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On the Primacy of the Exchange Complex on the Shear Strength of Marly Soil

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ABSTRACT

The influence of the exchange complex on shear strength behavior and the initial tangent modulus of elasticity of marly soil (a low active soil) were investigated. The investigation involved transformation of the naturally heterogeneous exchange complex into homogeneous exchange complex having only one type of exchangeable cation species present in the exchange complex. This step constitutes a fundamental step for assessing soil behavior of natural heterogeneous exchange complexes based on the physicochemical approach. Although the investigated soil is a low active soil, the influence of the exchange complex on shear strength was significant, or even substantial in some cases. Differences in soil cohesion associated with the tested exchange complexes reached 3 folds, and differences in the angle of friction reached about 50% to 90%, depending on the dry density of the soil and its moisture content. Influence of the exchange complex was minor on the exponent "n" of Janbu's formula; maximum variation was about 25%. A change in K_{ur} which is the second parameter of Janbu's formula due to changes in the exchange complex was substantial; variation reached as much as three folds.

Keywords: Marl, Exchange Complex, Homo-ionic, Compacted Soil, Shear Strength, Modulus of Elasticity.

INTRODUCTION

Soil behaviors, such as shear strength, soil consolidation, dispersive nature of soils, soil collapsibility and swell-shrink characteristics of soils, are considerably influenced by the exchange complex. The *exchange complex* is defined as the combination of the clay mineral particles, the diffuse double layer water and the adsorbed exchangeable ions (Marshall, 1977; Hillel, 1980). The degree by which the exchange complex influences soil properties and behaviors is dependent on the type of clay mineral involved as well as the pore water chemistry (Bolt, 1956; Olson and Mesri, 1970; Mitchell, 1993). Fundamentally, the type of clay minerals present in the soil, the type of cation species, and soil fabric significantly influence shear strength of soils. Soil particles' association with each other, soil structure and soil fabric, are directly and vastly influenced by the exchange complex. Consequently, soil shear strength is influenced by changes in the exchange complex and is function of it.

The exchange complex of natural soils is a heterogeneous one, i.e. containing mixture of various types of cation species, such as Na^+, K^+, Ca^{++}, H^+, NH_4^+ and Mg^{++}. For a specific soil the exchangeable cations are a prime factor that contributes to the aspects of the influence of the exchange complex on soil behavior. Consequently, variations in the percentages of various cation species present in a specific soil give rise to

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different trends in behavior of that particular soil. Knowledge of soil behavior as function of variations in the percentages of a mixture of various types of exchangeable cation species (heterogeneous exchange complex) requires knowledge of soil behavior of homo-ionic exchange complexes for each type of exchangeable cation specie. Soil behavior of a homo-ionic exchange complex constitutes a frame of reference for understanding and, then, predicting soil behavior under real or natural conditions of heterogeneous exchange complex.

In the past decade, a number of studies investigating role of the exchange complex on soil behavior was conducted. Kermi (1993), Marashdeh (1994) and Abdullah et al. (1997, 1999) studied the influence of the exchange complex on the shear strength, dispersive phenomenon, compressibility and swelling behavior of compacted clays, respectively. Anandarajah and Zhao (2000) studied the influence of the pore water fluid on the shear strength of kaolinite.

The chosen cation species for this investigation were Na^+, K^+ and Ca^{++}. In addition to the reason of their common existence in the exchange complex of natural soils, Na^+ represents monovalent species, Ca^{++} represents divalent species; while potassium ions K^+ represent a special case of cation species that have specific influence on clay minerals.

In order to explain the bonding influence of the potassium ions on clay mineral particles, it is necessary to refer to the silica sheet which represent one of the two building blocks of all clay minerals in addition to the octahedral sheet. The silica sheet is composed of basic units of silicon tetrahedrons (four oxygen coordinated by silicon) organized in a hexagonal arrangement (Fig. 1a, 1b and 1c). The silica sheet is an assemblage of the hexagonal units as in Fig. (2). The radius of each hexagonal hole of the silica sheet units is equal 1.32 Å (Fig. 1a and 1b).

The potassium, K^+, ions have unhydrated ionic radii of 1.33 Å, and hydrated ionic radii of 5.32 Å. Thus the hydrated potassium ions can not enter the hexagonal holes of the silica sheet. However, K^+ ions when entering the "*Stern Layer*" experience high electric polarization, which forces them (K^+ ions) to shed all their hydration water and become fully un-hydrated with ionic radii of 1.33 Å. Thus the un-hydrated K^+ ions readily enter the hexagonal holes (having a radius of 1.32 Å) of the siloxane sheet as shown in Fig. (3a and 3b) for a 2:1 mineral as an example, and provide a rather strong bonding force compared with the exchangeable cation linkage.

Scope of Work

The present work studied the influence of the exchange complex on the shear strength parameters of compacted low active soil (marly soil). The studied shear strength parameters were the unconsolidated undrained parameters as expressed by the equation;

$$\tau_{uu} = c_{uu} + \sigma \tan \phi_{uu} \qquad (1)$$

where: τ_{uu} = shear strength obtained from an unconsolidated undrained triaxial compression test, c_{uu} = unconsolidated undrained cohesion, ϕ_{uu} = peak angle of friction obtained from unconsolidated undrained triaxial test. For simplicity, soil cohesion and friction angle will be referred to as c and ϕ, respectively.

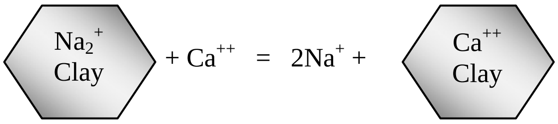
First; the heterogeneous exchange complex of the natural soil used for the present investigation was transformed into homo-ionic exchange complex. The transformation procedure from a heterogeneous exchange complex into a homo-ionic exchange complex was conducted according to Abdullah et al. (1997). The chosen types of cation species for this work were Na^+, K^+ and Ca^{++} for the reasons mentioned previously.

Compacted soil specimens were used so that clay structure influence on shear strength can be studied. Soil structure can be made to vary from a flocculated structure to a dispersed one according to the location of the compaction state on the ρ_d - w domain (Lambe, 1953; Seed and Chan, 1959). The shear strength parameters c and ϕ were obtained from unconsolidated undrained triaxial compression test.

Influence of the exchange complex on the initial tangent modulus and particularly on the two constants of Janbu's model of the initial tangent modulus was also studied.

Alteration of the Exchange Complex

Transformation of a heterogeneous exchange complex into a homogeneous one involves an exchange reaction which takes place in an aqueous environment. Applying a high concentration solution of a specific ion (Ca^{++} for instance) to a soil specimen forces the clay mineral particles to replace the existing cations on their surfaces with the applied cations in solution. An example of an exchange reaction involving clay minerals is given by;



$$\mathrm{Na_2^{+}\,Clay} + Ca^{++} = 2Na^{+} + \mathrm{Ca^{++}\,Clay} \qquad (2)$$

Soil Used for the Study

The marly soil used for this investigation was taken from Fuhais formation near Fuhais city which is located about 30 km North West of Amman; the capital city of Jordan. Fuhais formation has yellow color, and consists of about 80 m thick interchangeable layers of marl, marly limestone, limestone and silicified limestone. It was formed during the upper cretaceous era.

The basic properties of the marly soil are given in Table (1). The moisture-dry density relationship obtained from standard Proctor test conducted according to the ASTM D 698-78 is shown in Fig. (4), see Karmi (1994).

Clay Mineral Analysis

A random powder diffraction scan was made from the bulk sample after grounding to a fine powder in a ceramic mortar and pestle. To maximize random orientation, the powder was side-loaded into a circular sample holder approximately 25.43 mm in diameter and 1.62 mm deep, accommodating a total of about 1500 mg.

Diffraction data were collected using a PW1710 diffractometer using Cu Kα radiation transmitted through beam slits 2.0 mm by 4.0 mm. Detector slits were 0.1 mm by 4.0 mm. Applied voltage was 40 kV with a 25-mA current. The diffraction scan was made from 2^o to 60^o 2θ for the random sample.

The x-ray diffractogram for the random powder diffraction scan of the tested marly soil consists of calcite as a major component and kaolinite, montmorillonite and palygorskite as the minor components.

Approximate analysis of the percentages of the clay minerals present in the tested marly soil have shown that kaolinite constitutes about 15 – 20 % and palygorskite constitutes about 10%, in addition to a trace amount of montmorillonite.

Table (1): Properties of the tested marly soil (Karmi, 1993).

Soil Property	Value
Depth of Sample (m)	3 - 4
Specific Gravity	2.66
Activity	0.23
USC Classification	CL
Sand Size (%)	24
Silt Size (%)	29
Clay Size (%)	47
Liquid Limit LL	34
Plastic Limit PL	23
Plasticity Index PI	11
Maximum Dry Density $\rho_{d_{max.}}$ (g/cm^3)	1.7
Optimum Moisture Content O.M.C.%	16.5

TESTING PROCEDURE

Soil Preparation for Testing

The soil was first pulverized using rubber tipped pestle. The pulverized soil was, then, sieved through # 40 sieve and the larger sizes were discarded. The exchange complex of natural soils is heterogeneous having various types of cation species. The most common cation species present in the exchange complex of natural soils are Na^+, K^+, Ca^{++}, H^+, $NH_4^+$and Mg^{++}. In addition to the natural soil, three types of treated soils were produced from the natural soil. The three treated soils were of homo-ionic exchange complex nature. They were Na^+ - dominated, K^+ - dominated and Ca^{++} - dominated exchange complexes. Alteration of the exchange complex from a heterogeneous to a homogeneous exchange complex was conducted according to Abdullah et al. (1997).

Unconsolidated undrained triaxial compression tests were performed on compacted soil specimens. Four types of exchange complexes were investigated, the natural marly soil and the three artificially altered soil types. Each type of soil was investigated for five compaction states (prescribed moisture content and dry density) as given in Table (3), and shown graphically in Figure (4). To enable meaningful comparison of the test results, the five-compaction states were chosen so that the density once kept constant and the moisture content was allowed to vary from dry of optimum, at optimum, to wet of optimum. This variation in moisture content amounted to a change in the soil structure from flocculated to dispersed structure (Lambe, 1953; Seed and Chan 1959). Another set of comparison was made so that influence of dry density can be investigated. For this case the moisture content was fixed at the optimum moisture content and the density was allowed to vary in a range from below, at, to above the maximum dry density obtained from the standard Proctor test (Figure 4).

To prepare a specimen for the triaxial test, a certain amount of dry soil was thoroughly mixed with a predetermined quantity of distilled water to achieve the required compaction state as mentioned in Table (3). The mixture of soil and water was, then, compressed in a cylindrical split mold having an internal diameter of 38 mm and a height of 76 mm. Specimen compaction was conducted by pressing the soil/water mixture to the stated height of the specimen. The prepared specimens were tested according to ASTM D2850-87 (Standard Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression). The UU tests were conducted by a constant rate of deformation (strain-controlled) and the application of the axial compression test load where the specimen is subjected to a confining pressure in the triaxial cell.

Table (2): States of soil compaction for the experiments (Karmi, 1993).

State of Compaction	Dry Density (g/cm^3)	Moisture Content (%)
1	1.58	5.5
2	1.58	16.5
3	1.7	16.5
4	1.78	16.5
5	1.58	25.0

Table (3): Influence of exchange complex on Atterberg limits (* from Karmi, 1993).

	LL	PL	PI
Natural Soil *	34	23	11
Na^+- Soil	33	25	8
Ca^{++}- Soil	32	22	10
K^+- Soil	24	19	5

TEST RESULTS AND ANALYSIS

Atterberg Limits

Liquid limit test and plastic limit test were conducted according to ASTM D 4318 – 84 on the natural marly soil as well as the three artificially altered exchange complexes (Na-marly, K-marly and the Ca-marly soil). The results of these tests are given in Table (3). Minor changes in LL and PL resulted due to the employed changes in the exchange complex of the tested soil. Changes in plasticity index remain within the class of low plastic soils, however, noticeable reduction occurred in the PI of the K-dominated exchange complex (Table 3).

Unconsolidated Undrained Triaxial Compression Test

A set of three triaxial soil specimens (76 mm in height and 38 mm in diameter and a height to diameter ratio of 2) was prepared for each compaction state. The confining pressures used were 50 kPa, 100 kPa and 300 kPa. The triaxial unconsolidated undrained compressive tests were conducted according to the ASTM D 2850 – 87. Deviator stress, total major stress and axial strain were determined for each tested specimen. Stress-strain relationships and Mohr-Coulomb diagrams were plotted. The angle of internal friction ϕ and soil cohesion c were determined for all tested cases (namely the exchange complex and the compaction states). At least two specimens for each triaxial test were made and tested in order to insure reproducibility of specimens and test results.

To facilitate the study, the preeminence of the exchange complex and state of compaction on the shear strength parameters, soil cohesion c and friction angle ϕ were plotted as function of moisture content and dry density for the natural soil and the three altered exchange complexes. Influence of exchange complex, dry density and moisture content on soil cohesion and angle of friction ϕ is shown in Figures (5) through (8). As observed from these graphs, there is a common trend for all investigated exchange complexes: soil cohesion and friction angle increase as the dry density increase and both decreases as the moisture content increases. However, the rate of decrease in soil cohesion due to increase in moisture content (Figure 6) is more significant than the rate of increase in soil cohesion due to the increase in the dry density (Figure 5). This trend of behavior is common for the various tested exchange complexes.

Influence of the exchange complex on the Diffuse Double Layer (DDL) is best described by the Gouy-Chapman theory. The governing equation of the Gouy-Chapman theory is given by;

$$\frac{d^2\Psi}{dx^2} = -\frac{e}{\varepsilon}\sum v_i n_{i0} \exp\left[\frac{-v_i e\Psi}{kT}\right] \tag{3}$$

where; Ψ = electric potential, e = electronic charge, v_i= ionic valence, n_{i0} = ions' concentration in the bulk water, k = Boltzmann constant, T = absolute temperature and ε = permittivity.

By solving Eqn. (3) for a case of two ion species (cations and anions) of equal valence and concentration in the free water; the center gravity of the diffuse charges (taken as a measure of the DDL thickness) is given by;

$$\frac{1}{K} = \sqrt{\frac{\varepsilon_0 DkT}{2n_0 e^2 v^2}} \tag{4}$$

where; $1/K$ = measure of the thickness of the DDL, D= dielectric constant and ε_0 = permittivity of vacuum.

The "*thickness*" of the Diffuse Double Layer "DDL" is dependent on a number of factors (Eqn. 4). Most important of them are; type of clay mineral, type and valence of the exchangeable cations present on the clay mineral surfaces and their concentrations in the bulk solution. Gouy-Chapman DDL theory is based on the assumption of a soil particle in suspension in low concentration electrolyte solution. Therefore, if the amount of available moisture was not enough for the soil particles to have fully developed DDL, then its thickness would be (due to the partial development) thinner than the thickness predicted by the Gouy – Chapman DDL theory. Other assumption of the Gouy – Chapman theory is that the diffused ions are point charges with no interaction between them. This particular assumption has major contribution to the inaccurate prediction of the thickness of the DDL and the distribution of the diffused ions within it, especially for high ion concentration and high valence of the diffused ions. These limitations contribute to the inaccurate prediction of the Gouy-Chapman theory in such conditions. Despite these limitations, this theory can be used as a tool for interpretation of soil behavior (Lambe, 1953; Seed and Chan, 1959; Mitchell, 1993).

Although the soil under consideration is a low active soil; the changes made to the exchange complex of the tested soil gave rise to significant changes in the shear strength parameters; c and ϕ (Figures (5) through (8)). As far as soil *cohesion* is concerned; the Na-dominated exchange complex produced highest values amongst the investigated exchange complexes. However, the K-dominated exchange complex produced highest values of angle of friction amongst the investigated exchange complexes.

Divalent cations present in the exchange complex such as calcium ions cause reduction in the thickness of the DDL, Eqn. (4). A thin DDL promotes face to face aggregation of clay mineral particles (van der Waal’s forces of attraction overwhelms the repulsive forces due to the DDL (Mitchell, 1993)). Accordingly, the so-called clay *domains* (the aggregation of clay mineral particles) develop in size and also, new clay domains are formed due to aggregation of discrete clay particles. The process of aggregation and formation of new clay domains, as well as enhancing the already existing clay domains give rise to a soil with coarser texture (Abdullah et al., 1997). One of the results of such behavior is echoed on the dry density - moisture relationship (Abdullah et al., 1997). The dry density – moisture relationship of a soil experiencing aggregation process assumes new location on the ρ_d - w domain with higher maximum dry density and lower value of the optimum moisture content (Abdullah et al., 1997, 1999). On the other hand, an exchange complex dominated by monovalent cation species such as Na^+ behaves in an opposite mode with the resulting optimum moisture content assuming higher values. Because of that; a specimen compacted at moisture content in between these two optimum values represents a state of dry of optimum for a monovalent exchange complex and wet of optimum for a divalent exchange complex. This matter was clearly observed during molding soil specimens for the Na-soil and the Ca-soil. Soil specimens prepared from the Ca-soil were more pliable than soil specimens prepared from the Na-soil. Accordingly, for a soil specimen compacted at the said moisture content, the soil structure for the monovalent dominated exchange complex is flocculated while it is oriented for the divalent dominated exchange complex. Therefore, the Na-soil produces a cohesion higher than the Ca-soil (Figures 5 and 6).

The action of potassium ions on some clay minerals such as illite is well known in bonding clay mineral sheets together. The mechanism of the potassium binding force is due to number of factors. The ionic radius of the K ion is 1.33 Å, which becomes equal to 5.32 Å when hydrated. The hydrated K ions within the Stern layer, (ranges in thickness from 3 to 10 layers of water molecules Grim 1968) experience high electrical polarization, which forces the potassium ion to shed all its hydration water. The unhydrated K ion readily enters the hexagonal holes of the siloxane sheet and provides linkage between clay mineral particles. It is not possible for the hydrated K ion to enter the hexagonal holes (having a radius of 1.32 Å) of the siloxane sheet without shedding all its hydration water since its size in the hydration state is much bigger than the said holes. It is noteworthy to keep in mind that the barium Ba^{++} ion has almost the same unhydrated ionic radius as that of the K ion (1.35 Å), but does not function as the K ion. Charge density, which is the charge of the ion divided by its surface area, for the Ba is almost as double as the value of the K ion. Hence, the force of attraction between the Ba^{++} ion and its hydration water molecules is higher than that for the potassium ion. Therefore, the barium ion partially sheds its hydration water (keeps some of the water molecules) when it enters the “Stern layer”. Consequently, the net ionic size of the Ba^{++} ion is larger than the size of the hexagonal holes. Another example of the K ion bonding action is in vermiculite mineral. Vermiculite has a variable basal spacing (ranging from 10 Å to 15 Å) depending on the exchangeable cation present in the exchange complex. When the potassium is the exchangeable cation, vermiculite has a basal spacing of 10 Å. This thickness is the thickness of the 2:1 layers. This means that the K ions bond the vermiculite clay particles together.

Kaolinite is a 1:1 dioctahedral clay mineral with a very small amount of isomorphous substitution, Al^{3+} for Si^{4+} 1 in 400. This amount of isomorphous substitution accounts only for about 2 meq/100 g of the actual CEC of the kaolinite mineral, which is in the range of 3-15 meq/100 g of dry soil. This means that the position of about 20% of the exchangeable cations is within the cleavage surface of the clay mineral and the rest of the exchangeable cations are on the clay mineral edges. Stacking of large number of kaolinite particles (due to secondary valence bond and also, but more importantly, due to the hydrogen bond) causes the accumulation of the negative charge deficiency which arouses at the outer surfaces of these accumulating (domains) kaolinite platelets. For instance, and as an example of the accumulation of the charge deficiency, kaolinite mineral (CEC= 3-15 meq/100 g) has 83 Å^2 per one exchangeable ion while the montmorillonite clay mineral (CEC= 80 - 150 meq/100 g) has 133 Å^2 per exchangeable ion, which means that the kaolinite surface is more densely populated with exchangeable cations than montmorillonite surface (Lambe and Whitman, 1968; Mitchell, 1993). For a K-dominated exchange complex, electric neutrality is achieved by the potassium ions which enter the hexagonal holes of the siloxane sheet (having a radius of 1.32 Å) and thus, providing a rather strong linkage compared to the exchangeable cation bond. Since kaolinite is a 1:1 dioctahedral clay mineral, therefore, the linkage provided by the K ions is between the outer siloxane’s surface of one domain of (H-bond and S.V.B.) bonded particles and the outer siloxane’s surface of another domain of (H-bond and S.V.B.) bonded particles. The rather strong K-linkage between bonded domains of clay mineral particles transforms the soil into a coarser texture soil (Abdullah et al., 1999). This argument which is based on kaolinite mineralogy, chemistry of pore water and the characteristics of the potassium ion is supported by experimental results (Abdullah et al., 1999) and is in agreement with the shear strength results obtained for the K-dominated exchange complex (Figures 7 and 8). The friction angle of the K-dominated exchange complex is higher than the friction angle of the investigated exchange complex by a factor of 25% for the next value of ϕ to about 80% for the smallest value of ϕ (Figure 7). Moreover, the rate of decrease of ϕ (for the K-marl) with increase in moisture content was the smallest among the investigated exchange complexes (Figure 8). It is well know that the friction angle of coarse-grained soil is slightly influenced by the increase in moisture content. The ϕ value of the K-dominated exchange complex is least affected by the increase in moisture (Figure 8), which is a reflection of the increase in size of the soil particles due to linkage provided by the potassium ions.

Influence of Exchange Complex on the Modulus of Elasticity

Janbu (1963) proposed the following equation for the initial tangent modulus of elasticity as function of the confining pressure. Janbu’s equation is widely used in finite element analysis;

$$E_i = K_{ur}\, P_a \left[\frac{\sigma_3}{P_a}\right]^n \tag{5}$$

where: E_i = initial tangent modulus of elasticity; K_{ur} = dimensionless constant; P_a = atmospheric pressure expressed in the same units as σ_3; σ_3 = confining pressure; and n = exponent determining the rate of variation of E_i with σ_3.

Janbu's equation represents a straight-line relationship when plotted on a log-log scale for both E_i and σ_3. A typical relationship for dry density ρ_d = 1.58 g/cm^3 and moisture content w = 5.5% is shown in Figure (9). The best straight line fit (in terms of least square fit) is used to determine the two constants of Janbu's equation. K_{ur} can be determined as the intercept of the straight-line fit at $\sigma_3 = P_a$, and n is the slope of the straight-line fit, such that;

$$\log_{10} E_i = \log_{10} K_{ur} P_a + n \log_{10} \sigma_3 \tag{6}$$

The influence of the exchange complex and dry density on n and K_{ur} is shown in Figure (10) and Figure (11), respectively for a moisture content w =16.5%. Influence of exchange complex and moisture content on n and K_{ur} is shown in Figure (12) and Figure (13), respectively.

Exponent n remains, more or less, constant as far as changes in moisture content and changes in dry density were concerned for all investigated exchange complexes (Figure (10) and Figure (12)). However, changes in exchange complex brought about evident changes in the value of the exponent n. The K dominated exchange complex yielded highest value of n; about 35 %, above the n value for the natural heterogeneous exchange complex of the marly soil.

The modulus number K_{ur} is considerably influenced by changes in the exchange complex with Na- dominated exchange complex yielding highest value amongst the investigated exchange complexes (Figure (11) and Figure (13)). It is also noticeable that K_{ur} decreases rapidly as the moisture content increases in the soil, which was a common behavior of all tested exchange complexes.

SUMMARY AND CONCLUSIONS

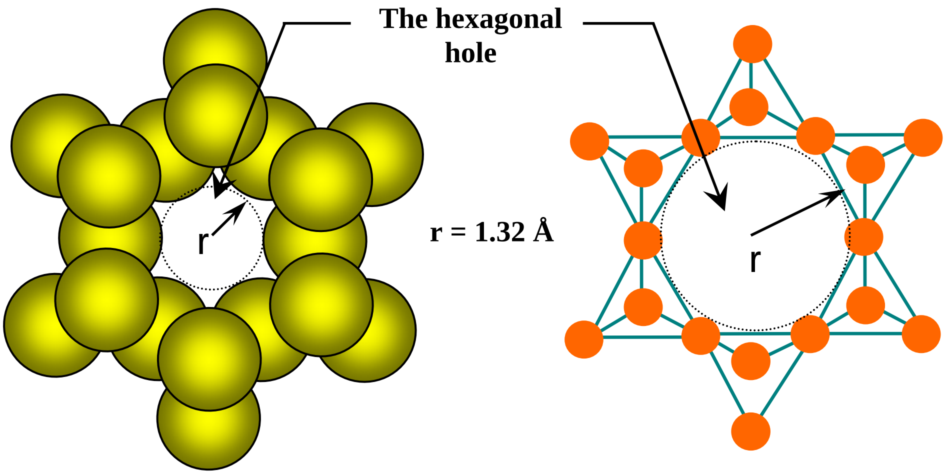
Influence of exchange complex on the shear strength parameters and modulus of elasticity of a marly soil was studied. The heterogeneous exchange complex of the natural marly soil was transformed into homogeneous exchange complex so that a frame of reference for the general condition of heterogeneous exchange complex could be established. The heterogeneous exchange complex was transformed into an Na-dominated, K-dominated and Ca-dominated soil. Friction angle, soil cohesion and the two dimensionless constants of Janbu's equation for the initial tangent modulus of elasticity K_{ur} and n were determined from unconsolidated undrained triaxial compression tests. The following conclusions were based on the results obtained from the test experiments conducted on the selected marly soil.

1. The Na- dominated and Ca-dominated exchange complexes have minor influence on Atterberg limits of the marly soil (low active soil) used in this study.
2. The K-dominated exchange complex has substantive influence on Atterberg limits and yielded lowest PI value amongst the investigated exchange complexes.
3. Though the tested soil is a low active soil, the exchange complex has significant influence on its shear strength behavior and also on its modulus of elasticity.
4. Influence of exchange complex on soil cohesion was substantial. Soil cohesion ranged from 30 kN/m^2 for the K-soil (lowest) to 140 kN/m^2 for the Na-soil at ρ_d = 1.58 g/cm^3, w = 16.5%, and from 100 kN/m^3 for the K-soil to 200 kN/m^3 for the Na-soil at ρ_d = 1.78 g/cm^3 at w = 16.5%.
5. Influence of exchange complex on friction angle was important. The friction angle of the K-soil (highest) was 90% above that of the natural soil (lowest) for (ρ_d = 1.58 g/cm^3, w = 16.5%) and 50% higher for (ρ_d = 1.78 g/cm^{3}at w = 16.5%).

6. Potassium ions provide linkage for clay mineral particles and cause enlargement of already existing clay domains as well as establishing new clay domains by bonding discrete clay particles. The mechanism of the binding force is due to the nature of the K ion, its valence, clay negative surface charge and the hexagonal holes of the siloxane sheet.
7. As a result of soil aggregation and increase in soil particle size (whether due to K-linkage or due to van der Waal's forces of attraction as the case of the Ca-soil), changes in the dry density-moisture content relation occurred and assumed new locations within the $\rho_d -$ w domain. The optimum moisture content of the K- and Ca –soils turns out to be less than that of the natural soil and the Na-soil.
8. The friction angle of the K dominated exchange complex produced highest values amongst the investigated exchange complexes. The linkage provided by the K-ions transformed soil particles into coarser size particles. Since K-linkage is stronger than the van der Waal's forces of attraction (the forces behind face to face aggregation in the Ca-exchange complex), therefore, clay domains produced by K-exchange complex are superior than those produced by Ca-exchange complex.
9. The initial tangent modulus of elasticity is significantly influenced by changes occurring in the exchange complex. The two constants of the Janbu's formula of the initial tangent modulus n and K_{ur} reflect changes in the initial tangent modulus.
10. The value of the exponent n was independent of changes in dry density and changes in moisture content. However, influence of exchange complex on n is noticeable. The maximum variation in n occurred between K-soil (highest) which was about 25% above and the natural soil (lowest) for the entire tested ranges of moisture content and dry density.
11. Influence of exchange complex on K_{ur} is substantial. The maximum variation in K_{ur} occurred between Na- soil (highest) which was about 3 times as high as the natural soil (lowest) for the entire tested ranges of moisture content and dry density.

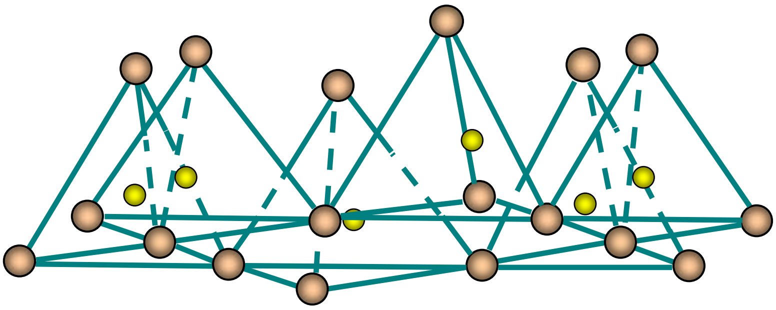
APPENDIX: NOTATIONS

c, and c_{uu} = soil cohesion obtained form a UU triaxial compression test;
CEC = cation exchange capacity;
DDL = diffused double layer;
E_i = initial modulus of elasticity;
H-bond = hydrogen bond;
K^+, Na^+, Ca^{++} = Potassium, sodium and calcium cations, respectively;
K_{ur} =dimensionless modulus number, one of Janbu's constants;
LL = liquid limit;
n = exponent, one of Janbu's constants;
P_a = atmospheric pressure in the same unit as $\sigma_{3;}$
PI = plasticity index;
PL = plastic limit;
S.V.B =secondary valence bond;
UU = unconsolidated undrained test;
ϕ and ϕ_{uu} = friction angle obtained from UU triaxial compression test;
ρ_d = dry density of soil;
w = moisture content



a. Actual assemblage of the silica sheet unit.

b. Simplified assemblage of the silica sheet unit.



c. 3 – D View of the silica sheet tips up.

Fig.(1): Unit of the silica sheet showing the hexagonal holes with r = 1.32 Å.

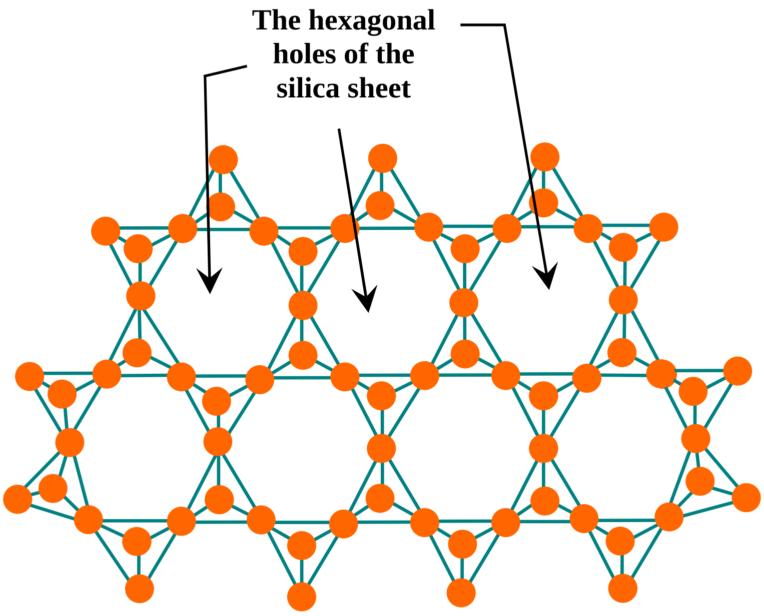
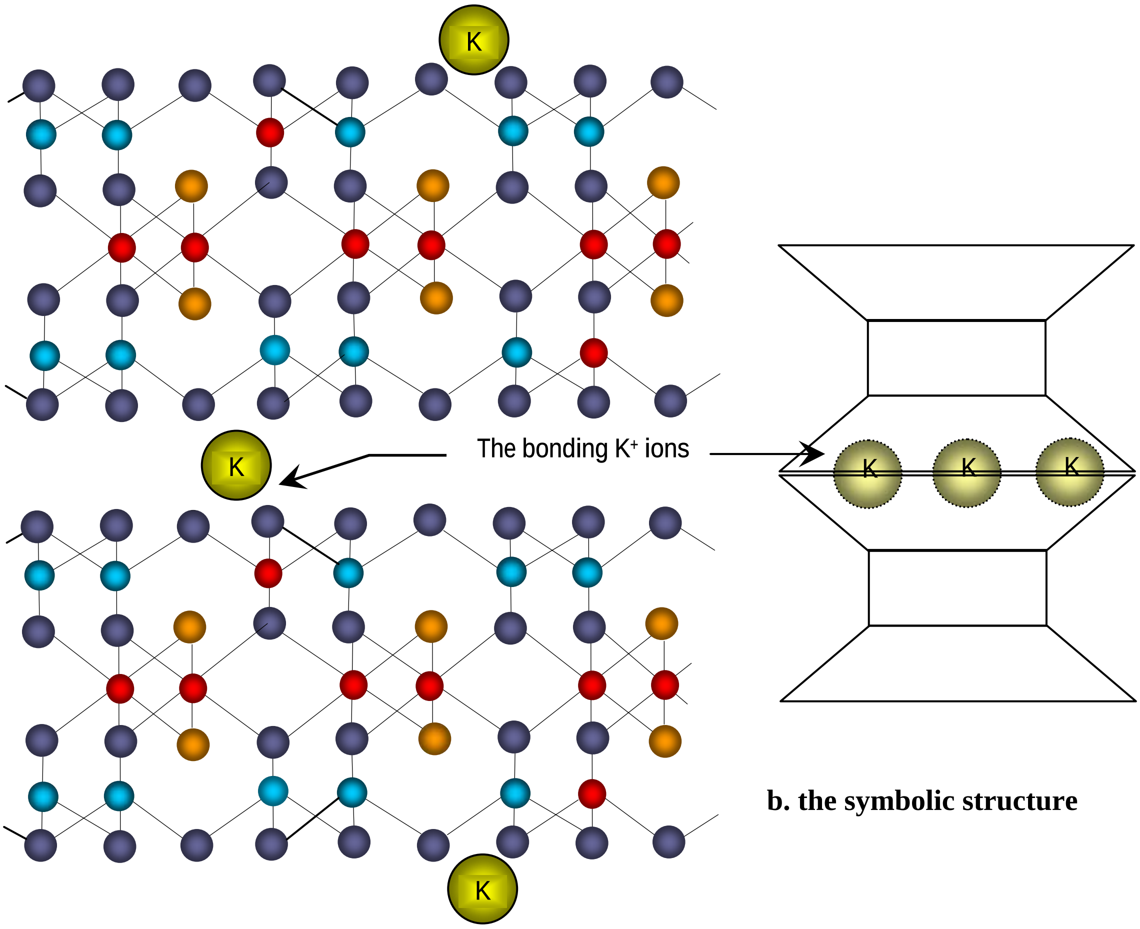


Fig. (2): Plan view of the silica sheet - the atomic structure.



a. **the atomic structure**

b. the symbolic structure

Fig.(3): The bonding mechanism of the potassium ions for a 2:1 mineral.

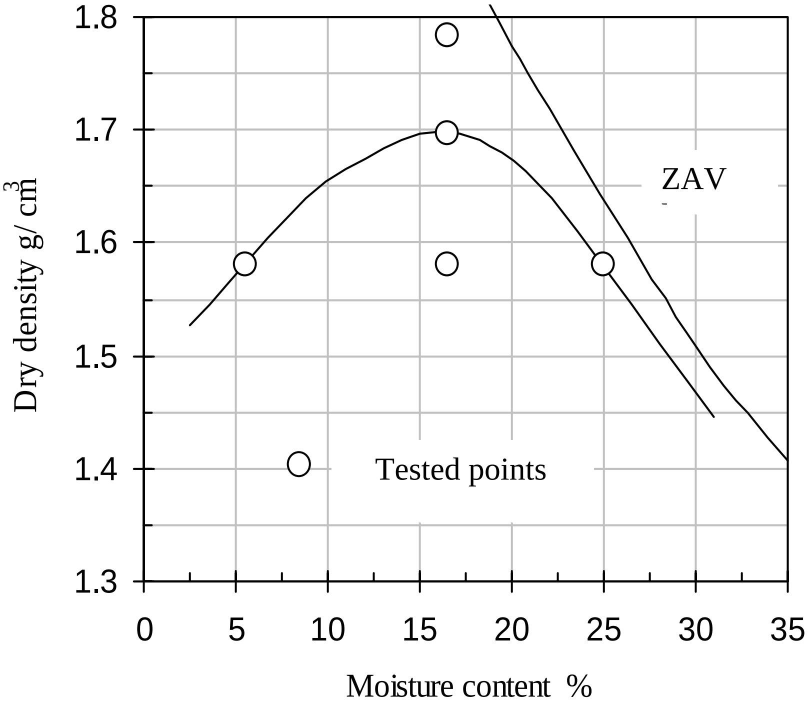


Fig. (4): Moisture –dry density relationship for the tested marly soil, ASTM 698-78 (Karmi, 1993).

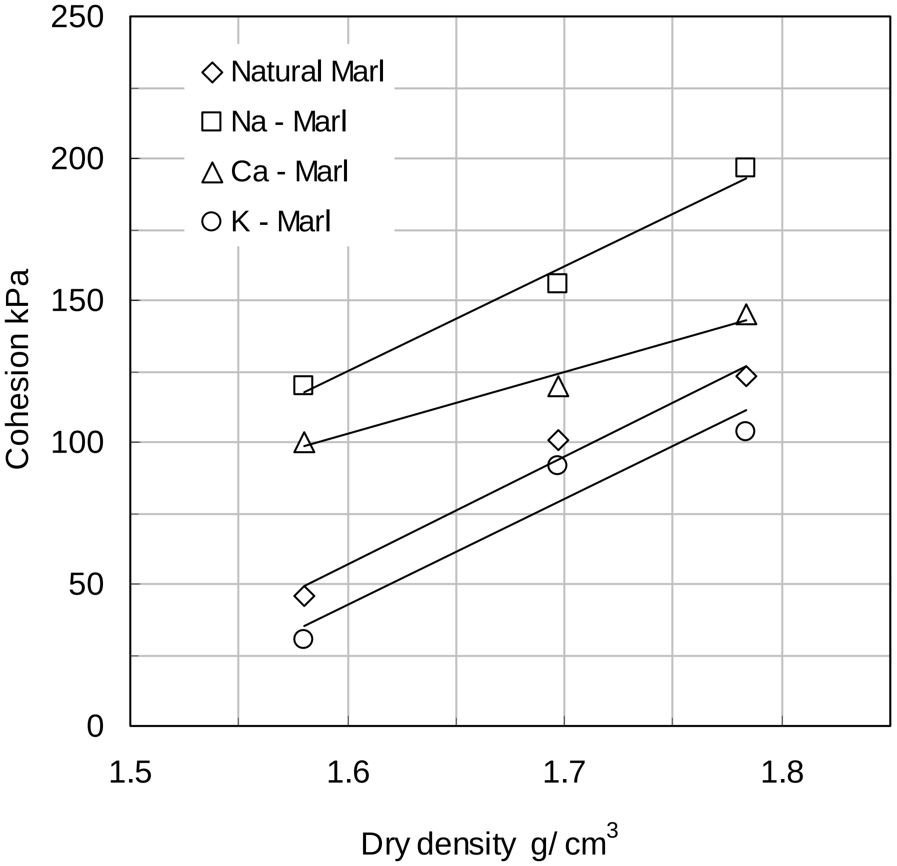


Figure (5): Influence of dry density and exchange complex on Soil cohesion, w = 16.5%, (Karmi, 1993).

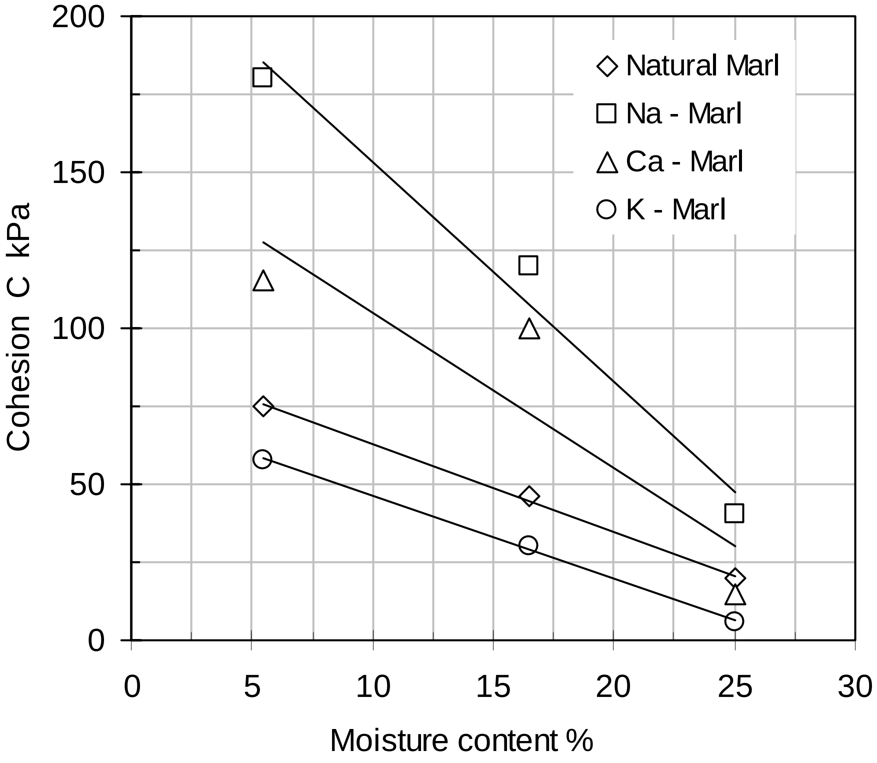


Figure (6): Influence of moisture content and exchange complex on cohesion, ρ_d = 1.58 g/cm^3 (Karmi, 1993).

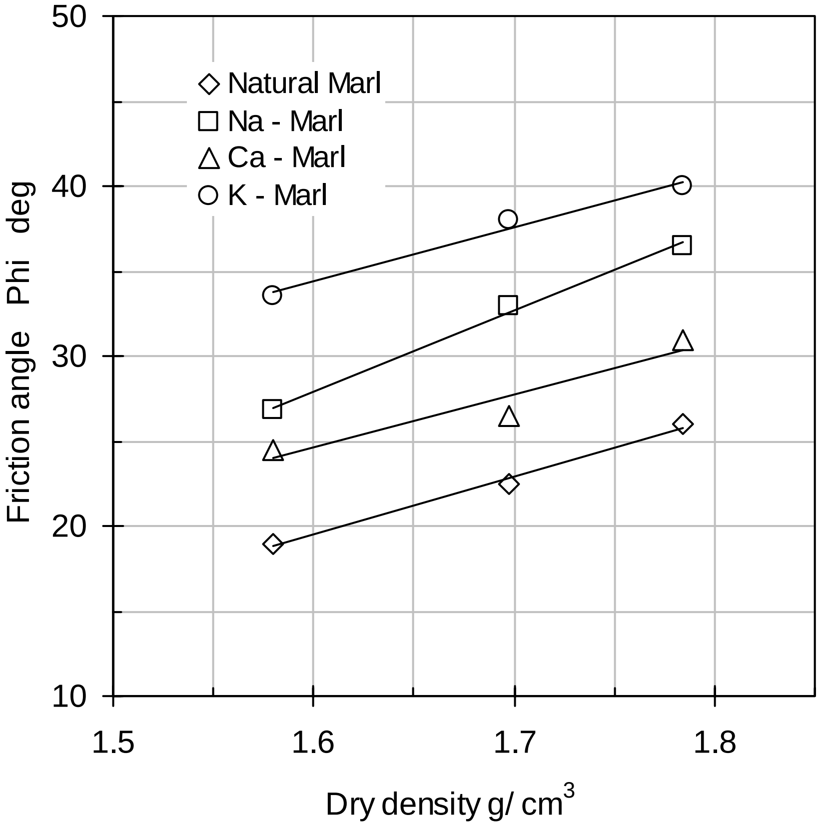


Figure (7): Influence of dry density and exchange complex on soil cohesion, w = 16.5% (Karmi, 1993).

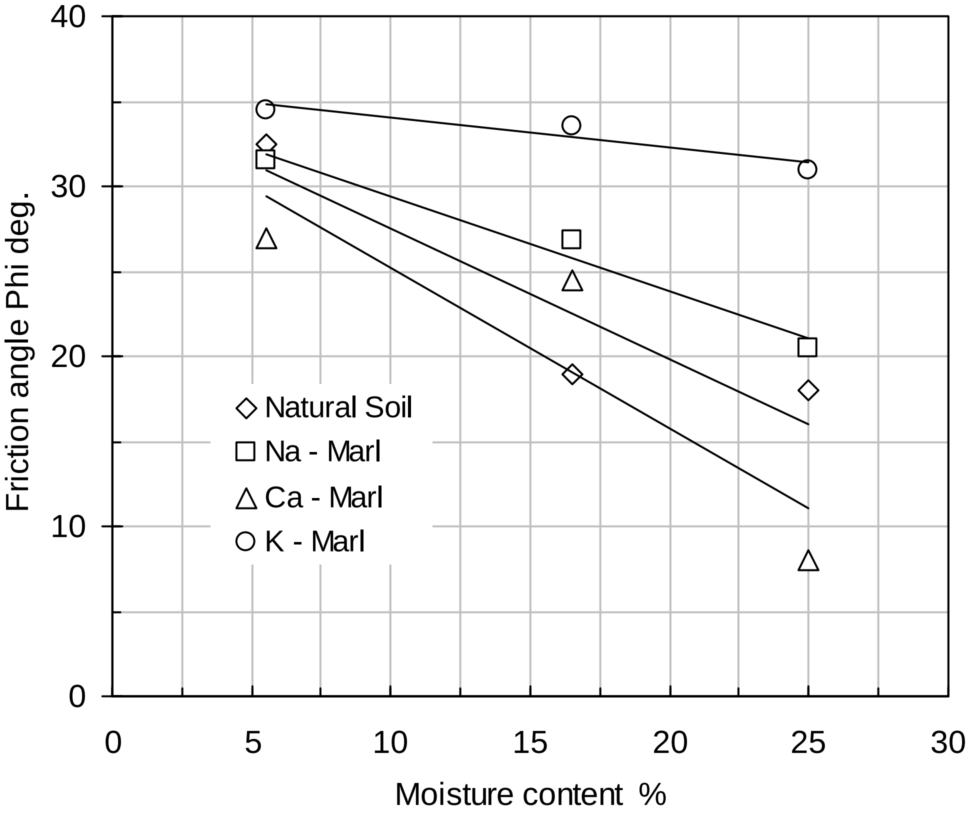


Figure (8): Influence of moisture content and exchange complex on the friction angle, ρ_d = 1.58 g/cm^3 (Karmi, 1993).

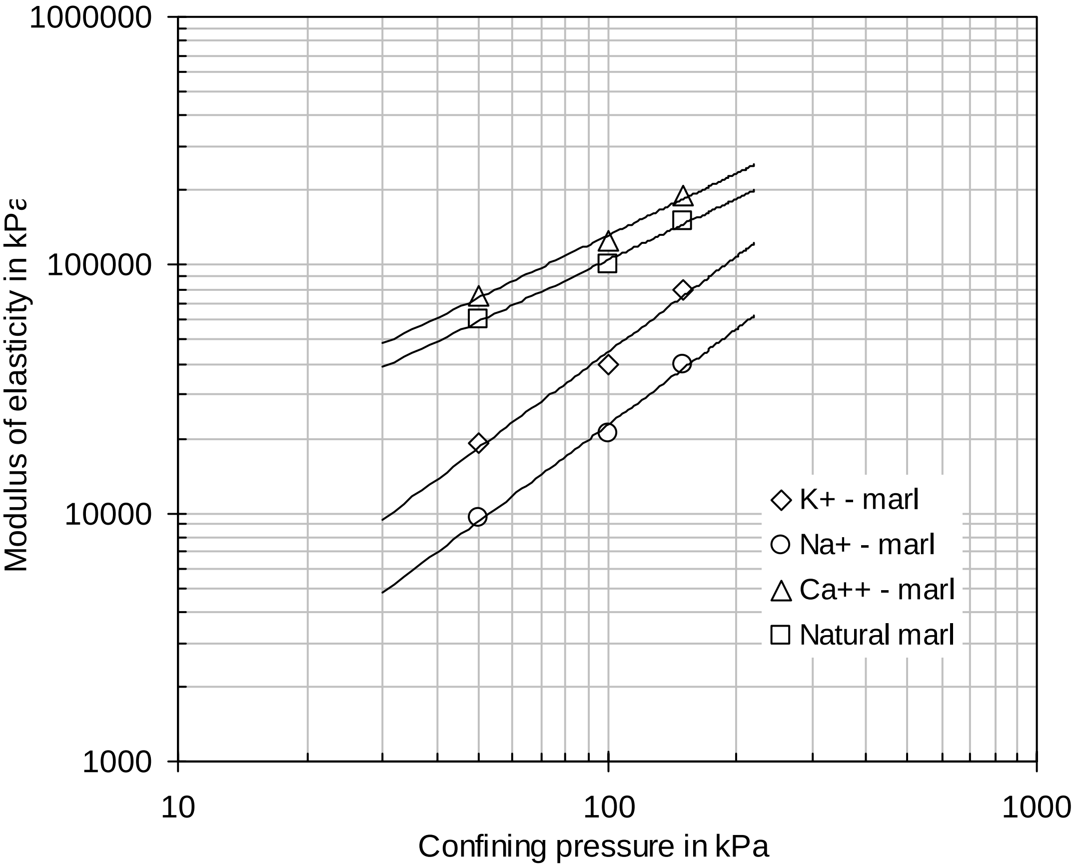


Figure (9): Influence of the exchange complex and the confining pressure on the modulus of elasticity - w= 5.5%, ρ_d = 1.58 g/cm^3 (Karmi, 1993).

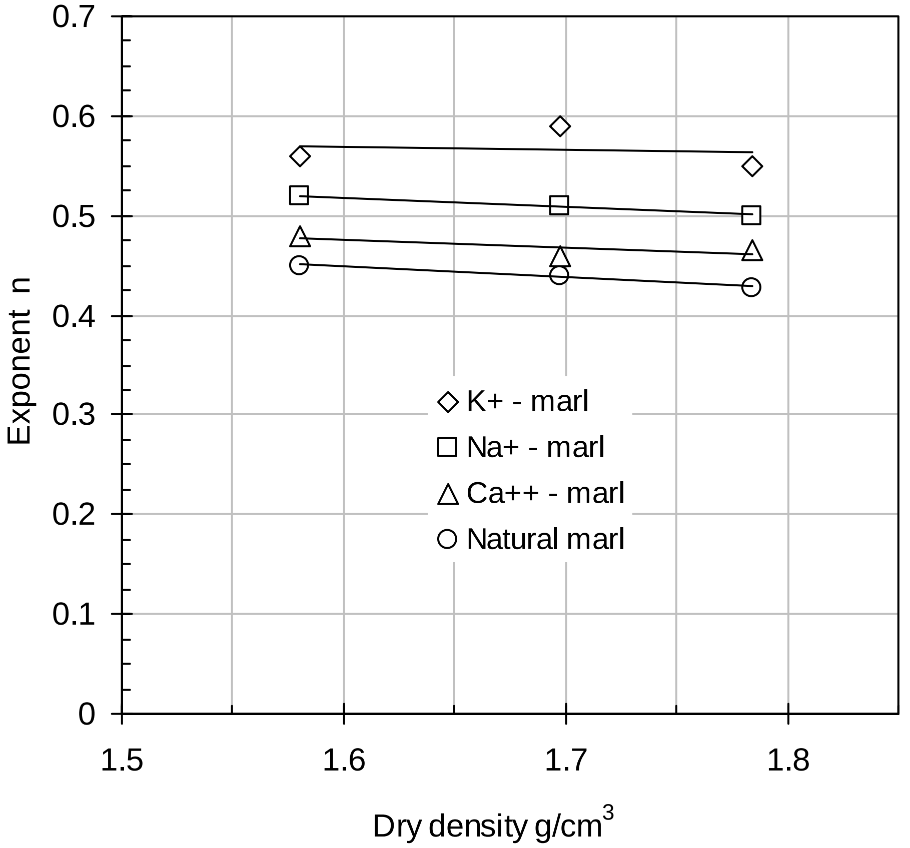


Figure (10): Exponent n versus exchange complex and dry density - w = 16.5% (Karmi, 1993).

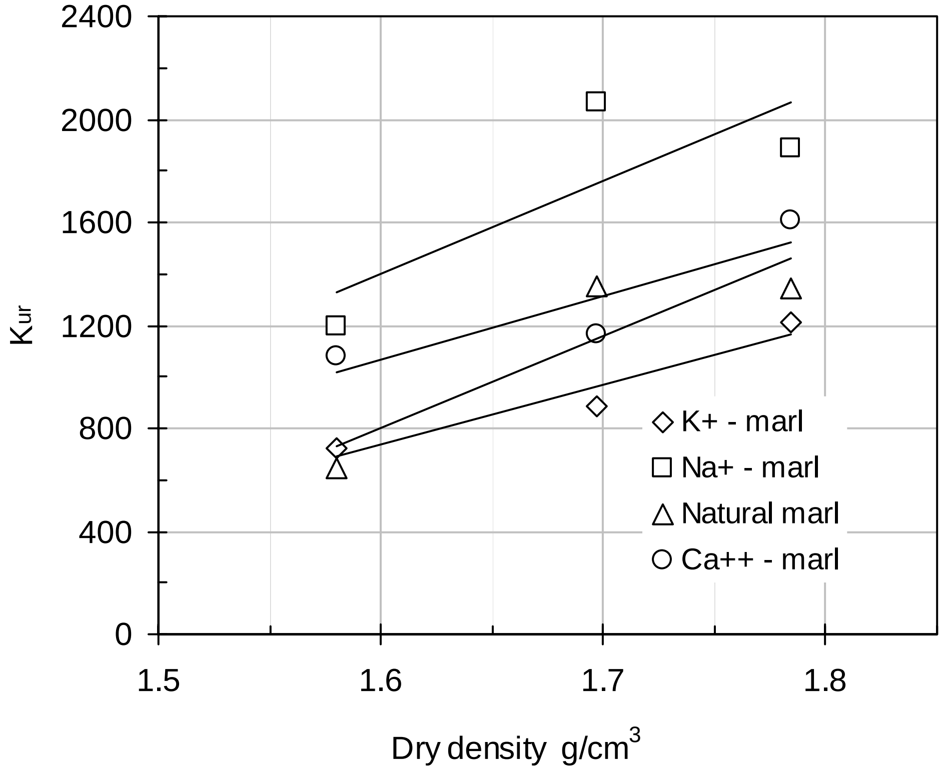


Figure (11): Influence of exchange complex and dry density on values of K_{ur}, w =16.5% (Karmi, 1993).

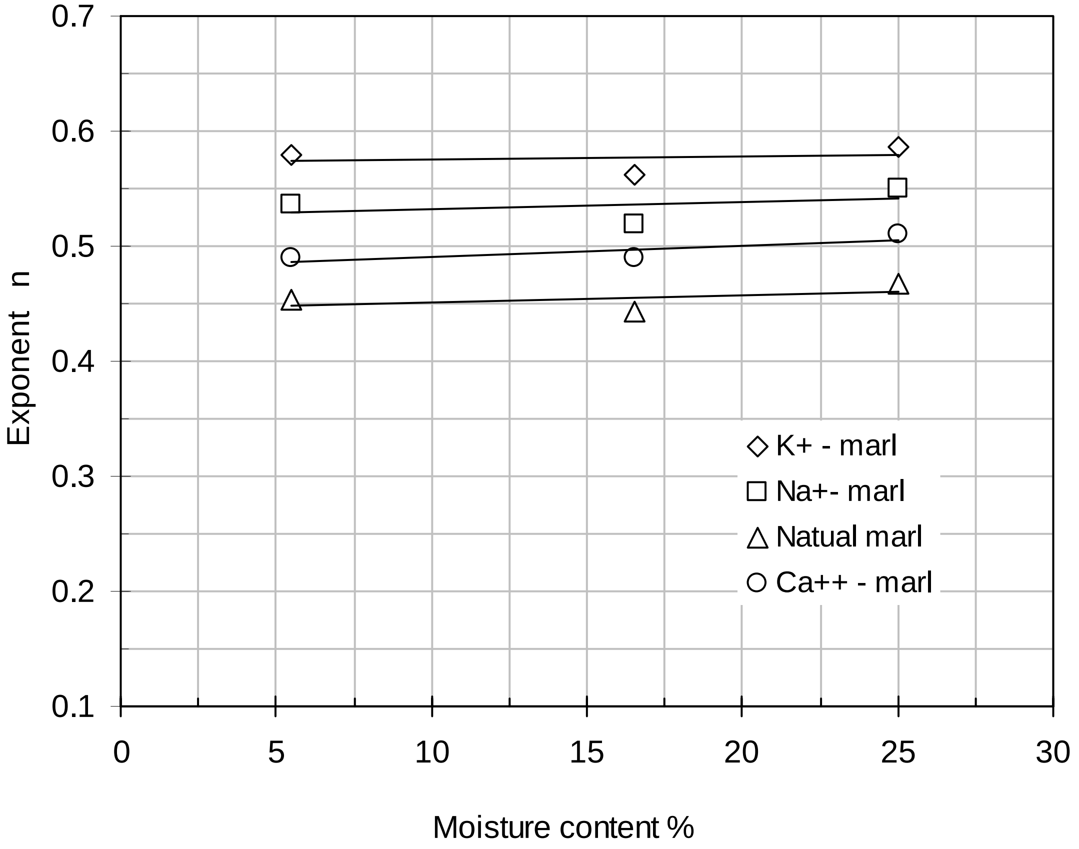


Figure (12): Influence of exchange complex and moisture content on exponent, n - $\rho_d = 1.58$ g/cm^3 (Karmi, 1993).

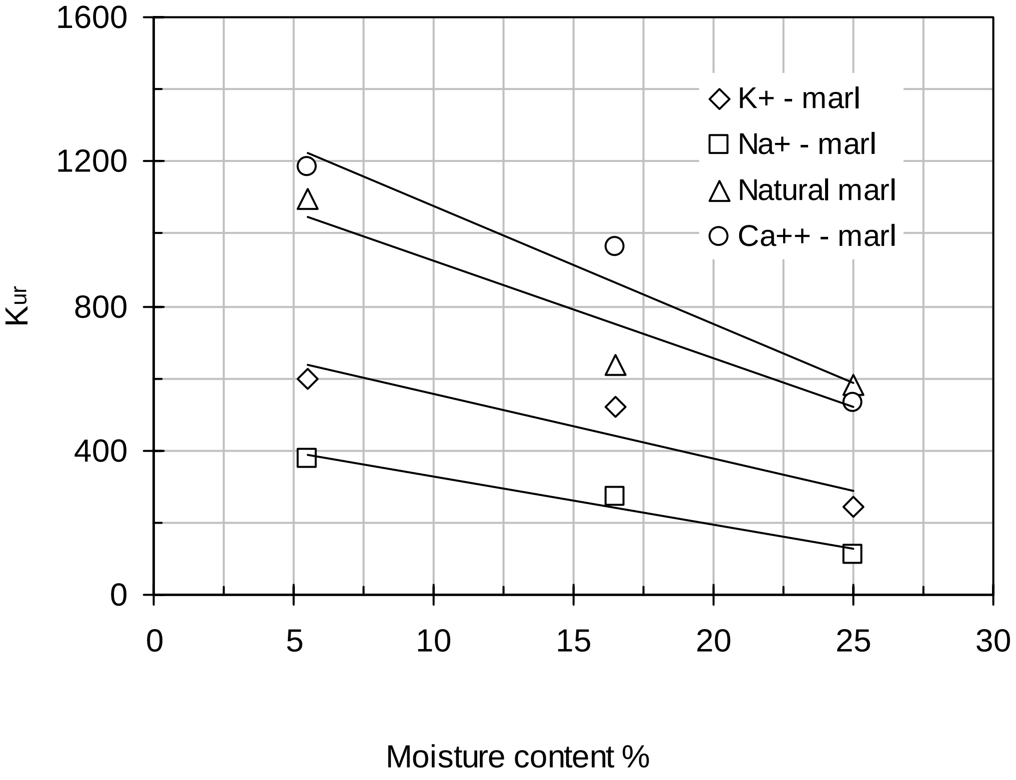


Figure (13): Influence of exchange complex and moisture content on Exponent n, ρ_d = 1.58 g/cm^3 (Karmi, 1993).

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