Experimental Study of the Mechanics of Gypsum Seam Hazard for Abu Dhabi

M. Opolot, W. Li, R.L. Sousa and A.L. Costa

Abstract Abu Dhabi is predicting a huge growth in population over the next 20 years (Plan Abu Dhabi 2030); further, it seeks to become an international destination for tourists, businesses, and investment while protecting its cultural heritage. A crucial aspect of achieving this goal is the development of large integrated transportation system, underground, and above ground, to ensure Abu Dhabi becomes a sustainable city on a global scale. The presence of gypsum rocks that occurs within Abu Dhabi's bedrock is a major threat to underground construction and understanding the phenomena is of paramount importance. They are persistent quasi-horizontal bands, at different levels (top level between 10 and 15 m and bottom level between 15 and 25 m), prone to volume change by dissolution or swelling, due to changes in the stress regime and water chemistry and flow. The dissolution of gypsum is also a cause for cavities that can be found within this formation in greater Abu Dhabi. In this paper, the description and results of an experimental study aimed at obtaining a better understanding of the gypsum dissolution process, as well determine factors affecting it, are presented. Tests on the dissolution process of gypsum rock were performed using artificially created intact and fractured gypsum samples which are a representative of the collected in situ fractured gypsum rock samples obtained from Abu Dhabi. The samples are subjected to flow-through tests. Results obtained show that for an initially saturated gypsum specimen, there is a sharp decline in concentration with time (Stage I), followed by a constant concentration (Stage II) before a slight gradual increase is

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observed (Stage III) with time. This is a fundamental study—part of a larger set of experiments studying the gypsum dissolution process in Abu Dhabi. Using the data collected from the field and the experiments mentioned above, gypsum geohazard risk-related maps which reflect subsidence, swelling, cavity collapse, and cavity flooding associated with Gypsum Karst shall be developed using Geographic Information Systems.

Keywords Gypsum dissolution · Groundwater flow · Underground construction · Subsidence · Collapse

1 Introduction

Gypsum ($CaSO_4.2H_2O$)—a white, translucent, pale grey or grey rock mineral—is known to occur worldwide in all geological sequences from the Cambrian (570 million years ago) to the recent deposits (Cooper and Calow 1998). In Abu Dhabi, gypsum occurs at different levels (top level between 10 and 15 m and bottom level between 15 and 25 m) within the Tertiary bedrock as persistent quasi-horizontal bands. Figure 1 shows samples from representative gypsum layers, retrieved at different depths in Abu Dhabi.

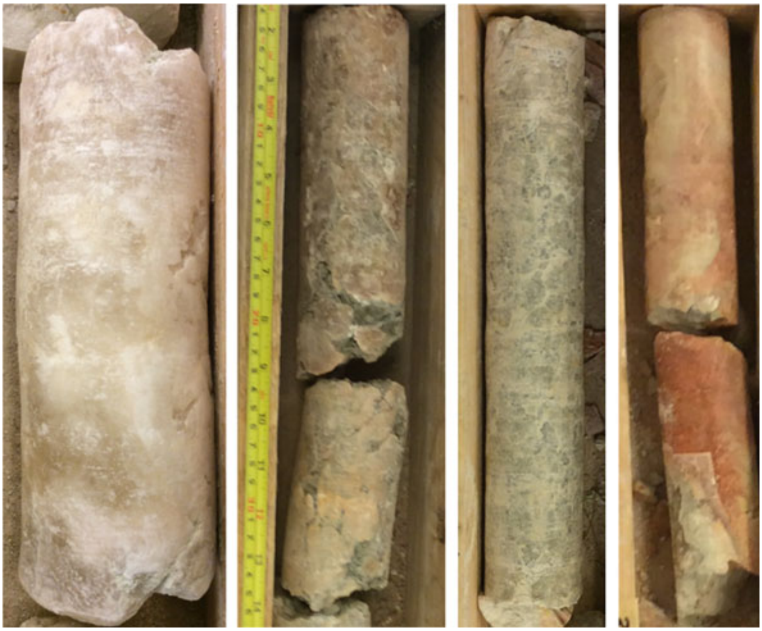

Fig. 1 Abu Dhabi gypsum rock samples

Gypsum is soluble in water, and it dissolves about 100 times faster than limestone (Yilmaz et al. 2011). In pure water at a temperature of about 200 °C, the solubility of gypsum is 2.531 g/L (Klimchouk 1996). Water flow velocity, temperature, salinity, applied pressure, gypsum content percentage, gypsum grain size, time of groundwater exposure are among other factors that influence the dissolution rate of gypsum. Gypsum is further affected by diagenesis—a process where primary (depositional) gypsum is transformed to anhydrite ($CaSO_4$) when buried. Anhydrite can also rehydrate to form gypsum if it is exposed to a weathering process under favourable conditions. Gypsum is also prone to volume change by dissolution or swelling due to stress regimes and groundwater chemistry as shown in Eq. (1) (Yilmaz et al. 2011; Llana-Fúnez et al. 2012).

$$\begin{array}{c} \underset{\text{gypsum}}{\mathrm{CaSO_4 \cdot 2H_2O}} \rightarrow \quad \underset{\text{bassanite}}{\mathrm{CaSO_4 \cdot \frac{1}{2}H_2O}} \quad + \underset{\text{water}}{\mathrm{\frac{3}{2}H_2O}} \\ \text{total volume increase} \rightarrow \\ \leftarrow \text{solid volume increase} \end{array} \tag{1}$$

When gypsum is exposed to groundwater flow, it may dissolve with the development of karst features. Continuous exposure to groundwater can further lead to subsidence or even collapse of the overlying ground surface. This is a major threat for underground construction over gypsiferous terrains—for which Abu Dhabi is part of—and understanding the phenomena is of paramount importance.

2 Abu Dhabi Geological Setting

2.1 Geology and Geotechnical Description

The Emirate of Abu Dhabi (see Fig. 2) alone is approximately 80% a sandy desert, and it covers about 85% of the entire United Arab Emirates land area (Shabbir et al. 2008). The Emirate is located in the north-east portion of the Arabian Plate, that formed during the Late Neoproterozoic era (~820–750 Ma) by the accumulation of island arcs and microcontinents to early Gondwana (Glennie 2013). The Zagros foreland basin and adjacent fold-belt bound Abu Dhabi to the north, the Omani thrust belt to the east, the Rub al Khali Basin to the south, and Qatar Arch to the west (Salah 1996).

In the present day Abu Dhabi, desert land surface sits on rocks deposited nearly 950 million years ago. The majority of the depositions happened below sea level. However, during lengthy periods of land surface uplift—an average rate of 3 mm/year for the past 25,000 years (Lokier and Steuber 2008)—and subaerial erosion, geological traces over that time period were washed away. The geological history of that time period is buried underneath the land surface and the Arabian Gulf (Shabbir et al. 2008), composed of various stratigraphic layering, including

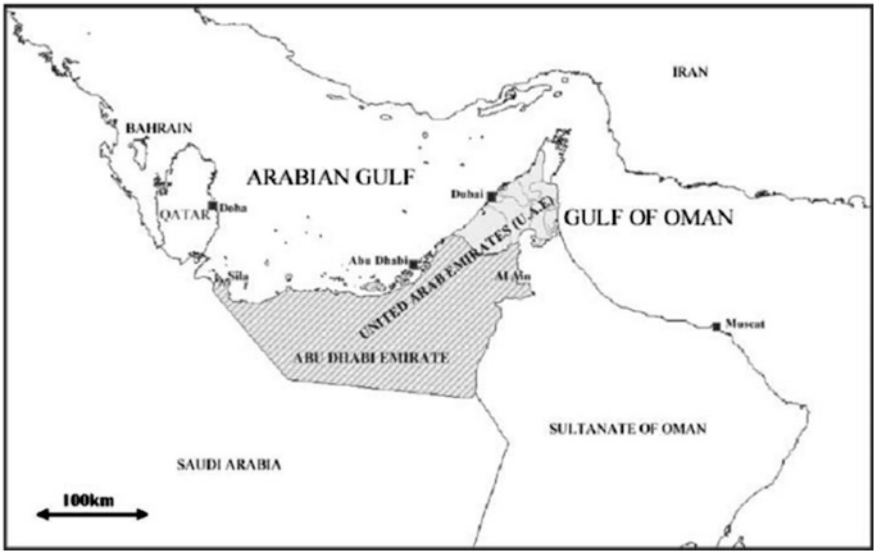

Fig. 2 Reference map of the Emirate of Abu Dhabi (Al-Katheeri 2008)

gypsum. A stratigraphic geological profile drawn during the fieldwork activity at about 20 km away from Masdar City (see Fig. 3) shows that there is an occurrence of gypsum at just about 30 m. A comparison with the Masdar City construction geotechnical reports shows bands of gypsum at almost the same depth. This, therefore, implies that areas with the same geological formation tend to have the same layering, hence in Abu Dhabi, gypsum occurrence can be noticed at just tens of metres below sea level.

2.2 Hydrogeology of Abu Dhabi

The Emirate of Abu Dhabi experiences arid desert conditions with minimal amounts of annual rainfall ranging from 0 to 30 mm/annum (Brook and Houqani 2003). It is also characterized by the absence of vegetation and very saline groundwater conditions. In addition, groundwater recharge is less than 4% of total annual rainfall, and there are no potential perennial surface water resources (Brook and Houqani 2003; Al-Katheeri 2008). In Abu Dhabi, groundwater lies in consolidated or unconsolidated surficial aquifers and as bedrock/structural aquifers (Shabbir et al. 2008).

Gypsum dissolution is enhanced by groundwater flow conditions. Groundwater flow systems can be divided into local, intermediate and regional flow systems. Flow nets that predict groundwater flow can be derived based on each of these

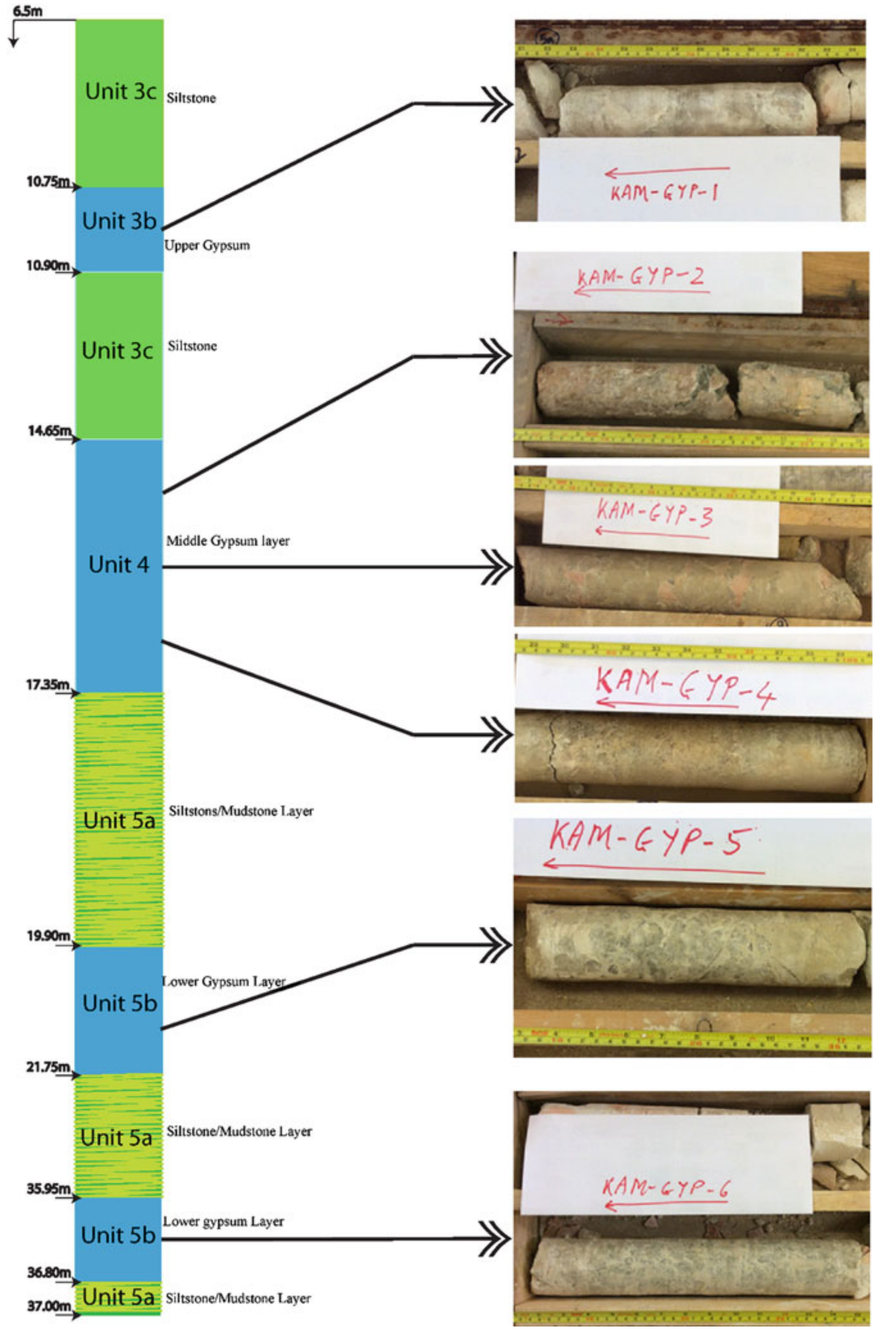

Fig. 3 Stratigraphy of the borehole located at 20 km away from Masdar City

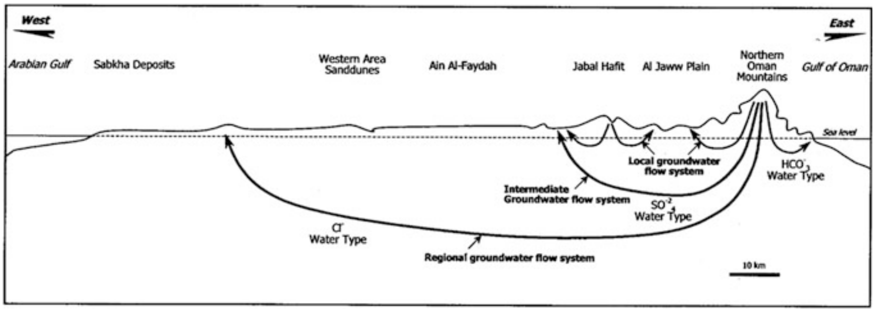

Fig. 4 Schematic showing groundwater flows regime in Abu Dhabi (Alsharhan et al. 2001)

Fig. 5 Karst features within Abu Dhabi (Modified) (Tayo 2014)

scales, and are dependent on many factors that include local topography and basin shape geometry. Based on the study by Toth (1963) and Alsharhan et al. (2001) came up with the schematic illustrating a flow regime in Abu Dhabi (see Fig. 4).

3 Gypsum Seam Hazards

Several cases of destruction by gypsum rock dissolution, subsidence and collapse have been recorded worldwide dating back to the nineteenth century. The gradual destruction process of gypsum rock dissolution can cause failure of tunnels and other infrastructures even after decades of operation (Kaiser et al. 2010). In-depth records of gypsum hazards are highlighted in the studies by Cooper (1998, 2006, 2008), Gutierrez and Cooper (2002), Kaiser et al. (2010), and Butscher et al. (2011).

Although there have been no catastrophic gypsum seam hazards recorded in Abu Dhabi yet, this does not prevent its future occurrence. Sinkholes can be observed in some areas of Abu Dhabi (see Fig. 5). This, therefore, calls for an understanding of the mechanics of gypsum seams in Abu Dhabi, which will later support the development of hazards maps for the region. These hazard maps will be developed using GIS based on the experimental data obtained in this study.

4 Experimental Setup

4.1 Overview

A mathematical model was developed by Li et al. (2015) to predict the dissolution process of a solution rock based on advection, diffusion and dispersion. The model is capable of predicting the concentration–time curve of the effluent. To validate the mathematical model, Li et al. (2015) and Opolot (2015) performed experiments.

4.2 Plaster of Paris Calibration Tests

To obtain the relationship between electric conductivity and concentration of the Plaster of Paris to be used for gypsum specimen moulding, a batch of calibration tests were performed. This was performed by preparing a saturated solution of Plaster of Paris and its saturated conductivity measured before subsequence dilution using distilled water is performed while measuring the corresponding conductivity up to when the conductivity is almost equal to that of distilled water. Using curve fitting, a log–log plot of the raw data (see Fig. 6) and an equation relating conductivity to concentration is derived as shown in Eq. (2).

$$\log(\text{Conc.}) = 1.225 \log(\text{E.C.}) - 3.749 \tag{2}$$

4.3 Specimen Preparation

In order to perform the flow-through tests, gypsum specimens were first moulded using the locally purchased Plaster of Paris. When water is mixed with Plaster of Paris at room temperature, gypsum is obtained as shown in Eq. (3).

$$\mathrm{CaSO_4} \cdot \frac{1}{2}\mathrm{H_2O} + \frac{3}{2}\mathrm{H_2O} \xrightarrow{\text{room temperature}} \mathrm{CaSO_4} \cdot 2\mathrm{H_2O} \tag{3}$$

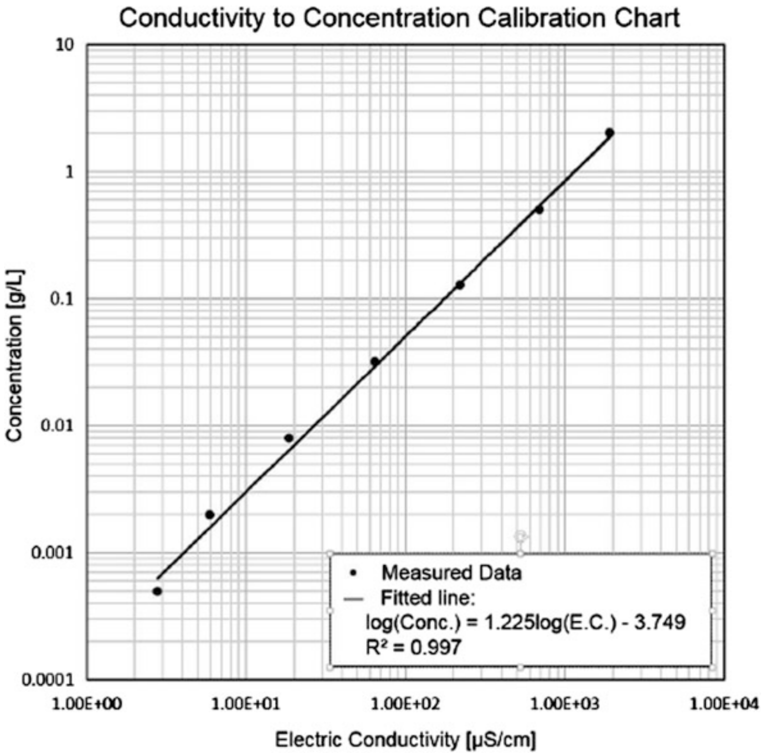

Fig. 6 Conductivity metre calibration

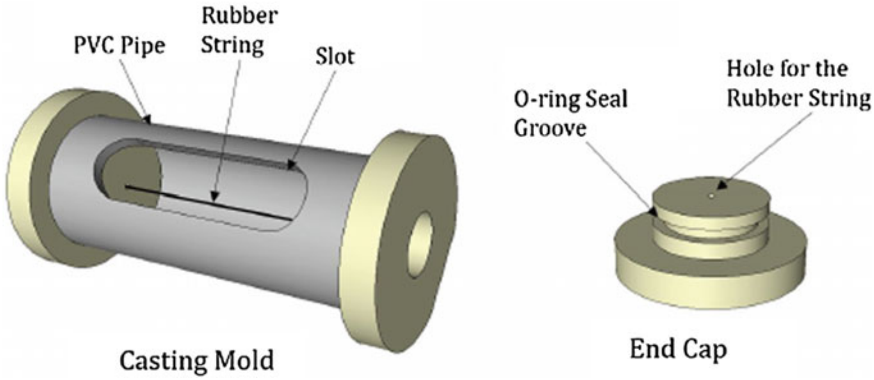

Fig. 7 Casting mould used for specimen preparation

A ratio of 0.6 of water to Plaster of Paris was poured into the mixture and mixed for about 2 min to obtain gypsum paste. A cylindrical mould (see Fig. 7) with a string of about 1 mm passing through was then placed on the vibrator before the prepared gypsum paste is poured into it to obtain the cylindrical specimen with an initial flow-through hole. The entire mould process is performed on the vibrator to eliminate any trapped air bubbles within the gypsum paste. After moulding, the specimen in transferred to an oven set at 40 °C to cure. In about 24 h, the rubber string is pulled off to leave an initial flow-through hole while the specimen is further cured in an oven. The whole specimen preparation process takes about 7 days to get it ready for flow-through tests. Before the specimen is used for flow-through tests, it first saturated in a fully saturated solution of gypsum. This is done for the specimen to get fully saturated and hence to prevent it from absorbing water during the flow-through batch tests.

4.4 Apparatus Setup

The flow-through apparatus consisted of the peristaltic/submerged pump, constant head reservoir, throttle valve and the gypsum specimen assembly as shown in Fig. 8.

The apparatus was first calibrated by letting distilled water flow through it to eliminate any trapped in the air before the specimen is connected at the end. The specimen is held tight using a C-clamp to avoid any leakage during the experimental run. A sampling of the effluent is performed in intervals from the outlet of

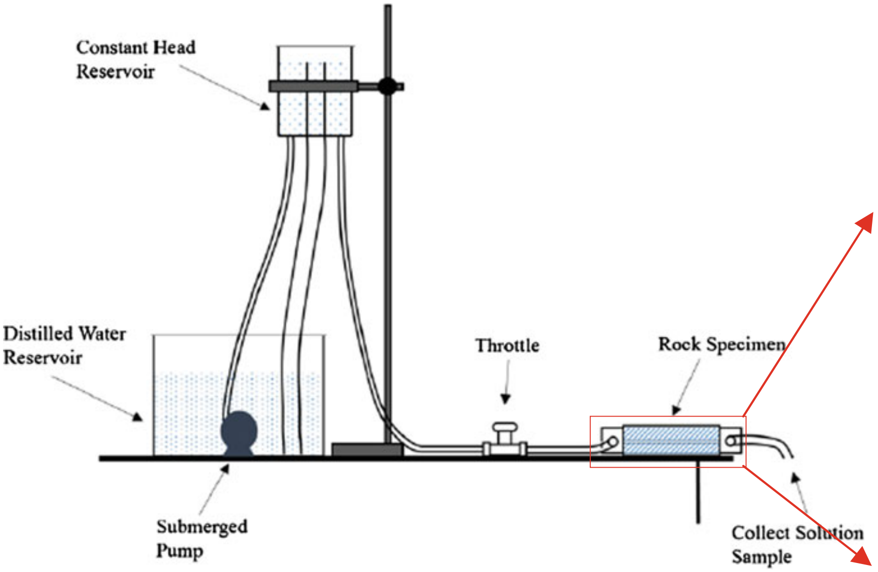

Fig. 8 Experimental setup

the gypsum specimen. The electric conductivity of the different samples collected is measured and the corresponding concentration calculated using Eq. (2) obtained during calibration.

5 Results and Discussions

When the gypsum specimens were fully saturated, flow-through tests were performed by sampling the outflow from the gypsum specimen at a given time interval for analysis. The electric conductivity of each sampled solution was then measured using the conductivity metre and its corresponding concentration calculated using Eq. (2) relating conductivity to concentration. A plot of concentration (g/L) versus time (s) shown in Fig. 9 illustrates that, for an initially saturated gypsum specimen, there is a sharp decline in concentration with time (Stage I), followed by a constant concentration (Stage II) before a slight gradual increase is observed with time (Stage III).

In Stage I, at early times, there is a high initial concentration of dissolved solutes in the water outflow. This concentration is similar in magnitude to the concentration of the dissolved solids in the water inside the specimen that was saturated for 4 days. With time, the injected distilled water dilutes the solution in the gypsum specimen opening, causing a decrease in concentration of the solutes. The time duration of this stage depends on the flow rate of the distilled water, where a lower flow rate leads to a longer dilution duration (Stage I) before Stage II is observed.

In Stage II, an almost constant concentration of dissolved solutes is observed with time. This is because as injected distilled water continues to flow through the gypsum specimen opening, the dissolution processes reach equilibrium, leading to a constant concentration.

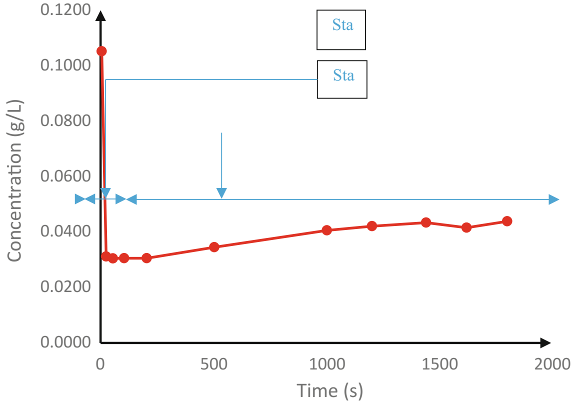

Fig. 9 Concentration variation with time

In Stage III, a gradual increase in concentration is observed with time. In this stage, and as water continues to flow through the opening, it dissolves the inner surface wall of the gypsum opening, causing an increase in the opening diameter. The increase in diameter results in a larger contact surface area between water and the gypsum opening. As this happens, the water flow rate decreases, which results in a longer exposure time to the flowing water. The combined effect of these phenomena leads to a longer reactive time between the water and the gypsum, causing a gradual increase in concentration with time.

6 Conclusions and Recommendations

6.1 Conclusions

The results of experimental analyses performed on gypsum specimens representative of the naturally occurring gypsum around Greater Abu Dhabi show that gypsum is subject to dissolution once exposed to water. The rate of gypsum dissolution is influenced by the time of exposure of the gypsum specimen to the flowing water.

A constant head experimental setup was used to study the effects of gypsum dissolution. The setup was first calibrated to determine the flow rate of water into the gypsum specimen. Equations relating concentration and conductivity were derived. The calibration charts obtained were in agreement with those suggested by Richards (1954).

The results of the solubility experiments performed in this study were compared to those by Klimchouk (1996). Klimchouk (1996) performed experiments using distilled water at a temperature of about 200 °C, and the solubility of gypsum obtained was 2.531 g/L. The experimental values obtained in this study were about 2.9 g/L for a fully saturated specimen, and hence both results are comparable. Differences in the results may be caused by, amongst other factors, the different experimental conditions.

The results show that at early times of gypsum dissolution, a sharp decline occurs before an almost constant dissolution rate with time is achieved. In general, during the early times, very little gypsum dissolution occurs, and the gypsum dissolution hazard to surface and subsurface infrastructure is low. With time, gypsum dissolution occurs, and the concentration of gypsum in the percolating water gradually increases. As this occurs, surface subsidence and the hazard of gypsum dissolution to surface and subsurface infrastructure may increase. Subsidence and collapse may therefore occur over the course of time.

These results are similar to observations made by Thompson et al. (1998), who suggest that collapse may occur either abruptly when the water flow rate is high, or over the course of time when the water flow rate is low.

The ambitious Abu Dhabi 2030 Vision calls for an aggressive development plan that includes surface and subsurface transportation networks and other critical infrastructure systems. Certain areas of Abu Dhabi where gypsum is naturally occurring are susceptible to gypsum dissolution (subsidence and collapse). The results of the experiments performed in this work represent a necessary step in the preparation and validation of gypsum dissolution hazard maps. These hazard maps can then be used by urban planners and policy makers as decision aids for better and safer land use planning.

6.2 Recommendations

The work presented in this paper is a necessary first step in understanding gypsum dissolution processes particularly for naturally occurring gypsum in Greater Abu Dhabi. Further sets of experiments are being performed to better understand the dissolution processes. These experiments include but are not limited to:

1. Using the actual Abu Dhabi in situ natural gypsum to perform experiments.
2. Additional experiments with the same conditions (initial and boundary) as performed in this thesis to be able to obtain an experimental sample of results. That is a repetition of the same experiments to obtain several results rather than relying on the results of a single experiment.
3. Additional experiments under different (more field representative of Abu Dhabi) conditions, for example, different initial concentrations.
4. Prolonged exposure of specimens to percolating water at various temperature and saline conditions.
5. The introduction of ions into the percolating water through the gypsum specimen, from which the pairing effect is monitored and analyzed to determine how it enhances or impedes gypsum dissolution.
6. Perform experiments under stress conditions that replicate the in situ stresses gypsum is subjected to (Triaxial).

The ultimate aim is to better understand the gypsum dissolution process to derive gypsum hazard maps for Abu Dhabi. Masdar and Zayed Cities were chosen for the preliminary hazard mapping. For Zayed City, data obtained from the Spatial Data Division of Abu Dhabi municipality was used. On the other hand, data obtained from Sharp (2010) was used for the study of Masdar City. Figure 10 shows the

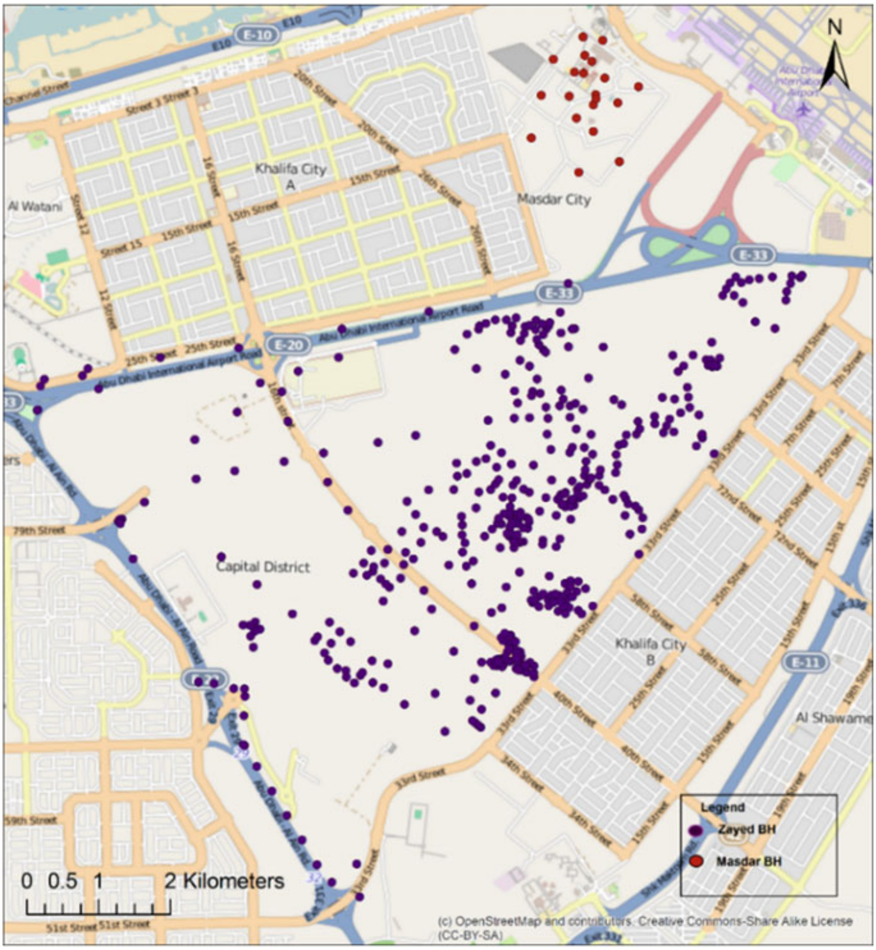

Fig. 10 Borehole logs for Masdar and Zayed Cities (Kaabi et al. 2015)

boreholes considered for this preliminary study, whereas Figs. 11 and 12 show initial results of how gypsum occurs in the two cities. A full understanding of the sampled cities will lead to the development of a hazard map for the whole Emirate of Abu Dhabi.

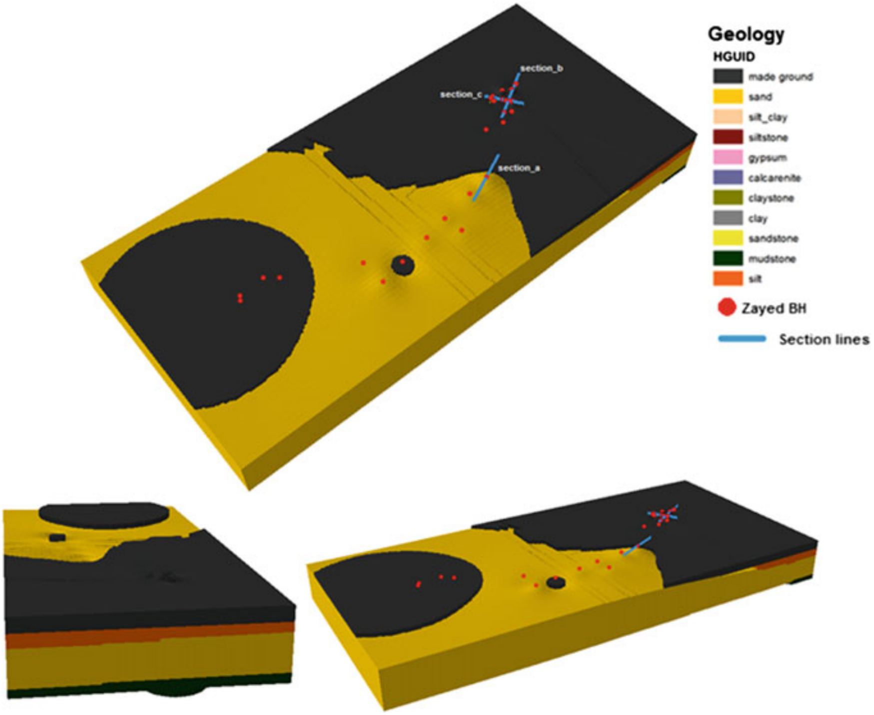

Fig. 11 Preliminary 3D geological model for Zayed City (Kaabi et al. 2015)

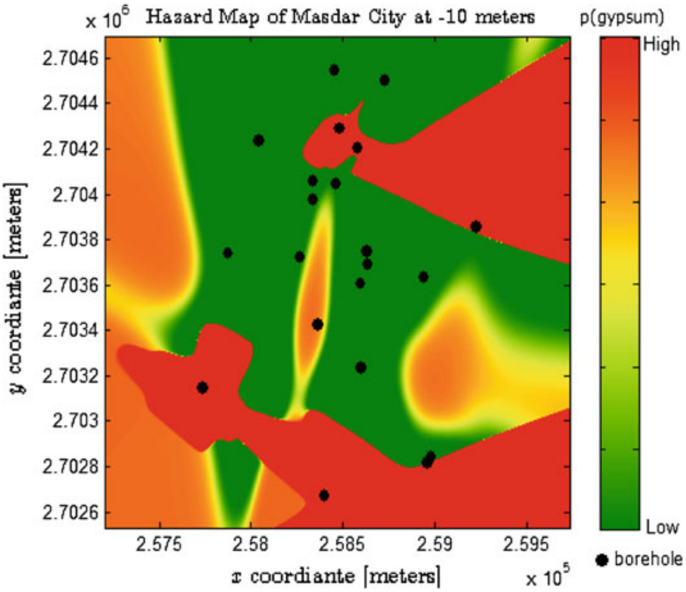

Fig. 12 Masdar City hazard map at $Z = 10$ m (Abdulla et al. 2015)

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