Geotechnical Characteristics of Anhydrite/Gypsum Transformation in the Middle Miocene Evaporites, Red Sea Coast, Egypt

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Abstract The Middle Miocene evaporites of Abu Dabbab Formation, north of Quseir City along the Red Sea coast of Egypt are composed mainly of thinly laminated, bedded and nodular anhydrite and microcrystalline gypsum especially in its lowermost part. Highly cracked inter-bedded clay, dolomite and stromatolite layers were recorded within the evaporite succession. The cracks in the inter-bedded clays are filled with evaporite materials indicating arid climatic conditions during exposure episodes. Swelling mechanisms in clay-evaporites include mechanical swelling due to hydration of clay minerals and transformation of the anhydrite into gypsum. Field observations as well as powder x-ray diffraction investigations have shown that anhydrite/gypsum modal ratio decreases gradually downward indicating that gypsum has transformed to anhydrite by solar heating. The clay minerals of the inter-bedded clay layers are dominated by smectite (46%), illite-smectite mixed-layer (18%), chlorite (13%), palygorskite (9%), kaolinite (8%), and illite (6%). The liquid limit of the Abu Dabbab Formation (anhydrite and inter-bedded clays) is higher than 65%, so considered as of very high swelling capabilities. Also, its swelling percentage was found to be (11–14%), (28–35%) and (58–65%) for gypsum, clay and anhydrite, respectively. The swelling pressure was found to be (1.4–1.5 kg/cm²), (2.3–3.1 kg/cm²) and (4.7–5.1 kg/cm²) for gypsum, anhydrite and inter-bedded clay. The swelling pressure of gypsum is moderate and for both anhydrite and clay is high. The highly swelling capability of anhydrite and the inter-bedded clays causes geotechnical problems when got into contact with water. Alternating volume change due to phase transformation and solubility of calcium sulfate adds to the severity of problems associated with the host expansive clay strata.

Keywords Anhydrite/gypsum · Clay · Swelling · Abu Dabbab evaporite
1 Introduction

The Egyptian Red Sea coastal region is characterized by an extreme degree of aridity, high ambient temperature and fluctuating relative humidity. The rainfall is scanty and sporadic and it is usual for the region to go for several successive months without any precipitation. The average rainfall ranges from \( <10-15 \) mm/year over the sea to a few millimeters per year along the coastline [1]. There is a remarkable variability in daily temperature between the northern and southern Red Sea coastal region. In the north, the maximum daily temperatures range from a low of 20 °C in January to a high of 35 °C in July whereas in the south the corresponding range is 29–40 °C [2]. The hot and arid climate and the saline environment that governs the geological development can influence the engineering behavior of local sedimentary soils [3]. The hydration–dehydration reactions, for example, can alter the crystalline structure of the resulting mineral. Anhydrite has an orthorhombic structure in which \( \text{Ca}^{2+} \) is surrounded by eight neighboring \( \text{SO}_4^{2-} \) ions, whereas the monoclinic structure of gypsum is held by weak hydrogen bonds between water molecules and \( \text{SO}_4^{2-} \) [4]. These molecular variations mean that estimates of volume change associated with mineral transformation must be on molar volumes of gypsum, anhydrite, and water [5]. Gypsum dehydrated when: (1) exposed at the surface to hot and dry conditions [6], (2) subjected to reaction with brines [7], (3) involved in burial diagenesis [8], and (4) affected by tectonic stresses [9]. Dehydration started at the surface and extended downwards for up to 1,500 m [10].

The highly swellable capability of anhydrite can only appear when it gets into contact with water. Anhydrite converts to gypsum when inundated with water as the \( \text{SO}_4^{2-} \) ion attracts the \( \text{H}_2\text{O} \) molecules because of the polar nature of the latter. The hydration of anhydrite produces a theoretic swelling of up to about 60% [10–15].

The gypsum/anhydrite transformation was recorded in many parts of the World for examples, (1) Middle Miocene evaporite in southern Poland [16], (2) evaporite succession in the Eastern Province of Saudi Arabia [17], (3) Messinian evaporites of central Tuscany, Italy [18], (4) Middle Triassic evaporites in south Germany and north Switzerland, Gypsum Keuper [19], and (5) in the Arabian Gulf coastal deposits [3].

The Egyptian Red Sea coastal region has undergone development activities such as urbanization, coastal development, tourism, coastal mining and quarrying activities. The construction in the coastal regions may face some obstacles. The soil inferior engineering properties, especially volume increase associated with mineral transition, do not match the heavy loads exerted by the huge projects. Unexpected construction and post-construction problems may arise in some of these projects. This type of problematic soil is considered as one of the obstacles that may face the development plans in this region. A lot of researchers have been conducted on stratigraphical and sedimentological characteristics of Abu Dabbab Evaporites, yet little information exits in the literature on their geotechnical properties. In particular there is little guidance available for practicing engineers on how to choose design parameters, especially for problems related to compression and strength. The objective of this paper is to study the mineralogical composition and the engineering geological aspects of the Abu Dabbab Evaporite section. Such information is essential for urban planers, engineers, and designers to recommend the most appropriate type and method of construction to ensure the stability of a structure in its natural setting.

2 Geological Setting of the Study Area

The Egyptian Red Sea coastal region can be divided into two structural provinces: the Nubian Shield rocks in the west and the coastal region in the east. The Nubian Shield rocks are ancient land masses that occur as belts parallel to the Red Sea coast and sloping gently towards the Red Sea. It consists of Precambrian basement of gneiss, metamorphic terrestrial sediments, volcanic rocks of the green schist facies, and countless granitoid plutonic bodies. In some places, the ground elevation is close to the sea level so that tidal changes cause the waterfront to shift back and forth up to hundreds of meters. Sabkha (salt flats) are common all along the coast. The rocks of the coastal region are represented by continental and shallow marine sediments of Neogene age. Arid climatic conditions and restricted lagoonal environment led to the formation of expansive evaporitic succession in the Egyptian Red Sea. This marks the closure of the Red Sea basin during Middle Miocene. The Middle Miocene evaporite sequence of the Abu Dabbab Formation unconformably overlies the older syn-rift and pre-rift strata (Fig. 1). The lateral variation of the Abu Dabbab Evaporites is mainly controlled by structural and topographic elements, including relay ramps between interacting normal fault segments, cross-trend transfer faults, reactivated Precambrian basement and the plunge directions of tilted fault blocks [20]. The inter-bedded clayey layers are formed during marine regression under these arid climatic conditions.

The stratigraphy of the Neogene sediments was studied by many authors [21–27]. [24] subdivided the Neogene sed-
iments that exposed along the Egyptian Red Sea Coast into three belts run parallel to the Red Sea Coast. The inner belt includes clastic rocks (Ranga Formation) and mixed clastic-carbonate rocks (Um Mahara Formation). The middle belt includes fine siliciclastic sediments (Syiatin Formation), Abu Dabbab Evaporite and carbonate rocks (Um Gheig Formation). The outer belt includes the siliciclastic Mersa Alam Formation and the mixed clastic-carbonate Shagra Formation.

The evaporite deposits are of wide spatial distribution in the Neogene sediments. They extend from Jabal El Zeit (90 km south Suez) to Ras Banas (90 km south Marsa Alam) and extend further southward inside the Sudanese land. The Middle Miocene evaporite represents the main evaporite unit in the Egyptian Red Sea coast. The Abu Dabbab Evaporite is the most famous one, which is characterized by yellowish white to dark grey colour and is easily identified in both field and satellite images. Nonetheless, relatively widespread outcrops can be found close to the present Red Sea Shoreline.

3 Experimental Tests

Twenty-three disturbed and undisturbed samples were collected from four selected sites of the Abu Dabbab Formation.
The samples represent natural evaporites (anhydrite and gypsum) and inter-bedded clays. Water content in the evaporites (gypsum and anhydrite) and clay was determined by heating up to 300 and 110 °C, respectively, for 24 h according to [28]. Specific gravity was determined according to [29]. Similarly, the liquid limit (LL) and plastic limit (PL) (pulverized pass ASTM Sieve No. 40 (0.425 mm) were determined according to [30]. The laboratory tests were designed to investigate the swelling behavior of the evaporite (anhydrite and gypsum) as well as the inter-bedded expansive clayey samples using oedometer testing [31]. The free swell test was carried out as described by [32]. Mineral identification, using x-ray diffraction techniques, has been carried out on selected samples of anhydrite, gypsum and clay. X-ray diffraction analyses for clay samples were performed on the <2 mm fraction, which was separated by standard pipette sedimentation technique. The identification of the clay minerals is based on the basal reflections (001), according to the x-ray powder diffraction results of many authors [33–38] and the ASTM cards. Table (1) summarizes the physical, mineralogical and geotechnical properties of the various anhydrite, gypsum and inter-bedded clay of Abu Dabbab Evaporite.

4 Results and Discussion

4.1 Anhydrite/Gypsum Transformation

Rocks containing clay minerals and anhydrite exhibit the property of volume increase caused by water absorption. This phenomenon is called rock swelling. It is well known that swelling in anhydrite is of a chemical nature and depends on the transformation of anhydrite into gypsum [13]. Mineral transition in the \( \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \) system takes place according to the following reversible hydration–dehydration reaction [39]:

\[
\text{CaSO}_4 \cdot 2\text{H}_2\text{O (gypsum)} \rightleftharpoons \text{CaSO}_4 \text{ (anhydrite)} + 2\text{H}_2\text{O}
\]  

(1)

Anhydrite precipitated as primary mineral in highly alkaline environments and at concentration five times that of seawater [7]. In contrast, gypsum precipitated as primary mineral in shallow evaporitic basins at a three-fold increase in seawater salinity [40]. Gypsum is the most abundant calcium sulphate minerals that form under normal sedimentary conditions [18]. However, anhydrite forms rarely at the surface under certain conditions (e.g. arid hot supratidal environments) [40–43]. Gypsum is the stable form of calcium sulphate in surface conditions and thus predominates in the outcrops except under arid climatic conditions (either cold or hot) where anhydrites appears at the surface [44,45]. The anhydrite deposits are formed from both syn-depositional growth and anhydritization of gypsum during early diagenesis [46]. Moreover, gypsum is readily transformed to anhydrite and water when heated to a temperature that is a function of salinity of the co-existing fluids. In this respect, [27] pointed out that the anhydrite of Abu Dabbab Evaporites in NW Red Sea has an epigenetic origin during several cycles of hydration and dehydration.

The thickness of Abu Dabbab Evaporites is about 45 m at Site I (Wadi Al-Quieh), 55 m at site II (Wadi Abu Hamra-Al-Qibli), 110 m at site III (Wadi Siyatín) and 85m at site IV (Wadi Al-Qusier Al Qadim), (Fig. 2). Field investigations indicated that the Abu Dabbab Evaporite consists mainly of bedded and thinly laminated and nodular evaporites (Fig. 3), which are capped by anhydrite and graded downward into gypsum. Mineral identification by powder x-ray diffraction analysis indicate that the evaporite cap samples are mainly composed of anhydrite (88–97 %) with subordinate gypsum (3–12 %), while samples from the lowermost part near the ground surface is consisting of gypsum (87–89 %) and anhydrite (11–13 %), (Table 1; Fig. 4).

The presence of dolomite layers within the Abu Dabbab Evaporite succession (Fig. 2) may indicate that the entire succession was formed by diagenetic processes. In such case, the possible mechanism by which gypsum and anhydrite have evolved is by extensive dolomitization of calcareous inter-bedded mudstone [47]. However, the inter-bedded mudstone contains aragonite and high-Mg calcite as predominant components and neither of these minerals is diagenetically stable outside the marine environment [48,49]. Mg\(^{2+}\) replaces some of the Ca\(^{2+}\) in the crystal lattice of aragonite. The displaced Ca\(^{2+}\) combines with SO\(^{2-}\) present in the sea water to precipitate as individual crystals of anhydrite and/or gypsum [47]. Therefore, the anhydrite cap in the Abu Dabbab Evaporite section that ranges in thickness from few meters to tens of meters was most probably formed through transformation processes of gypsum into anhydrite by subaerial weathering and solar heating in hot arid climate according to the following reaction:

\[
\text{CaSO}_4 \cdot 2\text{H}_2\text{O (gypsum)} \xrightarrow{\text{Arid condition+Solar heating}} \text{CaSO}_4 \text{ (anhydrite)} + 2\text{H}_2\text{O}
\]  

(2)

4.2 Mineralogical Composition of Inter-Bedded Clays

The clayey sediments that occur as inter-bedded layers within the evaporite succession are greenish to gray in colour and are highly desiccated and cracked. The cracks are filled with evaporite materials (Fig. 5) that may indicate exposure episodes during marine regression under arid climatic conditions. These evaporitic materials are composed mainly of...
Table 1  Basic physical, mineralogical and geotechnical properties of Abu Dabbab Evaporites

| Site | Sample no. | Rockunit | Physical properties | Consistency limits | Swelling characteristics | Mineral constitutes |
|------|------------|----------|---------------------|-------------------|--------------------------|---------------------|
|      |            |          | Water content (%)   | $G_s$ (gm/cm$^3$) | LL (%)   | PL (%)   | PI (%)   | Swelling (%) | Free swelling (%) | Swelling pressure (kg/cm$^2$) | Anhydrite | Gypsum |
| I    | A1         |          | 8.8                 | 2.74              | 103       | 65       | 38       | 64           | 150            | 3.1       | 97      | 3  |
|      | A2         |          | 8.9                 | 2.72              | 100       | 64       | 36       | 62           | 145            | 2.9       | 96      | 4  |
|      | A3         |          | 8.9                 | 2.69              | 98        | 55       | 43       | 61           | 140            | 2.6       | 94      | 6  |
|      | A4         |          | 8.9                 | 2.68              | 104       | 65       | 39       | 63           | 140            | 3         | 96      | 4  |
|      | A5         | Anhydrite| 9.1                 | 2.74              | 103       | 65       | 38       | 61           | 145            | 2.8       | 94      | 6  |
|      | A6         |          | 9.3                 | 2.72              | 100       | 64       | 36       | 60           | 142            | 2.6       | 93      | 7  |
|      | A7         |          | 9.2                 | 2.64              | 104       | 70       | 34       | 65           | 140            | 2.5       | 95      | 5  |
| II   | A8         |          | 9.5                 | 2.69              | 104       | 65       | 39       | 63           | 135            | 2.4       | 92      | 8  |
|      | A9         |          | 9.6                 | 2.68              | 103       | 66       | 37       | 62           | 132            | 2.4       | 90      | 10 |
|      | A10        |          | 9.8                 | 2.66              | 104       | 67       | 37       | 60           | 130            | 2.3       | 88      | 12 |
|      | A11        |          | 8.8                 | 2.74              | 105       | 75       | 30       | 63           | 142            | 3         | 96      | 6  |
|      | A12        |          | 8.9                 | 2.73              | 104       | 73       | 31       | 62           | 140            | 2.9       | 94      | 6  |
|      | A13        |          | 9                   | 2.73              | 103       | 73       | 30       | 60           | 140            | 2.6       | 92      | 8  |
|      | A14        |          | 9.1                 | 2.71              | 100       | 72       | 28       | 58           | 135            | 2.5       | 89      | 11 |
| Average value | | | 9.13              | 2.71              | 103       | 67       | 35       | 61.7         | 140            | 2.69      | 93.2    | 6.8 |
| I    | G1         | Gypsum   | 42.3                | 2.36              | 45        | 32       | 13       | 14           | 120            | 1.4       | 13      | 87 |
|      | G2         |          | 41.5                | 2.34              | 42        | 31       | 11       | 12           | 105            | 1.5       | 11      | 89 |
|      | G3         |          | 40.2                | 2.37              | 40        | 30       | 10       | 13           | 110            | 1.4       | 12      | 88 |
|      | G4         |          | 41.3                | 2.34              | 38        | 29       | 9        | 11           | 105            | 1.5       | 11      | 89 |
| Average value | | | 41.3              | 2.35              | 41.3       | 30.5     | 10.5     | 12.5         | 110            | 1.45      | 11.8    | 88.2 |
| I    | C1         | Clays    | 16.5                | 1.75              | 110       | 39       | 71       | 35           | 165            | 4.9       | 16      | 1.9 |
|      | C2         |          | 16.8                | 1.74              | 105       | 39       | 66       | 34           | 160            | 4.7       | 16      | 4.7 |
|      | C3         |          | 17.8                | 1.72              | 98        | 35       | 63       | 28           | 155            | 5         | 16      | 5  |
|      | C4         |          | 16.7                | 1.75              | 115       | 37       | 78       | 29           | 160            | 5.1       | 16      | 5.1 |
| IV   | C5         |          | 16.8                | 1.74              | 105       | 35       | 70       | 34           | 150            | 4.8       | 16      | 4.8 |
| Average value | | | 16.92              | 1.74              | 107       | 37       | 69.6     | 32           | 158            | 4.9       | 16      | 4.9 |
Table 1 continued

| Site | Sample no. | Rock unit | Smectite | Mixed-Layer | Chlorite | Palygorskite | Kaolinite | Illite |
|------|------------|-----------|----------|-------------|----------|--------------|-----------|-------|
| I    | A1         |           |          |             |          |              |           |       |
|      | A2         |           |          |             |          |              |           |       |
|      | A3         |           |          |             |          |              |           |       |
|      | A4         |           |          |             |          |              |           |       |
| II   | A5         |           |          | Anhydrite   |          |              |           |       |
|      | A6         |           |          |             |          |              |           |       |
|      | A7         |           |          |             |          |              |           |       |
| III  | A8         |           |          |             |          |              |           |       |
|      | A9         |           |          |             |          |              |           |       |
|      | A10        |           |          |             |          |              |           |       |
|      | A11        |           |          |             |          |              |           |       |
| IV   | A12        |           |          |             |          |              |           |       |
|      | A13        |           |          |             |          |              |           |       |
|      | A14        |           |          |             |          |              |           |       |
|      |            |           |          | IG1         |          |              |           |       |
|      |            |           |          |            |          |              |           |       |
|      |            |           |          |            |          |              |           |       |
|      |            |           | Clays    | C1          | 47       | 18            | 13        | 8     | 8     | 6     |
|      |            |           |          | C2          | 44       | 19            | 12        | 9     | 9     | 7     |
|      |            |           |          | C3          | 45       | 20            | 13        | 8     | 7     | 7     |
|      |            |           |          | C4          | 48       | 16            | 12        | 9     | 9     | 6     |
|      |            |           |          | C5          | 46       | 17            | 15        | 11    | 7     | 4     |
|      |            |           |          | Average value | 46   | 18            | 13        | 9     | 8     | 6     |
satin spar gypsum under effect of successive cycles of hydration and dehydration [50].

The obtained x-ray diffraction charts were used for identification and quantification of clay mineral. Six types of clay minerals were identified throughout the studied sequence of which smectite is the predominant clay mineral in all samples (46%) followed by illite–smectite mixed-layer (18%), chlorite (13%), palygorskite (9%), kaolinite (8%), and illite (6%), (Table 1; Fig. 6a, b).

The clay mineralogy of the inter-bedded clayey layers gives important information about the paleoenvironmental aspects of this evaporitic succession. Except palygorskite, it is believed that most of the clay minerals are detrital in origin. The source of the smectite group minerals of the studied area is volcanic rocks which are abundant in the Nubian Shield rocks and clay-rich units (Pre-Abu Dabbab Formation especially Cretaceous rock units and Siyatin Formation Fig. 1).

Usually the source of smectite group clays is volcanic and metamorphic rocks [51]. Illite, in the study area was derived from schists of Nubian Shield rocks. The diagenetic changes of clay controlled by burial effects usually do not occur in sedimentary series thinner than 2–3 km [52].

Palygorskite is common in the Middle Miocene clastic sediments of the underlying intertidal-lagoonal Siyatin Formation, an environment suitable for the neoformation of palygorskite [53]. Natural occurrences of palygorskite in sediments and soils of arid regions have been widely reported [54,55]. Tertiary sediments appear to be the main host of palygorskite in the Middle East [37,54–56]. [51] has shown that palygorskite derives from chemical precipitation in evaporative basins. He summarized the conditions for palygorskite formation as alkaline conditions in restricted basins subject to marine transgression, limited water exchange, warm and humidity, contrasted climate and strong evapora-
clays play a vital role in their swelling capability. As shown in Table 1, the water contents of the studied samples vary from 8.8 to 9.8 % in anhydrite, from 16.5 to 17.8 % in clay and from 40.2 to 42.3 % in gypsum. The high water content in gypsum samples relative to those of anhydrite is mainly due to the structural water molecules in gypsum.

4.4 Specific Gravity

Table (1) presents the specific gravity data of the studied evaporite and clay samples as follows: anhydrite (from 2.64 to 2.74 gm/cm³), gypsum (from 2.34 to 2.37 gm/cm³) and clay (from 1.72 to 1.75 gm/cm³). It can be seen from these data that the specific gravity of the field samples increases as the amount of calcium sulphate increase. It is also noticed that the specific gravity of the studied samples increases with decreasing water content.

4.5 Consistency Limits

Consistency limits are fundamental properties that extensively used in soil classification and to predict their engineering behavior such as swelling and compressibility. The plasticity index (PI) is a measure of the potential plasticity of soil and is widely used in the geotechnical community to assess shrink-swell potential. Soils with high PI-value are
considered to have the capacity for expansive behavior [57].

[58] have proposed classifications, which give the swelling potential as a function of PI. It is generally good indica-
tor of swelling potential [59], where expandable clay min-
erals give PI >50 and non-expandable types give PI values <50 [60].
The plasticity chart (Fig. 7) shows the locations of the studied samples (anhydrite, gypsum and clays). The anhydrite and gypsum samples plot below the A-line in the fields of low (ML) and high (MH) plasticity whereas clay samples lie above the A-line in field of (CH) high plasticity. Soils with a high content of active clay minerals, such as montmorillonite, typically plot well above the A-line [61]. The liquid limit of the study anhydrite and clays samples is higher than 65% (Table 1; Fig. 7), so these sediments are considered of very high swelling capabilities [62].

4.6 Swelling Pressure

Clay-sulfate rock (gypsum and anhydrite) develop considerably higher swelling pressures in swelling experiments than pure clay rocks [63,64] suggesting a vital role of the transformation of anhydrite into gypsum in the swelling process of clay-sulfate rocks. Evaporitic sediments commonly contain expansible clay minerals (phyllosilicates), which have the unusual trait that their d-spacing for (001) crystal planes vary with the cation population on their exchange complex [65,66]. The variable spacing for a given expansible clay minerals arises from changes in the balance of expansive and contractive forces within the hydrated interlayer region of the clay mineral [67,68].

Argillaceous sediments can cause heave when their moisture content increase, mainly due water adsorption. Sometimes heave may be due to the hydration of anhydrite to gypsum [69] as gypsification of anhydrite results in a volume increase of about 62% [12]. Hydration of anhydrite creates swell pressure and floor heave in dams [10]. Serious structural damage can be attributed to heaving and settlement of soils containing anhydrous calcium sulphate when they are periodically and/or differentially exposed to wetting even without a rise in the level of the ground water. Dehydration of gypsum is associated with a volume decrease of about 38% [70], which may lead to excessive settlement of the overlying structures. Furthermore, shrinkage in the gypsum layer and the pore pressure effects of the released water from the crystal structure of gypsum can change the state of stress within the sediments and causes significant deformation and fracturing [71].

One of the most important properties of soft and disintegrated rocks is that they have high strength in their dry state and low strength when wet. These kinds of rocks exhibit swelling behavior when they contain anhydrite and smectite group minerals such as montmorillonite. Increase in the time-dependent volume of rocks containing swelling minerals like montmorillonite and anhydrite due to physico-chemical reaction with water is defined as swelling [72]. Swelling mechanism can be expressed by combination of physico-chemical reaction with water and stress relief. This reaction usually plays the most important role but swelling can only take place simultaneously with or following stress relief [73].

It is essential to have laboratory measurement of swelling characteristics on undisturbed samples for prediction the field behavior. The conventional one-dimensional odometer swell tests were performed using free axial swell. Twenty-three undisturbed representative samples (anhydrite, clay and gypsum) were chosen. The samples were prepared by cutting pieces of dimensions 6.35 cm diameter and 1.9 cm high from a hard soil block using mechanical saw machine. The samples were carefully placed in the oedometer mould. The water was allowed to imbibe at stages of saturation 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50% of original weight of samples and saturation state. The dial gauge records any value of swelling in these stages until the value of maximum swelling. The load (P) was applied until keep it to its initial height. Swelling pressure ($P_S$) equal to the load ($P$) divided by the cross-sectional area ($A$) of the sample and was calculated using the following equation:

$$P_S = \frac{P}{A} \quad (3)$$

where:

- $P_S$ = Swelling pressure (kg/cm$^2$)
- $P$ = The total load required to prevent swell of the sample (kg)
- $A$ = Cross sectional area (cm$^2$)

The swelling pressure was found to be (from 1.4 to 1.5 kg/cm$^2$ with an average value 1.45 kg/cm$^2$), (from 2.3 to 3.1 kg/cm$^2$ with an average value 2.69 kg/cm$^2$) and (from 4.7 to 5.1 kg/cm$^2$ with an average value 4.9 kg/cm$^2$) for gypsum, anhydrite and clay, respectively (Table 1; Fig. 8). The swelling pressure of gypsum is moderate and for both anhydrite and clay is high [74]. The swelling pressure of Abu Dabbab Evaporite samples increases with increasing anhydrite and smectite content (Table 1; Fig. 9). [75,76] have pointed out that the adsorption of water by clays leads to expansion that its magnitude varies widely depending mainly upon the kind and the amount of swelling clay minerals present.
The swelling ability of gypsum samples is mainly due to presence of about 12 % of anhydrite within these samples, whereas the high swelling pressure of the inter-bedded clays is due to the dominance of smectite (46 %), (Table 1).

4.7 Swell Percent

The swelling percentage is defined as the percentage ratio between the increasing in specimen height \( \Delta H \) under a standard stress to the initial height of specimen \( H_0 \). The swell percentage is calculated as follows:

\[
S = \frac{\Delta H}{H_0} \times 100
\]

where:

- \( S \) = Swelling percentage
- \( H_0 \) = Initial height of the sample (mm)
- \( \Delta H \) = Increasing in the height of the sample (mm)

The calculated swelling percentages of the studied samples are 11–14 % with an average value 12.5, 28–35 % with an average value 32 and 58–65 % with an average value 61.7 % for gypsum, clay and anhydrite, respectively (Table 1). It is found that the swelling percent of Abu Dabbab Evaporites samples increases with increasing anhydrite and smectite content (Table 1; Fig. 10).

4.8 Free Swelling

The free swell test was carried out as described by [32]. A sample was dried, broken down, grinded and sieved by sieve No. 40 (0.425 mm). The material passing was again dried and poured gently to fill a 10 cm\(^3\) graduated glass cylinder. This volume of the soil was quickly poured into a 100 cm\(^3\) graduated glass cylinder filled with distilled water. The suspension was left for 24 h. The volume of the sample was seen to increase to \( V_2 \). The free swell test value is given by:
Free swelling value (% ) \[ V_2 - 10 \] \[ \times 100 \] \[ (5) \]
where \( V_2 \) is in cm\(^3\).

The free swelling values of the studied samples are found to be (from 150 to 165 %, with an average value 158 %), (from 130 to 150 % with an average value 140 %) and (from 105 to 120 % with an average value 110 %) for clay, anhydrite and gypsum, respectively (Table 1). The swelling potential for gypsum is moderate, while for both anhydrite and clays are critical [32]. It is clear that the free swelling of Abu Dabbab Evaporite samples increases with increasing anhydrite percent (Table 1; Fig. 11).

5 Conclusions

The present study is considered as a model for the effect of hydration and dehydration reaction on the mineralogical and geotechnical properties of the Middle Miocene Evaporite (Abu Dabbab Formation), Red Sea coastal region, Egypt. Experimental investigations allow reaching the following conclusions:

1. The Middle Miocene evaporite of the Abu Dabbab Formation crop out north of Quseir City along the Egyptian Red Sea Coast. It is composed mainly of anhydrite cap formed during several cycles of dehydration processes of primary gypsum under arid alkaline conditions.
2. The Abu Dabbab Evaporites are mainly composed of anhydrite (88–97 %) with subordinate gypsum (3–12 %). The lower most part near the ground surface is consisting of gypsum (87–89 %) and anhydrite (11–13 %).
3. Anhydrite exhibits chemical swelling behaviour such as clay minerals (smectite) when inundated with water. Its swelling potential has direct relationship with the anhydrite content.
4. The ability of evaporitic materials to swell depends on the amount anhydrite, which has high capability to absorb water. The hydration of anhydrite produces a chemical swelling of up to about 60 %.
5. The inter-bedded clays within the evaporite section consist of smectite (46 %), illite-smectite mixed-layer (18 %), chlorite (13 %), palygorskite (9 %), kaolinite (8 %), and illite (6 %). The swelling potentials of these clays increase with increasing smectite content.
6. The geologic, geotechnical and environmental data must be integrated to define the swelling potential of this type of soil and its failure modes.
7. A sufficient safety factor must be done in the design of any construction on this type of swell-able soil.

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