# Characterization of Unsaturated Shrink-Swell soils properties, and Factors Affecting Swelling Behaviour of Expansive soils in Egypt.

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**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. In this paper 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. Also, the effect of some factors influencing of the swelling behaviour of expansive soils in Egypt were discussed.*

**KEYWORDS:** *Expansive soil, Shrink-Swell Soil, Soil water characteristic curve, Swell potential, Volumetric change, and Unsaturated soils.*

## I.   INTRODUCTION.

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

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

Briaud etal.(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, E. (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.

Israr, J. et al. (2014) found that there exist unique relationships between the index properties and the swelling characteristics of swelling soils. Expansion of soils can directly bemeasured in the laboratory, by immersing a remoldedsoil sample and measuring its volume change through 24-hour free swell test,(Hammam, A. H. andAbdel-Salam, A. E.2013).The results showed that,the increasing Atterberg's limits suchas plasticity index (P.I.) from 18% to 150% impart significant increasesin 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.

Zapata, C. 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 propertiesis 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 toAL-Shihabi, O. (2010), suction compressibility indices ($\gamma_h$) can be obtained by determination of the slope of Soil Water Characteristic Curve(SWCC).

Jian-lin, Y. and Jian , Z. (2005) discussed the main influencing factors on the SWCC. Among these factors stress state and initial water content have the greatest influence. However, at high suction values the effect of these factors tends to diminish.

The main objective of this paper is to assess soil engineering properties (mainlyvolumetric change and moisture diffusioncharacteristics) for expansivesoilssamples obtained from various sites in Egypt, and study the factors influencing swelling behaviour of expansive soils.A new proposed set of relationshipswere developed that may be treated as areliable tool to estimate the swellingand shrinking characteristicswith carefully evaluated index properties in hand.

## II.  LABORATORY INVESTIGATIONS.

In this study, a comprehensive experimentalscheme has been undertaken atGeotechnicalEngineering Laboratory, Faculty of Engineering, and EL-MiniaUniversity, to investigatevarious factors controlling the swelling and shrinkingcharacteristics 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 has been reported herein. Theinterpretations facilitated the development of a set of simpleempirical correlations between soil index properties and key swelling and shrinkingparameters ofexpansive 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- 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 **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 oedometercells 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).

**Figure1.** *Map of Egypt with locations of the samples sites.*
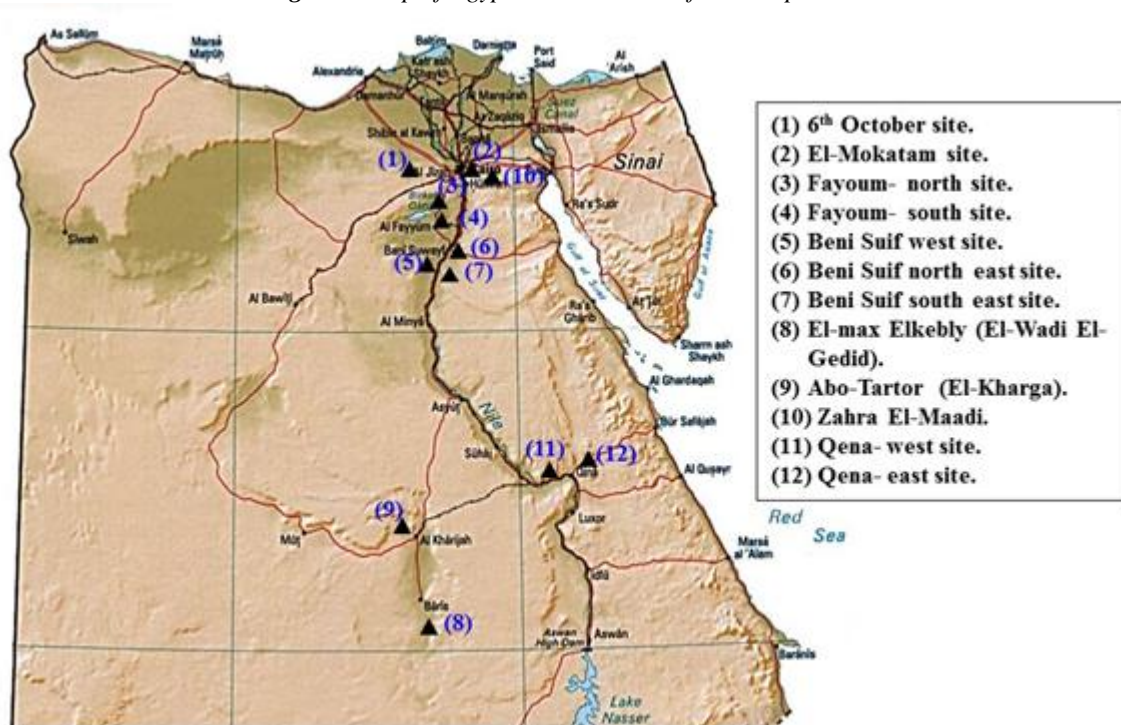


### 2.2. Bentonite-Silty Clay Soil Mixtures

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

(OCMA DFCP.4) is acommercial bentonite, produced by Egyptian Gulf Chemical Company "EGCC", located at Sadat city –Industrial Zone 6 – Cairo,which hasbeen 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-swellingnatural 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.

## III. TESTING PROGRAM.

### 3.1. Soil Index Properties

Identification tests were performed in order to have a background data base for the soilproperties. 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 ($\gamma_{dry}$), 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, R. I. (2007) procedure.

### 3.2. Moisture Diffusionand 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 ($\alpha_{sh}$) were determined using $\alpha$-shrink test procedure developed by Abdelmalak, R. I. (2007). However,coefficients of soil unsaturated diffusivity in swell condition ($\alpha_{sw}$) were determined using 1-D time factors similar to commonly used in consolidation test, Das, B. M. (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, R. I. (2007).In $\alpha$-shrink test, a cylindrical soil specimen shrinks in both the vertical and horizontal directions (i.e. 2-D axisymmetric problem), which obliged Abdelmalak, R. I. (2007) to develop time factors for 2-D axisymmetric diffusion problem.Meanwhile, in $\alpha$-swelltest, 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, E., (2005) andBulut, R., (2001). Slope of the straight line in the desaturation zone were determined, which equals to the suction compressibility index ($\gamma_h$).

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 of2.5, 3.5, 4.5 and 5.5 pF using saturated salt solutions ofNaCL.

## IV. FACTORS AFFECTING SWELLING BEHAVIOUR.

Melek, R. I. (2000) reported that El-Sibaie, (1992) summarized that: the swelling behaviour of clays is influenced by:

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 this paper, the effect of plasticity index, free well, and dry unit weights on the swelling behaviour of sixty two (62) expansive soils obtained from various sites all over Egypt are discussed.

Based on the tests results, the samples can be classified as:

• 100 Bent., 80 Bent, 60 Bent., 40 Bent., 20 Bent., ( 4 ) Fayoum South, ( 1 ) 6th Oct., ( 1 ), ( 11 ) Qena West., ( 8 ) El Max.Very high potential expansiveness.

• ( 5 ) Beni Swif West, ( 3 ) Fayoum North, ( 9 ) Abo Tartor. High potential expansiveness.

• ( 2 ) El Mokatam, ( 10 ) Zahra EL Maadi, ( 7 ) Beni Swif  South East, ( 12 ) Qena East, ( 6 ) Beni Swif North East.Medium potential expansiveness.

## V.  RESULTS AND DISCUSSION

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

*Figure.2. Effect of Bentonite content in Bentonite-soil mixtures*
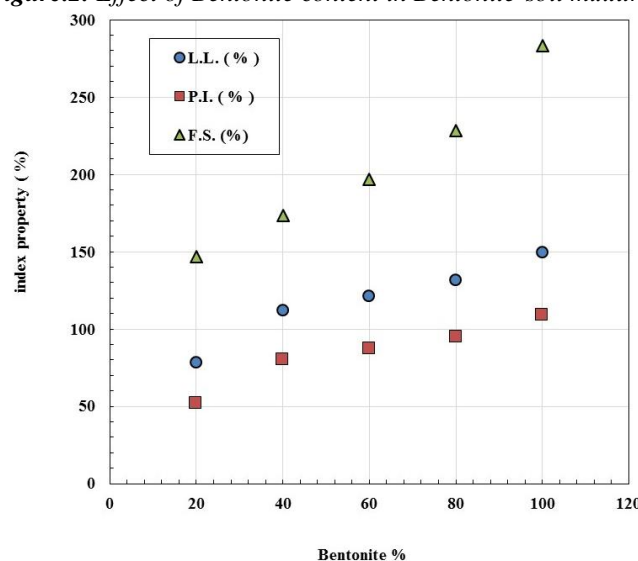
Ten different regression equations were established among swelling characteristics and soil index properties, as illustrated in **Tab. 1.** For example, to develop reliable predictive equation for the soil suction compressibility index ($\gamma_h$), relationships between ($\gamma_h$)and many parameters and combinations of parameters(such as: $\alpha_{sh}$, $\alpha_{sw,}$ SP, P.I./$\gamma_{dry}$, P.I., L.L./$\gamma_{dry}$, P.L./$\gamma_{dry}$) have been investigated. Variousmathematical functions were employed to find the best curve fitting for each relationship such as: exponential, linear, $2^{nd}$ degree polynomial, hyperbolic, and logarithmic.**Tab. 2.**presents resulting ($R^2$) values from curve fittings. Logarithmic curve fitting equation between ($\gamma_h$) and (P.I./$\gamma_{dry}$) 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 **Tab. 1**. , were developed.

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

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

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

| Curve Fitting | $\alpha_{sh}$ | $\alpha_{sw}$ | SP | P.I./$\gamma_{dry}$ | P.I. | L.L./$\gamma_{dry}$ | P.L./$\gamma_{dry}$ |
|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|
| **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 |

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

**5.1.1.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 **Tab. 1.**), which confirms the existence of strong correlation betweenshrink- swell index and plasticity index of soil.

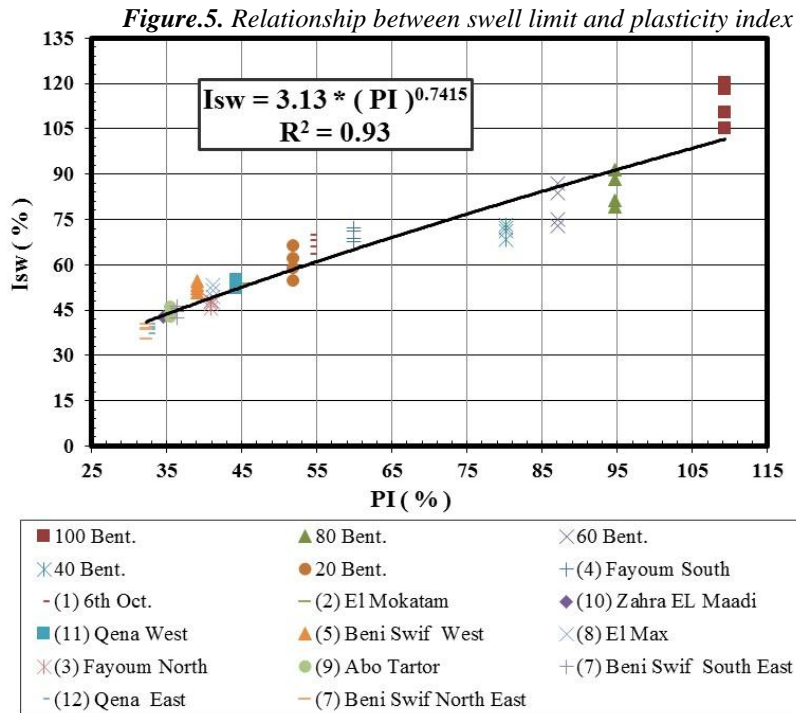*Figure.3. Relationship between soil shrink-swell index and plasticity index.*
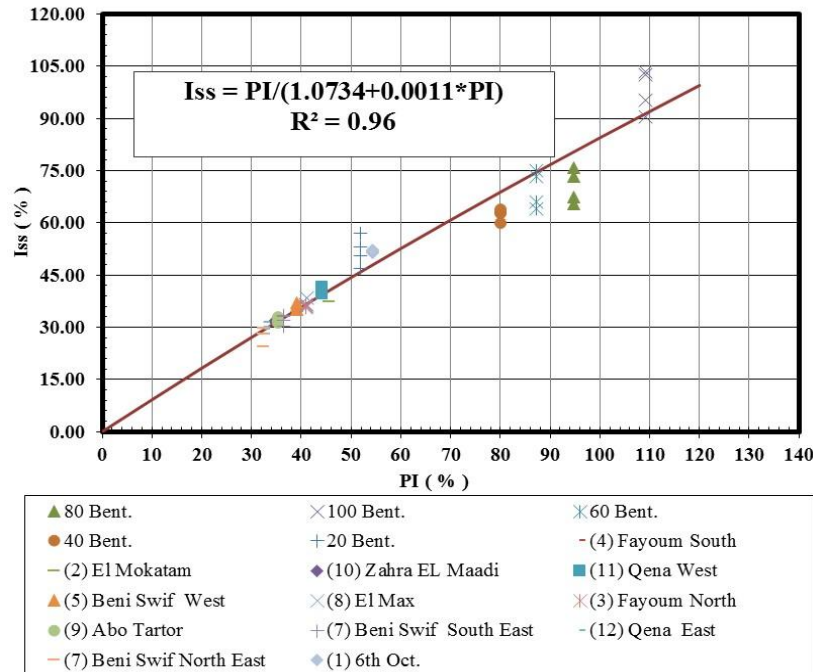


Similarly, soil shrink- swell indices were plotted against free swell values, as shown in **Fig. 4**. The data indicatethe existence of a linear relationship between soil shrink-swell index andfree swell. The determined coefficient of determination value ($R^2$ = 0.93, refer to **Eq.2** in **Tab. 1.**)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

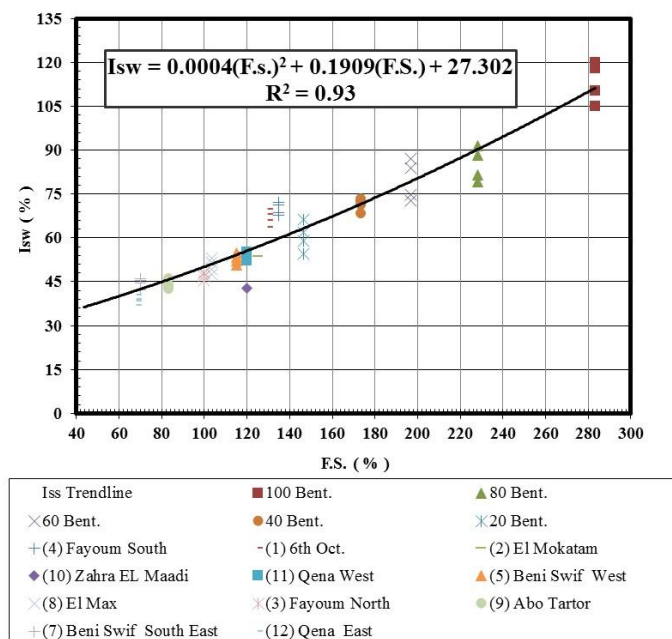*Figure.4. Relationship between soil shrink-swell index and free swell.*
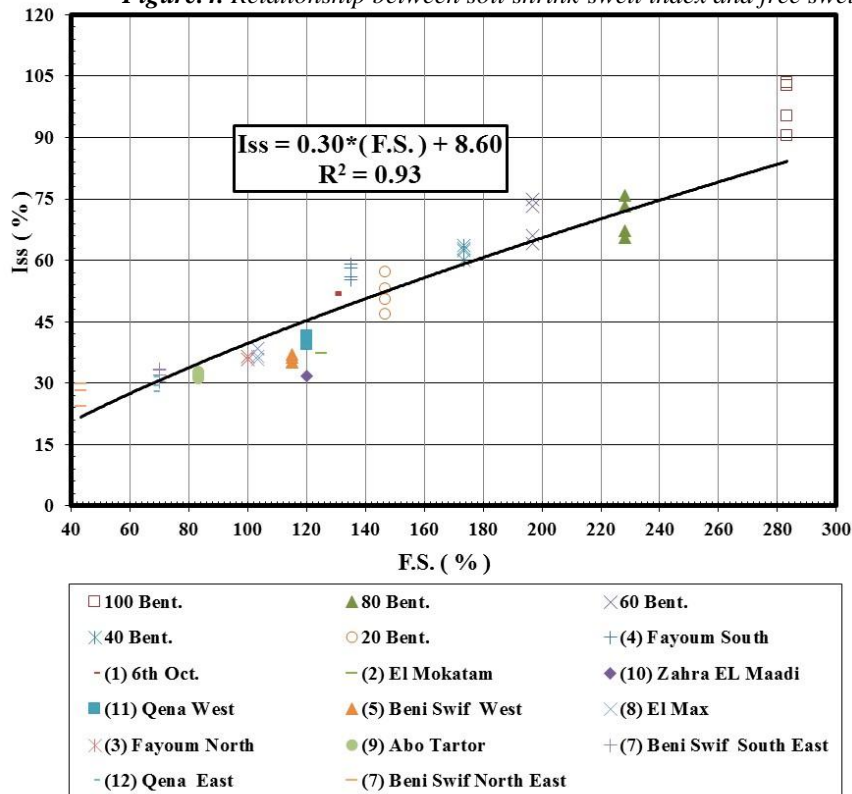
**5.1.2.Soils well limit**

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

***Figure.5.*** *Relationship between swell limit and plasticity index*



$$Isw = 3.13 * ( PI )^{0.7415}$$
$$R^2 = 0.93$$

| ■ 100 Bent. | ▲ 80 Bent. | ✕ 60 Bent. |
| ✳ 40 Bent. | ● 20 Bent. | + (4) Fayoum South |
| - (1) 6th Oct. | — (2) El Mokatam | ◆ (10) Zahra EL Maadi |
| ■ (11) Qena West | ▲ (5) Beni Swif West | ✕ (8) El Max |
| ✳ (3) Fayoum North | ● (9) Abo Tartor | + (7) Beni Swif South East |
| - (12) Qena East | — (7) Beni Swif North East | |

The same level of correlation was found between the soil swell limit and free swellvalue, as illustrated in **Fig.6.**A2nd degree polynomial well represented the relationship between soil swell limitandfree swell with a high coefficient of determination ($R^2$= 0.93, **Eq. 4** in **Tab. 1.**).

***Figure. 6***. *Relationship between swell limit and free swell.*



$$Isw = 0.0004(F.s.)^2 + 0.1909(F.S.) + 27.302$$
$$R^2 = 0.93$$

| Iss Trendline | ■ 100 Bent. | ▲ 80 Bent. |
| ✕ 60 Bent. | ● 40 Bent. | ✳ 20 Bent. |
| + (4) Fayoum South | - (1) 6th Oct. | — (2) El Mokatam |
| ◆ (10) Zahra EL Maadi | ■ (11) Qena West | ▲ (5) Beni Swif West |
| ✕ (8) El Max | ✳ (3) Fayoum North | ● (9) Abo Tartor |
| + (7) Beni Swif South East | - (12) Qena East | |

### 5.1.3.Suction compressibility index

**Fig.7.**demonstratesthe relationship between measured soil suction compressibility indices and their corresponding determined ratios between plasticity index and dry unit weight. Logarithmicregression (**Eq. 5** in **Tab. 1.**) reflected the good correlation between suction compressibility of soil and the ratio of plasticity index to dry unit weight ($R^2$=0.83).

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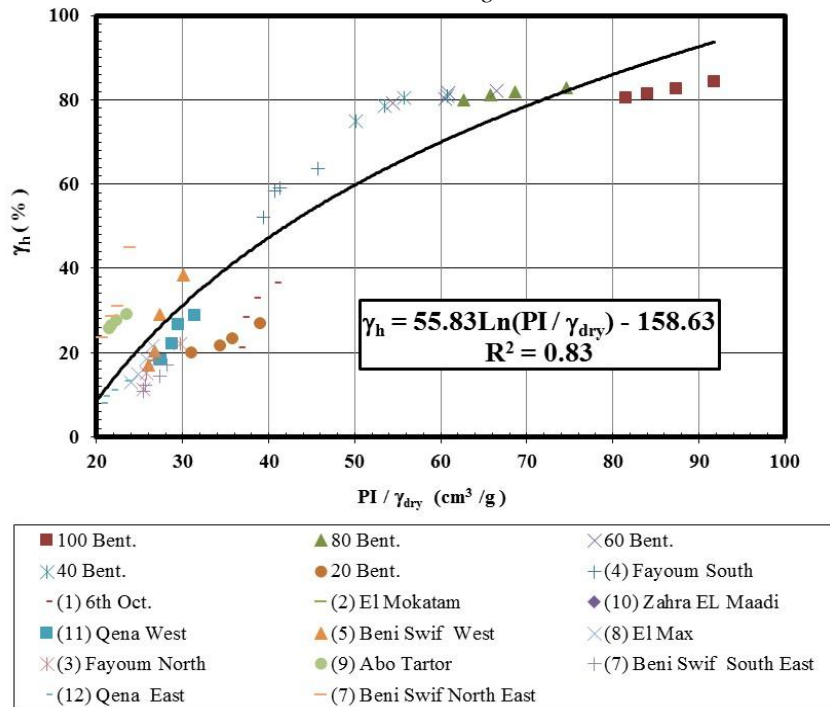


### 5.1.4.Soil coefficients of unsaturated diffusivity

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

To investigate the correlation between soil coefficients of unsaturated diffusivities in shrink condition ($\alpha_{sh}$) and in swell conditions ($\alpha_{sw}$), **FIig. 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 **Tab. 1.**

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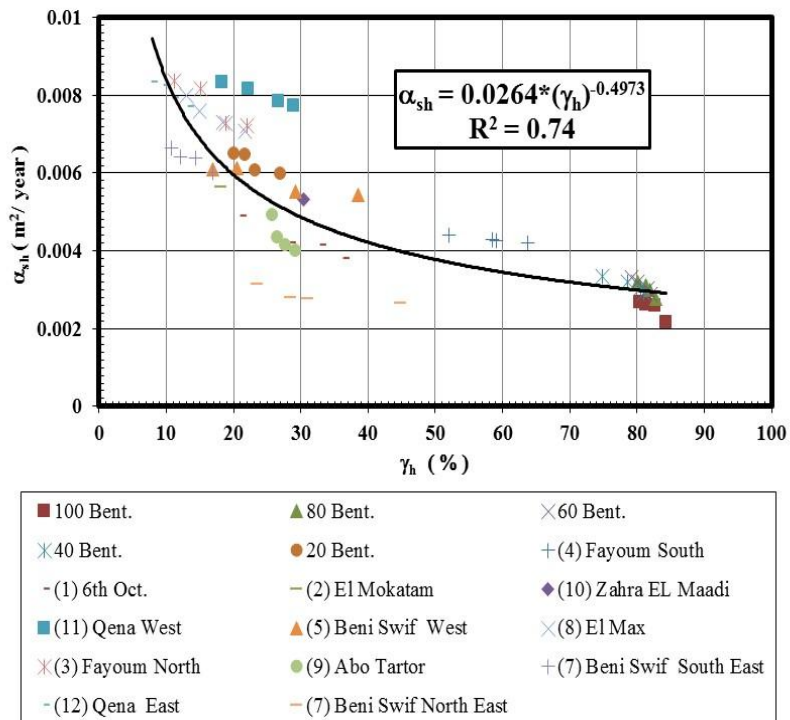


***Figure. 9.*** *Relationship between soil coefficient of unsaturated diffusivity in shrink condition and ratio of suction compressibility index to dry unit weight.*
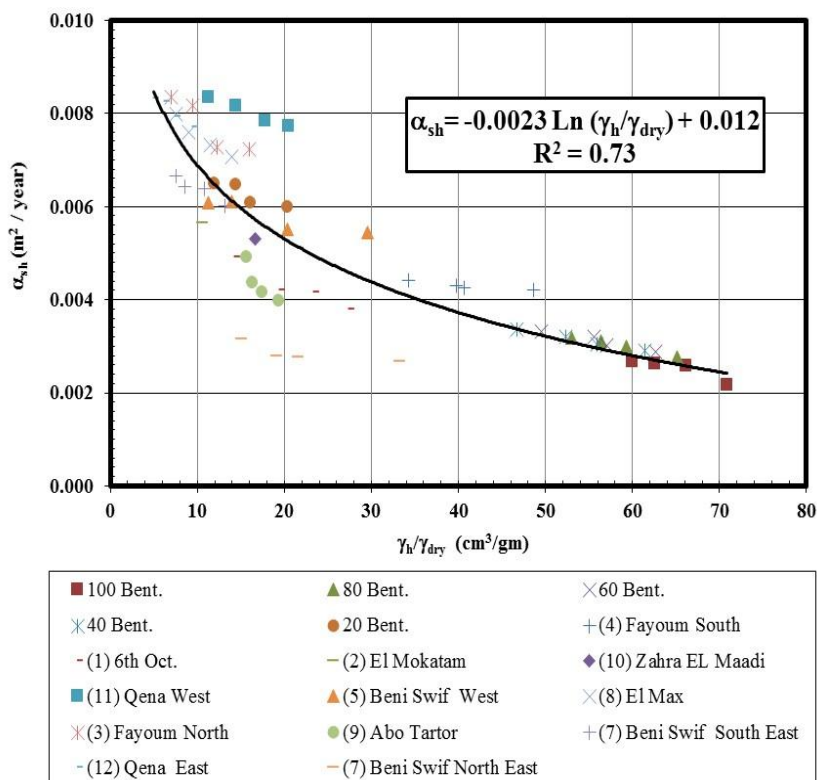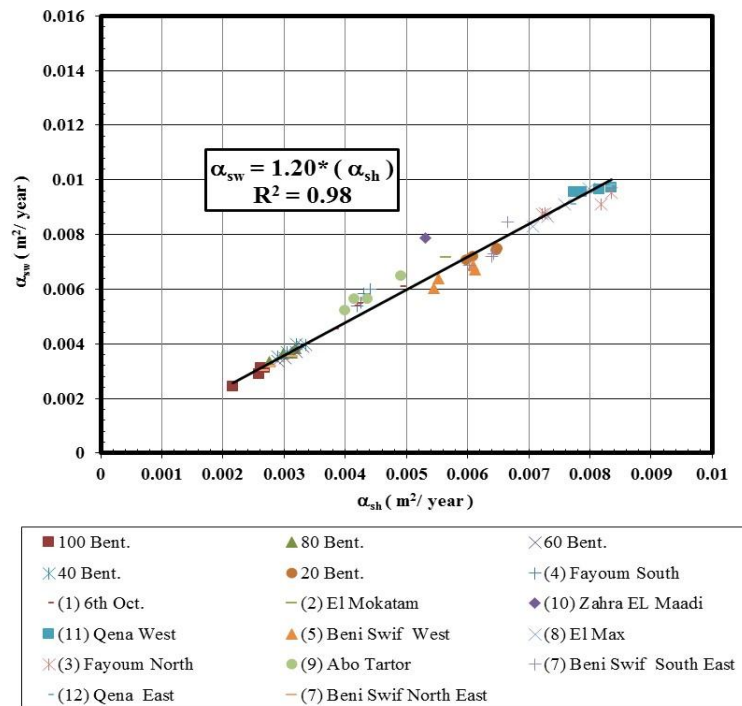
***Figure. 10.*** *Relationship between soil coefficients of unsaturated diffusivities in shrink and swell conditions.*



.1.5.Soil swell potential

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

***Figure. 11.*** *Relationship between soil swell potential and plasticity index.*
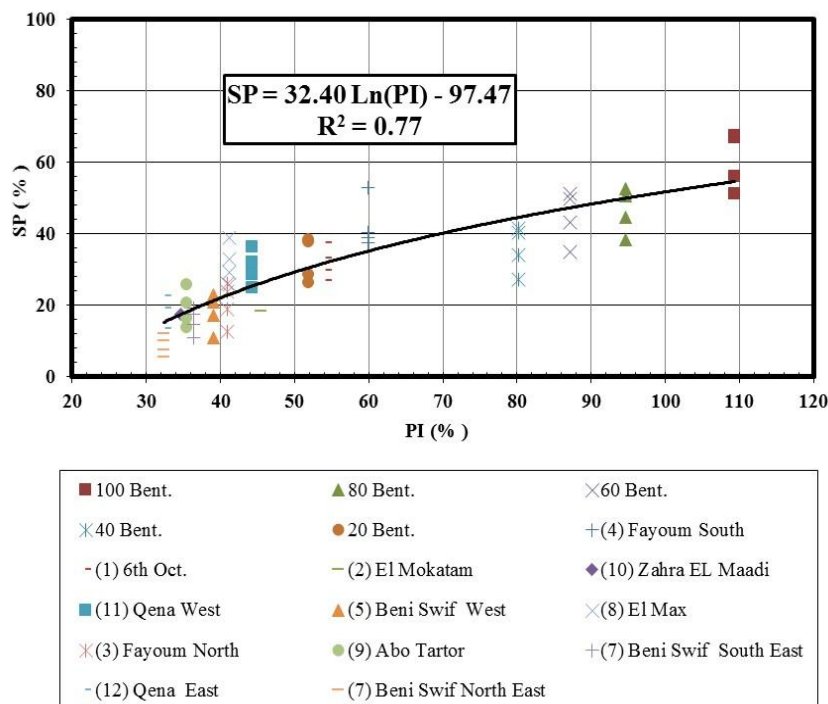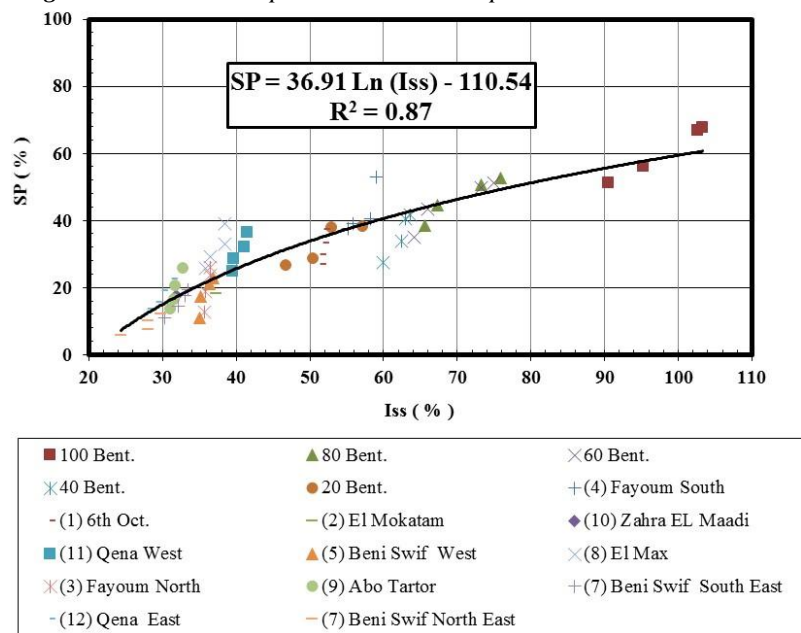
***Figure. 12.*** *Relationship between soil swell potential and shrink-swell index.*
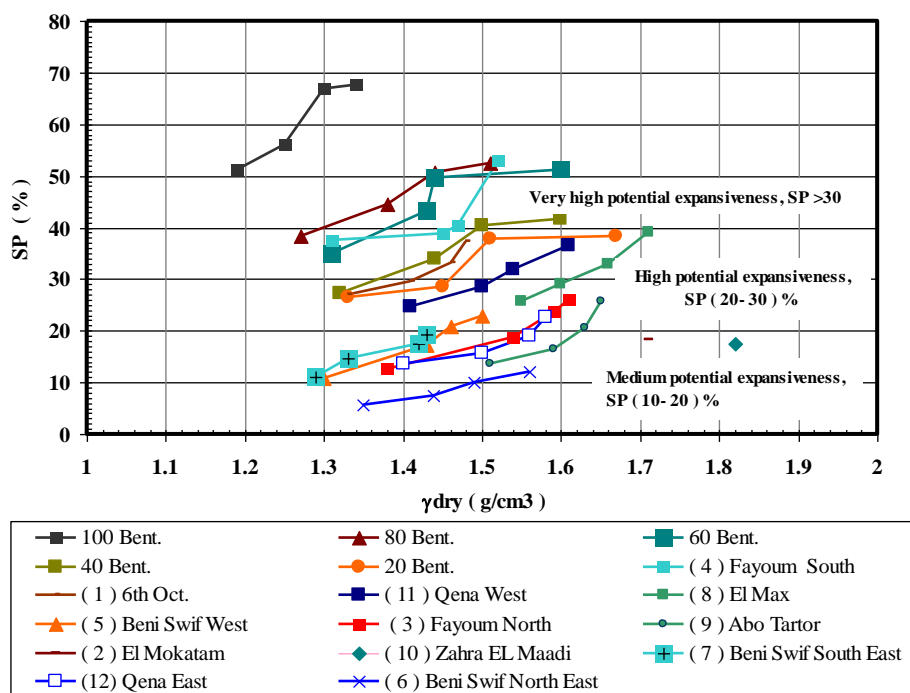


**5.2. Factors Affecting Swelling Behaviour in Egypt.**
**5.2. 1. Effect of dry unit weight on the swelling potential of soil.**
For very high potential expansiveness samples, the increase in dry unit weight of soil (from 10.32% to25.56%) increases the percentage of swelling potential (from 32.18% to52.23%). For high potential expansiveness samples, the increase indry unit weight of soil (from 9.27% to16.67%) increases the percentage of swelling potential (from 88.69% to109.18%). 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% to116.82%).

**Fig. 13.** illustrated the effect of dry unit weight on the swelling potential of soil.

***Figure. 13.*** *Effect of dry unit weight on the swelling potential for the soil samples.*

**5.2.2. Effect of dry unit weight on the coefficient of unsaturated diffusivity of soil (αsh).**

**Fig. 14.** illustrated the effect of dry unit weight on the coefficient of unsaturated diffusivity of soil. 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% to28.87%).

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% to18.08%).

***Figure. 14.** Effect of dry unit weight on the coefficient of unsaturated diffusivity of soil ( αsh ) for the soil samples.*
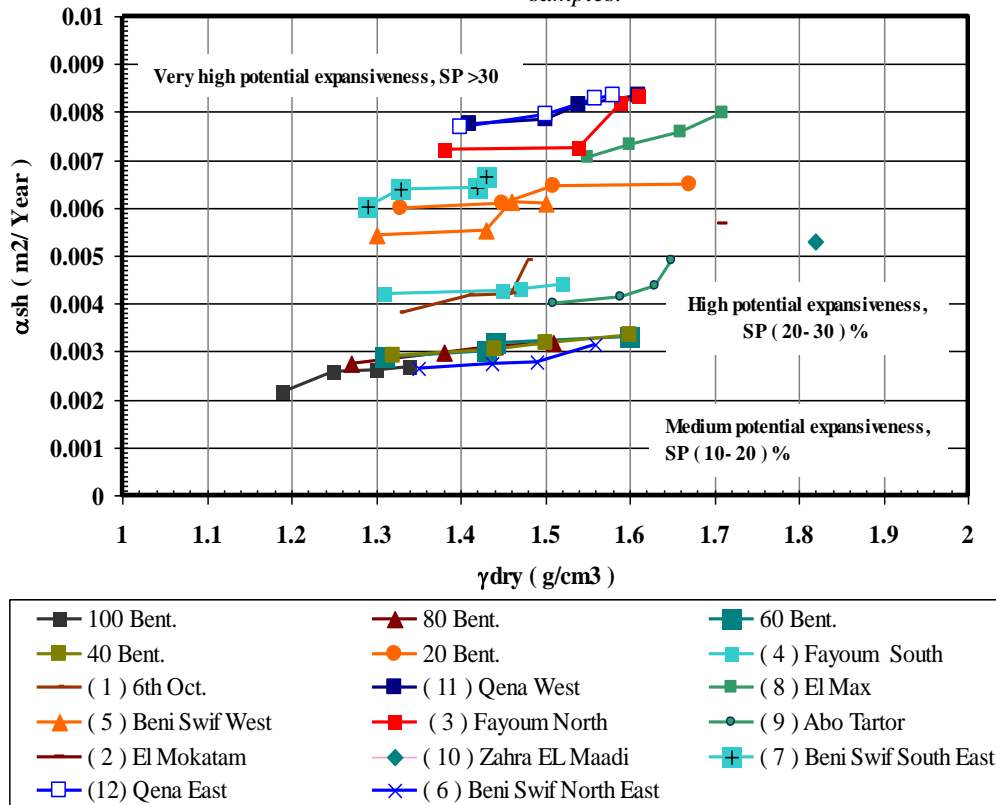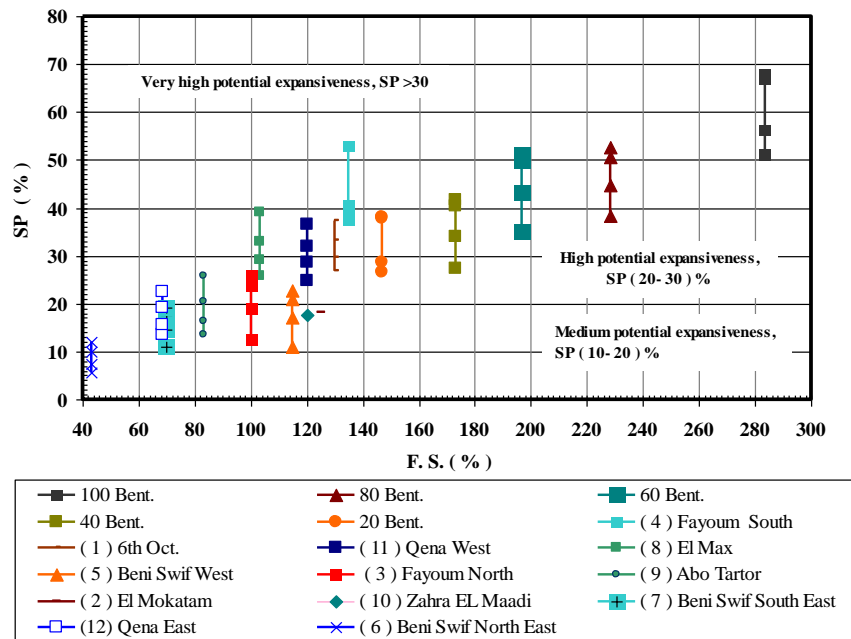


**5.2.3. Effect of free swellon the swelling potential of soil.**

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% to52.23%). 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% to109.18%). 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%).

**Fig. 15.** illustrated the effect of free swell on the swelling potential of soil.

*Figure .15. Effect of free swell on the swelling potential for the soil samples.*



**5.2.4. Effect of free swellon the coefficient of unsaturated diffusivity of soil (αsh).**

**Fig. 16.** illustrated 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% to8.40%).

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% to18.08%).

*Figure .16. Effect of free swell on the swelling potential for the soil samples.*
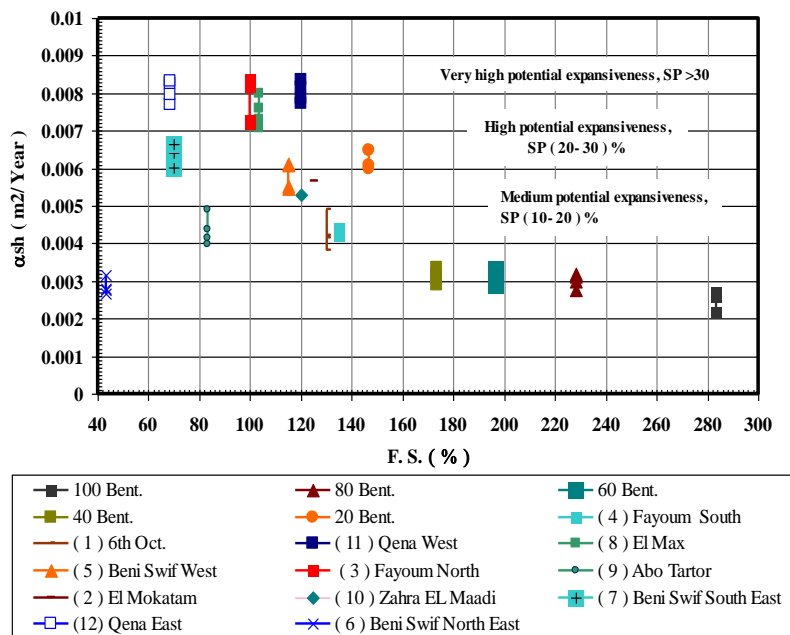
## VI. MODEL VERIFICATION.

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 ($I_{sw}$, $I_{ss}$, $\alpha_{sh}$, $\alpha_{sw}$, $\gamma_h$, and SP) as well as values of soil index properties (LL, PL, PI, $\gamma_{dry}$) were determined via laboratory testing program as explained above. **Tab.3** presents 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 **Tab. 4**, to check the validity of the developed predictive model. Comparisons show the presence of reasonably good agreement between predictions and measurements.

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

| Soil Sample | L.L. ( % ) | P.L. ( % ) | P.I. ( % ) | $\gamma_{dry}$ (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 |
| | $\alpha_{sh}$( cm$^2$/min ) | 0.000074 | 0.0001037 | -0.000030 | 40.54 |
| | $\alpha_{sw}$( cm$^2$/min ) | 0.0000589 | 0.0000888 | -0.000003 | 5.09 |
| | $\gamma_h$( % ) | 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 |
| | $\alpha_{sh}$( cm$^2$/min ) | 0.000083 | 0.0001032 | -0.000020 | 24.09 |
| | $\alpha_{sw}$( cm$^2$/min ) | 0.0001103 | 0.0000996 | 0.000011 | 9.97 |
| | $\gamma_h$( % ) | 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 |
| | $\alpha_{sh}$( cm$^2$/min ) | 0.00008 | 0.0001163 | -0.00036 | 45 |
| | $\alpha_{sw}$( cm$^2$/min ) | 0.0001112 | 0.000096 | 0.000015 | 1.34 |
| | $\gamma_h$( % ) | 18.39 | 24.88 | -6.49 | 35.29 |
| | SP ( % ) | 35.11 | 20.98 | 14.13 | 40.24 |

## VII. 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 theindex properties and the swellingcharacteristics ofthe tested swelling soils.

A new set of correlation equations was proposed to estimate the swelling characteristicswith 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 rationallyverified 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.

There exist unique relationships between the index properties and the swellingcharacteristics of swelling soils. The increasingof free swell increases the values of swelling potential, 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 dry unit weight of soil.

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