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SECTION 3. Nanotechnology. Physics.

EVOLUTION OF EXPANSIVE SOILS STRUCTURE WITH DIFFERENT SOLICITATIONS AND EFFECT OF SOME PARAMETERS ON SWELLING PROPERTIES – REVIEW ARTICLE

Abstract: *In addition to mechanical conditions, the swelling of expansive soils is generated mainly by the interaction of water with the minerals of clay particles, thus, the soil structure is changing with water content variations (wetting, drying or wetting – drying cycles). Moreover, the swelling properties (swelling potential and pressure) of these soils are influenced by some physico-chemical characteristics (such as surface charge density and cation valency) and some geotechnical characteristics (such as plasticity , initial water content , initial dry density and soil structure).*

Key words: *expansive soil, swelling, wetting, drying, water content, structure, swelling potential, swelling pressure, plasticity.*

Language: *English*

Citation: EL BRAHMI J, ZOUKAGHE M (2016) EVOLUTION OF EXPANSIVE SOILS STRUCTURE WITH DIFFERENT SOLICITATIONS AND EFFECT OF SOME PARAMETERS ON SWELLING PROPERTIES – REVIEW ARTICLE. ISJ Theoretical & Applied Science, 05 (37): 68-77.

Soi: http://s-o-i.org/1.1/TAS-05-37-14   *Doi*: cross ref http://dx.doi.org/10.15863/TAS.2016.05.37.14

INTRODUCTION

Water parameters of soil (water content or moisture content and degree of saturation) vary with time and depend on environmental factors such as temperature, precipitation and groundwater flow. When expansive soils (rich in montmorillonite) are subjected to variation in moisture content, they change in volume; the soil swells when the water content increases and, similarly, a decrease in the moisture induces soil shrinkage. Structures and their contents may be damaged by this behaviour (Chen, 1975; Philipponant, 1991; Derriche, 1999; Djedid, 2001; etc.). The objective of this article is to point the evolution of the soil structure with different solicitations and recall the various parameters influencing its swelling properties.

STRUCTURAL MINERALOGY OF CLAYS

The physico-chemical nature of clay minerals (coming from the slow degradation of pre-existing minerals) which governs the rheological behaviour of clays cannot be defined without characterization of the three elements constituting a soil sample that is the sheet, the particle and the aggregate.

▪ **The sheet** is defined as a superposition of two types of layers:

- The tetrahedral layer (figure -1-a, -1-b and -1-c) whose thickness is 3Å, have SiO_4 as general formula. Oxygen atoms occupy the vertices of the tetrahedron while a silicon atom occupies the center.

- The octahedral layer (figure -1-d, -1-f and -1-g) whose thickness is 4Å have $Al_2(OH)_6$ (or $Mg_3(OH)_6$) as general formula. The vertices of the octahedron are occupied by hydroxyl OH, while the center is occupied by an atom of aluminum or magnesium atom.

A sheet made of a tetrahedral layer bonded to an octahedral layer is called 1:1 or Te-Oc (kaolinite sheet for example, figure -2-a), and a sheet formed by interleaving octahedral layer between two tetrahedral layers is called type 2:1 or Te-Oc-Te (montmorillonite sheet for example, figure -2-b) (Mitchell , 1993).

Types of layers constituting the clay sheet and their arrangement play a very important role in predicting the characteristics of the clay and its hydromechanical behaviour.

Given that :

- some cations constituting the layers may incur isomorphic substitutions; for example the replacement of Si^{4+} by Al^{3+} or Fe^{3+} in tetrahedral layers, and Al^{3+} by Mg^{2+} or Fe^{2+} in the octahedral layers;

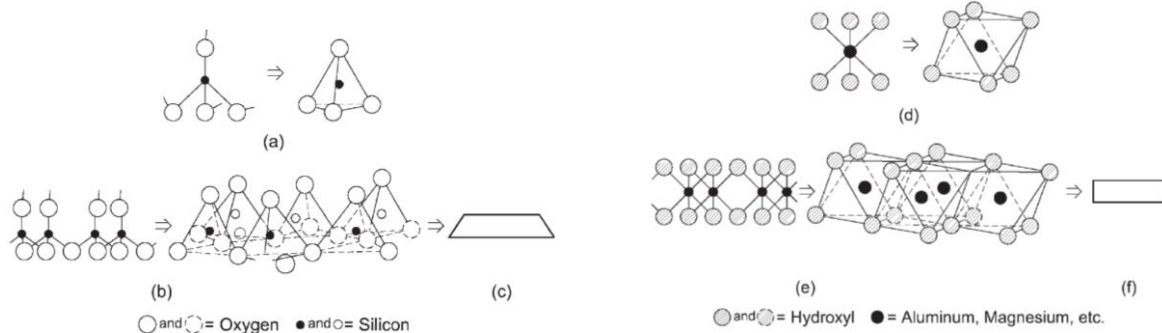- Incomplete charge neutralization phenomena in end atoms can take place;

Figure 1- Atomic structure of silicon tetrahedra and alumino magnesium octahedra: a- silicon tetrahedron, b- silica sheet, c- symbolic structure for silica sheet, d- alumino-magnesium octahedron, e- octahedral sheet, f- symbolic structure for octahedral sheet (after Lambe and Whitman, 1959; Mitchell and Soga, 2005).
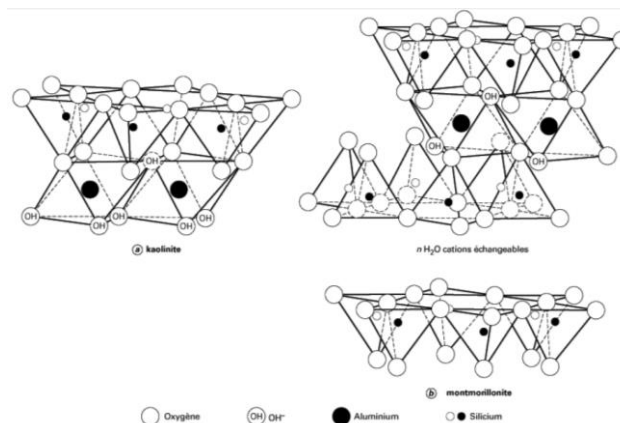

Figure 2- Structure of sheets of kaolinite and montmorillonite (Mitchell, 1993)

- Edge loads can occur when a particle breaks.

The sheets are not always electrically neutral. To compensate for this deficit charge, the cations present in the environment come to locate in the vicinity of the sheet, especially in the interfoliar space. These cations are not part of the layer structure and can be replaced or exchanged by other cations in solution and they play a big role on the properties of clays (Saiyouri 1996). To measure a surplus in the amount of negative charge, the concept of Cation Exchange Capacity is used (CEC).

▪ **The clay particle**, with a maximum size of 2µm, is a stack of clay sheets by different configurations. The position of the sheets with each other and their number per particle, vary according to the type of clay and water content (Ben Rhaeim 1986). The clay particle has a negative charge on its surface; this electronegativity is a fundamental characteristic of the clays.

▪ **The aggregate** or the grain is a messy assembly between the clay particles whose shape and dimensions can vary .

THE MAIN TYPES OF CLAY

Geotechnical classification of clays is an elusive subject, given the diversity of their Properties. However, three main groups of clays are often encountered in geotechnical engineering: kaolinites, illites and smectites (Mitchel and Soga, 2005). These pure clays are references to the classification of different clays.

▪ **Kaolinite**

Kaolinite are clay minerals of 1:1 (Te-Oc) type with fixed equidistant sheets of 7A° (Figure -3-a). When two Kaolinite sheets are superposed, the O- present on the upper surface and the H + of the lower surface develop a strong hydrogen bond OH between them,

conferring with the van der Waals bonds a great stability to the stack of sheets against the action of water. This strong hydrogen bonding between the layers explains the importance of the number of sheets per Kaolinite particle (from tens to hundreds of sheets tightly bounded to each other) and the low value of the specific surface area not exceeding usually 45m^2/g. due to the physical stability of its structure, isomorphic substitutions are infrequent in such clays. In addition, its layers in contact with each other are stacked in an orderly manner so that only the outer surface to the particle that remains accessible to water.

▪ Smectites

Smectites or montmorillonites are clay minerals of 2:1 (Te-Oc-Te) type that have an extremely large lateral extent relative to their thickness (about 9,6A°). The constitution of the lower and upper sides of such clay (Figure -3-c) does not allow the development of a hydrogen bond between the layers, and thus facilitates their separation and adsorption of various molecules (cations, water,..) at the interlayer spaces. Therefore, smectites are very sensitive to water and significant swelling of the particle can occur by adsorption of water molecules between the layers. This swelling can reach values exceeding the thickness of the sheet itself. Smectites particles comprise a stack of sheets between 1 to 10 units or more for a sodium montmorillonite and between 10 to 40 units or more for a calcium montmorillonite. Atomic substitutions are important.

▪ Illites

The illite clay minerals are of 2: 1 (Te - Oc -Te) type, with fixed equidistant sheets of 10A°. They have the same composition as montmorillonite (Figure -3-b), but the sheets are strongly bonded by potassium cations K$^+$. This character gives them less swelling potential than smectites .
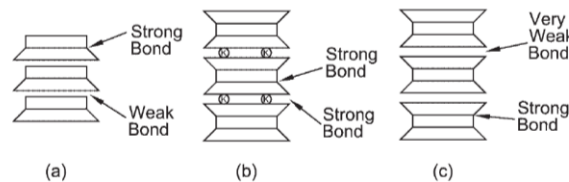

Figure 3- Schematic diagrams of the structure: a- kaolinite; b- illite; c-montmorillonite.
EVOLUTION OF EXPANSIVE CLAY STRUCTURE WITH DIFFERENT SOLICITATIONS

In given conditions, the soil structure is in an equilibrium state. Changing water and/or mechanical conditions produce a change in this structure.

➢ Case of water solicitation:

When we are interested in clayey particles, we can observe two types of porosities: the inter-foliar porosity defined between two sheets constituting the same particle and the interparticle porosity defined between two external surfaces of two particles.

▪ Wetting case:

- Crystalline swelling :

Upon hydration of dry clay specimen, and when bounding between sheets are so weak to allow water to penetrate into the interfoliar spaces (eg the case of montmorillonite), the water penetrates within the particles and is organized in monolayers in the interfoliar spaces , then interacts with the sheets and the cations already present through several mechanisms of physico-chemical interactions namely: hydrogen bonding, exchangeable cation hydration (Fripat and Gatineau, 1984) and Van Der Waals forces (Low, 1961; Mitchell, 1993; and Morel, 1996). (Figure -4)
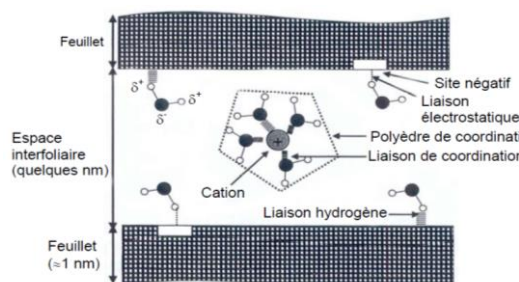

Figure 4- Possible bonds of the interfoliar water (Morel, 1996)

This hydration develops the creation of a pressure, called disjunction pressure, which causes the increase in interfoliar spacing and therefore a crystalline swelling (Morel 1996). The percentage of crystalline swelling represents, approximately, a dozen of the total macroscopic swelling (Tessier, 1990). It is therefore necessary, according to Tessier, to consider another swelling mechanism apart that which emanate of change in the interfoliar spacing.

- The osmotic swelling :

The swelling process generates, gradually, the microdivision of particles, increasing the number of sheets from a hundred, for the strong suction values, to a dozen of sheets, for the lowest values of suction. This leads to the creation of sub-particles which act independently (Saiyouri, 1996). For even smaller suctions, a gradual distancing between the sub-particles formed follows the process. This distance or repulsion called osmotic swelling is generated, according to Mitchell (1993), firstly, by:

1. The formation of the diffuse double layer DDL. Indeed, the clay particles are negatively charged on their surfaces and contain exchangeable cations little related to their structure. In the presence of water, which still contains cations, a movement of these latter, called cation exchange occurs of the clay particle to the fluid and vice versa. The result of this phenomenon is manifested by the creation of an atmosphere of exchangeable cations close by the surface of the particle that takes the name of diffuse double layer (Gouy, 1910; Chapman, 1913). Thus, the overlap of two diffuse double layers of the same sign is responsible for the repulsion of two particles. Applied to the multitude of particles constituting clay specimen, this theory allows to explain the macroscopic swelling and the reduction of macroporosity.

Tessier (1984) states that the diffuse double layer cannot develop in the interfoliar spaces because of their limited size.

2. Water adsorption on the clay surfaces (dipolar attraction or attraction by osmosis) on the other hand (Figure -5).
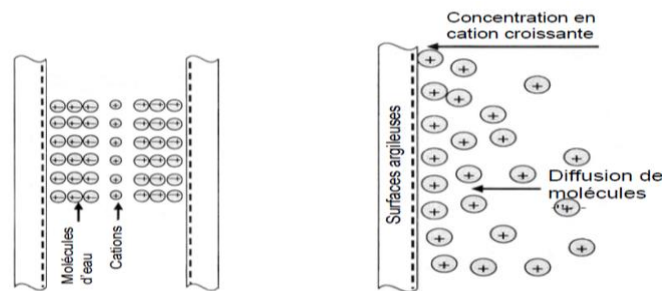

Figure 5- Water adsorption mechanisms on clay surfaces : a- Attraction by osmosis, b- dipolar Attraction (Mitchell, 1993)

Indeed; because of concentration differences in the diffuse double layer, osmotic pressures are developed whenever two double layers of clay particles overlap. Thus, the particle surfaces negatively charged play a comparable role to that of a semipermeable membrane separating two salt solutions of different concentrations (however no cation pass through the clay surface). The osmotic pressure difference created between the clay particle and the solution at the surrounding equilibrium is called "repulsive interparticle pressure". we can imagine that this microscopic phenomenon repeated a very large number of times, is reflected by the appearance of observable swelling on the macroscopic scale.

▪ **Drying Case**

According to Tessier (1991), three stages can be considered during the desiccation of montmorillonite. An increase in suction causes, first, the departure of water located between the elementary stacks, which results in a decrease in interfoliar spacing. This phenomenon continues, for greater suctions, by development of larger elementary stacks including an increasing number of sheets. Beyond a certain value of suction, interfoliar water tends to be eliminated. The progressive water departure causes reduction in the volume of the clay particle by reducing interfoliar spacing, which produces a macroscopic contraction of the material; that is the shrinkage phenomenon. This contraction is interrupted from a threshold suction where all macropore spaces are occuped by air and state of constant volume is reached, the corresponding water content being the shrinkage limit.

▪ **Case of wetting-drying cycles**

Several studies have been conducted on different expansive materials, to study the evolution

of the swelling properties (swelling potential and pressure) during successive drying-wetting cycles. Indeed, the swelling properties evolve with the number of wetting-drying cycles. AL Hamoud and al. (1995), working on six different intact soils (compound of 50% to 80% of clay, 80% of smectite-illite and the rest is kaolinite), showed a decrease in swelling properties with the number of cycles (Figure-6). The results obtained show a fatigue phenomenon of swelling potential resulting of humidification - drying cycles. The first cycle cause the maximum reduction of the swelling potential. Equilibrium is reached after 4 to 5 cycles. The authors attribute this phenomenon of fatigue to continuous rearrangement of the soil particles during wetting-drying cycles leading increasingly to the destruction of the internal structure of the clay. This leads to less swelling structure.
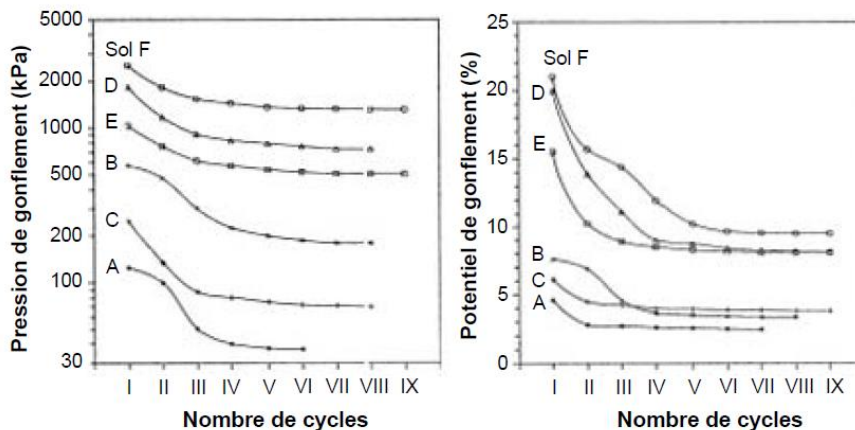

Figure 6- Evolution of swelling properties with the number of wetting-drying cycles on six intact soils (AL-Hamoud et al., 1995)

> **Case of mechanical stress**

The work of Delage and al. (1984) on a clay of Quebec and that of Qi and al. (1996) on a Na Laponite have shown that the reduction of void ratio during mechanical stresses was due to a reduction in the macroporosity, microstructure remaining virtually unchanged . Indeed, the application of external stresses tends initially to bring closer the aggregates, then flatten and weld them if the stresses are important.

INFLUENCE OF CERTAIN PARAMETERS ON THE SWELLING PROPERTIES

> **Effect of physicochemical characteristics**

The volume changes of clays are not only proportional to the variations of their water content, but they also depend on their composition and their mineralogical nature, that is to say, their physicochemical composition.
- Effect of surface charge density

D_s surface charge density is defined as the ratio of the cation exchange capacity CEC on the specific surface S_a of the particle:

$$D_s = \frac{CEC}{S_a} \qquad (1)$$

More the surface charge density is important, the greater the particle attracts cations, which causes condensation of the diffuse double layer, thus a reduction in its thickness. Consequently, the repulsion among particles decreases resulting in a reduction of the swelling pressure (Lefevre and Lajudie 1987 and Istraelchvili, 1992) and finally the swelling becomes less important.

According to formula (1); the cation exchange capacity CEC is evolving in the same direction as the surface charge density D_s, Thus clays with a high value of CEC (while specific surface being equal), will tend to slightly swell (Lefevre and Lajudie., 1987). By against, the increase of the specific surface S_a causes the reduction of the surface charge density and promotes thereby swelling (Lefevre and Lajudie 1987 and Komine and Ogata, 1996). Indeed, clays whose particles have important specific surfaces, are very expansive compared to those whose the rest of the features would be idem.
- Effect of cation valence

The thickness of the DDL is directly related to the type of cations contained in the soil. More the cation valence will be low and present in low concentration, most the DDL will be developed and therefore the amplitude of swelling will be greater and vice versa.. Dardaine et al. (1986), Lefevre et al. (1987) and Lin (2000) studied the effect of nature of cations arising from water of hydration (and not from the clay structure) to get to the same conclusions on clay particles.

Even the crystalline swelling is influenced by the nature of the interlayer cations. Thus, sodium montmorillonite (Na+) swells more than calcium montmorillonite (Ca2+) (Dardaine et al., 1985; Saiyouri, 1996).

> ➢ **Effect of plasticity**

The predominant clay minerals in the soil are reflected in the plasticity. Depending on the nature of such minerals, that swelling potential will be more or less important. This brings to mind the existence of a correlation between the plasticity of a soil and its swelling potential.

Figure-7 shows the zones occupied by clay minerals (kaolinite, illite and montmorillonite) on the plasticity chart. The zone for montmorillonite clays is located close to the U- line. It can be expected, therefore, that the plasticity of an expansive soil is located close to the zone indicated for montmorillonite. This is, in fact, in agreement with the actual data ; it was observed that for soils classified as little plastic clays (CL), the plasticity of the most expansive soil plot close of U-line (Holtz and Kovacs Sheahan 2011).
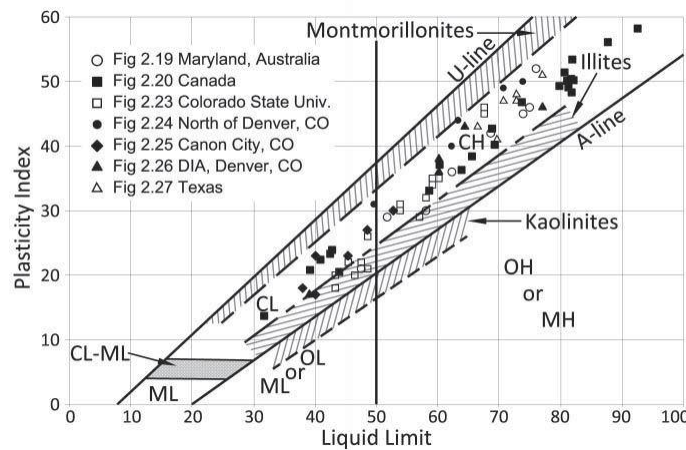

Figure 7- Plasticity characteristics of clay minerals (shaded mineral areas as identified in Holtz, Kovacs, and Sheahan 2011).

Other correlations were earlier researched between Atterberg limits and swelling properties of soils (eg Holtz and Gibbs classification, 1956), Chen (1975) classification and the Indian classification IS 1498 based on the plasticity index (Figure-8).

| | Ip | | Swelling rate |
Holz et Gibbs	Chen	IS 1498	
<20	0-15	<12	low
12-34	10-35	12-23	medium
23-45	20-55	23-32	High
>32	>35	>32	Very high

Figure 8- Swelling rate classification according to the index plasticity (Sridhan 2000).

We can also found Seed, Woodward and Lundgren classification (1962), which refers to the activity of material and its clay particle content (Figure-9). As for Altemeyer (1955), he proposed the classification of soils according to shrinkage limit as summarized in Figure-10.
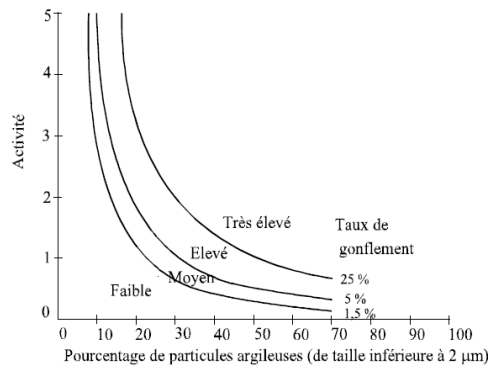
Figure 9- swelling ratio classification diagram according to activity and to clay particle content (Seed et al., 1962).

Ws	Swelling rate
<10	High
10-12	Critical
>12	Low

Figure 10- classification of swelling rate according to shrinkage limit.

➢ Effect of soil structure

Depending on the conditions during deposition, soil particles may have varying orientations. Figure-11 depicts the particle orientation for flocculated and dispersed soil structure. Both structures represent in fact two extreme cases, whereas in the real case, the orientation of particles should be somewhere between fully flocculated state and completely dispersed.
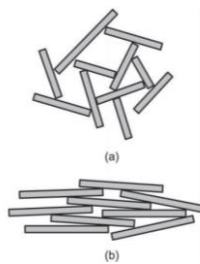

Figure 11- soil particle structures: a- flocculated orientation, b- dispersed orientation (Lambe and Whitman 1969)

For a flocculated structure, the interaction between particles is influenced mainly by the contact between the ends of particles and the faces of adjacent ones. The spacing between the particles is larger in the flocculated structure than in the dispersed structure. It is, therefore, evident that crystalline and osmotic swelling would be less effective in the flocculated structure than for the dispersed structure. For highly overconsolidated clays, the soil structure would tend more to the dispersed structure. In addition to the particle orientation, spacing between them and the hydration states of cations will influence the expansion potential (John D. Nelson, 2015).

➢ Effect of initial water content and initial dry density

The higher the initial dry density of the soil, the greater the swelling properties. in addition, the drier the initial state of the soil, the more it swells. This has been confirmed by the experiments of Chen (1973 and 1988). Indeed; this author conducted a first series of oedometer tests on samples prepared from the same initial density and different levels of initial water content (Figure-12-a) and a second series of tests on samples that have the same initial moisture content and different dry densities (Figures-12-b and -12-c).
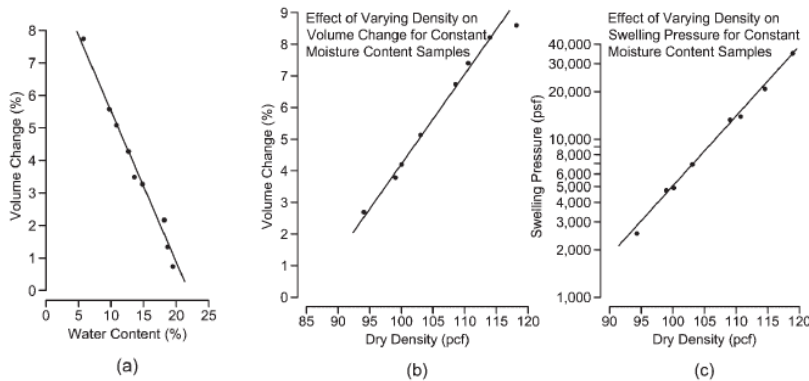
Figure 12- Effect of initial water content and dry density on expansion properties: a- water content versus volume change, b- dry density versus volume change, c- dry density versus swelling pressure (Chen 1973).

> **Effect of water permeability**

As for permeability, it influences rather the swelling quickness as its properties. Clay soils containing sand particles swell faster than pure clays because water moves quicker in the soil and thus promotes a more intense saturation of the clay particles. Gromko (1974) also observed that a soil less expansive but more permeable may swell faster than a soil more expansive but less permeable.

CONCLUSIONS AND PROSPECTS

Contrary to mechanical stresses which act only on the soil macrostructure, water solicitations make changes in microstructure and macrostructure.

Swelling properties are influenced by some physico-chemical parameters and some geotechnical ones. Indeed; the swelling increases with:

- reduction in surface charge density
- reduction of cation exchange capacity
- Increasing of specific surface
- Reduction of cations valence and their concentration
- Increasing the plasticity and its proximity to the line U
- Reduction of initial water content
- increasing of initial dry density

Also, the dispersed structure swell more than flocculated one.

This article is an introduction to the study of the hydromechanical behavior of unsaturated expansive soils. it will be followed by other articles on behavior modeling and implementation in a computer program.

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