Prediction of Swelling Pressure and Factors Affecting the Swell Behavior of an Expansive Soil

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ABSTRACT

Side friction and nonuniform distribution of moisture content over the soil specimen during saturation were the main sources of error in determining the swelling properties of an expansive soil. To decrease the frictional stresses between the soil and the confining ring of the oedometer apparatus, several techniques were used. A description of the test apparatus and the different techniques to reduce frictional effects are discussed. The merit and the theoretical background of each technique are evaluated. On the basis of experimental results of 28 soil specimens, a semiempirical equation is deduced to determine the value of swelling pressure in terms of initial dry density, initial water content, and clay content of the soil. This equation is compared with other methods of predicting swelling pressures. The semiempirical equation proposed in this paper can be used as a design guide to predict swelling pressures for the expansive soil studied.

Ramamurthy showed that side friction and nonuniform distribution of moisture over the soil specimen during saturation were the main sources of error in laboratory studies investigating the swelling properties of soil (1). By using a cylindrical soil specimen of a low height and a rubber membrane, the side friction could be considerably reduced. Laboratory research conducted by Ramakrishna showed that during the measurement of swelling percent and swelling pressure in an oedometer, the skin friction was eliminated by a thin rubber membrane between the soil and the confining ring that was coated with silicon grease (2).

El-Ramli found that the swelling pressure could be obtained from the following empirical equation (3):

$$P_s = 1{\cdot}2\ \gamma_d/w_s \qquad (1)$$

where P_s is swelling pressure (kg/cm^2), γ_d is dry density (g/cm^3), and w_s is shrinkage limit. The effect of initial water content on swelling pressure is not considered in this equation.

Komornik and David proposed the following relationship to estimate the swelling pressure (4):

$$\text{Log } P_s = \bar{2}.132 + 0.0208\ w_L + 0.000665\ \gamma_d - 0.0269\ w_n \qquad (2)$$

where

w_L = liquid limit,
w_n = natural water content,
P_s = swelling pressure (kg/cm^2), and
γ_d = dry density (g/cm^3).

This equation involves the main parameters that influence swelling pressure, but it is quite insensitive to variations in dry density; therefore, it should not be used if the dry density changes.

Zacharias and Ranganatham derived the following equation for the swelling pressure, p (kg/cm^2) (5):

$$P_s = a\ (SI) + b\ (w_L - w^*) + C\ (SI)\ (1/S_r) \qquad (3)$$

where

SI = shrinkage index,
S_r = degree of saturation of specimen before start of test,
w^* = water content at S_r = 100 percent, and
a = -225/6.4, b = 290/6.4, and C = 1.2/6.4.

The dry density that has an important role to play in the swelling pressure is not included in this equation, and therefore the relationship is limited to dry densities ranging between 17 and 18 kN/m^3. This restricts the application of this equation considerably.

Dedier produced two equations for the relation between swelling pressure, dry density, and clay percentage as follows (6):

$$\text{Log } P_s = 2.55\ \gamma_d/\gamma_w - 1.705 \qquad (4)$$

$$\text{Log } P_s = 0.0294C - 1.923 \qquad (5)$$

where C is clay content (%), γ_w is density of water (g/cm^3), and P_s is given in kg/cm^2.

Neither Equation 4 nor Equation 5 considers the initial water content of the soil. Because the initial water content has a great effect on the value of both swelling percent and swelling pressure, the equations cannot be applied to soils having different initial water contents.

Rabba produced two equations for the relationship between swelling pressure, initial dry density, and clay percentage in cases of sandy-clay and silty-clay soils as follows (7):

For sandy-clay soils

$$\text{Log } P_s = 2.17\ (\gamma_d + 0.084C) - 3.91 \qquad (6)$$

For silty-clay soils

$$\text{Log } P_s = 2.5\ (\gamma_d + 0.006C) - 4 \qquad (7)$$

Units of P_s and γ_d are given in the previous equations. Equations 6 and 7 are limited to an initial water content of 8 percent.

The purpose of this laboratory study was to investigate the effect of side friction of the swelling behavior of an expansive soil found in Nasr City, a satellite city of Cairo, Egypt [for a detailed description of this soil see the paper titled "Treatment of Expansive Soils: A Laboratory Study" elsewhere in this record and Mowafy et al. (8)].

TEST APPARATUS AND TECHNIQUE

The ring of the oedometer used in the swelling tests had an internal diameter of 63 mm and a height of 25 mm. The swelling pressure is defined as the external pressure required to consolidate a preswelled sample to its initial void ratio.

Preparation of Test Specimens

An amount of soil was oven dried at a constant temperature (105 to 110° C) for 24 hr. The sample was mixed with the calculated amount of water to give the required initial water content, then it was kneaded thoroughly by hand until it became homogeneous (uniform color). The soil was then pressed into the mold. A pressure pad was applied at the sample surface. The specimen was then statically compacted until the required height corresponded to the specified density. Filter papers and porous plates were applied at the top and bottom of the specimen.

After preparation of the specimen, the mold containing the soil was put into the loading apparatus. An initial load of 100 kPa was applied and the reading of the dial gauge was recorded. After the pressure application, the specimen was submerged in distilled water. As soon as water was added the deformation of the specimen was recorded. The test was continued until the deformation of the specimen ceased. This generally occurred after 96 hr. After the swelling was complete the specimen was reconsolidated to its original void ratio. The corresponding pressure was termed the swelling pressure of the soil.

METHODS OF REDUCING FRICTIONAL STRESSES

There are several components of stresses that are brought into effect by the preparation of the soil sample (compaction) and by the loading procedures. The sum of the radial stresses is the confining pressure of the soil specimen that the confining ring exerts on the soil. During the compaction of the soil specimen inside a mold, a radial stress, σ_i, is exerted on it. An additional horizontal stress ($\Delta\sigma_{h1}$) will act on the circumference of the soil specimen due to the swelling of the soil. If the soil specimen is subjected to an initial preload, this again will produce a radial stress ($\Delta\sigma_{h2}$) due to the consolidation of the soil. The resultant normal stress (σ_n), when multiplied by the coefficient of friction (μ) between the soil and the confining ring material, is the tangential stress τ, that will hinder the free swell of the soil. Complete elimination of this tangential stress is not possible, but several methods were investigated to study the effect of side friction on the swelling properties of the soils investigated: These include (a) the conventional method, (b) the filter paper method, and (c) the rubber membrane method.

Conventional Method

This method did not differ appreciably from the procedure in a standard oedometer test. No attempt was made to reduce the side friction effects on the soil specimens, and the results were used as reference values to which the other test results were compared.

Filter Paper Method

Before the soil was poured into the mold, the mold was lined with filter paper. After compaction, the specimen was extracted and the filter paper was carefully removed. The extracting force was determined for the cases of no filter paper, one layer of filter paper, and two and three layers. The extracting force for the various conditions and the resulting amount of swell are given in Table 1 for one initial moisture and preload pressure. It is clear

TABLE 1 Extracting Force After Compaction

Property of Specimen	Number of Filter Papers	Extracting Force, N	Swelling Percent
$\gamma_d = 15.9$ kN/m^3	None	650	6
$w_i = 15\%$	One	350	6.6
$h_i = 15$ mm	Two	73	7.2
$P_o = 100$ kPa	Three	40	7.3

from the results given in Table 1 that side friction has a marked effect on the free swell of the soil. The horizontal normal stress after compaction and before swelling can be given by

$$\sigma_n = K\sigma_i \tag{8}$$

The corresponding shear stress, τ, is equal to zero, because no movement (swell) has occurred to mobilize it. The value K in Equation 8 is a coefficient to incorporate the effect of the filter papers. From the results given in Table 1 and similar tests on specimens of various initial moisture contents, the K-values were determined as follows:

K = 1 (without filter paper),
K = 0.5 (with one filter paper),
K = 0.1 (with two filter papers), and
K ~ 0 (with three filter papers).

As soon as swelling of the soil begins, the confining stress, σ_n can be expressed as

$$\sigma_n = K(\sigma_i - \Delta\sigma_i) + \Delta\sigma_{h1} \qquad \tau = \mu\sigma_n \tag{9}$$

where $\Delta\sigma_i$ is the increment of vertical stress on the specimen due to swelling. All other terms in the preceding equations have been defined earlier. After completion of the swell test, the specimen is reconsolidated to its initial void ratio. The confining and shear stresses representing this condition can be given as

$$\sigma_n = K(\sigma_i - \Delta\sigma_i) + \Delta\sigma_{h1} + \Delta\sigma_{h2} \qquad \tau = \mu\sigma_n \tag{10}$$

Rubber Membrane Method

In this method the inside of the mold was lubricated with silicon grease and lined with a thin rubber membrane. Compaction was performed as outlined earlier. The soil specimen was not extracted from the mold as in the case of the filter paper method.

The confining (radial) stresses and the shear stresses at the contact surface between soil and mold can be expressed as follows:

After compaction and before swelling begins

$$\sigma_n = \sigma_i$$
$$\tau = 0 \qquad (11)$$

During swelling

$$\sigma_n = \sigma_i - \Delta\sigma_i + \Delta\sigma_{h1}$$
$$\tau = \alpha\ (\mu\sigma_n) \qquad (12)$$

where α is coefficient of friction between soil and membrane (for rubber $\alpha < 1$). After the specimen has been reconsolidated to its original void ratio

$$\sigma_n = \sigma_i - \Delta\sigma_1 + \Delta\sigma_{h1} + \Delta\sigma_{h2}$$
$$\tau = \alpha\ (\mu\Delta_n) \qquad (13)$$

To evaluate the various radial stresses acting on the soil specimen during the several phases of a complete swelling test, a special instrumented compaction ring is needed. Such a cell has not yet been built to the knowledge of the authors.

PRESENTATION AND ANALYSIS OF RESULTS

Effect of Filter Paper on Swelling Behavior

Figure 1 shows that the relationship between the extracting force and swelling percent is linear in

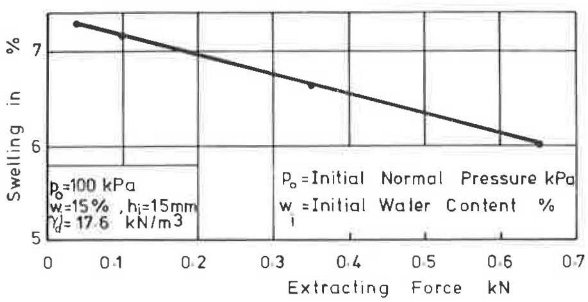

FIGURE 1 Relationship between swelling percent and extraction force.

the case where filter papers were used. Furthermore, this figure indicates that the decrease in the extracting force is accompanied by an increase in the swelling percent. Such phenomenon may be attributed to the horizontal soil stress that produces a tangential stress and that will counteract the free swell of the soil.

Figure 2 shows the relationship between swelling percent and the initial pressure for different numbers of filter papers used. It indicates that the swelling pressure decreases with the increase in the extracting force. In general, it appears that the swelling pressure increases with the number of filter papers used and the minimum swelling pressure corresponds to the case where no filter paper was used.

Effect of Rubber Membrane on Swelling Behavior

The relationship between swelling percent and water content for the conventional and the rubber membrane methods are shown in Figures 3 and 4. As expected,

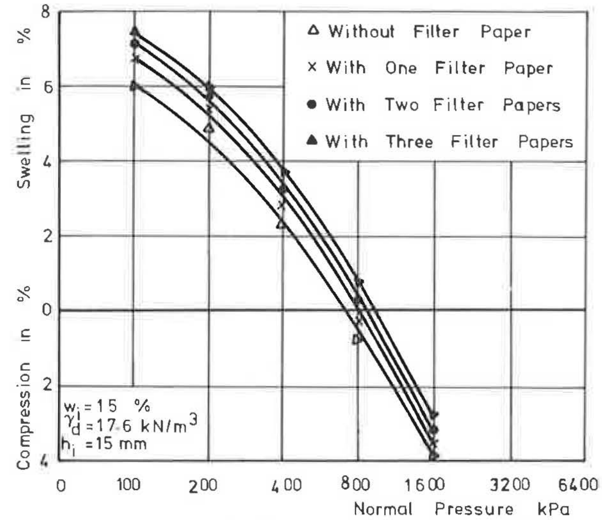

FIGURE 2 Relationship between swelling percent and normal pressure.

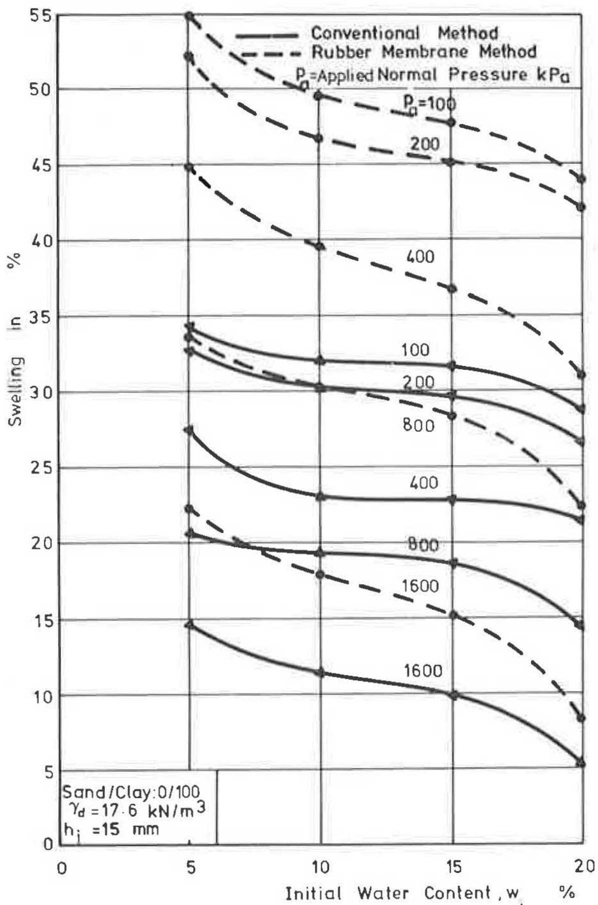

FIGURE 3 Relationship between swelling percent and initial water content.

the swelling percent is greater in the rubber membrane method than in the case where no membrane was used. For instance, at an initial water content of 5 percent and initial normal pressure of 100 kPa at a clay content of 100 percent, the increase in swelling percent is about 60 percent. Furthermore, such increase in the swelling percent is less pronounced

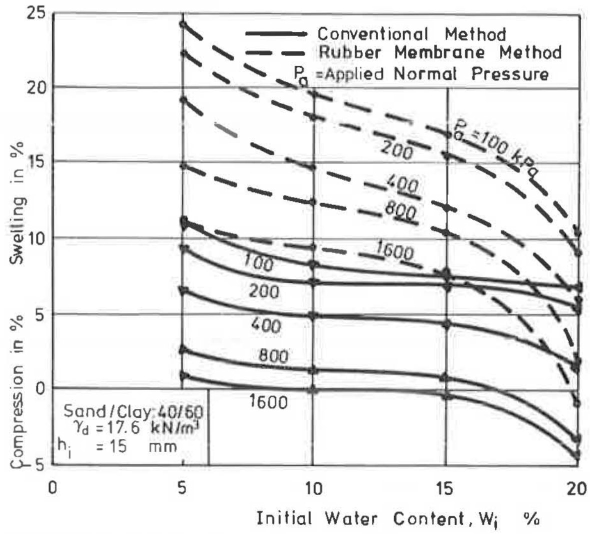

FIGURE 4 Relationship between swelling percent and initial water content.

with the increase in initial applied load for the same initial water content. For instance, in the case of an initial water content of 10 percent, the swelling percent is 50 percent for the rubber membrane method and only 33.5 percent for the conventional method. In both cases the initial normal pressure was 100 kPa. In a similar comparison in which the normal pressure was 1600 kPa, the amount of swell was 18 percent in the case in which a rubber membrane was used compared to 11 percent when the conventional method was used.

In the case of a clay content of 100 percent, the swelling percent is considerably higher than that for a clay content of 60 percent. It is obvious that the increase in the swelling percent when the rubber membrane is used is due to the reduction of the tangential stresses.

From Figure 5, which shows the relationship between swelling percent and initial pressure, the following observations can be made. At high initial water contents there is no difference in the swelling pressure regardless if the rubber membrane or the conventional method is used. On the contrary, at low initial water contents, the swelling pressures are lower when rubber membranes were used than the corresponding values when the conventional method was used. For instance, at 20 percent initial water content, the swelling pressure is 2400 kPa for both the rubber membrane and the conventional methods, whereas at 5 percent initial water content, the swelling pressure is 3200 kPa for the rubber membrane method and 4800 kPa for the conventional method.

NEW SWELLING PRESSURE EQUATION

A general equation for the swelling pressure is proposed as follows:

$$\text{Log } p_s = A\gamma_d + Bc - Dw_n - E \quad (14)$$

where

p_s = swelling pressure in MPa,
γ_d = dry unit weight in kN/m³,
c = clay content in percent,
w_n = initial water content in percent, and
A, B, D, and E are constants to be determined experimentally.

From the 28 specimens tested having various clay,

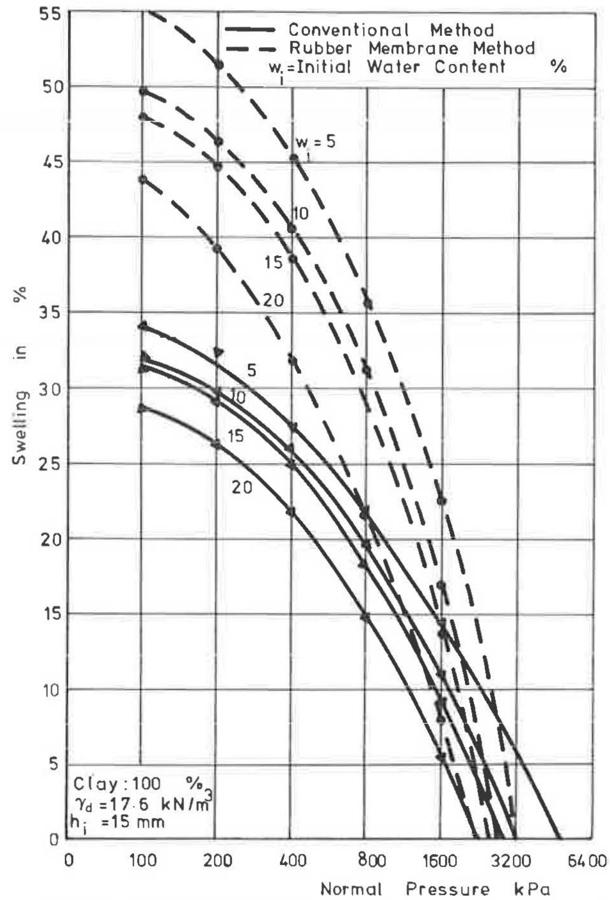

FIGURE 5 Relationship between swelling percent and normal pressure.

silt, and sand contents and different dry densities and initial water contents, a multiple regression analysis was performed using the least square method. From this analysis the constants for A, B, D, and E were determined as follows:

$A = 1.366$
$B = 8.951 \times 10^{-3}$
$D = 2.179 \times 10^{-2}$
$E = 2.840$

Coefficient of correlation: $R = \sqrt{R^2} = 0.71$
Coefficient of determination: $R^2 = 0.50$
Standard deviation: $\sigma^2 = 0.071$
Standard error or regression: $\sigma = 0.27$

Substituting the values for the constants A, B, D, and E in the general relationship will yield the following equation for the swelling pressure for the soil from Nasr City:

$$\log p_s = 1.366\ \gamma_d + 8.951\ (10^{-3})\ C - 2.179\ (10^{-2})\ \omega_n - 2.840 \quad (15)$$

This equation should be used with caution and it is recommended that it be compared to measurements from field tests.

Figures 6-8 show a comparison between the new equation and equations suggested by various researchers. It should be noted that most equations to predict swelling pressures are linear in nature and are partly empirical. Only the equation by Komornik and David and the equation proposed by the authors take the initial water content into consideration.

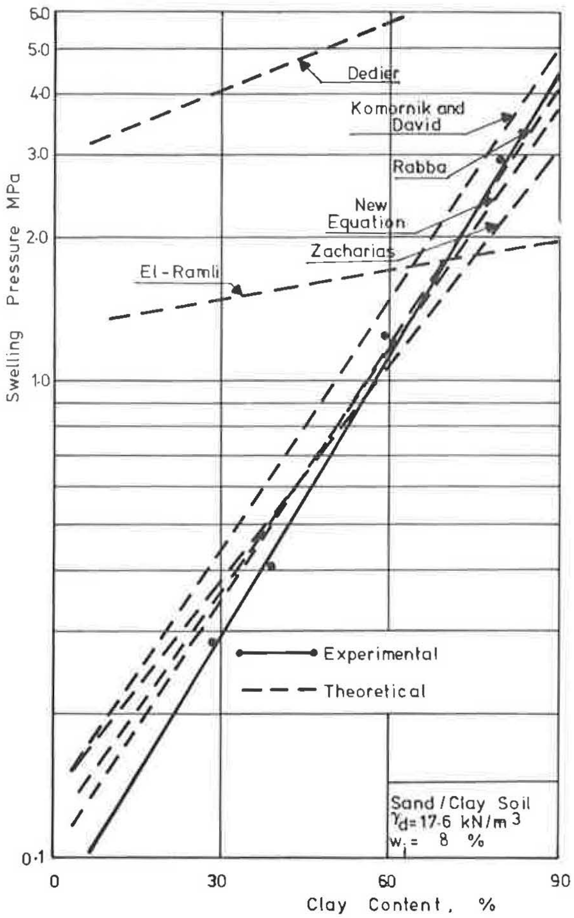

FIGURE 6 New equation plotted in relationship to other equations.

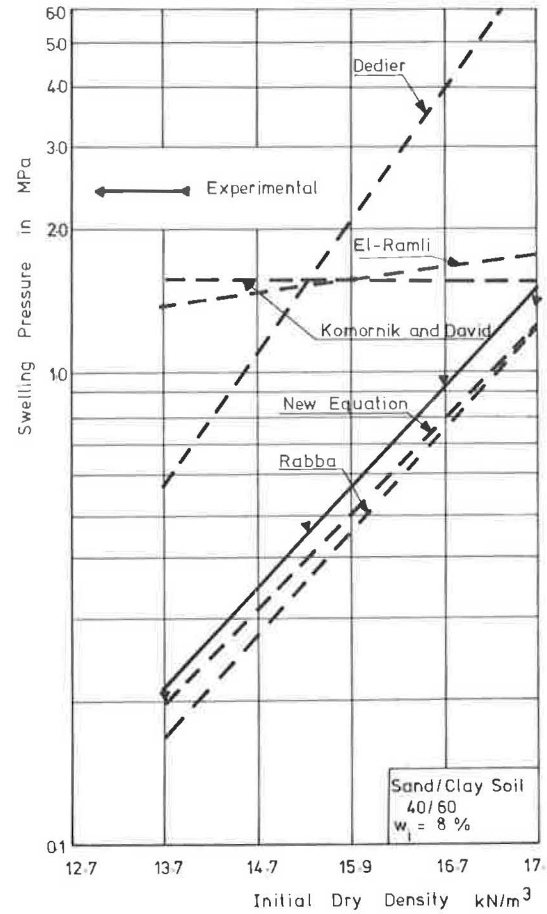

FIGURE 7 New equation plotted in relationship to other equations.

As has been shown, the initial water content has a marked effect on both the resulting swelling pressure and on the amount of swell for the soils investigated.

The proposed relationship (Equation 15) can be used in design problems to estimate the expected swelling pressures for the expansive soil found in Nasr City. It should be tested, however, for other expansive soils before a universal application can be advocated.

CONCLUSIONS

From the test results and the subsequent analysis and discussion of results, the following conclusions appear warranted.

1. Frictional stresses that are mobilized between a soil specimen and a rigid confining ring during swelling of the soil cannot be eliminated completely.
2. Side frictional effects can be reduced considerably during swelling by lining the oedometer ring with filter papers or with a thin rubber membrane. One of the two methods is therefore recommended in order to determine the swell properties of expansive soils using an oedometer ring.
3. A semiempirical relationship between the swelling pressure, the dry unit weight, the initial moisture content, and the clay content of the clay was given. This equation may be used to estimate the

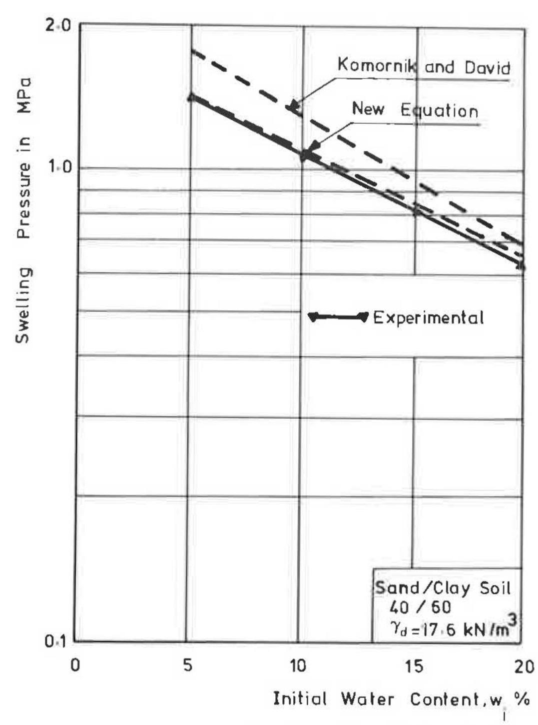

FIGURE 8 New equation plotted in relationship to other equations.

swelling pressures to be expected in the field for the soil investigated. It is speculated that the reduction of swell due to the mobilization of frictional stresses in a one-dimensional oedometer is equivalent to a reduction in soil heave in the field due to radial expansion (axisymmetric swelling).

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Role of Mineralogical Composition in the Activity of Expansive Soils

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ABSTRACT

Heave-susceptible soils often contain swelling clay minerals. Knowledge of the mineralogy of soils and rocks plays a large part in understanding the mechanical behavior of these materials. This knowledge is used to the best advantage when it is combined with information about the engineering properties and geological history of the deposits. The object of this paper is to use the knowledge of microstructure and composition of expansive clayey soils to evaluate the activity as defined by various researchers. Therefore, different kinds of clayey soils were investigated for their index properties, activities, and mineralogical compositions. Samples for study were taken from Madinet Nasr, an area in the suburbs of Cairo where expansive soil deposits predominate. The activities of soil samples were determined by using formulae proposed by different researchers. The values of activities were then correlated to the mineralogical compositions of tested soils. The study indicated that the activity is a property of clay mineral rather than a property of whole sample and confirmed the effect of nonclay mineral or coarse-grained fraction on activity values of expansive soil deposits.

MINERALOGY OF EXPANSIVE SOILS

Expansive clays and clay bed rock formations are made up of several mineral constituents. In Egypt the responsible clay minerals are generally detrital and have been inherited from older rocks. Elsewhere swelling clay minerals have formed by in situ weathering of parent rocks as, for example, in South Africa. The amount of potential volume change is dependent on the mineralogical composition: clay mineral type, clay mineral content, and exchangeable ion.

Kerr has indicated that approximately 15 minerals are ordinarily classed as clay minerals (1). These minerals possess in common an extraordinary ability to attract to their surface dipolar water molecules and various cations. Lambe and Whiteman found that swellability varies with the type of clay mineral; it decreases in the order montmorillonite, illite, attapulgite, and kaolinite (2). Mitchel found that