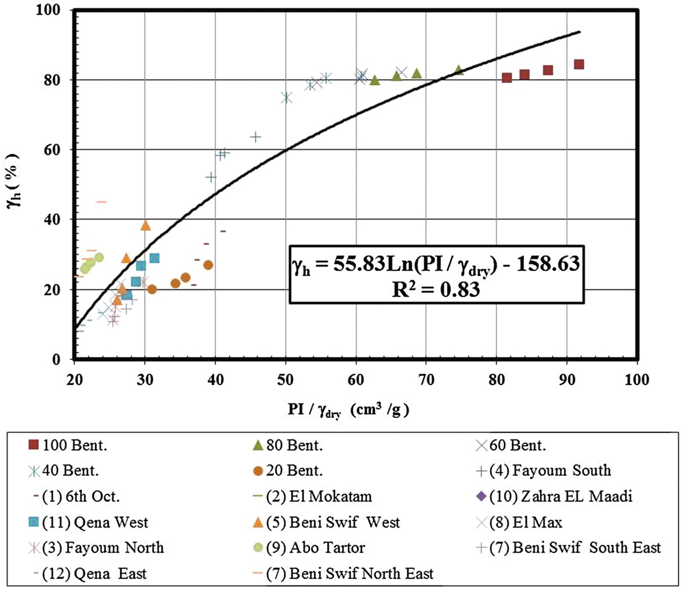

Fig. 7. Relationship between suction compressibility index and the ratio between plasticity index and dry unit weight.

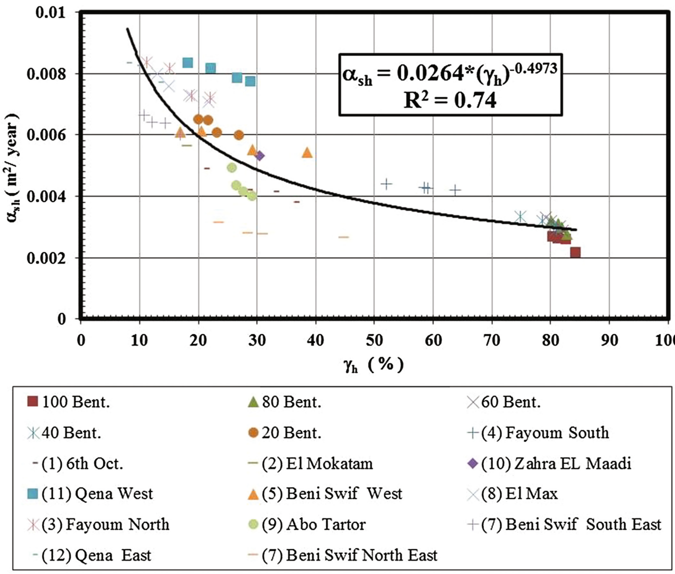

Fig. 8. Relationship between soil coefficient of unsaturated diffusivity in shrink condition and suction compressibility index.

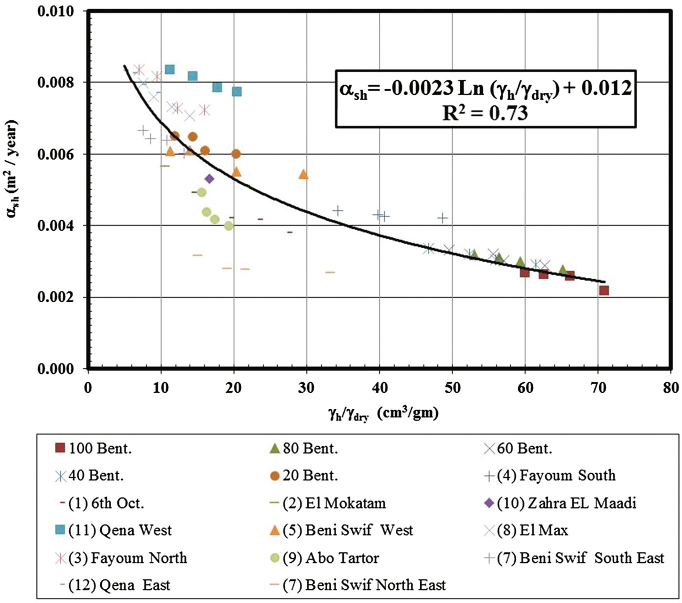

Fig. 9. Relationship between soil coefficient of unsaturated diffusivity in shrink condition and ratio of suction compressibility index to dry unit weight.

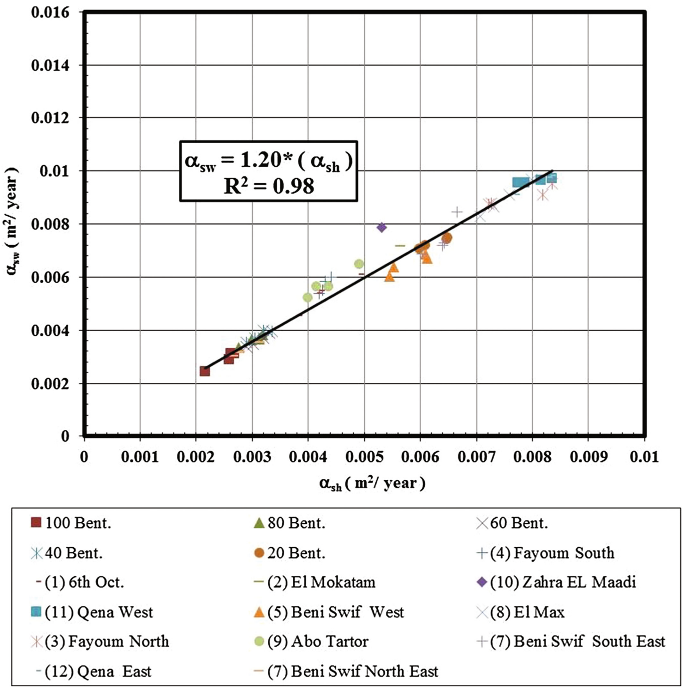

Fig. 10. Relationship between soil coefficients of unsaturated diffusivities in shrink and swell conditions.

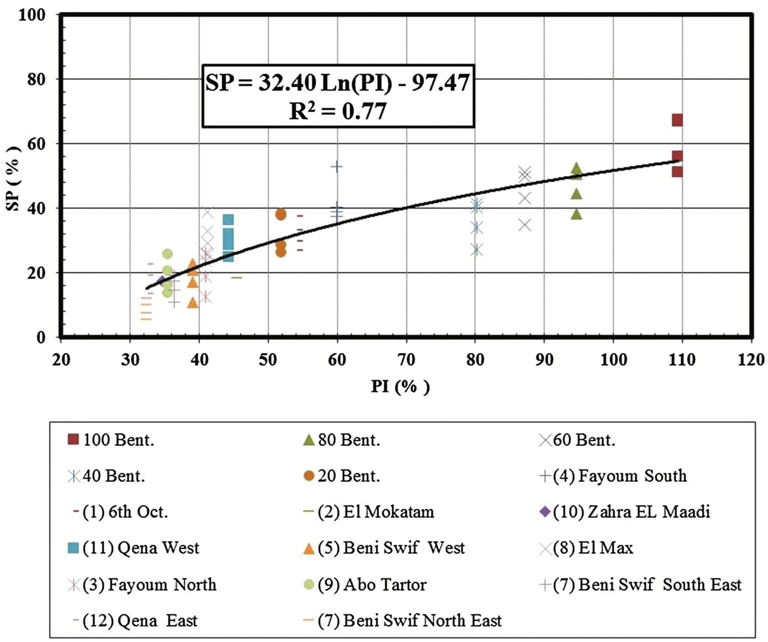

Fig. 11. Relationship between soil swell potential and plasticity index.

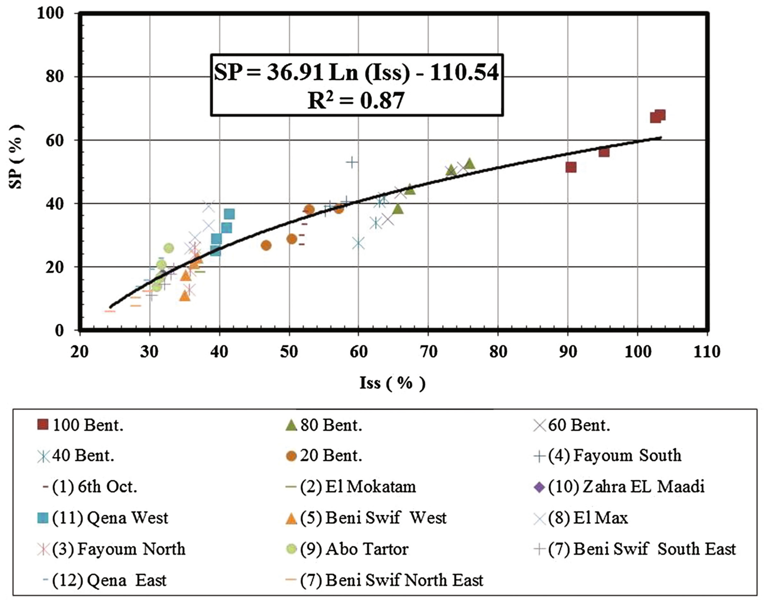

Fig. 12. Relationship between soil swell potential and shrink-swell index.

5 Model Verification

The Assuit Transformers electric substation is located about 370 km south of Cairo on the eastern plateau, within premises on New Assuit city. The electric substation is founded on a dry clay formation with high shrink-swell characteristics. Three undisturbed soil samples were obtained from executed boreholes located around the main building (a two-story reinforced concrete structure), which suffered from severe cracks. Values of main shrink-swell characteristics (I_{sw}, I_{ss}, α_{sh}, α_{sw}, γ_h, and SP) as well as values of soil index properties (LL, PL, PI, γ_{dry}) were determined via laboratory testing program as explained above. Table 3 presents soil samples index properties.

Table 3. Soil samples index properties for Assuit Transformers Station.

Soil sample	L.L. (%)	P.L. (%)	P.I. (%)	γ_{dry} (KN/m^3)
(1)	61.53	20.66	40.87	15
(2)	71.54	22.84	48.7	14.15
(3)	61.64	22.84	38.8	14.5

Table 4. Comparison of experimental scheme and predicted equations for Assuit Transformers Electric Substation Samples.

Soil sample	Soil properties	Measured values	Predicted values	Difference	% Difference
Sample (1)	**I_{sw} (%)**	52.18	49.02	3.16	6.05
	I_{ss} (%)	38.94	36.66	2.28	5.85
	αsh (cm^2/min)	0.000074	0.0001037	−0.000030	40.54
	αsw (cm^2/min)	0.0000589	0.0000888	−0.000003	5.09
	γ_h (%)	23.13	25.88	−2.75	11.88
	SP (%)	37.91	24.63	13.28	35.03
Sample (2)	**I_{sw} (%)**	60.21	55.83	4.38	7.27
	I_{ss} (%)	45.67	43.34	2.33	5.10
	αsh (cm^2/min)	0.000083	0.0001032	−0.000020	24.09
	αsw (cm^2/min)	0.0001103	0.0000996	0.000011	9.97
	γ_h (%)	23.26	38.93	−15.57	66.93
	SP (%)	46.96	30.51	16.45	32.93
Sample (3)	**I_{sw}(%)**	48.08	47.17	0.91	1.89
	I_{ss} (%)	35.28	34.87	0.41	1.16
	αsh (cm^2/min)	0.00008	0.0001163	−0.00036	45
	αsw (cm^2/min)	0.0001112	0.000096	0.000015	1.34
	γ_h (%)	18.39	24.88	−6.49	35.29
	SP (%)	35.11	20.98	14.13	40.24

Furthermore, the same main shrink-swell parameters were estimated using the developed correlation equations based on measured index properties of the obtained soil samples. Hence, comparisons between measured and corresponding estimated parameter were carried out, as shown in Table 4, to check the validity of the developed predictive model. Comparisons show the presence of reasonably good agreement between predictions and measurements.

6 Conclusions

Extensive experimental work has been conducted on sixty two (62) soil samples obtained from twelve (12) sites scattered all over Egypt as well as carefully prepared bentonite-silty clay soil mixtures. Most of the soil samples were remolded using different remolding pressures, yet few natural soil samples were undisturbed. The experimental laboratory testing program revealed the following main findings:

The liquid limit, plasticity index, as well as free swell of the soil samples increased with the increase of bentonite percentage for the bentonite-soil mixtures. There exist unique relationships between the index properties and the swelling characteristics of the tested swelling soils.

A new set of correlation equations was proposed to estimate the swelling characteristics with carefully evaluated index properties in hand. Despite the obvious scattering and variability of the collected and prepared swelling soil samples, high degrees of correlations were proven in the developed equations, which may entitle them to be treated as a reliable tool. The developed equations were rationally verified using available laboratory measurements from another site located south east of Cairo.

The main intend for developing these relationships is to provide geotechnical practitioners with first order estimations of main shrink-swell parameters using available conventional soil index properties.

Notations

L.L. = Liquid Limit.
P.I. = Plasticity Index.
P.L. = Plastic Limit.
SWCC = Soil Water Characteristic Curve.
γ_h = Suction Compressibility.
U = Total Suction expressed as logarithmic unit (pF).
u_w = Total Suction expressed in units of cm of water head.
γ_{dry} = Dry Unit Weight.
G_s = Specific Gravity of Soil Solids.
I_{sw} = Swell Limit.
I_{sh} = Shrink Limit.
I_{ss} = Shrink-Swell Index.
F.S. = Free Swell.

SP = Swelling Potential.
α_{sh} = Coefficient of Unsaturated Diffusivity in shrink condition.
α_{sw} = Coefficient of Unsaturated Diffusivity in swell condition.

References

Abdelmalak, R.I.: Soil Structure Interaction for Shrink-Swell Soils: A New Design Procedure for Foundation Slabs on Shrink-Swell Soils. Ph.D. Dissertation, Texas A&M University (2007)

AL-Shihabi, O.: Estimation of soil suction using salt solutions method and filter paper. Damascus J. Agric. Sci. (DJAS) **26**(2), 59–76 (2010)

Briaud, J.-L., Zhang, X., Moon, S.: Shrink test–water content method for shrink and swell predictions. J. Geotech. Geoenvironmental Eng. ASCE **129**(7), 590–600 (2003). doi:10.1061/(ASCE)1090-0241(2003)129:7(590)

Bulut, R.: Total and matric suction measurements with the filter paper method. Ph.D. thesis, Texas A&M University (2001)

Dafalla, M.A., Shamrani, M.A., Puppala, A.J., Ali, H.E.: Use of rigid foundation system on expansive soils. In: Geo-Florida 2010: Advances in Analysis, Modeling & Design (GSP 199) 2010, ASCE, BRCES, Civil Engineering Department, King Saud University, Riyadh, Saudi (2010)

Das, B.M.: Advanced Soil Mechanics, 3rd edn., pp. 288–289 (2008). ISBN: 0-203-93584-5 Master e-book ISBN. http://www.taylorandfrancis.com

Erzin, Y., Erol, O.: Swell pressure prediction by suction methods. Eng. Geol. **92**, 133–145 (2007). doi:10.1016/j.enggeo.2007.04.002. Received 4 August 2005, ENGEO-02678

Hammam, A.H., Abdel-Salam, A.E.: Comparisons between behaviors of undisturbed and remolded swelling soil. In: Pan-Am CGS Geotechnical Conference, Montreal, Canada (2013)

Israr, J., Farooq, K., Mujtaba, H.: Modelling of swelling parameters and associated characteristics based on index properties of expansive soils. Pak. J. Eng. Appl. Sci. **15**, 1–9 (2014)

Jahangir, E., Deck,O., Masrouri, F.: Influence of foundation embedding on clays shrinkage-swelling hazard consequences. In: Vogt, N., Schuppener, B., Straub, D., Bräu, G. (eds.) ISGSR 2011. Bundesanstalt für Wasserbau (2011). ISBN: 978-3-939230-01-4

Lajurkar, S.P., Khandeshwar, S.R., Dhoble, R.S., Bade, R.G.: Experimental study on shrink-swell behavior of expansive soil. Int. J. Innovative Res. Sci. Eng. Technol. **2**(6), 2085–2090 (2013). ISSN: 2319-8753

Sood, E.: Determination of the diffusion coefficient for unsaturated soils. M.Sc. thesis, Texas A&M University (2005)

Zapata, C.E., Houston, W.N., Houston, S.L., Walsh, K.D.: Soil – water characteristic curve variability. Adv. Unsaturated Geotechnics **287**, 84–124 (2000). doi:10.1061/40510(287)7

http://www.springer.com/978-3-319-61930-9

Advances in Characterization and Analysis of Expansive Soils and Rocks
Proceedings of the 1st GeoMEast International Congress and Exhibition, Egypt 2017 on Sustainable Civil Infrastructures
Hoyos, L.R.; McCartney, J.S. (Eds.)
2018, VIII, 222 p. 137 illus., Softcover
ISBN: 978-3-319-61930-9