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FACTORS INFLUENCING CHARACTERISTICS OF UNSATURATED SHRINK-SWELL SOILS

Fayek Hassona[1], PhD, Remon I.Abdelmalak[2], PhD and
Beshoy M. Hakeem[3], MSc.

[1]Professer,Civil Engineering Department, Faculty of Engineering, El-Minia University, El-Minia, Egypt.Email: Fhassona@gmail.com.
[2]Assistant Professor, Civil Engineering Department, Faculty of Engineering, El-Minia University, El-Minia, Egypt. Email: remonisaac@gmail.com.
[3]Assistant Lecturer, Civil Engineering Department, Higher Institute of Engineering and Technology,El-Minia, Egypt. Email: civileng_beshoy@yahoo.com.

ABSTRACT.

Expansive soils show high volumetric changes with changes in water content. 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 properties, foundation type, nature of 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. In this paper, the effect of some factors influencing such as the swelling potential, soil coefficient of unsaturated diffusivity, and suction compressibility index on the behavior of expansive soils were discussed. Test results confirm that volumetric change and moisture diffusion characteristics for unsaturated soils can be reasonably related to conventional soil index properties. From this study, it was found that: the swelling potential and soil coefficients of unsaturated diffusivity increases with the increase of the soil density, while the soil sample with the high density developed less suction compressibility index than the low density soil. Another important factors influencing of the swelling behavior of expansive soils are concluded and discussed.

KEYWORDS.

Expansive soil, Shrink-Swell Soil, Soil water characteristic curve, Swell potential, Bentonite, Soil water characteristic curve (SWCC), and Unsaturated soils.

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. 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. According to Mokhtari and Dehghani (2012) the swelling potential of the expansive soil mainly depends upon the properties of soil and environmental factors. These are a worldwide problem that poses several challenges for civil engineers.

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 1kPa, for a very wet soil close to 100% degree of saturation, to a 10^6kPa, 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). 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 soil samples obtained from various sites in Egypt. The main factors influencing swelling behavior of expansive soils were studied. 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.

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 analyses 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.

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- maxElkebly (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 **Figure 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.

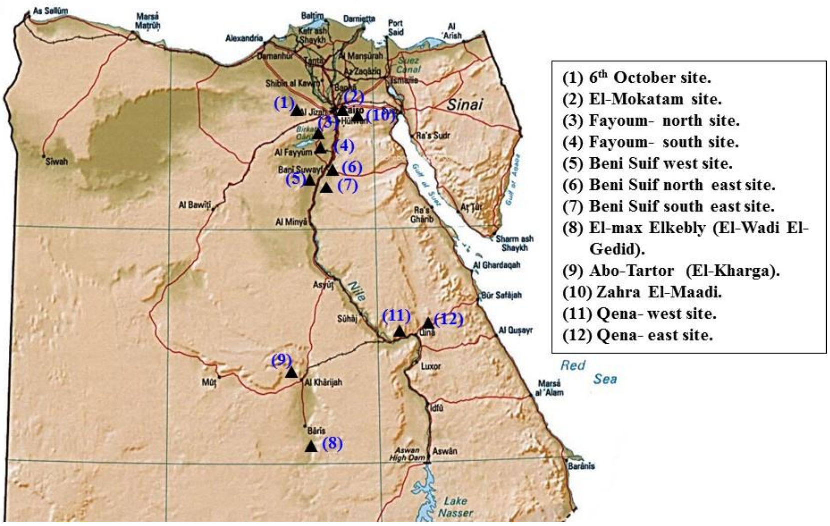

Figure.1. Map of Egypt with locations of the samples sites.

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.

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 plasticity 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.

TESTING PROGRAM

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.: The minimum water content at which the soil is still in liquid state), Plastic Limit (P.L.: The moist content, in percent, at which the soil crumbles when rolled into threads of 3.0 mm diameter), and Plasticity Index. Plasticity Index(P.I.= L.L. – P.L) represents the range of consistency within which a soil exhibits plastic properties) , according to (ECP 202-2001).
- Dry unit weight (γ_{dry}: The ratio of the weight of soil solids to the total volume), and specific gravity of soil solids (G_s: The ratio between unit weight of soil solids to that of water), according to (ECP 202-2001).
- Free swell (F.S. %), and swelling potential (SP %), according to (ECP 201-2001).

  Free swell (F.S. %): The ratio of the increase in volume of the soil from a loose dry powder form to the equilibrium sediment when it is poured into water, expressed as the percentage of the original volume.

  Swelling potential (SP %) : Is defined as the percentage of vertical strain of laterally confined sample soaked under 0.07 kg/cm^2 surcharge when flooded with water after being compacted to maximum density at optimum water content.
- Swell limit (I_{sw}: The maximum water content at which soil sample doesn't increase its volume), shrink limit (I_{sh}: The minimum content at which soil sample doesn't decrease its volume), and shrink-swell index (I_{ss}) following Abdelmalak (2007) procedure. Shrink-swell index (I_{ss}) is defined as the difference between swell and shrink limit. $I_{ss} = I_{sw} - I_{sh}$.

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). Coefficients of soil unsaturated diffusivity is used to determine the diffusivity of moisture through unsaturated soil mass that causes shrink-swell soils to increase in its volume. 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 NaCL.

FACTORS INFLUENCING THE SWELLING POTENTIAL OF EXPANSIVE SOILS IN EGYPT.

Melek (2000) and El-Sibaie (1992) discussed the main influencing factors on the swelling behavior of clays. Among these factors are:

1) Factors affecting the nature and physical properties of the soil particles such as clay mineralogy, clay content, soil structure, initial water content, initial dry density, pore fluid.
2) Soil placement and environmental condition in the field or in laboratory such as effect of surcharge pressure, effect of stress history, effect of temperature...etc.

In light of the above, the effects of plasticity index, free swell, and dry unit weights on the swelling behavior of sixty two (62) expansive soils obtained from various sites all over Egypt are discussed.

RESULTS AND DISCUSSION

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

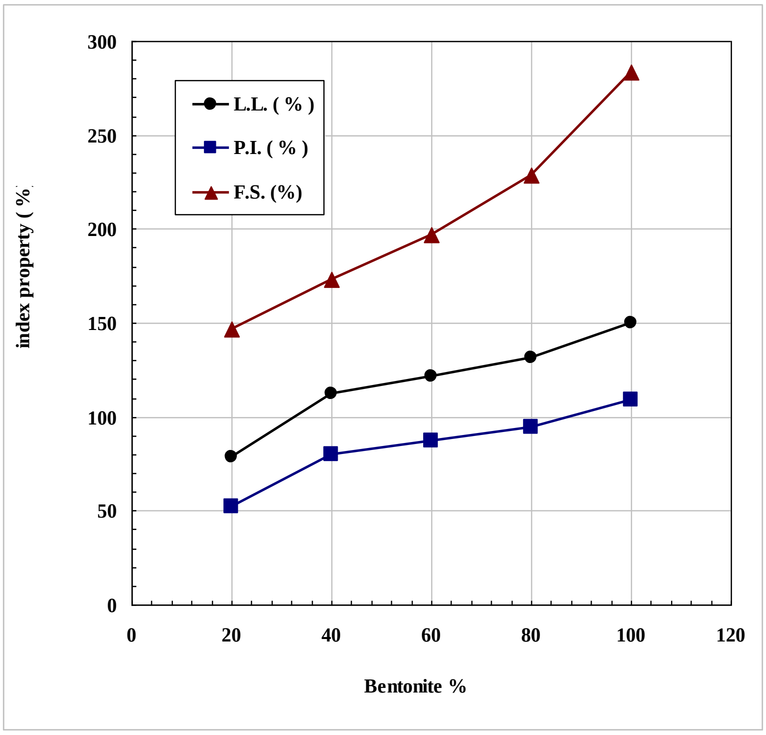

Figure.2. Effect of Bentonite content in Bentonite-soil mixtures.

Based on test results, the samples were categorized according to their potential expansiveness as per the Egyptian Code (ECP 202-2001) as follows:

- Very high potential expansiveness for samples have SP greater than 30%, and plasticity index greater than 35%; such as: 100 Bent., 80 Bent, 60 Bent., 40 Bent., 20 Bent., (4) Fayoum South, (1) 6th Oct., (11) Qena West., (8) El Max.
- High potential expansiveness for samples have SP ranged from (20 – 30 %), and plasticity index ranged from (25 – 41 %); such as: (5) BeniSwif West, (3) Fayoum North, (9) Abo Tartor.
- Medium expansiveness for samples have SP ranged from (10 – 20 %), and plasticity index ranged from (15 – 28 %);such as: (2) El Mokatam, (10) Zahra EL Maadi, (7) BeniSwif South East, (12) Qena East, (6) BeniSwif North East.

Soil dry unit weight.

High initial dry density results in closer particle spacing's, smaller void ratios, larger volumetric changes, and hence more shrink-swell response to change in water contents.

For very high potential expansiveness samples, the increase in dry unit weight of soil (from 10.32% to 25.56%) increases the percentage of swelling potential (from 32.18% to 52.23%). Similarly for high potential expansiveness samples, the increase in dry unit weight of soil (from 9.27% to 16.67%) increases the percentage of swelling potential (from 88.69% to 109.18%). Meanwhile, for medium potential expansiveness samples, the increase in dry unit weight of soil (from 10.85% to 15.56%) increases the percentage of swelling potential (from 65.39% to 116.82%). **Figure 3.** illustrates the effect of dry unit weight on the swelling potential of soil. This implies that the effect of dry unit weight on the swelling potential becomes more manifested with soils of low potential expansiveness according to the obtained results.

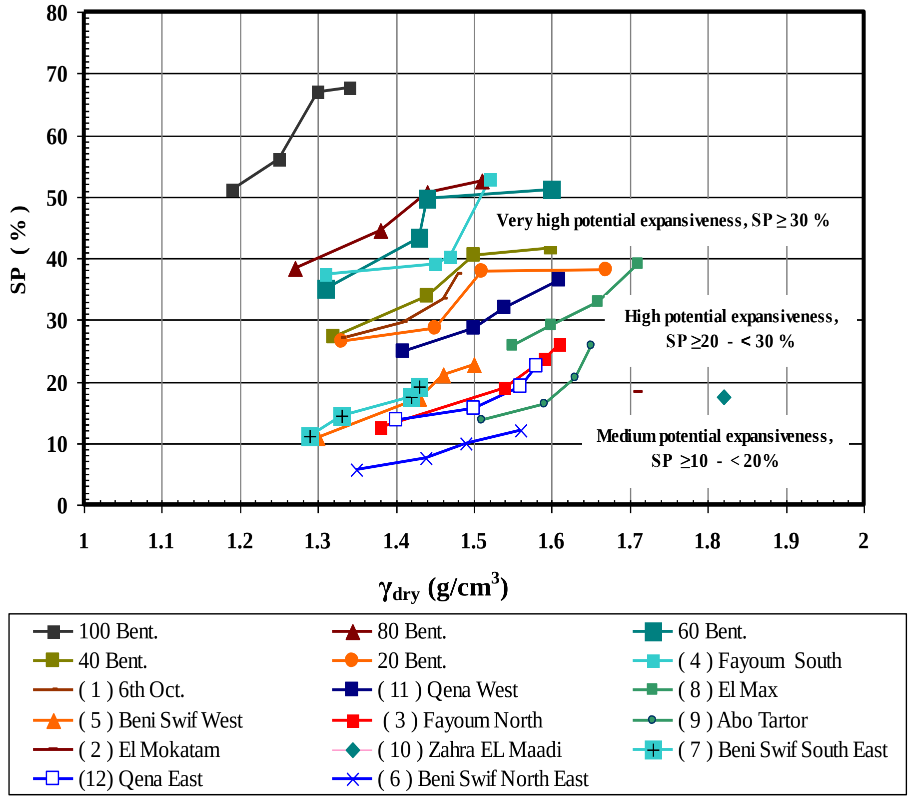

Figure3. Effect of dry unit weight on the swelling potential for the soil samples.

The effect of dry unit weight on the coefficient of unsaturated diffusivity of soil is shown in **Figure 4.** For very high potential expansiveness samples, the increase in dry unit weight of soil (from 10.32% to 25.56%) increases the percentage of the coefficient of unsaturated diffusivity of soil (from 8.4% to 28.87%).
It was noticed that the percentage of coefficient of unsaturated diffusivity of soil increases (from 11.82% to 23.02%) due to increasing the dry unit weight of soil (from 9.27% to 16.67%) for high potential expansiveness samples. For medium potential expansiveness samples, the increase in dry unit weight of soil (from 10.85% to 15.56%) increases the percentage of the coefficient of unsaturated diffusivity of soil (from 8.31% to 18.08%).This suggests that the effect of dry unit weight on the coefficient of unsaturated diffusivity becomes more manifested with soils of high potential expansiveness and then decreases with soils with medium and very high potential expansiveness. However, the effect of dry unit weight on soil unsaturated diffusivity is to some extent much less than that on the swelling potential.

Similarly, suction compressibility index of soil is plotted against dry unit weight values as shown in **Figure 5.** The relation indicates that the increase in dry unit weight of soil (from 10.32% to 25.56%, values of dry unit weight of soil illustrated in Figure 5) decreases the percentage of suction compressibility index of soil (from 25.96 % to 3.27 % for samples with F.S. greater than 135%, for samples with F.S. less than 135% suction compressibility index decreases till 42.18%) for very high potential expansiveness samples. For high potential expansiveness samples when dry unit weight of soil increases (from 9.27% to 16.67%) the percentage of suction compressibility index of soil decreases (from 55.90% to 11.72%).
It was noticed that the percentage coefficient of unsaturated diffusivity of soil decreases (from 47.50% to 36.20%) due to increasing dry unit weight of soil (from 10.85% to 15.56%) for medium potential expansiveness samples. Generally, increase in dry unit weight slightly decreases the suction compressibility index.

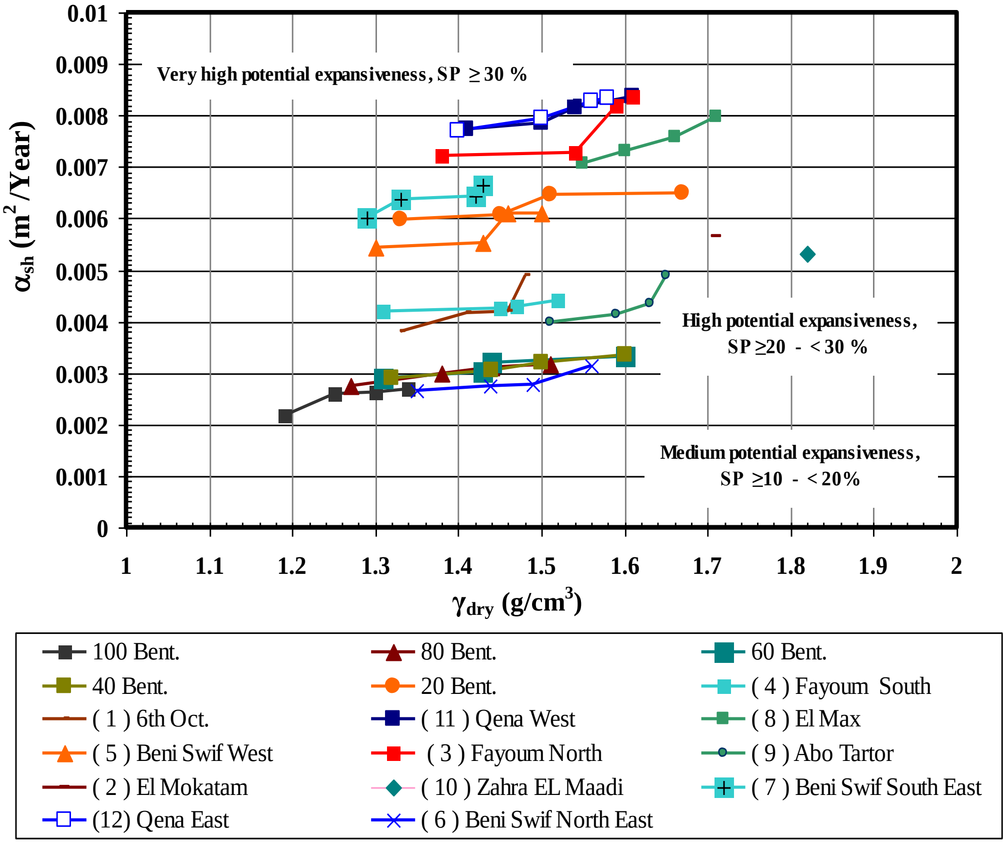

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Figure 4. Effect of dry unit weight on the coefficient of unsaturated diffusivity of soil (α_{sh}) for the soil samples.

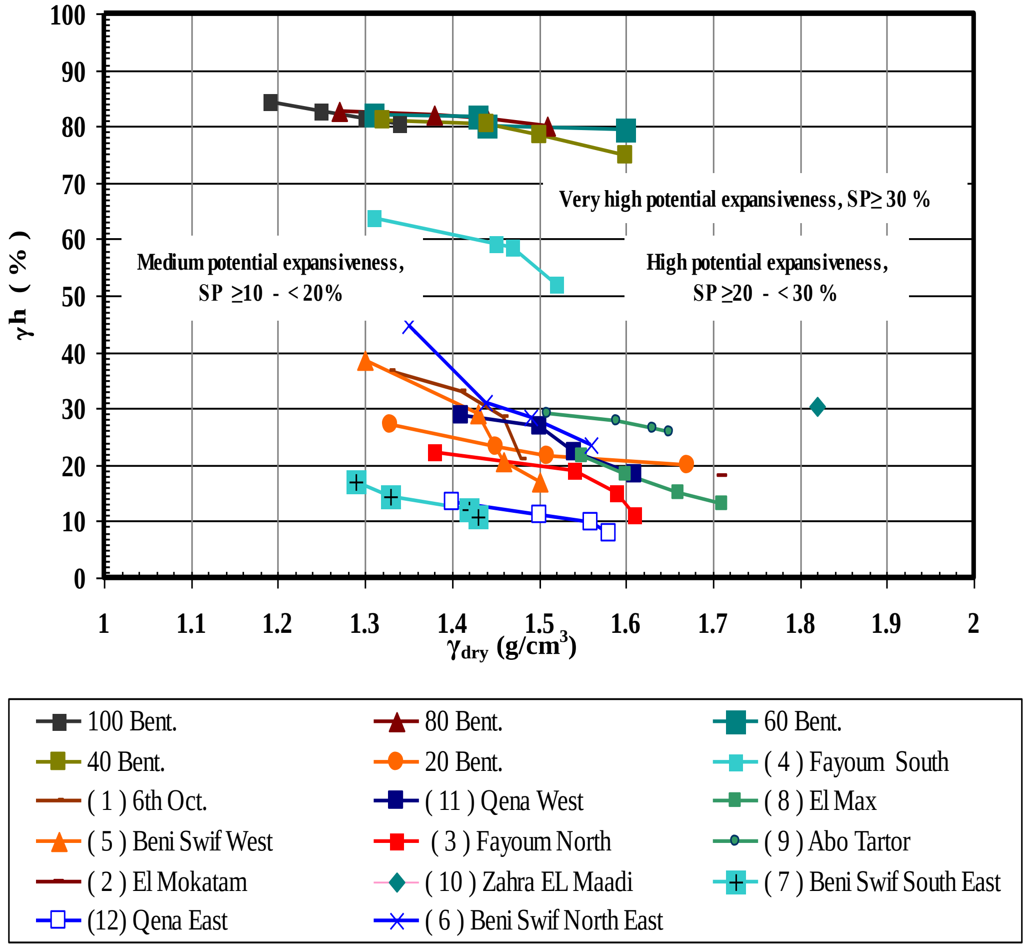

Figure 5. Effect of dry unit weight on the suction compressibility index of soil. (γ_h)for the soil samples.

Soil plasticity.

Soil plasticity could be envisioned as a reflection to clay content and clay mineralogy, which have direct impact on soils shrink-swell behavior.

For very high potential expansiveness samples, the increase in plasticity index of soil (from 41.17% to 109.28%) increases the percentage of swelling potential (from 32.18% to 52.23%). For high potential expansiveness samples, the increase in plasticity index of soil (from 35.50% to 40.96%) increases the percentage of swelling potential (from 88.69% to 109.18%). For medium potential expansiveness samples, the increase in plasticity index of soil (from 32.31% to 36.40%) increases the percentage of swelling potential (from 65.39% to 116.82%). **Figure 6** illustrates the effect of plasticity index on the swelling potential of soil. This indicates that the effect of plasticity index on the swelling potential becomes more demonstrated with soils of low potential expansiveness.

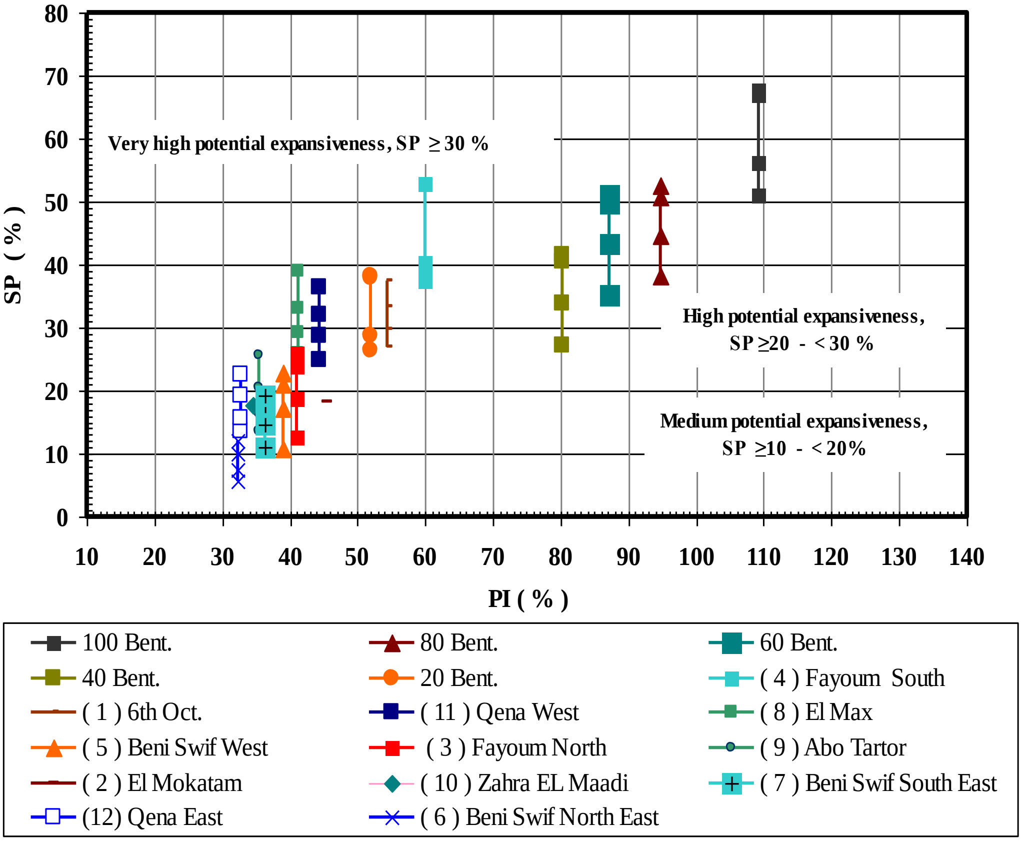

Figure 6. Effect of plasticity index on the swelling potential for the soil samples.

Figure 7 presents the effect of plasticity index on the coefficient of unsaturated diffusivity of soil. For very high potential expansiveness samples, the increase in plasticity index of soil (from 41.17% to 109.28%) decreases the percentage of the coefficient of unsaturated diffusivity of soil (from 28.87% to 8.40%).

It was noticed that the percentage of coefficient of unsaturated diffusivity of soil decreases (from 23.02% to 11.82%) due to increasing the plasticity index of soil (from 35.50% to 40.96%) for high potential expansiveness samples.

For medium potential expansiveness samples, the increase in plasticity index of soil (from 32.31% to 36.40%) decreases the percentage of the coefficient of unsaturated diffusivity of soil (from 18.08% to 8.31%). That means, increase in soil plasticity index generally decreases the soil coefficient of unsaturated diffusivity especially for medium potential expansiveness soils.

Suction compressibility index of soil was plotted against plasticity index values as shown in **Figure 8.** The data indicated that the increase plasticity index of soil (from 41.17% to 109.28%) increases the percentage of suction compressibility index of soil (from 3.27 % to 25.96 % for samples with F.S. greater than 135%, for samples with F.S. less than 135% suction compressibility index increases till 42.18%) for very high potential expansiveness samples. For high potential expansiveness samples when plasticity index of soil increases (from 35.5% to 40.96%) the percentage of suction compressibility index of soil increases (from 11.72% to 55.90%).

It was noticed that the percentage coefficient of unsaturated diffusivity of soil increases (from 36.20% to 47.50%) due to increasing plasticity index of soil (from 32.31% to 36.40%) for medium potential expansiveness samples. Therefore, increase in soil plasticity index generally increases the soil suction compressibility index; this effect becomes larger with the decrease in potential expansiveness of the soil.

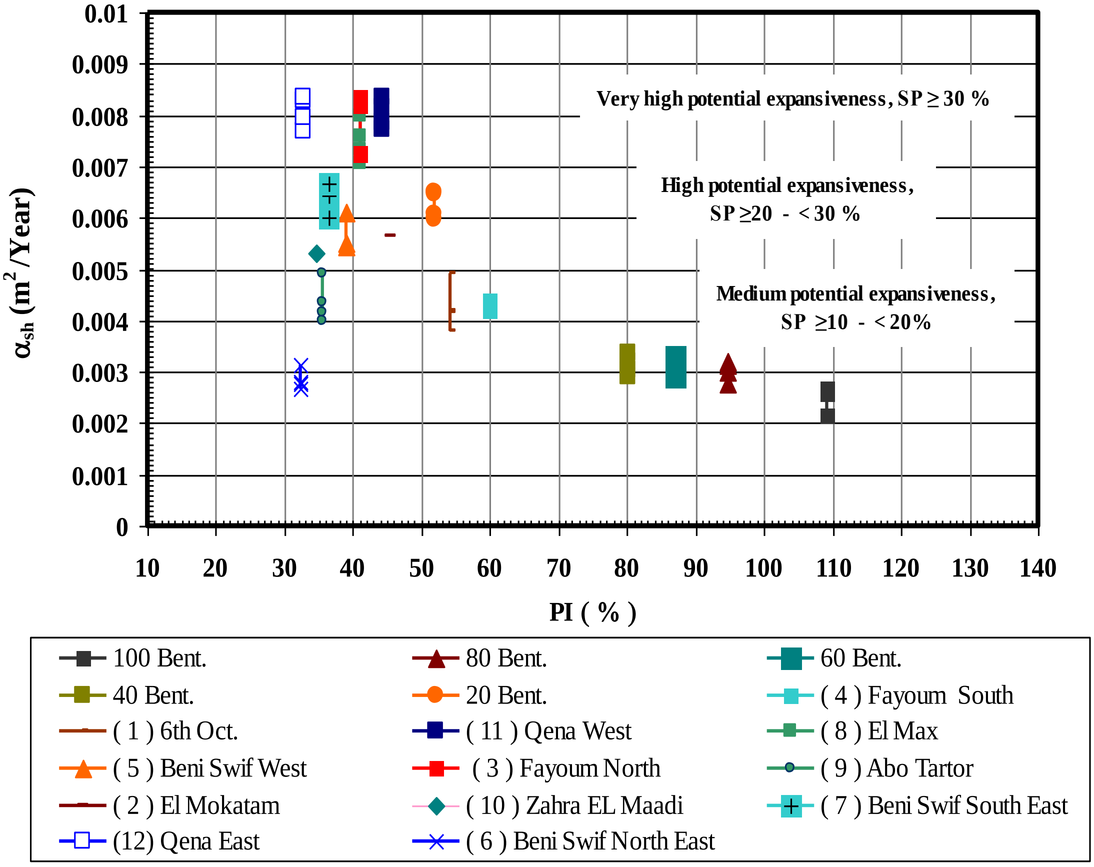

Figure 7. Effect of plasticity index on the coefficient of unsaturated diffusivity of soil (α_{sh})for the soil samples.

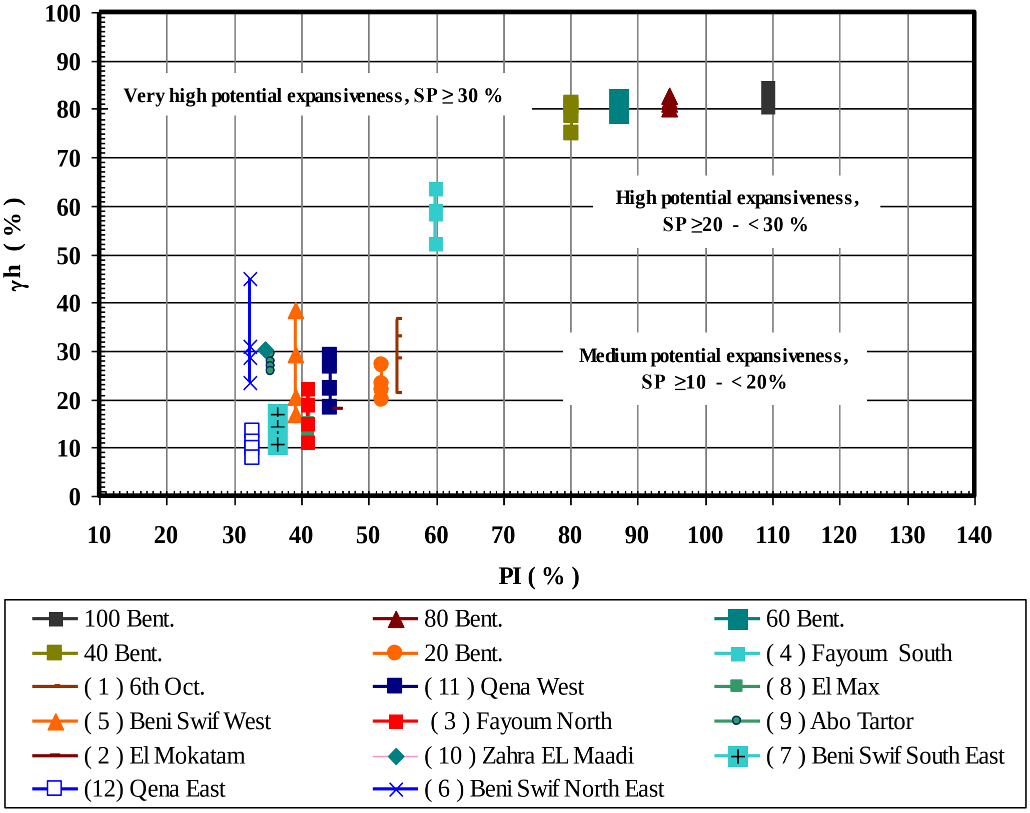

Figure 8. Effect of plasticity index on the suction compressibility index of soil. (γ_h)for the soil samples.

Soil physical properties.

Dominant clay mineral is considered the most significant soil physical property that contributes to the shrink-swell behavior. Free Swell Index (the increase in volume of a soil, without any external constraints, on submergence in water) is simple indicator to clay content and clay mineralogy, which have direct impact on soils shrink-swell behavior. Prakash and Sridharan (2004) concluded that free well test has emerged as a simple methodology to predict the clay mineral(s) satisfactorily. They have validated this method via exhaustive experimental data.

For very high potential expansiveness samples, the increase in free swell of soil (from 120% to 283.33%) increases the percentage of swelling potential (from 32.18% to 52.23%). For high potential expansiveness samples, the increase in free swell of soil (from 83.33% to 115%) increases the percentage of swelling potential (from 88.69% to 109.18%). For medium potential expansiveness samples, the increase in free swell of soil (from 43.33% to 70%) increases the percentage of swelling potential (from 65.39% to116.82%). **Figure 9** illustrates the effect of free swell on the swelling potential of soil.

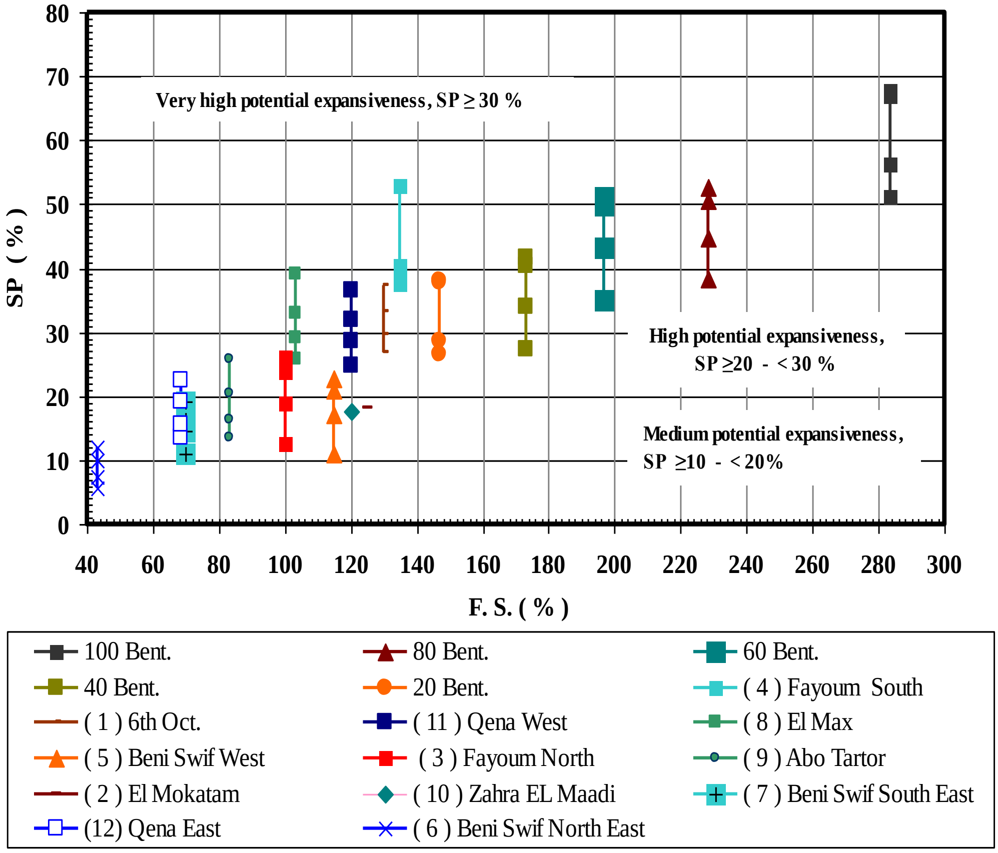

Figure 9. Effect of free swell on the swelling potential for the soil samples.

Figure 10. illustrates the effect of free swell on the coefficient of unsaturated diffusivity of soil. For very high potential expansiveness samples, the increase in free swell of soil (from 120% to 283.33%) decreases the percentage of the coefficient of unsaturated diffusivity of soil (from 28.87% to 8.40%). It was noticed that the percentage of coefficient of unsaturated diffusivity of soil decreases (from 23.02% to 11.82%) due to increasing the free swell of soil (from 83.33% to 115%) for high potential expansiveness samples. For medium potential expansiveness samples, the increase in free swell of soil (from 43.33% to 70%) decreases the percentage of the coefficient of unsaturated diffusivity of soil (from 8.31% to 18.08%).

Similarly, suction compressibility index of soil were plotted against Free Swell values as shown in **Figure 11.** The data indicated that the increase in free swell of soil (from 120% to 283.33%) increases the percentage of suction compressibility index of soil (from 3.27 % to 25.96 % for samples with F.S. greater than 135%, for samples with F.S. less than 135% suction compressibility index increases till 42.18%) for very high potential expansiveness samples. For high potential expansiveness samples when free swell of soil increases (from 83.33% to 115%) the percentage of suction compressibility index of soil increases (from 11.72% to 55.90%).It was noticed that the percentage coefficient of unsaturated diffusivity of soil increases (from 36.20% to 47.50%) due to increasing free swell of soil (from 43.33% to 70%) for medium potential expansiveness samples.

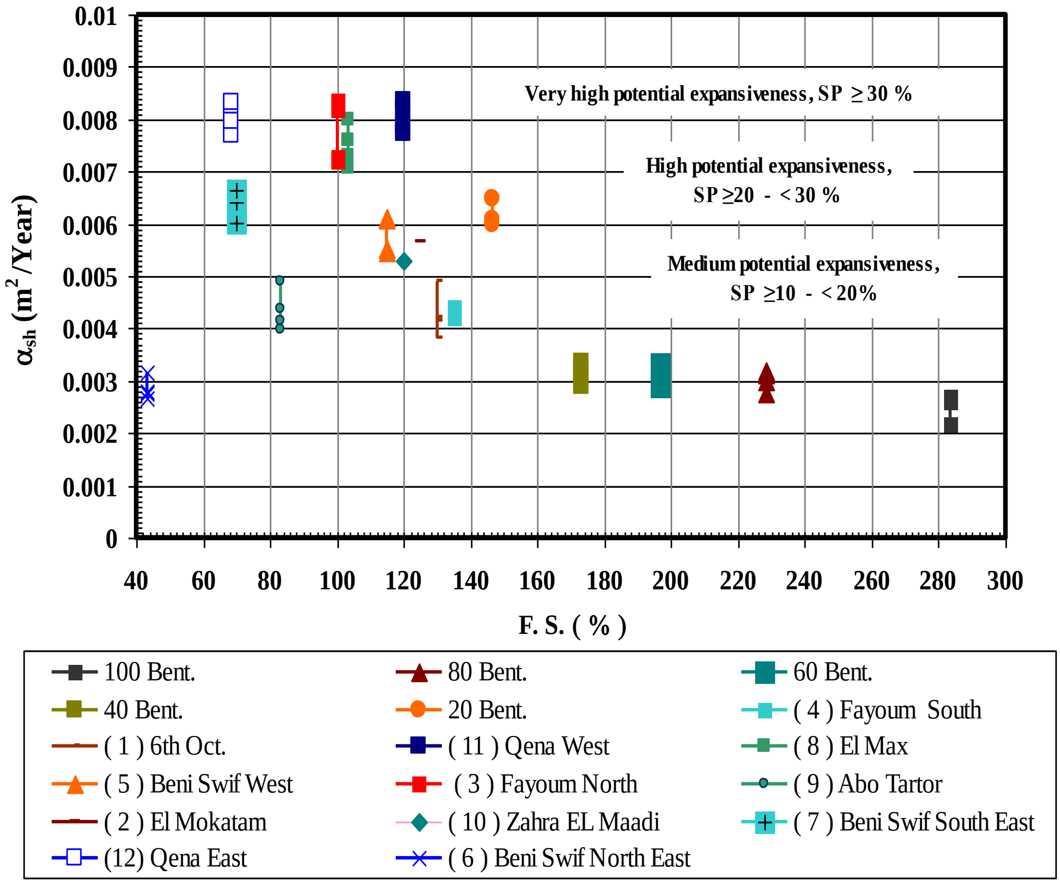

Figure10. Effect of free swell on the coefficient of unsaturated diffusivity of soil (α_{sh})for the soil samples.

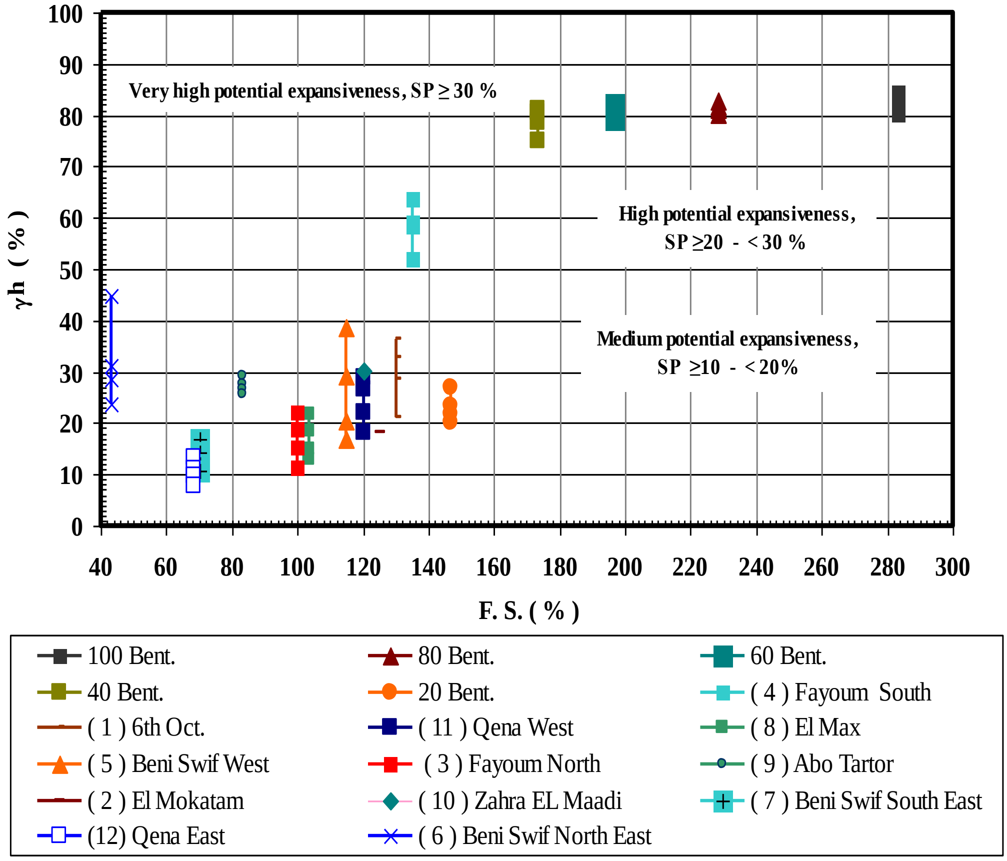

Figure11. Effect of free swell on the suction compressibility index of soil. (γ_h)for the soil samples.

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 1** presents of soil samples index properties.

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 2**, to check the validity of the developed predictive model. Comparisons show the presence of reasonably good agreement between predictions and measurements.

Table 1. Soil samples index properties for Assuit Transformers Station.

Soil Sample	L.L. (%)	P.L. (%)	P.I. (%)	γ_{dry} (g/cm^3)
(1)	61.53	20.66	40.87	1.5
(2)	71.54	22.84	48.7	1.4.15
(3)	61.64	22.84	38.8	1.45

Table 2. Comparison of experimental scheme and predicted equations for Assuit Transformers Electric Substation Samples.

.	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

$I_{ss} = I_{sw} - I_{sh}$.

To verify the proposed predictive model, three undisturbed soil samples were obtained from executed boreholes at Assuit transformers electric substation, which suffered from severe cracks. Values of main shrink-swell characteristics (Isw, Iss, αsh, αsw, γh, and SP) as well as values of soil index properties (LL, PL, PI, γdry) were determined as discussed in this paper. 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, to check the validity of the developed predictive model. Comparisons show the presence of reasonably good agreement between predictions and measurements.

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 increase 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.

There exist clear effects of soil index properties on the behavior of shrink-swell soils. The increase in soil plasticity increases the values of swelling potential, increases the values of suction compressibility, and decreases the coefficient of unsaturated diffusivity of soil.

The increasing of free swell increases the values of swelling potential, increases the values of suction compressibility, and decreases the coefficient of unsaturated diffusivity of soil.

The percentage of swelling potential, and percentage of coefficient of unsaturated diffusivity of soil increasing due to the increasing of dry unit weight of soil. But suction compressibility index of soiled decreases due to the increasing dry unit weight of soil. The increase in soil plasticity increases the values of swelling potential of soil.

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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.

الملخص العربى:

التربة الإنتفاشية هي نوع من أنواع التربة التي تسبب مشاكل إضافية من وجهة النظر الهندسية وذلك نتيجة لظروف تكوينها أو للتغير في الظروف البيئية المحيطة. ومن خصائص هذه التربة أنها تعطي زيادة كبيرة في الحجم عند امتصاصها للماء كما أنها تعطي نسبة انكماش عالية عند خروج الماء منها. وبالتالي فيحدث لها تغير حجمي ملحوظ مع تغير قيمه المحتوى المائي لها. والتأسيس علي هذه التربة يكون مصحوبا بمشاكل بسبب حدوث الحركة النسبية في المنشأ نتيجة الانتفاخ والهبوط وقد تحدث أضرار بالغة تؤدي إلي الانهيار.

تتواجد هذه التربة بمصر ضمن الترسيبات الصحراوية الجافة أو ضمن الترسيبات الساحلية المشبعة، والعامل الأساسي الذي يؤثر في خواص التربة القابلة للانتفاخ هو التركيب المعدنى لمحتوي الطين.

في هذا البحث تم دراسة خواص الإنتفاش لبعض العينات من التربة الإنتفاخية (٤٢) عينة تم تجميعها من عده مناطق بداخل مصر وهي : المقطم – زهراء المعادي – مدينة ٦ أكتوبر – بني سويف – الفيوم – الوادي الجديد – قنا. بالإضافة إلي (٢٠) عينة تم تجهيزها بخلط نسب مختلفة من البنتونيت التجاري مع الطين ، وفي هذا البحث أيضا تم دراسة بعض العوامل التى تؤثر علي طاقة الانتفاش ، معامل الإنتشار، و إنضغاطية الإمتصاص.

تم إجراء دراسة معملية مكثفة لإستنتاج الخواص الاساسية (حدود أتربرج – الوزن النوعي – الكثافة الجافة – حد الإنتفاش – حد الإنكماش – الإنتفاش الحر)، وتم أيضا تحديد خواص الإنتفاش مثل طاقة الإنتفاخ ، قيمة معامل الإنتشار (α - shrink و α - swell) باستخدام (α – shrink test) كما هو موضح بالبحث.وكذلك تم دراسة ورسم منحنى (SWCC) ومن هذا المنحني تم تعيين قيمه (γ_h) وهي إنضغاطية الامتصاص Suction Compressibility وذلك لكل عينه علي حده.

ومن هذه الدراسة تم التوصل الي العديد من النتائج الهامه ومن أهمها : زيادة ملحوظة في قيمه طاقة الانتفاخ و معامل الإنتشار مع زيادة كثافة العينات، زيادة قيمة الانتفاش الحر وحد السيولة ومعامل اللدونة بزيادة نسبة البنتونيت. ولقد تم التوصل من هذه الدراسة الي العديد من العلاقات الهامة والتى يتم بواسطتها تحديد خواص الإنتفاش باستخدام خواص التربة الأساسيه مثل حدود أتربرج، وجميع هذه المنحنيات والعلاقات الناتجه منها موضحة بهذا البحث.