Sohag Journal of Science
*An International Journal*

# Geological evolution and swelling potentiality of Paleonile Clays in Nile Valley, east Sohag, Upper Egypt

*El-Sayed Sedek Abu Seif* [1*], *El-Shater A.A.*[1], *Ammar Amin*[2]

[1] Geology Department, Faculty of Science, Sohag University, P.O. Box 82524, Sohag, Egypt.

[2] Faculty of Earth Sciences, King Abdulaziz University, P.O. Box 80206, Jeddah, Saudi Arabia.

Received: 23 Jan. 2022, Revised 1 May. 2022, Accepted: 5 May. 2022.

Published online: 1 Sep. 2022

**Abstract:** From Late Eocene to Holocene, the Egyptian Nile Valley has been subjected to six stages (or phases) of geological evolution which considered as a reflection of intensive tectonic events took place in the neighboring sedimentary basins (e.g. NE-Africa basin, the Eastern Mediterranean basin and Red Sea basin uplifting). Consequently, the geological setting of Upper Egypt generally can be considered as a representative model in which all evolutional stages of Egyptian Nile Valley were typically represented. The Paleonile Clays (Pliocene) are widely distributed in Upper Egypt as surface and subsurface sequences. These fine-grained clayey-sediments are affected negatively on construction activities owing to their highly swelling potentiality. Montmorillonite represents an essential component of clay mineralogy of Paleonile Clays with others (illite-montmorillonite mixed-layer, kaolinite, illite and trace amount of chlorite). The Exchangeable Sodium Percentage (ESP) values of Paleonile Clays are very low additionally its plasticity index values are exceeded than 35%. This indicated that the studied Paleonile Clays are swell-able clay type (non-dispersive type) and its dispersive ability is not significant. The Paleonile Clays (Pliocene) micro-fabrics are dominated mainly by flocculation and aggregation fabric types, which had relatively higher swelling potentiality. The swelling potentiality of the studied Paleonile Clays has strong relations with clay-sized fraction (%), montmorillonite (%), plasticity index (PI) and amount of exchangeable cations (CEC).

**Keywords**: Paleonile Clays – Upper Egypt – Cations – Clay mineralogy – Microfabrics – Swelling potentiality.

## 1 Introduction

There are strong mutual relationships between the engineering behavior of any fine-grained clayey soils sediments and their geological origin (e.g., compositional and environmental factors). The compositional factors are included amount of clayey-sized fractions and type of clay mineral species [**1**-**3**], the shape, size distribution of fine particles [**4**, **5**], adsorbed cations, and inter-particles water chemistry [**5**, **6**]. The environmental factors are contained water content [**7**], density, confining pressure, fabrics, and temperature. The expansive soils are composed mainly of fine-grained clayey-sized particles of high plasticity behavior owing to presence of swelling clay mineral species (e.g., montmorillonite) that tend to absorb water and swell. These expansive clayey materials are found in more than 60 countries and regions [**8**] especially in tropical and subtropical regions. This swelling behavior is considered as a multi-factorial phenomenon that controlled mainly by integrated parameters (e.g., grain-size, clay mineral percentages, micro-structures or fabric, moisture content and density [**9**].

In Upper Egypt, the expansive (Paleonile Clays) soils are widely distributed especially in the new desert cities where clayey-rich soils are represented as surface and sub-surface sequences. These new cities had been constructed by the Egyptian Government (e.g., New Assuit City, Al-Kawther City in NE-Sohag, New Campus of Sohag University in Al-Kawamel District and the industrial zone in Qena Governorate). The possibilities of damage to constructions are owing to their highly swelling behavior of these soils. Accordingly, several geotechnical problems were raised (e.g., walls cracks and tilting of foundations). Thus, the geological evolution of Paleonile Clays in Nile Valley, Upper Egypt, must be understood to clarify assessment their geotechnical characteristics (e.g., swelling potentiality). This work aims to geotechnical evaluate the swelling potentiality of Pliocene Clays, Nile Valley, Upper Egypt.

## 2. Geologic setting

The study area locates in east Sohag Governorate (Upper Egypt, between latitudes 32°20` and32°15` E and longitudes 26°10` and 26°45` N, Fig. 1, [**10**]. From

* Corresponding author E-mail: elsayed.abdelah@science.sohag.edu.eg 

geological point of view, the study area has been subjected to many previous studies [11-21]. Generally, the geology this area can be summarized as follows:

**2.1. Lower Eocene Sequence**, consisting mainly of limestone plateau that bounded the study area in the east and west sides. Based on its facies variations it divided essentially into two distinct formations; Thebes Formation and followed upwards by Drunka Formation.

a. **Thebes Formation** [15] is considered as the oldest carbonate rock unit in the study area. It represents the basal part of Lower Eocene sequence. It consists mainly of yellowish and white laminated and bedded limestone with bands of chert and flint. It is enriched with index fossil of Ypresian (Lower Eocene, e.g. Operculines, Assilines and Nummulites) [20].
b. **Drunka Formation** conformably overlies the Thebes Formation and characterizes by well-known and differentiated snowy white colour. The silicified concretions (~1.2m) are considered as a diagnostic feature especially in its lowermost part. Its uppermost section (100-120m thick) composes of gray, grayish white and white bedded bioturbated hard limestone [20].

**2.2. Madmoud Formation** [11, 12-14] represents a Paleonile stage that began in the Early Pliocene with Mediterranean Sea transgression. It is unconformably overlain by the sediments of the Armant and Issawia formations. Madmoud Formation (Paleonile Clays) is outcropping along Lower Eocene Sequence especially in eastern cliffs (Fig. 1)

**2.3. Issawia Formation** [11, 12, 14] is belonging to Early Pleistocene and consisting mainly of well-cemented and very hard red and reddish white. Its clasts vary 0.3m to 3m in diameter [20]. Issawia Formation attains 10-12m in thickness and usually crops out along Lower Eocene escarpment.

**2.4. Armant Formation** (Lower Pleistocene) is exposed as terraces overlying unconformably Eocene limestone [11, 12, 14].

**2.5. Qena Formation** (Qena Sands, Middle Pleistocene [14] is occurred as hills adjacent the cultivated lands of flood plain. Its fine aggregates (sands) were extracted from many open cast quarries and used as construction materials [21].

**2.6. Abbassia Formation** (Upper Pleistocene) is overlying conformably Qena Sands and is representing by an easily distinguished sequence of yellow and yellowish white coarse-grained gravels [11, 14].

**2.7. Dandara Formation** (Upper Pleistocene) nearly occurs closely to the cultivated lands of flood plain as fine-grained loose sediments [14].

**2.8. The Holocene Sequence** can be classified into two parts [19, 22] as follows:

a. **Flood Plain** (cultivated lands) attains 10-12m thick of silts, clays and fine sands intercalations. It restricted besides the two banks of River Nile.
b. **Wadi Deposits** are consisting of very coarse gravels and sands that formed as a result of flash flood events.

## 3 Methodology

To geotechnical evaluation the swelling potentiality of Pliocene Clays in Nile Valley, Upper Egypt, forty-four (disturbed and undisturbed) representative samples of Paleonile Clays (Madmoud Formation) were collected (Figs. 1 and 2) and subjected to intensive laboratory tests. The initial water content and specific gravity of these samples were determined [23, 24]. Grain-size analysis was done by sieving (sand-sized fractions) and hydrometer (silt and clay-sized fractions). Then, liquid limit (LL) and plastic limit (PL) were estimated [25]. To evaluate the relation between swelling potentiality of Paleonile Clays and their micro-structure, two cubes (vertically and horizontally) were cut by sharp knife from 6 representative samples were done and then were slowly dried at constant 20°C for three weeks. A V-shaped groove was done at the middle of each cube [25]. Then these cubes were scanned [26]. The swelling potentiality of Paleonile Clays was determined using odeometer apparatus [27]. The free swelling was done [28]. Also, the exchangeable cations Paleonile Clays were extracted and determined [29]. The clay mineral constitutes of Paleonile Clays (<2µm fractions) were done using X-ray diffraction (XRD). The relative abundance of clay mineral species was calculated [30-33].

## 4. Geological evolution and characteristic features of Pliocene Clays

The Egyptian Nile Valley and its delta had been tectonically greatly affected by the tectonic events that took place in the neighboring sedimentary basins (e.g. NE-Africa basin), the Eastern Mediterranean basin and Red Sea basin. These sedimentary basins had been originated throughout combination and integration of intensive tectonic events and climatic fluctuations which had their impacts on the evolution of the Egyptian Nile Valley itself [34-41]. Thus, the geological evolution of the study area (Sohag, Upper Egypt) had been affected of the directly by Egyptian

Nile Valley geological evolutional stages. Additionally, the distribution of Post-Eocene rock units in the Egyptian Nile Valley is greatly controlled mainly by regional tectonics events (e.g. Red Sea opening [42-46] and locally occurrence of Cretaceous and younger faulting [47, 48] as well as climate fluctuations (Messinian Salinity Crisis and the emergence of the Sahara [49, 52]. Consequently, the sediments (fluviatile sediments and other associated sediments) of the Egyptian Nile Valley were subdivided into distinctly five rivers (stages, Fig. 3).

In Sohag Governorate (Upper Egypt), dependently upon the distinctly variations in stratigraphical relationships, lithology, and mineral composition another evolutional stage named Pre-Eonile (Stage I, Fig. 3, Oligocene) was defined and recorded [20, 53, 54]. During Paleonile Stage, the canyon transgresses by the advancing Mediterranean as it is started filling up during Pliocene. The sediments of Paleonile Stage are consisting of a long series of inter-bedded brownish gray clayey-sized clastic sediments with intercalations of thin fine sands and silts (Madmoud Formation) [11]. This stage (Stage III) represents Pliocene interval which formed as a result of a dropping in the Mediterranean Sea level within Late Miocene (Messinian Salinity Crisis), [11, 14].

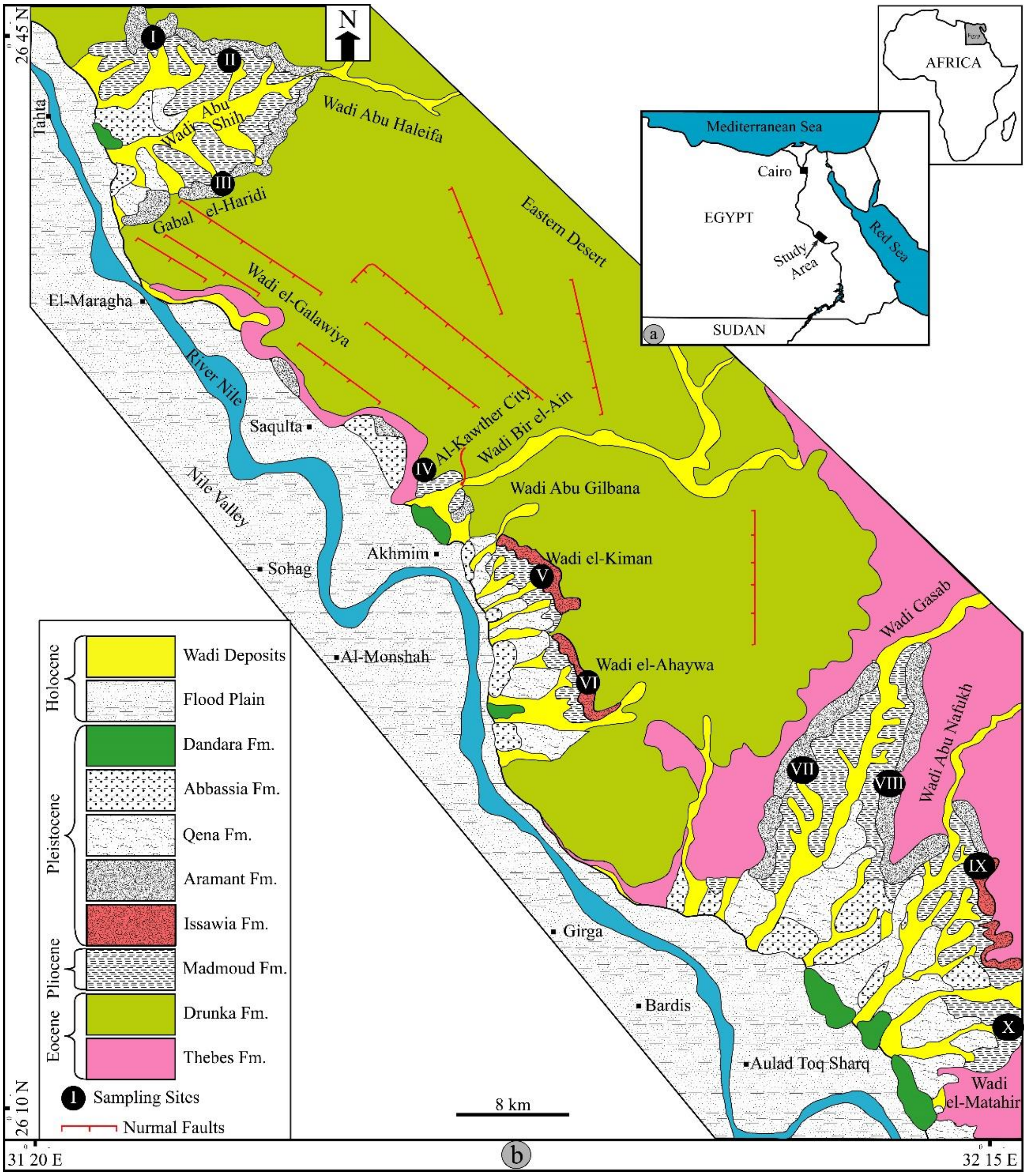


**Fig 1**: Location map (a) and geological map (b) of east Sohag Governorate [10]

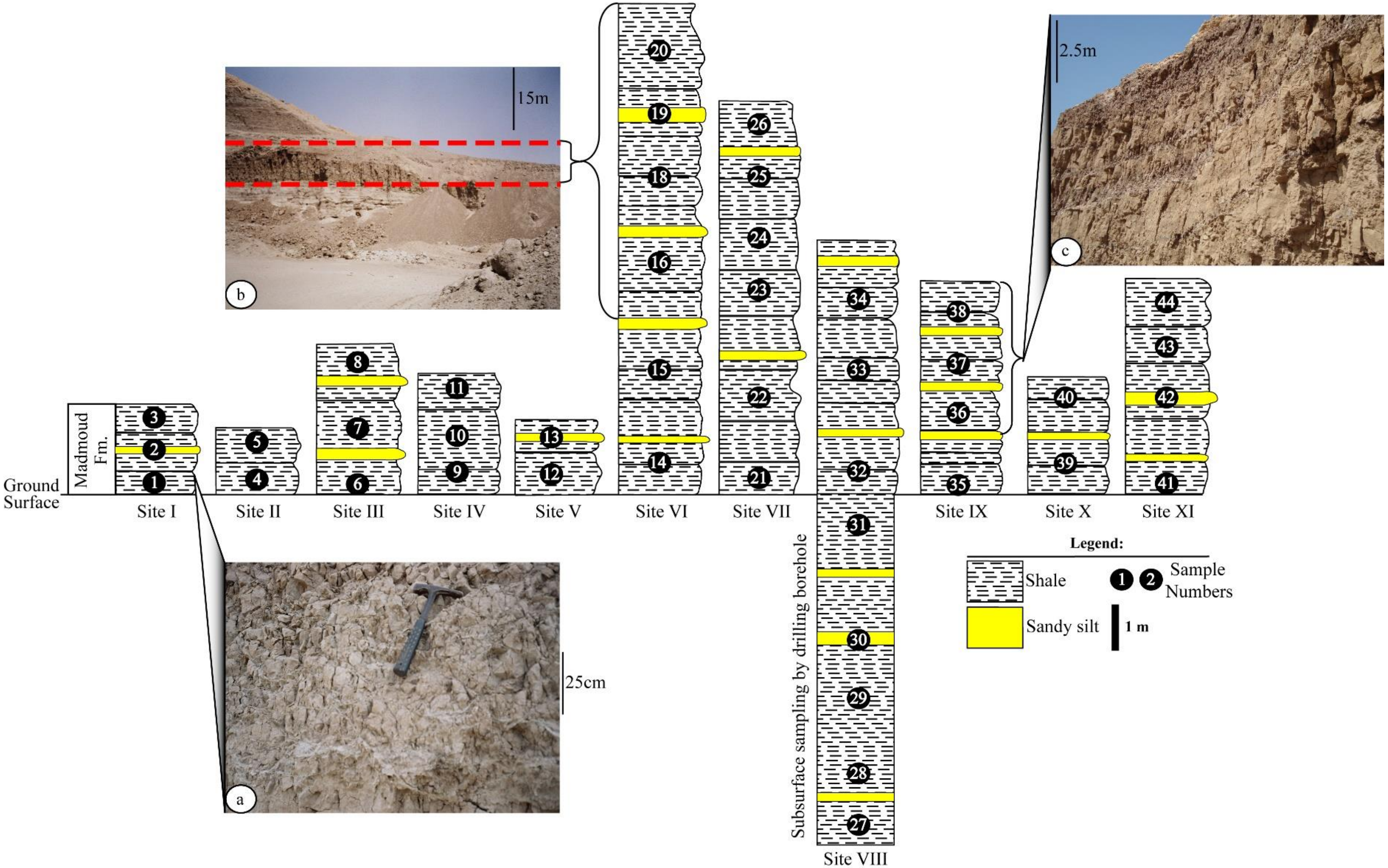


**Fig. 2:** Columnar sections and sample numbers of the studied Paleonile Clays (Madmoud Formation) and representatives field photographs (a; b and c)

In Upper Egypt, especially in the study area, Madmoud Formation (Paleonile Clays) is described as a base of inner terrace nearer to the Lower Eocene scarp. Based on field observations, Madmoud Formation can be distinguished and defined easily by its distinct chocolate to dark brown colours where it crops out along the pediment of the Eocene cliffs and the dissecting side wadis (Figs. 1, 2) and unconformably overlain by the sediments of Issawia and Armant formations. Madmoud Formation is mainly composed of thick bedded shale with thinly bedded sandy silt intercalations (Fig. 4). Madmoud Formation attains its maximum thickness (15m thick) at the northern flank of Wadi Ber Al-Ain (Site IV, Figs. 1 and 2). The vertical variation in thickness is attributed to the effect of channels that cut through these soft sediments during the sedimentation of younger terraces such as Armant Formation, especially, in areas facing the tributaries that dissected the Eocene plateau (Figs. 1 and 2). In the study area, the clayey-rich sediments of Madmoud Formation had been classified into mottled bedded brown and grey clayey-rich shales which intercalate with massive to laminated sandy siltstone and claystone at the uppermost part. The shale beds contain organic matters and calcrete concretions. Furthermore, these sediments are mainly represented by highly desiccated and cracked cycles (Figs. 2 and 4). These cracks are usually filled with calcified white materials owing to episodes of arid climatic exposures during marine regression. Additionally, the shale beds and sandy silts are enriched with sapropelic organic matters, calcrete nodules and mud cracks are recognized. The horizontally laminated siltstones and claystones of this association are interpreted to represent overbank-flood plain deposition. The prevalence of mud cracks in these facies suggests that this fluvial system was of relatively low-gradient. The presence of calcrete nodules and organic matters are another evidence supporting flood plain deposition [20, 55]. The fining upward cyclic of sandy silts and the even laminated silts and clays indicate that the deposition had taken place in an overbank-flood plain environment [56]. Additionally, the presence of intersecting cracked surfaces in these clayey-sediments are greatly increased the amount of water to easily penetrate within these layers and causes an increasing in their original volume of these clayey sediments.

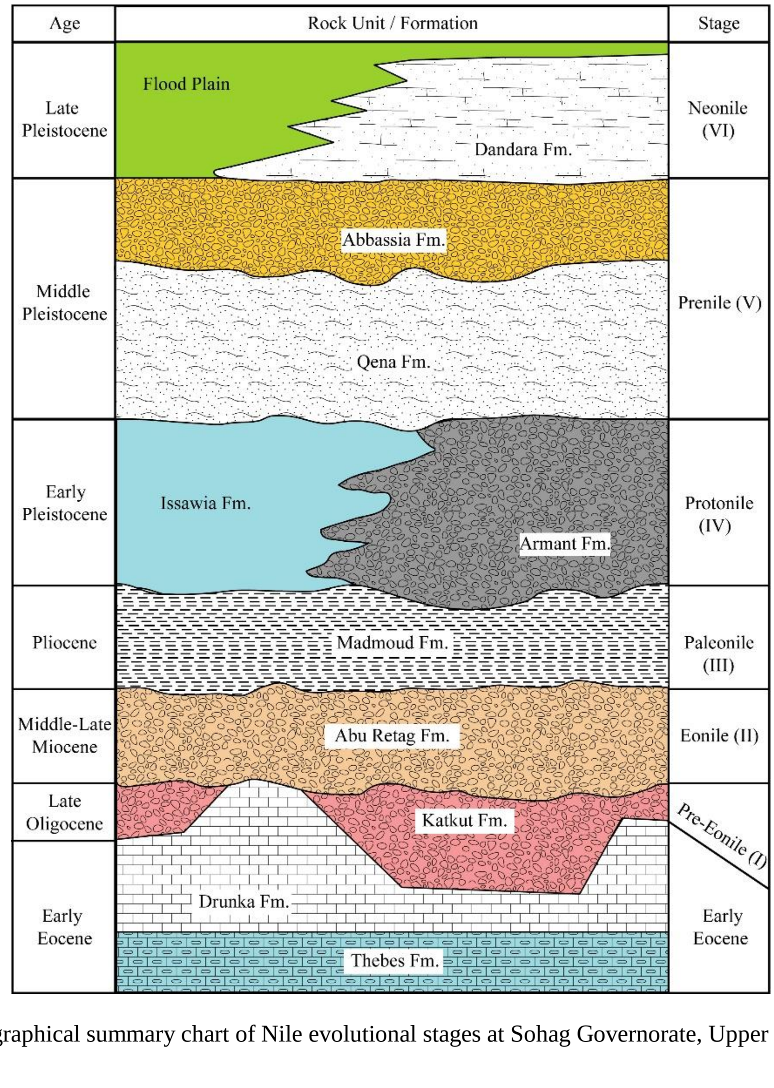


**Fig. 3**: Stratigraphical summary chart of Nile evolutional stages at Sohag Governorate, Upper Egypt [20, 21]

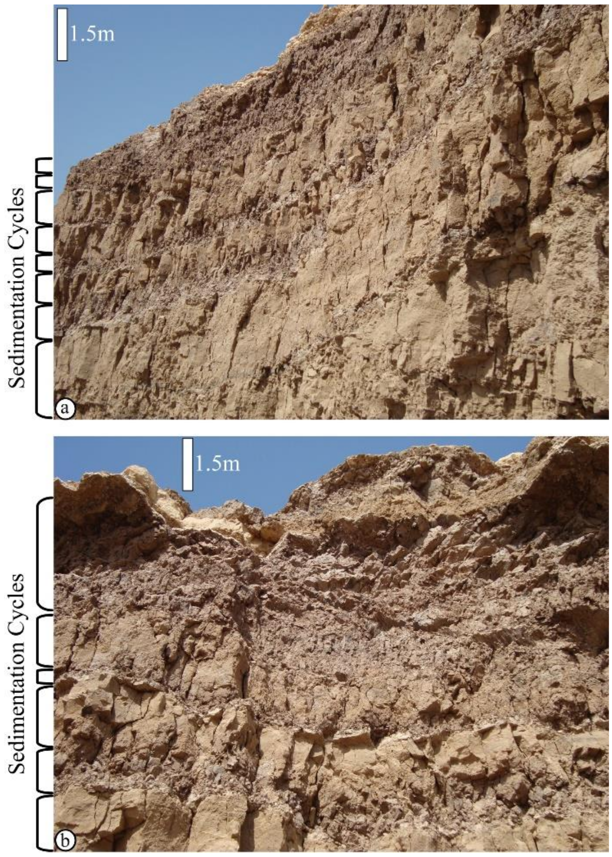


**Fig. 4**: Field photographs showing characteristic features of Paleonile clayey shale beds (Madmoud Formation explaining bedded shale beds in cyclic manner of sedimentation separated by erosion surfaces and showing highly cracked clayey rich shale beds (a and b).

## 5. Results and discussion

The obtained results are indicated that, the swelling ability of clayey-rich shale of Paleonile Clays (Madmoud Formation) are depends mainly on several factors which are linked together and harmoniously integrated (e.g. grain-size distribution, type and amount of clay minerals present, cation exchange capacity, macro-fabrics and initial moisture content). These factors will be explained and interpreted in detailed in the followings.

### 5.1 Grain size

The grain-size distribution of fine-grained shale or soil plays an essential rule in its swelling potentiality. The swelling potentiality will be increased with increasing of clay-sized fractions (<0.002mm) as a result of larger specific surface area of clay-sized grains. The studied Paleonile (Madmoud Formation) samples (shale and sandy silts samples) are having nearly smooth grain size curves so that these clayey sediments can be have a sizeable inter-particle voids (Fig. 5). These inter-particle voids will be filled with water and will lead to increasing the ability of these soil samples to swell. The studied Paleonile Clays (Madmoud Formation) samples are consisting mainly of clays (58% to 73%), silts (23% to 38%), and trace amounts of sands (2% to 8%, Table 1). Whereas, the sandy silt layers are composed mainly of silts (63% to 69%), sands (13% to 19%) and clays (18% to 23%, Table 2). Accordingly, based upon Unified Soil Classification System (USCS), the studied Madmoud Formation shale samples are classified into clays of high plasticity (CH) whereas the sandy silt samples were classified as inorganic silts of high plasticity (MH, Table 1).

### 5.2. Initial moisture content

When shale and fine-grained soil samples are moist that led to the clay minerals (2:1) surfaces of negatively charges attracted water molecules of positive charges allowing the water molecules to enter between the clay minerals layers. The inter-layered water molecules cause the sheet-like clay particles to swell, forcing the whole shale or fine-grained soil to expand. On the contrary, when shale or fine-grained soil dries, the trapped water molecules that occurred within the clay mineral layers will be released, thus its volume will be decreased. Thus, the initial moisture content of the studied samples plays a vital rule in their swelling potentiality. The initial moisture content of the studied Paleonile Clays (Madmoud Formation) samples varies from 12.4% to 25% for shale samples and from 8.6% to 16% for sandy silt samples (Table 1).

## 5.3. Dry density

Dry density of any fine-grained shale or soil had been considered as an effective factor that is controlling its swelling potentiality. Dense shale or clayey soil means that there are lager amount of clay particles that are captured into its unit volume than in the looser ones. Consequently, it will absorb larger amounts of water within and on its particles then higher swelling potential. The dry density of the studied Paleonile Clays (Madmoud Formation) samples fluctuate from 2.03 to 2.22 gm/cm3 in shale samples and from 2.3 to 2.32 gm/cm3 in sandy silt samples (Table 1). This dense soil which has very small grain-size particles will absorb a large amount of water owing to its relatively lager surface area.

## 5.4. Clay mineralogy

Clay mineral constitutes is represented an essential parameter that are controlling the swelling potentiality of fine-grained shale or soil. The engineering properties of swelling shale and soil seem to be related to mineralogical composition including clay-water system. The XRD-pattern of the studied Paleonile Clays (Fig. 6) indicating that montmorillonite (63% to 72%) is the most dominance species. Other clay mineral species including illite-montmorillonite mixed layer (12% to 18%), kaolinite (2% to 13%), illite (5% to 17%) and scarce amount of chlorite were also present (Table 1). Indirectly, the clay mineralogy of the studied Paleonile Clays had been qualitatively determined (Fig. 7), [57, 58]. Where, all shale samples of Madmoud Formation plotted within the montmorillonite zone above the A-line while sandy silt samples arranged in the kaolinite zone below the A-line. The plasticity chart (Fig. 7) indicated that the studied samples are classified into high and extremely high swelling potential types. Additionally, XRD-chart (Fig. 6a) as well as the relative abundance of clay mineral species of the studied soils (Fig. 6b) indicated dominance of montmorillonite specie which characterized by its relatively higher swelling potentiality.

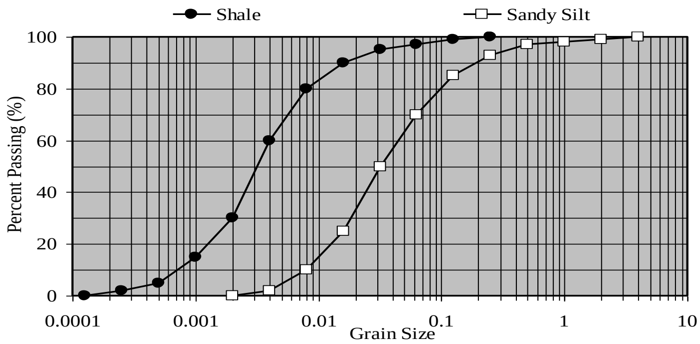


**Fig. 5**: Grain size distribution curves of the studied Madmoud Formation samples

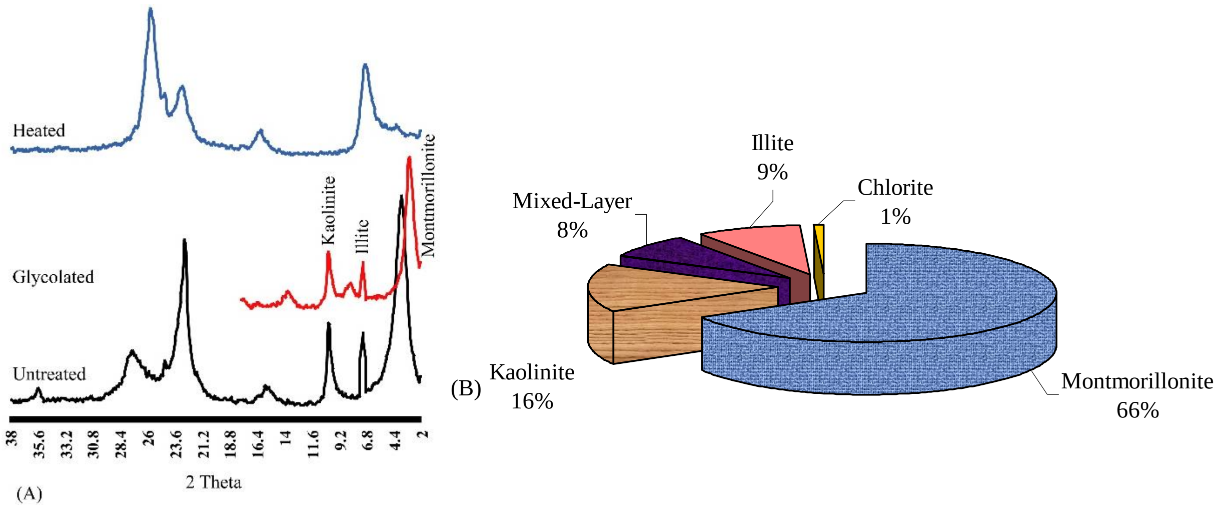


Fig. 6: XRD chart and abundance of clay mineral species of the studied Madmoud Formation shale samples (average values, a and b respectively)

### 5.5. Consistency limits

The consistency limits of shale and fine-grained soil samples are usually used as a fundamental classification key and are widely used indirectly to quantitatively evaluation the swelling potentiality of these samples. The studied shale samples of (Madmoud Formation) have liquid limit values more than 65% (82-100%, Table 1), thus these shale samples are classified into very high swelling potentiality sediments [59]. Figure 9 (plasticity chart) is mostly indicated that the studied samples of Paleonile Clays were plotted above the A-line field (extremely swelling) whereas the sandy silt samples of Madmoud Formation were plotted below the A-line (high swelling).

Furthermore, the plasticity index (PI) of the studied Madmoud Formation shale samples are mostly more than 50% and the liquid limit values are higher than 65% (Table 1). Accordingly, the shale samples are classified as expandable clayey-rich sediments [1, 4, 8, 59, 60]. Based on the binary variable relationship between clay-sized content and plasticity index chart [61] the swelling potentiality of the studied shale and sandy silt samples of Madmoud Formation is ranged from very high to high respectively (Fig. 8). The relative higher percentages of clay-sized contents and higher plasticity index of the studied soils had been led to the majority of these soil samples were plotted within the very high expansion zone (Fig. 8). Additionally, the initial moisture content values of dense Paleonile Clays are less than liquid limit values (Table 1) this indicate these soil samples will absorb a large amount of water owing to its relatively lager surface area and will largely swell.

### 5.6. Cation exchange capacity (CEC)

Cation exchange capacity of shale or fine-grained clayey soil is initially represented the amount of positive charged ions that required making balance state with the deficiency charges on surface of clay particles. So, cation exchange capacity (CEC) of shale or fine-grained clayey soil has been directly great effects on its ability to swell [62, 63]. Nearly, the presence higher amounts of clay-sized fractions in shale or fine-grained clayey soil side by side higher organic matter percentages will lead to presence higher positively charged ions [64-65]. Usually most common exchangeable cations of clay mineral species are $Ca^{2+}$, $Mg^{2+}$, $H^{+}$, $K^{+}$, $NH_4^{+}$ and $Na^{+}$ [44]. These exchangeable cations are retaining in an exchangeable state, except for smectites where exchangeable cations are held on external surfaces of these clay minerals. The estimated CEC-values of the studied Paleonile Clays samples indicated that $Ca^{++}$ and $Mg^{++}$ are the dominance exchangeable cation with fewer quantities of $K^{+}$ and $Na^{+}$ (Table 1). Based on the binary variable relationship (CEC and LL), the studied Madmoud Formation samples were classified into very high swelling type (Fig. 9), [66]. The studied soil samples are having a relatively high capacity of cation exchange capacity (CEC) thus these samples are having a high comparatively ability to swell. The exchangeable sodium (ESP) of shale or fine-grained clayey soil can be used as a discrimination factor to evaluate its dispersive potentiality. The ESP-value can be explained as:

$$\mathrm{ESP} = \frac{\text{exchangeable sodium}}{\text{cation exchange capacity}}\,\% \qquad (1)$$

The estimated ESP-values of Madmoud Formation samples are very low (varies from 0.3 to 2.7, Table 1). Additionally, its plasticity index (PI) values are more than 35% that confirmed that, the studied Paleonile Clays are actually swelled sediments type (non-dispersive) and their dispersion effects are not significant. This is owing to dominance of montmorillonite that characterized by its higher swelling potentiality than less sensitive kaolinite clay minerals species [67-70].

### 5.7. Microfabrics

The micro-structures (particle arrangement, fabrics) of shale or fine-grained clayey soil are playing an effective role in its swelling potentiality. Two shale or soil samples may be have the same grain-size, initial water content, clay mineral contents and the same void ratios exhibiting two different swelling potentialities owing to difference in their fabrics. Accordingly, the studying of the fabrics of shale or soil considered very essential for well understanding its swelling behavior. Initially, Paleonile Clays studied specimens were scanned at low and intermediary magnification to generally infer orientation of clay particles (fabrics, Fig. 10a). The magnification must be increased gradually to deduce carefully the orientation of clay particles (miro-fabrics) so the distribution of clay particle interaction and their inter-particle voids and pores will be well seen.

The high magnification of the studied Paleonile Clays samples are suggested that these clays were consolidated normally and oriented mostly in flocculation and aggregation manner (Figs. 10b and 10c). Aggregation is generally increasing viscosity within clay particles whereas flocculation leads to higher viscosity and high values of yield stress. The Flocculation fabrics make shale and soil to be very stiff and easily liquids movement thus its permeability will be increased then high swelling potentiality will be happened [62-64].

**Table 1**: Physico-chemical and swelling characteristics mechanical properties of Paleonile expansive shale (Madmoud Formation) in the study area (*)

| Site | Sample No. | Grain Size | | | Dry Density ($gm/cm^3$) | Water Content (%) | CEC (meg/100 gm) | | | | | | Consistency Limits (%) | | | Activity (A) | Swelling Characteristics | | | Clay mineral species (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sands (%) | Silts (%) | Clays (%) | | | $Ca^{++}$ | $Mg^{++}$ | $K^{+}$ | $Na^{+}$ | Total | ESP | LL | PL | PI | | Free Swelling (%) | Swelling Pressure ($kg/cm^2$) | Swelling Percent (%) | Montmorillonite | Mixed-Layer | Kaolinite | Illite | Chlorite |
| I | 1 | 4 | 33 | 63 | 2.1 | 12.5 | 37.7 | 9 | 12 | 1.4 | 60.1 | 2.3 | 100 | 48 | 52 | 0.83 | 100 | 48 | 52 | | | | | |
| | 2 | 19 | 63 | 18 | 2.31 | 8.6 | 24.1 | 5.6 | 7.5 | 0.3 | 37.5 | 0.8 | 84 | 48 | 36 | 2.00 | 84 | 48 | 36 | | | | | |
| | 3 | 2 | 28 | 70 | 2.09 | 12.7 | 37.8 | 9 | 12.1 | 1.4 | 60.3 | 2.3 | 100 | 47 | 53 | 0.76 | 100 | 47 | 53 | 65 | 18 | 11 | 5 | 1 |
| II | 4 | 4 | 26 | 70 | 2.11 | 12.6 | 37.8 | 9 | 12.1 | 1.4 | 60.3 | 2.3 | 103 | 50 | 53 | 0.76 | 103 | 50 | 53 | | | | | |
| | 5 | 4 | 25 | 71 | 2.1 | 13.1 | 38.1 | 9.1 | 12.2 | 1.4 | 60.8 | 2.3 | 102 | 50 | 52 | 0.73 | 102 | 50 | 52 | | | | | |
| III | 6 | 4 | 23 | 73 | 2.03 | 12.9 | 38.9 | 9.3 | 12.4 | 1.5 | 62.1 | 2.4 | 100 | 49 | 51 | 0.70 | 100 | 49 | 51 | 64 | 18 | 12 | 6 | - |
| | 7 | 2 | 31 | 67 | 2.1 | 12.9 | 40 | 9.6 | 12.8 | 1.6 | 64 | 2.5 | 98 | 49 | 49 | 0.73 | 98 | 49 | 49 | | | | | |
| | 8 | 2 | 27 | 71 | 2.08 | 13.1 | 41.9 | 10.1 | 13.4 | 1.8 | 67.1 | 2.7 | 98 | 50 | 48 | 0.68 | 98 | 50 | 48 | | | | | |
| IV | 9 | 4 | 28 | 68 | 2.08 | 12.8 | 40.2 | 9.7 | 12.9 | 1.6 | 64.4 | 2.5 | 100 | 50 | 50 | 0.74 | 100 | 50 | 50 | 72 | 18 | 3 | 7 | - |
| | 10 | 6 | 29 | 65 | 2.08 | 12.9 | 42.8 | 10.3 | 13.7 | 1.8 | 68.7 | 2.6 | 97 | 50 | 47 | 0.72 | 97 | 50 | 47 | | | | | |
| | 11 | 4 | 30 | 66 | 2.1 | 12.8 | 42.1 | 10.1 | 13.5 | 1.8 | 67.5 | 2.7 | 97 | 49 | 48 | 0.73 | 97 | 49 | 48 | | | | | |
| V | 12 | 4 | 31 | 65 | 2.12 | 12.9 | 43.9 | 10.6 | 14.1 | 1.9 | 70.5 | 2.7 | 99 | 51 | 48 | 0.74 | 99 | 51 | 48 | 69 | 18 | 6 | 7 | - |
| | 13 | 17 | 64 | 19 | 2.32 | 9.4 | 22.5 | 5.2 | 7 | 0.1 | 34.8 | 0.3 | 82 | 49 | 33 | 1.74 | 82 | 49 | 33 | | | | | |
| VI | 14 | 4 | 26 | 70 | 2.21 | 13.1 | 43.6 | 10.5 | 14 | 1.9 | 70 | 2.7 | 101 | 50 | 51 | 0.73 | 101 | 50 | 51 | | | | | |
| | 15 | 6 | 27 | 67 | 2.22 | 23.5 | 38.7 | 9.3 | 12.4 | 1.5 | 61.8 | 2.4 | 99 | 50 | 49 | 0.73 | 99 | 50 | 49 | | | | | |
| | 16 | 4 | 25 | 71 | 2.18 | 23 | 38.2 | 9.2 | 12.2 | 1.5 | 61 | 2.5 | 99 | 49 | 50 | 0.70 | 99 | 49 | 50 | 66 | 16 | 9 | 9 | - |
| | 17 | 4 | 34 | 62 | 2.19 | 24 | 38.7 | 9.3 | 12.4 | 1.5 | 61.8 | 2.4 | 98 | 48 | 50 | 0.81 | 98 | 48 | 50 | | | | | |
| | 18 | 2 | 28 | 70 | 2.07 | 25 | 39.3 | 9.4 | 12.6 | 1.5 | 62.9 | 2.4 | 98 | 49 | 49 | 0.70 | 98 | 49 | 49 | | | | | |
| | 19 | 15 | 64 | 21 | 2.31 | 16 | 21.5 | 5 | 6.6 | 0.1 | 33.2 | 0.3 | 83 | 47 | 36 | 1.71 | 83 | 47 | 36 | | | | | |
| | 20 | 4 | 31 | 65 | 2.09 | 12.6 | 40.3 | 9.7 | 12.9 | 1.6 | 64.5 | 2.5 | 100 | 48 | 52 | 0.80 | 100 | 48 | 52 | 72 | 18 | 2 | 8 | - |

**Table 1 (Continued):** Physico-chemical and swelling characteristics mechanical properties of Paleonile expansive shale (Madmoud Formation) in the study area (*)

| Site | Sample No. | Grain Size | | | Dry Density ($gm/cm^3$) | Water Content (%) | CEC (meg/100 gm) | | | | | | Consistency Limits (%) | | | Activity (A) | Swelling Characteristics | | Clay mineral species (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sands (%) | Silts (%) | Clays (%) | | | $Ca^{++}$ | $Mg^{++}$ | $K^{+}$ | $Na^{+}$ | Total | ESP | LL | PL | PI | | Free Swelling (%) | Swelling Pressure ($kg/cm^2$) | Swelling Percent (%) | Montmorillonite | Mixed-Layer | Kaolinite | Illite | Chlorite |
| VII | 21 | 3 | 28 | 69 | 2.11 | 12.5 | 40.4 | 9.7 | 12.9 | 1.6 | 64.7 | 2.5 | 99 | 48 | 51 | 0.74 | 99 | 48 | 51 | | | | | |
| | 22 | 4 | 29 | 67 | 2.1 | 12.4 | 41.1 | 9.9 | 13.2 | 1.7 | 65.9 | 2.6 | 98 | 49 | 49 | 0.73 | 98 | 49 | 49 | | | | | |
| | 23 | 4 | 30 | 66 | 2.08 | 12.4 | 39.7 | 9.5 | 12.7 | 1.6 | 63.5 | 2.5 | 99 | 48 | 51 | 0.77 | 99 | 48 | 51 | 68 | 15 | 2 | 11 | 4 |
| | 24 | 5 | 32 | 63 | 2.08 | 12.5 | 40 | 9.6 | 12.8 | 1.6 | 64 | 2.5 | 105 | 48 | 57 | 0.90 | 105 | 48 | 57 | | | | | |
| | 25 | 4 | 31 | 65 | 2.07 | 12.6 | 40.7 | 9.8 | 13 | 1.7 | 65.2 | 2.6 | 100 | 48 | 52 | 0.80 | 100 | 48 | 52 | | | | | |
| | 26 | 6 | 34 | 60 | 2.08 | 12.4 | 40.6 | 9.8 | 13 | 1.7 | 65 | 2.6 | 98 | 49 | 49 | 0.82 | 98 | 49 | 49 | 67 | 12 | 6 | 13 | 2 |
| VIII | 27 | 5 | 35 | 60 | 2.1 | 18.3 | 41.6 | 10 | 13.3 | 1.7 | 66.6 | 2.6 | 98 | 49 | 49 | 0.82 | 98 | 49 | 49 | | | | | |
| | 28 | 3 | 36 | 61 | 2.09 | 17.9 | 41.6 | 10 | 13.3 | 1.7 | 66.7 | 2.5 | 97 | 49 | 48 | 0.79 | 97 | 49 | 48 | | | | | |
| | 29 | 4 | 34 | 62 | 2.08 | 18.1 | 42.2 | 10.1 | 13.5 | 1.8 | 67.6 | 2.7 | 100 | 49 | 51 | 0.82 | 100 | 49 | 51 | 64 | 12 | 5 | 17 | 2 |
| | 30 | 13 | 69 | 18 | 2.30 | 13.8 | 22.1 | 5.1 | 6.8 | 0.1 | 34.2 | 0.3 | 84 | 46 | 38 | 2.11 | 84 | 46 | 38 | | | | | |
| | 31 | 4 | 31 | 65 | 2.07 | 18.2 | 42.8 | 10.3 | 13.7 | 1.8 | 68.7 | 2.6 | 99 | 49 | 50 | 0.77 | 99 | 49 | 50 | | | | | |
| | 32 | 4 | 34 | 62 | 2.08 | 12.9 | 42 | 10.1 | 13.5 | 1.8 | 67.4 | 2.7 | 108 | 49 | 59 | 0.95 | 108 | 49 | 59 | | | | | |
| | 33 | 4 | 35 | 61 | 2.07 | 13.1 | 42.5 | 10.2 | 13.6 | 1.8 | 68.1 | 2.6 | 99 | 49 | 50 | 0.82 | 99 | 49 | 50 | 66 | 15 | 8 | 11 | - |
| | 34 | 4 | 38 | 58 | 2.09 | 13.2 | 42.6 | 10.2 | 13.7 | 1.8 | 68.3 | 2.6 | 101 | 50 | 51 | 0.88 | 101 | 50 | 51 | | | | | |
| IX | 35 | 6 | 36 | 58 | 2.09 | 12.9 | 42.6 | 10.2 | 13.7 | 1.8 | 68.3 | 2.6 | 100 | 50 | 50 | 0.86 | 100 | 50 | 50 | | | | | |
| | 36 | 4 | 32 | 64 | 2.10 | 12.7 | 43.5 | 10.5 | 14 | 1.9 | 69.8 | 2.7 | 102 | 50 | 52 | 0.81 | 102 | 50 | 52 | 67 | 14 | 11 | 8 | - |
| | 37 | 4 | 32 | 64 | 2.09 | 12.9 | 43.1 | 10.4 | 13.8 | 1.9 | 69.2 | 2.7 | 108 | 50 | 58 | 0.91 | 108 | 50 | 58 | | | | | |
| | 38 | 5 | 30 | 65 | 2.11 | 13.3 | 41.5 | 10 | 13.3 | 1.7 | 66.5 | 2.6 | 107 | 51 | 56 | 0.86 | 107 | 51 | 56 | | | | | |
| X | 39 | 4 | 34 | 62 | 2.10 | 13.4 | 42.1 | 10.1 | 13.5 | 1.8 | 67.5 | 2.7 | 107 | 51 | 56 | 0.90 | 107 | 51 | 56 | 63 | 17 | 13 | 7 | - |
| | 40 | 5 | 31 | 64 | 2.12 | 13.3 | 42.1 | 10.1 | 13.5 | 1.8 | 67.5 | 2.7 | 108 | 49 | 59 | 0.92 | 108 | 49 | 59 | | | | | |
| XI | 41 | 6 | 32 | 62 | 2.09 | 13.5 | 41.9 | 10.1 | 13.4 | 1.8 | 67.1 | 2.7 | 105 | 50 | 55 | 0.89 | 105 | 50 | 55 | | | | | |
| | 42 | 14 | 63 | 23 | 2.32 | 15.5 | 20.6 | 4.8 | 6.3 | 0.1 | 31.8 | 0.3 | 85 | 48 | 37 | 1.61 | 85 | 48 | 37 | | | | | |
| | 43 | 8 | 28 | 64 | 2.09 | 13.5 | 41.5 | 10 | 13.3 | 1.7 | 66.5 | 2.6 | 110 | 52 | 58 | 0.91 | 110 | 52 | 58 | 65 | 15 | 10 | 10 | - |
| | 44 | 7 | 33 | 60 | 2.10 | 13.4 | 42.3 | 10.2 | 13.6 | 1.8 | 67.8 | 2.7 | 104 | 49 | 55 | 0.92 | 104 | 49 | 55 | | | | | |

*Sandy silts samples are shadowed

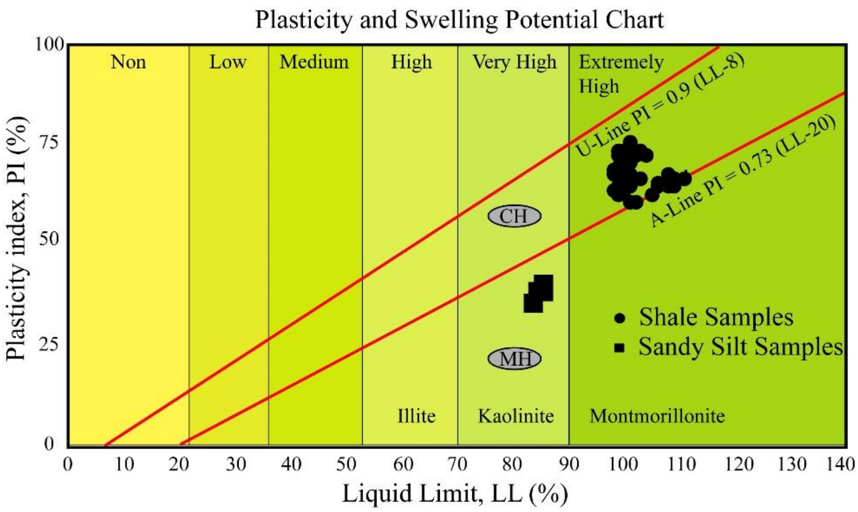


**Fig. 7**: Plasticity chart of the studied Madmoud Formation samples [57]

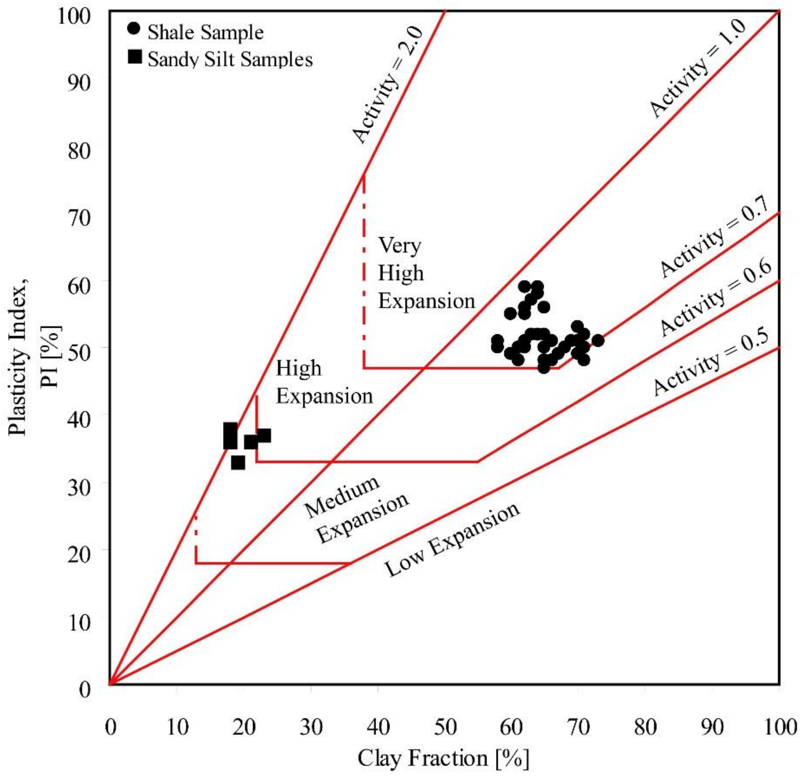


**Fig. 8**: Swelling potential classification [61]

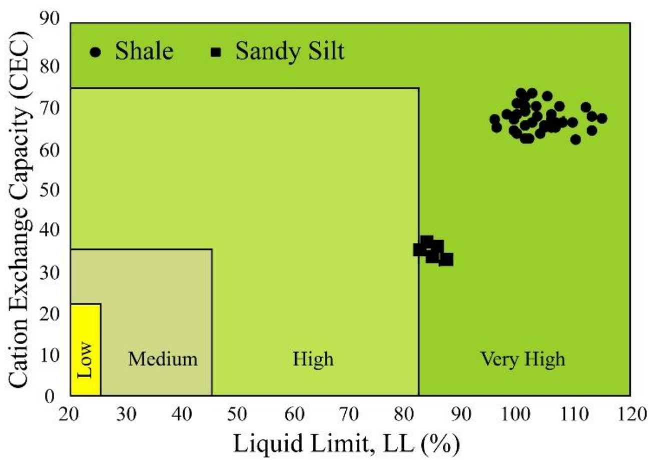


**Fig. 9**: Swelling potential chart [66]

Based on the micro-fabrics of the studied soil samples which are dominated by flocculation and aggregation manner (Figs. 10b and 10c), this type of micro-fabrics of the studied Paleonile Clays have a considerable amount of voids which play an essential role in its higher swelling potentiality.

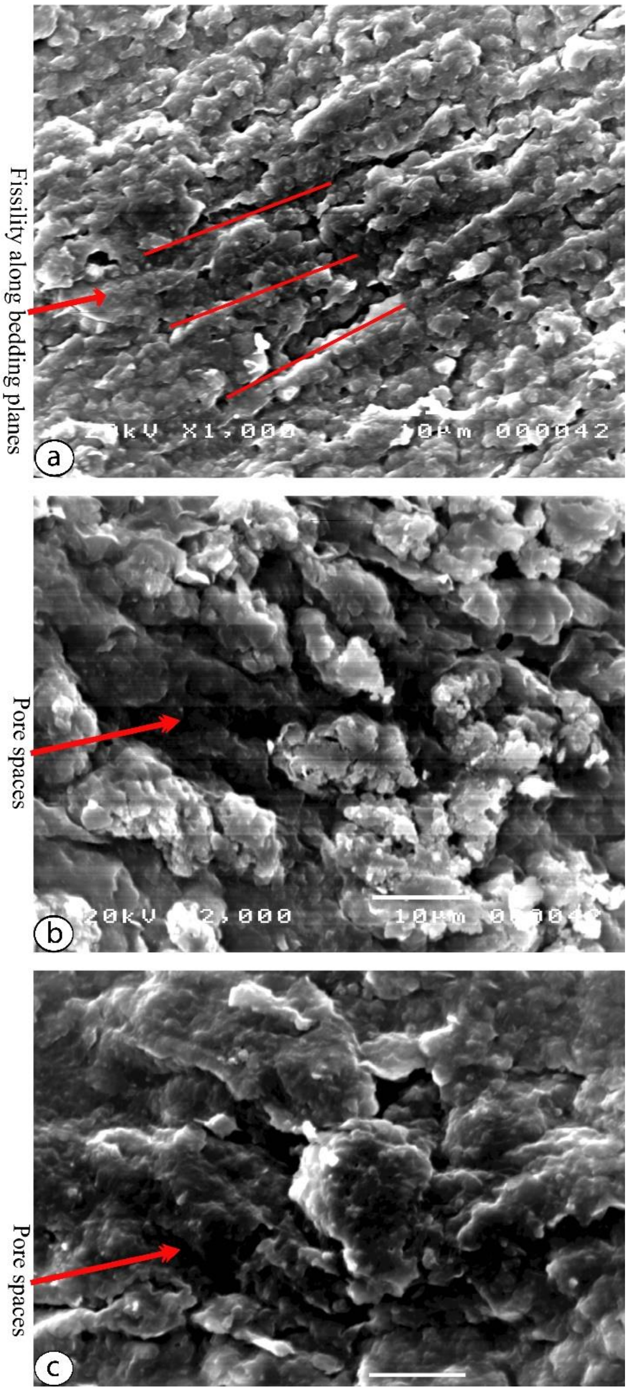


**Fig. 10**: SEM-photographs of the studied samples, (a): relatively low-magnification showing clay-sized particles oriented perpendicular to bedding plane and (b and c) high magnification showing clay-sized particles oriented as flocculation and aggregation manner.

## 6. Swelling characteristics

### 6. 1. Swelling pressure

It is necessary to measure the swelling characteristics of undisturbed shale or fine-grained soil samples to predict its real and actual engineering behavior. Thus one-dimensional swelling tests were done using the free axial swelling oedometer for eighteen representative undisturbed samples. Initially, these samples were prepared (6.35 cm diameter and 1.9cm height) and carefully were placed in the mould and water was allowed to imbibe till saturation (5, 10, 15, 20, 25, 30, 35, 40, 45, and 50% of the original weight of the studied Paleonile Clays samples). Then gradual loading (P) is applied then the swelling pressure (PS) of the studied samples was calculated according to the following equation:

$$P_S = \frac{P}{A} \qquad (2)$$

Where $P_S$=Swelling pressure (kg/cm2),
P= the total load (kg), and
A= the cross-sectional area ($cm^2$).

The swelling pressure of the studied Paleonile Clays samples is 4.4 –4.8 $kg/cm^2$ and 1.8 -2.1 $kg/cm^2$ for shale and sandy silt samples, respectively (Table 1, Fig. 11). The swelling pressure of the studied Madmoud Formation is classified as high swelling (shale samples) and moderate swelling (silt samples) potential respectively [59]. Figure 11 indicates higher swelling potentially of clayey soil samples than silty soil samples owing to nature of clay particle and higher surface area of clay particles than silt particles.

## 6. 2. Swell percent

The swelling percentage is usually defined as the increasing height ratio (ΔH) under standard stress and it is calculated as follows:

$$S = \frac{\Delta H}{H_\circ} \times 100 \qquad (3)$$

Where S=Swelling percentage,
Ho= Initial height (mm), and
ΔH= Increase in the height (mm).

The calculated swelling percentage of the studied Madmoud Formation samples is 53-65%, and 23-28% for shale samples and sandy silt samples, respectively (Table 1).

## 6. 3. Free swelling

The studied Paleonile Clays samples were dried and grinded and then sieved by sieve No. 40 (0.425 mm). These materials were gently poured to fill a glass 10cm3 graduated cylinders then were poured into another glassy 100 $cm^3$ graduated glass cylinder that filled with distilled water and the suspension of these materials must be left for 24 hours [28].

The suspension volume of these samples will be increased into $V_2$. The value of free swelling can be given by:

$$\text{Free swelling value (\%)} \frac{V_2 - 10}{10} x100 \qquad (4)$$

where $V_2$ is in $cm^3$.

The obtained free swelling of the studied Paleonile Clays (Madmoud Formation) samples are ranging from 115-150%, and 85-95% for shale samples and sandy silt samples, respectively (Table 1). Accordingly, the swelling potentiality of shale samples and sandy silt samples of the studied Madmoud Formation are classified as critical and moderate respectively [28].

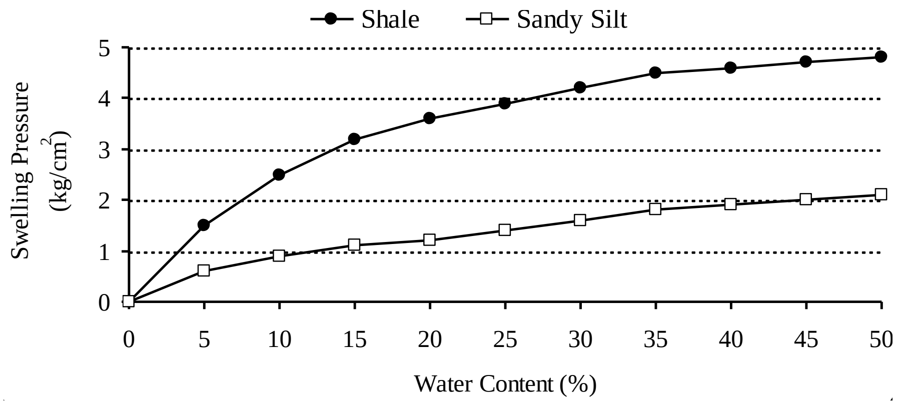


**Fig. 11:** Relation between swelling pressure and water content of the studied samples

The correlation methodology (statistically and graphically) has an essential importance as a significant part to document the strength of the relationship between some factors related to the swelling potentiality of the studied Paleonile Clays (Madmoud Formation). It is observed that, the swelling pressure ($kg/cm^2$) of the studied Paleonile Clays has a direct proportional relationship with free swelling, plasticity index (PI), cation exchange capacity (CEC) and montmorillonite percent (Fig. 12). Furthermore, the clay fraction percent of the studied samples of Paleonile Clays has a strong direct proportional relation with free swelling, plasticity index (PI) and cation exchange capacity (CEC) (Fig. 13).

Statistically, based on the r-values indicated that the clay-sized fractions (%) of the studied samples has a positively significant correlation (r) with liquid limit (%), plastics limit (%), plasticity index (%), and free swelling (%) as well as a negatively significant correlation with dry density (g/cm³) with r-values = 0.898, 0.805, 0.445, 0.798 and 0.800 respectively.

On the contrary, dry density (g/cm³) has a negatively significant correlation with clay content (%), liquid limit (%), plastics limit (%), plasticity index (%), and free swelling (%) with r-values = -0.867, -0.769, -0.36, -0.77 and -0.762 respectively. Consequently, the cation exchange capacity (CEC) has a positively strong significant correlation with liquid limit (%), plastics limit (%), plasticity index (%), free swelling (%) with r-values = 0.847, 0.555, 0.823 and 0.843, respectively. Liquid limit (%) correlates significantly with plastics limit (%), plasticity index (%), free swelling (%) with r-values= 0.574, 0.987, and 0.843 respectively (Table 2).

Figures (12 and 13) are represented graphically irrefutable evidence of the extent of the interdependence and consistency of these factors which essentially control swelling potentially of Paleonile Clays samples, some of these factors are directly and inversely proportional with the ability to swell as is well known in similar studies. This is well documented statistically (Table 2).

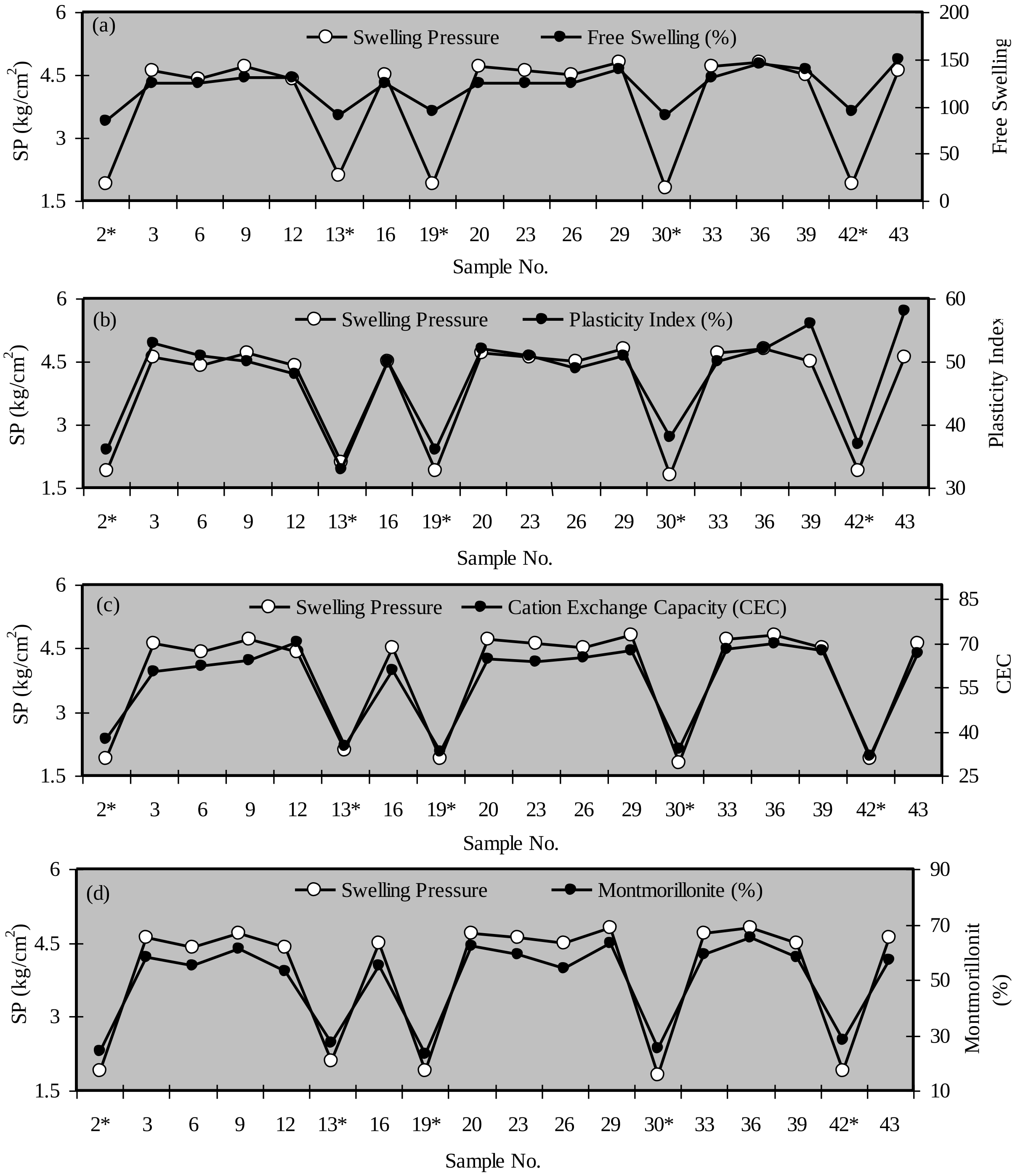


**Fig. 12:** Relationship between swelling pressure and free swelling (a), plasticity index (b), cation exchange

capacity (c) and smectite percent (d).

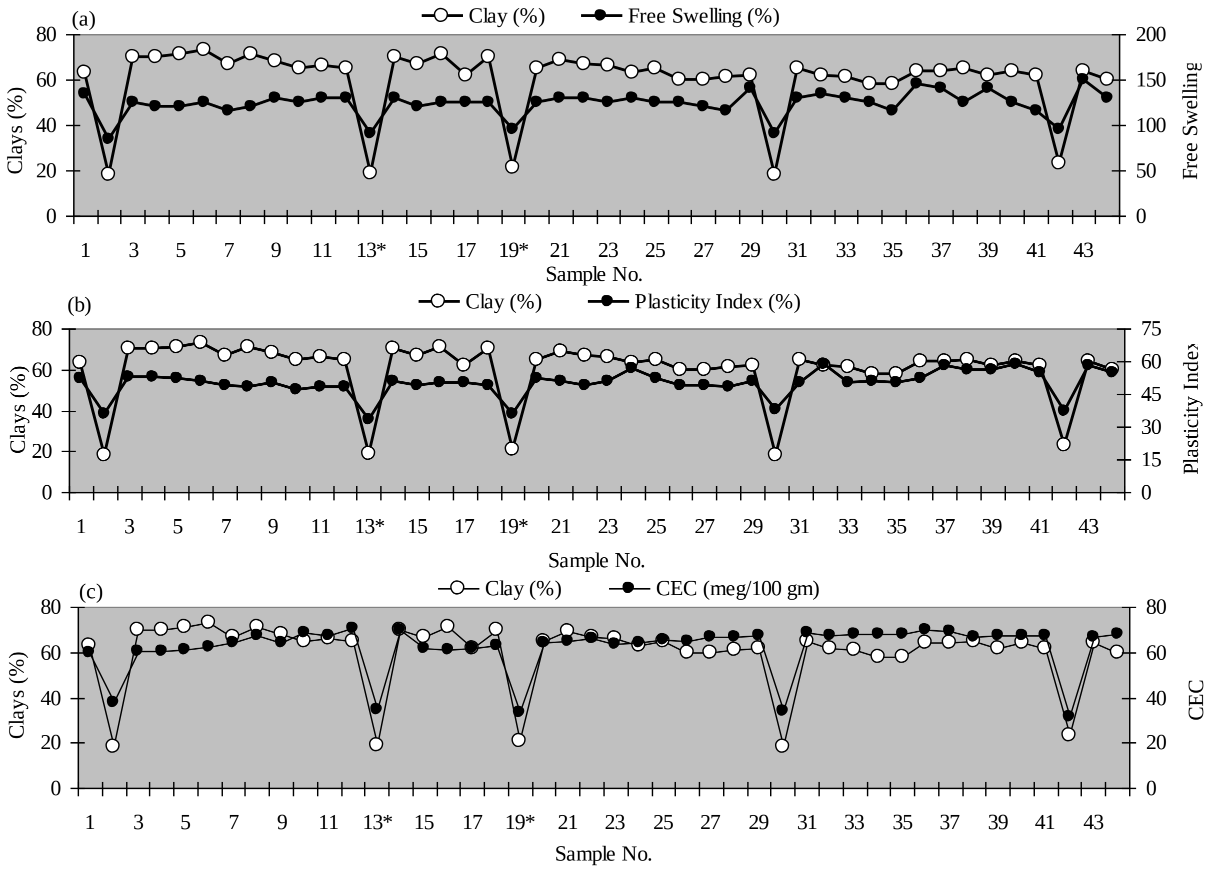


Fig. 13 Relation between clay fraction percent, free swelling (a), plasticity index (b) and cation exchange

Table 2: Correlations of the parameters of Paleonile expansive shale (Madmoud Formation) in the study area

| | Clay (%) | Dry Density (g/cm³) | CEC (%) | Liquid Limit (%) | Plastics Limit (%) | Plasticity Index (%) |
|---|---|---|---|---|---|---|
| Clay (%)<br>Sig | | | | | | |
| Dry Density (g/cm³)<br>Sig | -0.842**<br>S | | | | | |
| CEC (%)<br>Sig | 0.898**<br>S | -0.867**<br>S | | | | |
| Liquid Limit (%)<br>Sig | 0.805**<br>S | -0.769**<br>S | 0.847**<br>S | | | |
| Plastics Limit (%)<br>Sig | 0.445**<br>S | -0.366*<br>S | 0.555**<br>S | 0.574**<br>S | | |
| Plasticity Index (%)<br>Sig | 0.798**<br>S | -0.773**<br>S | 0.823**<br>S | 0.987**<br>S | 0.436**<br>S | |
| Free Swelling (%)<br>Sig | 0.800**<br>S | -0.762**<br>S | 0.843**<br>S | 0.843**<br>S | 0.490**<br>S | 0.830**<br>S |

a: List wise N= 44.
S: Correlation is significant.
NS: Correlation is not significant.
** Correlation is significant at the 0.01 level (2-tailed)

## 7. Conclusions

The present work represents a case study of swelling potentiality of Paleonile Clays and its effecting by geological and mineralogical factors in Nile Valley, Upper Egypt. The main findings of this study are:

- The Paleonile Clays (Pliocene, Madmoud Formation) are mainly composed of bedded shale sequence with thinly intercalations of sandy silt that had a cyclic sedimentation manner. These cyclic soils are highly cracked so the penetration of water within these sediments is very easily so that these soils are highly swelled.
- From clay mineralogical point of view, Madmoud Formation consists of montmorillonite (63% - 72%), illite-montmorillonite mixed layer (12% - 18%), kaolinite (2% to 13%), subordinated amounts of illite (5% to 17%) and scarce amount of chlorite. This mineralogical association is characterized by extremely expansion nature.
- The swelling potentiality of Paleonile Clays has direct relationships with clay-sized fractions (%), cation exchange capacity (CEC) and plasticity index (PI),
- Statistically and graphically, the clay-sized fractions (%) had significant relations with plasticity index (PI), free swelling and cation exchange capacity (CEC).
- Madmoud Formation shale samples are mainly dominated by flocculation and aggregation fabric type which had highly swelling potentiality.
- Sufficiently safety factor must be put in geotechnical engineer considerations when constructions that were built on or in like this type of swell-able shale.

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