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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/cm^2), (2.3–3.1 kg/cm^2) and (4.7–5.1 kg/cm^2) 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

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الخلاصة

تتكون متبخرات الميوسين الأوسط التابعة لمكون أبو دباب والواقعة بالمنطقة الممتدة شمال مدينة القصير بساحل البحر الأحمر (مصر) أساسا من الأنهيدريت الذي يتواجد على شكل رقائقي أو طبقي أو على شكل درنات، ويتخلل الانهيدريت رقاقات من الجبس دقيق التبلور، وبخاصة بالأجزاء السفلية لمكون أبو دباب، ويشتهر مكون أبو دباب بوجود اكتنافات بينيه من الرواسب الطينية التي يوجد فيها العديد من الشقوق التي تمتلئ بمتبخرات والتى تشير بدورها إلى الظروف المناخية الجافة خلال فترات انحسار مياه البحر ونكشاف الحوض الترسي. هذا بالإضافة لوجود العديد من الاكتنافات بمكون أبو دباب من الدلوميت وراقات من الشترماتوليت.

وتعزى آلية انتفاخ رواسب المتبخرات إلى تشرب المعادن الطينية للماء، وأيضا تميؤ الأنهيدريت وتحوله إلى جبس. ومن خلال المشاهدات الحقلية ونتائج حيود الأشعة السينية لمسحوق المتبخرات وجد أن نسبة الأنهيدريت / الجبس تقل تدريجيا للأسفل داخل التتابع الصخرى لمكون أبو دباب، وهذا التناقص يرجع في الأساس إلى تحول الجبس إلى الأنهيدريت بفقده للماء عن طريق التسخين بوساطة حرارة الشمس، وتحت الظروف المناخية الجافة.

إن التركيب المعدني لطبقات الطين المكتنفة بالمتبخرات لمكون أبو باب يترتب بحسب وفرتها النسبة كالتالي السمكتيت، والإليت-السمكتيت مزدوج الطبقة، والكلوريت، والبالوجورسكيت، الكاولينيت والإليت.

ومن خلال التجاب المعملية لرواسب المتبخرات والمكتنفات الطينية لها فقد وجد أن قيمة حد السيولة أعلى من 65٪، ولذلك تعتبر هذه الرواسب من المواد ذات القدرة العالية جدا للانتفاخ عند تشربها بالماء. أيضا ، وتم تعيين نسبة الانتفاخ للجبس والطين والأنهيدريت، ووجد انها على التوالي (11٪ -

14٪)، (28٪ -35٪) و (58٪ -65٪). وكذلك ضغط الانتفاخ للجبس وجد أنه من النوع المتوسط فى حين أنه من النوع العالي بالنسبة لكل من الأنهيدريت، وطبقات الطين مما يتسبب عنهما حدوث العديد من المشاكل الجيوتقنية عند تشربهما بالماء. وهذا التغير المتكرر فى حجم المتبخرات علاوة على انتفاخ طبقات الطين التى تكتنفها هذه المتبخرات يؤدي بدوره إلى زيادة حدة هذه المشاكل الجيوتقنية.

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 Ca^{2+} is surrounded by eight neighboring SO_4^{2-} ions, whereas the monoclinic structure of gypsum is held by weak hydrogen bonds between water molecules and 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 swelling capability of anhydrite can only appear when it gets into contact with water. Anhydrite converts to gypsum when inundated with water as the SO_4^{2-} ion attracts the H_2O 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 sedimentolgical 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-

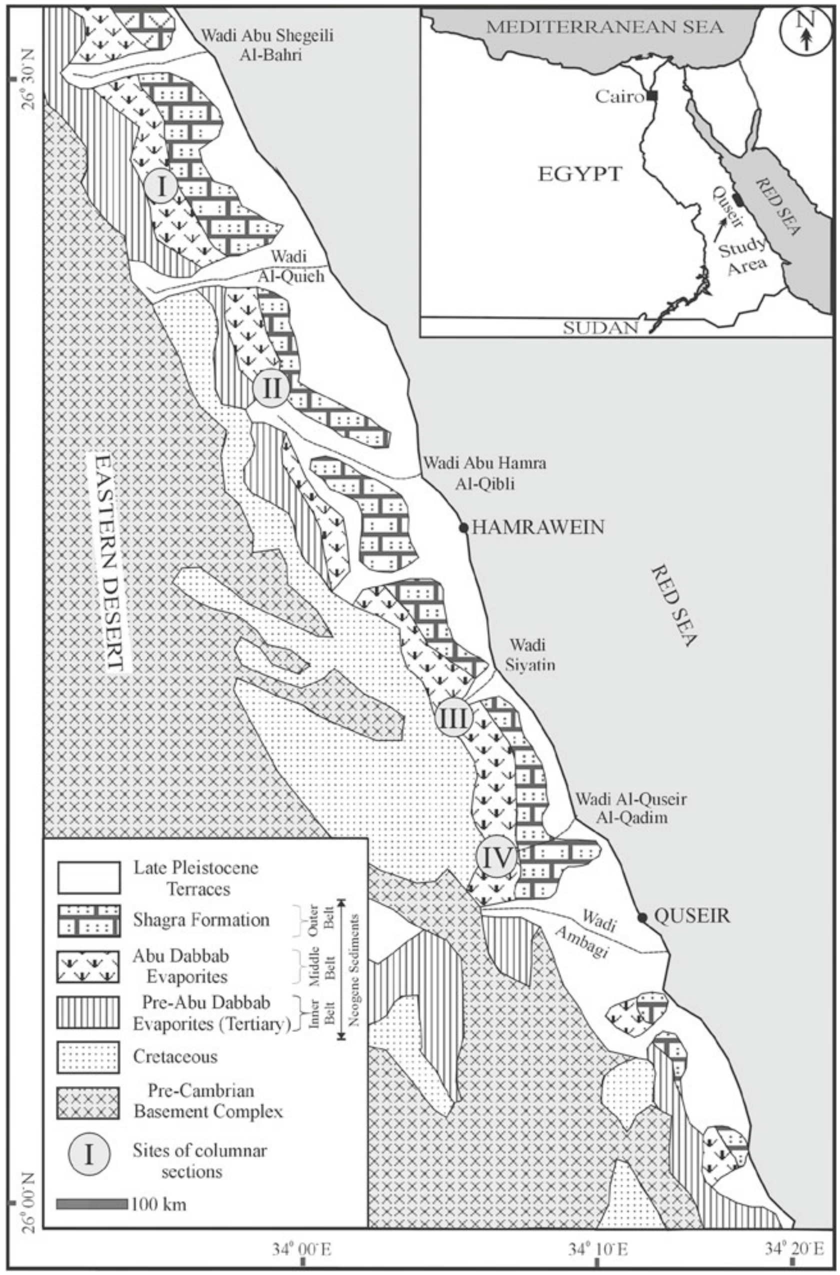

Fig. 1 Geological map of the study area

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 odeometer 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 $CaSO_4 \cdot 2H_2O$ system takes place according to the following reversible hydration–dehydration reaction [39]:

$$CaSO_4 \cdot 2H_2O \text{ (gypsum)} \longleftrightarrow CaSO_4 \text{ (anhydrite)} + 2H_2O \qquad (1)$$

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 Siyatin) 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_4^{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 hearting in hot arid climate according to the following reaction:

$$CaSO_4 \cdot 2H_2O \text{ (gypsum)} \xrightarrow{\text{Arid condition+Solar heating}} CaSO_4 \text{ (anhydrite)} + 2H_2O \qquad (2)$$

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	Anhydrite	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
II	A4		8.9	2.68	104	65	39	63	140	3	96	4
	A5		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
III	A7		9.2	2.64	104	70	34	65	140	2.5	95	5
	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
IV	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	67.1	35.4	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
II	G2		41.5	2.34	42	31	11	12	105	1.5	11	89
III	G3		40.2	2.37	40	30	10	13	110	1.4	12	88
IV	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		
II	C2		16.8	1.74	105	39	66	34	160	4.7		
III	C3		17.8	1.72	98	35	63	28	155	5		
	C4		16.7	1.75	115	37	78	29	160	5.1		
IV	C5		16.8	1.74	105	35	70	34	150	4.8		
Average value			16.92	1.74	107	37	69.6	32	158	4.9		

Table 1 continued

Site	Sample no.	Rock unit	Mineral constitutes					
			Smectite	Mixed-Layer	Chlorite	Palygorskite	Kaolinite	Illite
I	A1							
	A2							
	A3							
	A4							
II	A5							
	A6	Anhydrite						
	A7							
III	A8							
	A9							
	A10							
	A11							
IV	A12							
	A13							
	A14							
Average value								
I	G1							
II	G2	Gypsum						
III	G3							
IV	G4							
Average value								
I	C1		47	18	13	8	8	6
II	C2	Clays	44	19	12	9	9	7
III	C3		45	20	13	8	7	7
	C4		48	16	12	9	9	6
IV	C5		46	17	15	11	7	4
Average value			46	18	13	9	8	6

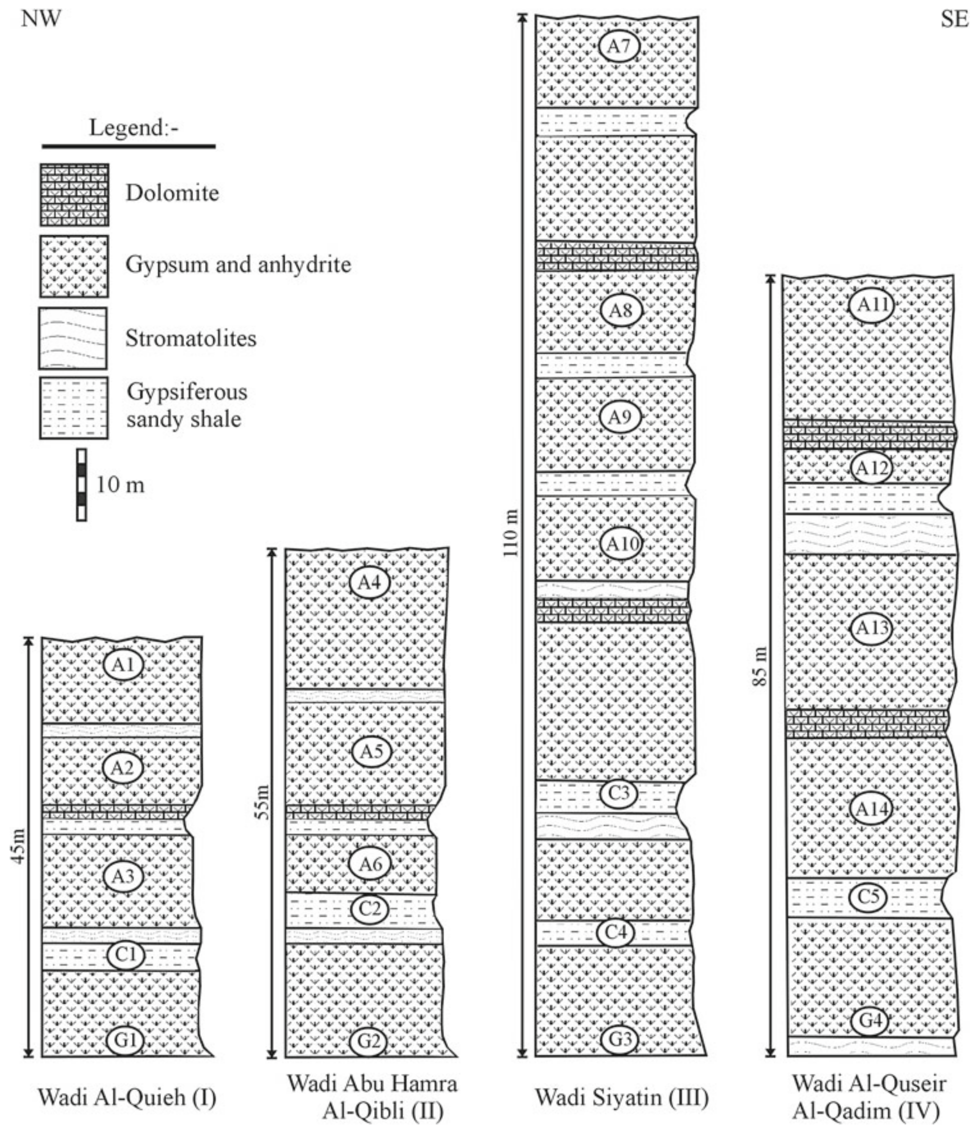

Fig. 2 Columnar sections and sampling numbers of Abu Dabbab Evaporites in the study area

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-

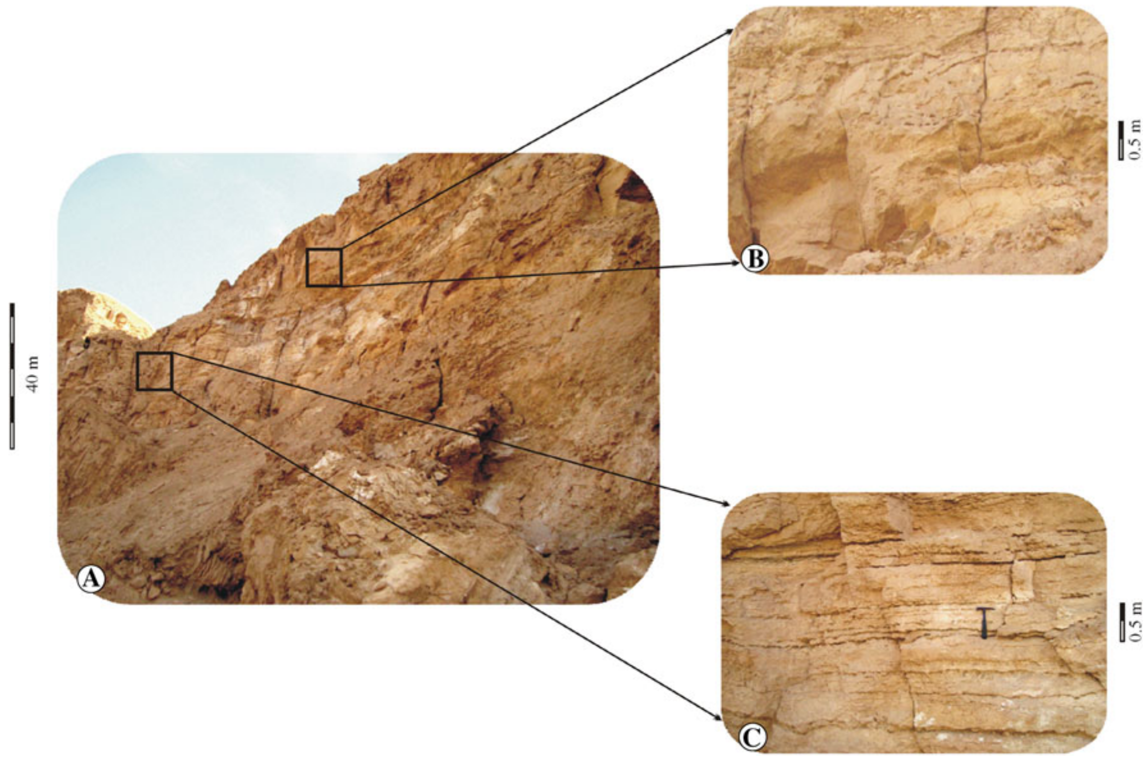

Fig. 3 **a** General view of Abu Dabbab Evaporites at Wadi Siyatin (16 km north Quseir), **b** bedded anhydrite, **c** Thinly bedded anhydrite

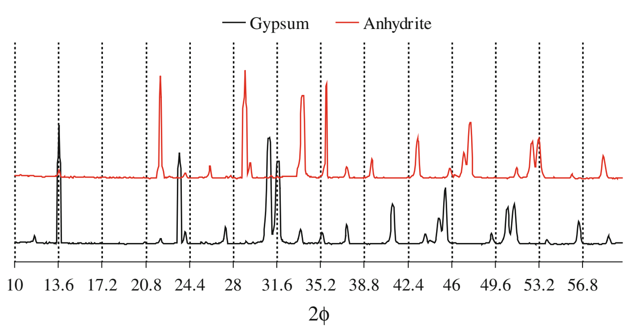

Fig. 4 X-ray diffraction pattern of anhydrite and gypsum samples of Abu Dabbab Evaporite

tion. It seems that these conditions are suitable for the formation of palygorskite as neoformed clay mineral in restricted back-reef and lagoons of the evaporite beds of the Abu Dabbab Formation.

4.3 Water Content

An expansive soil tends to swell when there is an increase in its water content. If the soil is confined, it may exhibit considerable swelling pressure. The latter depends on the nature of expansive soil, type of structure and environmental conditions. The water content (moisture or structural) of the studied evaporites (gypsum and anhydrite) and inter-bedded clays play a vital rule 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/cm^3), gypsum (from 2.34 to 2.37 gm/cm^3) and clay (from 1.72 to 1.75 gm/cm^3). 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

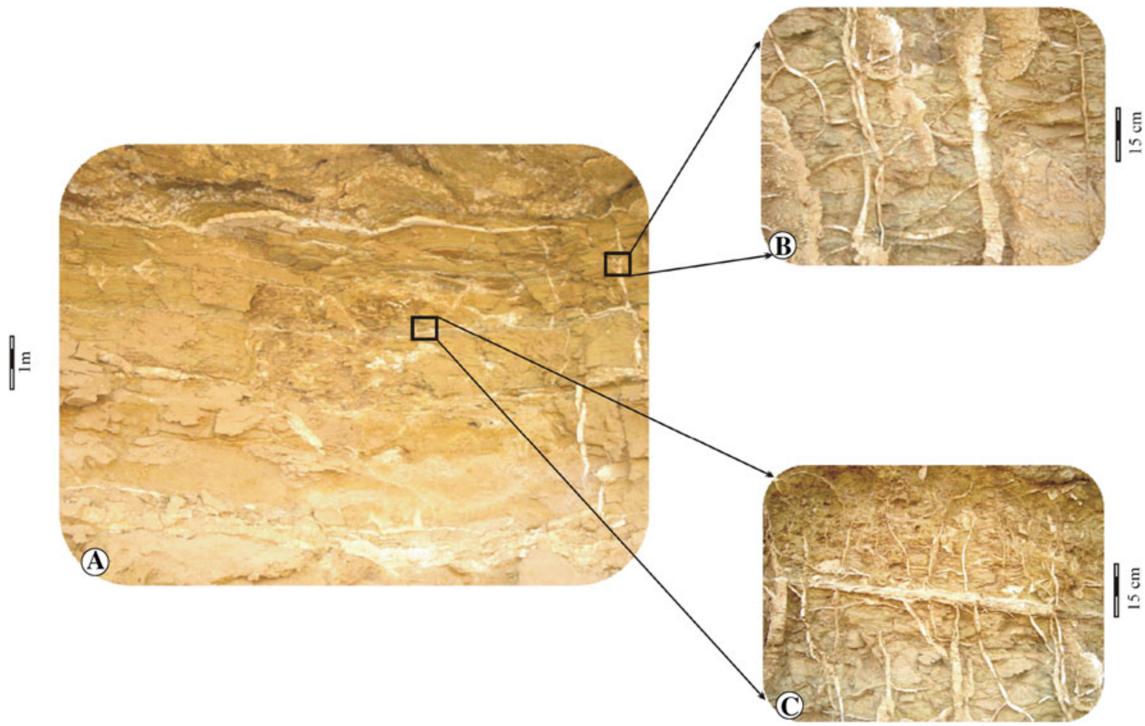

Fig. 5 **a** General view of the host expansive clay strata at Wadi Al-Quseir Al-Qadim (8 km north Quseir), **b** large vertical cracks filled with evaporite materials, **c** vertical and horizontal cracks filled with evaporite materials

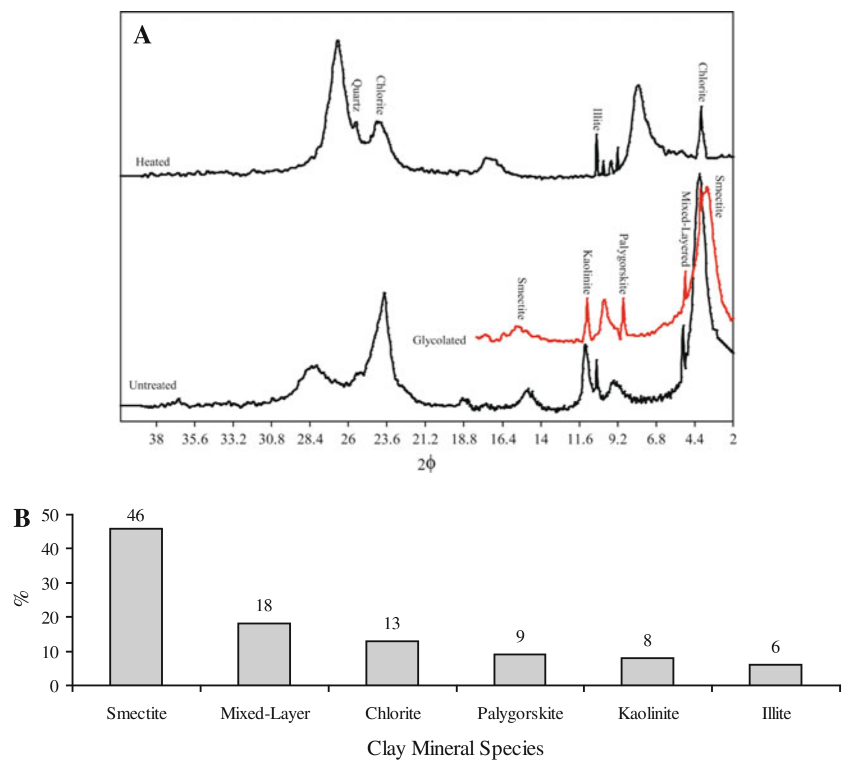

Fig. 6 **a** X-ray diffraction pattern of Abu Dabbab Evaporite inter-bedded expansive clays. **b** Relative abundance of clay mineral species of Abu Dabbab Evaporite inter-bedded expansive clays

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 indicator of swelling potential [59], where expandable clay minerals give PI >50 and non-expandable types give PI values <50 [60].

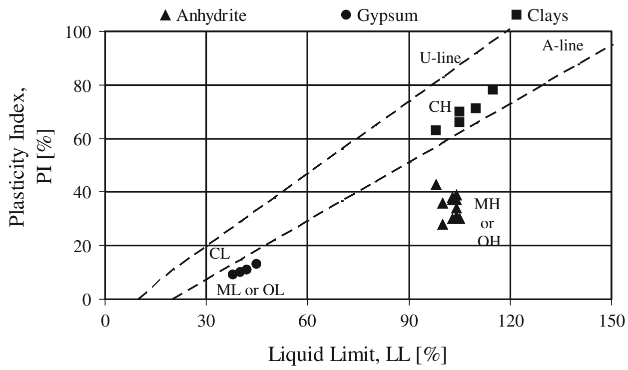

Fig. 7 Plasticity chart of the study samples

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.

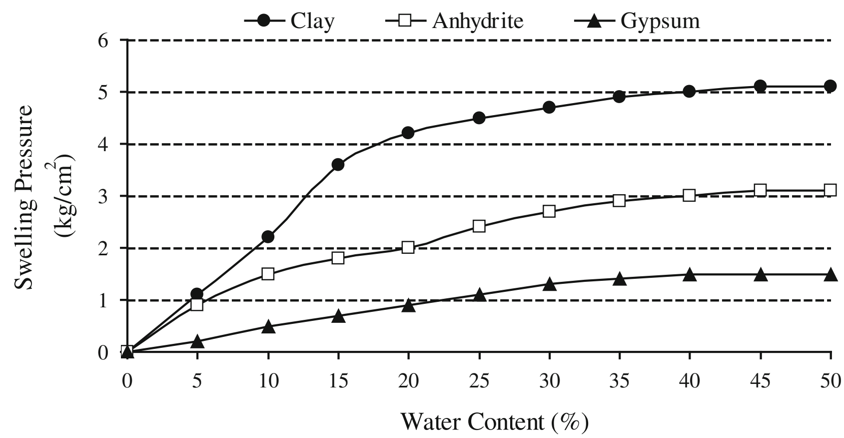

Fig. 8 Relationship between water content and swelling pressure

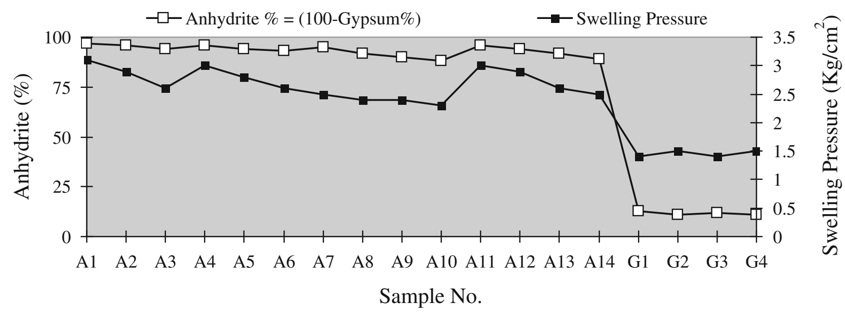

Fig. 9 Relationship between anhydrite content and swelling pressure of Abu Dabbab Evaporite

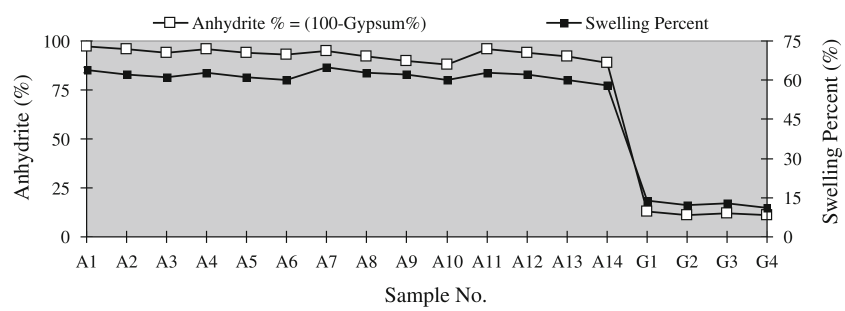

Fig. 10 Relationship between anhydrite content and swelling percent of Abu Dabbab Evaporite

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 (ΔH) under a standard stress to the initial height of specimen (H_0). The swell percentage is calculated as follows:

$$S = \frac{\Delta H}{H_0} \times 100 \quad (4)$$

where:

S = Swelling percentage
H_0 = Initial height of the sample (mm)
ΔH = 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:

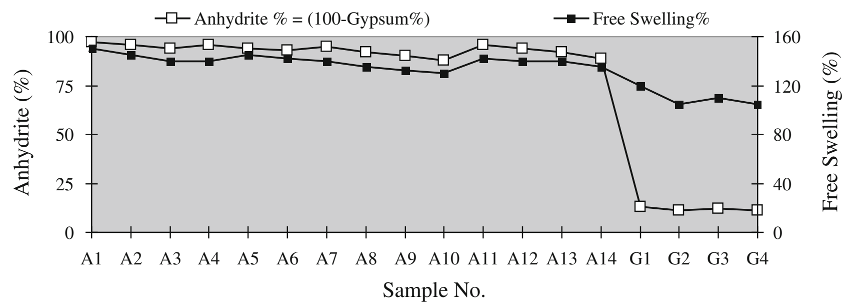

Fig. 11 Relationship between anhydrite content and free swelling (%) of Abu Dabbab Evaporite

$$\text{Free swelling value }(\%) \frac{V_2-10}{10} \times 100 \quad (5)$$

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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