Predicting Weathering Characteristics of Carbonate Rocks Under Different Geo-Environmental Conditions

Hasan Arman 1, Saber Hussein 1, Haneen Edhar Y Abouhaligah 1, Malaz Osman 1, Moza A Baloch 1, Diab Bakri Abdelrahman Hag 1, Hamdan Abdo Ali Algaishi 1

1 United Arab Emirates University, College of Science, Geology Department, P.O. Box: 15551, Al Ain, United Arab Emirates

hasan.arman@gmail.com

Abstract. Rock moisture content, temperature and physical and chemical conditions of water in the rock mass vary under different geoenvironmental conditions. These factors are critical in the mechanical and chemical disintegration of rocks with time. Changes in weathering characteristics of a rock mass correlate with major changes in shear strength and deformability of rocks. Therefore, durability is an important parameter for rocks and weathered rocks in predicting and assessing long term problems in their use for engineering purposes. Carbonate rocks are generally considered as durable strong rocks. It is important to test this claim in the UAE, where carbonate rocks are the main available rock materials in many locations e.g. in Al Ain city. The slake durability index (SDI), with tests involving several cycles of wetting and drying, is widely recognized and has been used to measure the durability of weathered rocks. Carbonate rocks in the Jabel Hafit mountain, Al Ain region, have highly fractured and cavernous surface and near surface structures. In this study, degradability of samples from three different carbonate sequences: the Rus, Dammam, and Asmari Formations, were studied petrographically, mineralogically and texturally before and after slaking. A number of slaking tests were performed on twenty-one rock samples, seven from each rock formation, in order to investigate the effect of various geoenvironmental conditions on carbonate rocks weatherability at various pH levels 2, 4, 6, 8, 10, 12 and 14. Detailed mineralogical examinations, rock thin sections, Scanning Electronic Microscope (SEM) and X-ray diffractometry (XRD) were employed to reveal the relationship between mineralogy and weathering characteristics of rocks on the representative rock samples, before and after the slake durability tests. Furthermore, the index properties of all samples such as unit weights (dry, \( \gamma_d \) and saturated, \( \gamma_{sat} \)), the water absorption (\( w_a \)), the porosity (\( n \)), void ratio (\( e \)) and the specific gravities (\( G_{s,(OD)} \), \( G_{s,(SSD)} \), \( G_{s,(A)} \)) were measured. The study reveals that the weathering characteristics of carbonate rocks under different geoenvironmental conditions is strongly controlled by the mineralogical composition and textural features of the rocks. The impact of slaking fluid in the degradability of limestone is very limited due to chemical reaction of \( \text{CaCO}_3 \) especially in lower pH level acidic fluid, which reduced the bonding strength between grains. The findings will certainly help to resolve durability problems associated with engineering applications such as tunnels, slope stability, and etc. in the region and elsewhere.

1. Introduction

Rock mass durability assessment under different geoenvironmental conditions is an essential task to assure safety and sustainability of constructions. The slake durability index (SDI), particularly for weak rocks, has been successfully used over many years to estimate rock degradability. Due to various
chemical and mechanical deteriorations, rocks begin to degrade and their degradability is thought to be controlled by mineralogical composition and the textural features of rocks [1-9].

The nondurable behaviour of the rocks comes from the long and short term influences of chemical and mechanical deteriorations [10, 11]. It is therefore necessary assess the weathering processes and slaking property of rocks. It is also highly important to examine the mineralogical and textural properties of the rocks, in order to clarify their influence on rock durability under different geoenvironmental conditions. Furthermore, the slake durability may also be influenced by rock alteration associated with weathering, diagenesis and hydrothermal processes on the geological scale [12].

The slake durability test plays an important role in the development of various durability classifications for different type of rocks [10, 13, 14]. All previous durability classifications have been based on the second cycle slake durability index (I2). However, some researchers emphasize that the two-cycle slake durability test does not yield an acceptable durability of rocks [15-17, 6, 18]. For example, Idress et al. (2012) performed ten-cycle slake durability index tests on limestone and noted that a considerable decrease in the slake durability index as the number of wetting and drying cycles increased. These cycles induce dissolution, recrystallization and lead to the deterioration of this rocks [18].

Arman et al. (2016) reported inconsistent behaviour of the slake durability of limestones collected from one region [19]. This could be due to the slow water absorption of the calcareous walls of the microfossils, preserved in the chalky limestone, and low porosity of chalky limestone itself during interaction of the slaking fluid. The study on Al Masjid Al-Haram marble provided good durability characteristics based on regression coefficients and can be readily used for construction projects. The derived empirical equations can also be used for estimating durability of similar rock types [20]. Yagiz (2018) stated that no correlation was found between the slake durability of carbonate rocks and the pH of the testing liquid, which was prepared as either acidic or basic [21]. He further found that density, porosity and texture of rocks had a notable impact on degradability of rock, and that fine grained rocks are more susceptible to degradation than coarse grained rocks.

The aim of this study is to estimate the degradability of carbonate rocks sampled from the Rus, Dammam and Asmari Formations, due to the processes of mechanical and chemical breakdown, which are closely related to mineralogical composition and the texture of rocks. Mineralogical examinations such as thin sections, Scanning Electronic Microscope (SEM) and X-ray diffractometry (XRD), and comprehensive slake durability tests were carried out on twenty-one rock samples, seven from each carbonate formation, to examine the effects of different geoenvironmental conditions on carbonate rock degradability at various pH levels; 2, 4, 6, 8, 10, 12 and 14 and to understand the relationship between mineralogy, texture and degradability of rocks. The area selected for study is Jebel Hafit mountain, south of Al Ain. This mountain is 29 km long, 3.5 km width and has maximum elevation about 1240 m above sea level, and is almost entirely composed of carbonate rocks of the Rus, Dammam and Asmari Formations (Figure. 1).

2. Study area, geological settings and rock units

Al Ain city is one of the most rapidly urbanized cities in the UAE [22] (Figure 1). Ongoing development of the city has encountered a range of geo-engineering problems, including slope instability, rock falls, karstic cavitation and caving, etc. [23, 24].

The main structure in the study area is the Jabal Hafit anticline, a large doubly plunging highly asymmetric anticline that formed above two large thrust faults underlying its eastern and western limbs. The beds on the eastern limb dip steeply (70 – 90°) toward the NE, whereas those on the western limb dip gently (20 – 30°) toward the SW (Figure. 2). Faults and fractures generally trending between NW–
SE and east–west (approximately orthogonal to the fold hinge), in addition to a subordinate NE–SW trend [25]. Some of these brittle structures are thought to have been rejuvenated 25 – 15 Ma ago [26–28].

Jabal Hafit exposes a sequence of Tertiary carbonates that includes three main rock units (Figure 1). The oldest unit is the Rus Formation (Early Eocene; 55 – 49 Ma). The overlying rock unit is the Dammam Formation (Middle to Late Eocene; 49 – 34 Ma). The youngest rock unit in the sequence is the Asmari Formation (Early Oligocene; 34 – 29 Ma), [22, 29-31].

Figure 1. Study areas and geological settings (red dots indicate sampling location).

3. Materials and methods
Representative limestone rock samples were collected from fresh outcrops of the study areas (Figure. 1). For Rus, Dammam and Asmari Formations, seven samples of limestone were analysed. Each sample location is marked in green in Figure 1.

Approximately equant blocks (0.3 m in each dimension) of 21 rock samples were collected from outcrops. Each sample was careful inspected to ensure it was free of visible fractures, veins and any inhomogeneities in texture and colour. Samples were taken, keeping in mind the need to obtain a fully representative set covering the variations in limestone rock types for the Rus, Dammam and Asmari Formations. Before slake durability tests, mineralogical, textural and physical properties of each samples were determined based on the standard testing procedures. These include dry and saturated densities ($\gamma_d$
and $\gamma_{sat}$), the water absorption ($w_a$), the porosity ($n$), the void ratio ($e$) and the specific gravities ($G_{s,OD}$, $G_{s,SSD}$, $G_{s,A}$) of the samples (Table 1). To investigate the possible effects of slaking fluids on rock samples, before and after slake durability tests, rock composition and textural features were examined using an optical microscope, XRD and SEM on selected samples. To assess the effects of various geoenvironmental conditions on limestone durability, slaking fluids of different pH levels 2, 4, 6, 8, 10, 12 and 14 were prepared by adding appropriate amount of $HCl$ (for acidic solutions) and $NaOH$ (for basic solutions) in distilled water.

4. Petrographic properties
The engineering properties of rocks are greatly affected by the mineral constituents and grain textures, such as crystal interlocking, crystal shape and size, surface roughness, crystal area and crystal perimeter length. Before and after slake durability tests, the mineral composition of samples was carefully studied in thin sections using a polarizing microscope. Lithological nomenclature for the limestones is based on the Dunham and Folk classification (Fig. 2a-f) [32, 33].

![Photomicrographs of limestone thin sections](image)

**Figure 2.** Photomicrographs of limestone thin sections showing (a-b) fine-grained limestone (Rus Formation) before and after slaking tests (c-d) Foraminifer limestone (Dammam Formation) before and after slaking test (e-f) Oolitic limestone (Asmari Formation) before and after slaking test.

The Rus Formation sample in Figure 2a is a foraminiferal biomicrite. It contains a few microfractures filled with calcite. Following exposure to fluids with different pH levels, the same sample is now a very fine grained limy mudstone with very low permeability (Figure 2b). The Dammam Formation biosparite shown in Figure 2c shows coarse crystalline calcite grains filling the spaces between the skeletal grains. This pore filling may slightly reduce the rock permeability. After the durability test, the fractures appear slightly different (Figure 2d). The Asmari Formation shown in Fig. 2e is an oosparite, mainly consisting
of ooids set in carbonate cement. There are large voids indicating high permeability and porosity. It shows deposition of calcite crystals in open fractures. The cementing carbonate is derived from the dissolution of skeletal grains (Figure 2e). After the durability test, the sample shows no evident petrographic changes (Figure 2f).

X-ray diffraction (XRD) is a versatile, non-destructive analytical technique for identification and quantitative determination of crystalline compounds. XRD analyses were carried out on rock powder samples prepared from Rus, Dammam and Asmari Formation limestones, before and after slake durability tests (Figure 3a-f). The analyses on Rus Formation, Dammam and Asmari Formations before the slaking tests show that they are nearly pure calcite aggregates with 97%, 99% and 98% CaCO₃, respectively. The Rus Formation limestone has 2% dolomite (CaMg(CO₃)₃) as a minor component and 1% quartz (SiO₂) (Figure 4b). 1% of dolomite (CaMg(CO₃)₃) and other trace impurities are identified in Dammam Formation limestone. 2% gypsum (CaSO₄·2H₂O) and quartz (SiO₂) are the minor components in the Asmari Formation limestone (Figure 3e). On the other hand, the XRD on samples after slaking tests point to minor changes in proportions of these components, amounting to about 1-2% increase or decrease. This could be due to the interaction between the elements and slaking fluids, the dissolution of the element into the slaking fluid and sample characterization.

A Scanning Electron Microscope (SEM) can provide information about the surface ultramicrotopography and composition of samples. Figure 4 shows SEM images of texture of the limestone samples from Rus, Dammam and Asmari Formations, before and after the slake durability

**Figure 3.** XRD analyses of the samples before and after slake durability tests: Rus Formation (a,b), Dammam Formation (c,d) and Asmari Formation (e,f).
tests. The main features shown in the SEM images of unslaked limestone are pores filled with clay minerals, while after slaking the main feature is an open porosity in some areas. The samples before slaking are more compact and less porous in texture, compare with slaked samples, since some clay minerals dissolve during the slake durability test. Figures 4a and c shows packstone with small intercrystalline pores and less authigenic quartz distributed between the micritic calcite. Figures 4d and f display wackstone with a well-connected intercrystalline micropore network between calcite crystals.

![SEM images of limestone](image)

**Figure 4.** SEM images of limestone from the Rus Formation (a,b), Dammam Formation (c,d) and Asmari Formation (e,f) taken before and after slaking tests in each case.

5. **Rocks index properties**

The dry density ($\gamma_d$), the saturated density ($\gamma_{sat}$), the water absorption ($w_a$), the porosity ($n$) and the specific gravities ($G_{s,(OD)}, G_{s,(SSD)}, G_{s,(A)}$) were determined on the limestone samples, based on the standard testing procedures, BSI (British Standard Institute) and presented in Table 1. These are basic physical parameters of rocks. There are some variations among the data presented in Table 1. The water absorption and porosity indicates rather large differences between minimum and maximum values for the tested limestone, especially for Rus and Asmari Formations. This could be related to the tested sample nature, heterogeneity, in term of mineralogical and textural features. The other parameters show normal variations as expected.
Table 1. Index properties of different limestone (Rus, Dammam, and Asmari Formation) from Jabel Hafit.

| Rock type          | Sample no. | Density (ρ) (g/cm³) | Water absorption (w_o) | Porosity (n) | Void Ratio (e) | Specific gravity (G_i) (A) |
|--------------------|------------|---------------------|------------------------|--------------|----------------|----------------------------|
|                    | Dry (ρ_d)  | Saturated (ρ_s)     |                        |              |                |                            |
| Limestone (Dammam) | 1          | 2.45                | 2.51                   | 2.66         | 6.52           | 0.07                       | 2.54 | 2.61 | 2.73 |
|                    | 2          | 2.63                | 2.65                   | 0.6          | 1.59           | 0.02                       | 3.02 | 3.03 | 3.07 |
|                    | 3          | 2.67                | 2.7                    | 0.98         | 2.62           | 0.03                       | 2.48 | 2.54 |
|                    | 4          | 2.74                | 2.76                   | 0.73         | 2              | 0.02                       | 2.73 | 2.75 | 2.78 |
|                    | 5          | 2.66                | 2.69                   | 1.16         | 3.1            | 0.03                       | 2.48 | 2.51 | 2.56 |
|                    | 6          | 2.68                | 2.73                   | 1.78         | 4.76           | 0.05                       | 2.37 | 2.41 | 2.48 |
|                    | 7          | 2.63                | 2.65                   | 0.87         | 2.27           | 0.02                       | 2.66 | 2.68 | 2.72 |
| Min                |            | 2.45                | 2.51                   | 1.59         | 0.02           |                            | 2.37 | 2.41 | 2.48 |
| Max                |            | 2.74                | 2.76                   | 6.52         | 0.07           |                            | 3.02 | 3.03 | 3.07 |
| Mean               |            | 2.63                | 2.66                   | 1.34         | 3.44           | 0.04                       | 2.63 | 2.66 | 2.71 |
| Limestone (Rus)    | 1          | 2.47                | 2.52                   | 2.20         | 5.43           | 0.06                       | 2.54 | 2.60 | 2.69 |
|                    | 2          | 2.61                | 2.75                   | 5.48         | 14.29          | 0.17                       | 2.17 | 2.29 | 2.46 |
|                    | 3          | 2.53                | 2.59                   | 2.32         | 5.87           | 0.06                       | 2.23 | 2.28 | 2.35 |
|                    | 4          | 2.50                | 2.52                   | 0.82         | 2.05           | 0.02                       | 2.57 | 2.59 | 2.63 |
|                    | 5          | 2.28                | 2.38                   | 4.49         | 10.20          | 0.11                       | 2.33 | 2.44 | 2.61 |
|                    | 6          | 2.36                | 2.42                   | 2.47         | 5.83           | 0.06                       | 2.39 | 2.45 | 2.54 |
|                    | 7          | 2.51                | 2.55                   | 1.21         | 3.04           | 0.03                       | 2.33 | 2.35 | 2.39 |
| Min                |            | 2.28                | 2.38                   | 0.82         | 2.05           | 0.02                       | 2.17 | 2.28 | 2.35 |
| Max                |            | 2.61                | 2.75                   | 5.48         | 14.29          | 0.17                       | 2.57 | 2.67 | 2.69 |
| Mean               |            | 2.46                | 2.54                   | 2.81         | 7.01           | 0.08                       | 2.37 | 2.43 | 2.52 |
| Limestone (Asmari) | 1          | 2.27                | 2.37                   | 4.14         | 9.4            | 0.1                        | 2.07 | 2.15 | 2.26 |
|                    | 2          | 2.2                 | 2.3                    | 4.35         | 9.58           | 0.11                       | 2.2  | 2.3  | 2.44 |
|                    | 3          | 2.26                | 2.36                   | 4.34         | 9.8            | 0.11                       | 2.25 | 2.34 | 2.49 |
|                    | 4          | 2.28                | 2.4                    | 5.11         | 11.67          | 0.13                       | 2.05 | 2.16 | 2.29 |
|                    | 5          | 1.86                | 2.02                   | 8.54         | 15.89          | 0.19                       | 1.87 | 2.03 | 2.22 |
|                    | 6          | 2.16                | 2.26                   | 4.34         | 9.38           | 0.1                        | 2.17 | 2.26 | 2.39 |
|                    | 7          | 2.23                | 2.31                   | 3.96         | 8.8            | 0.1                        | 2.25 | 2.34 | 2.47 |
| Min                |            | 1.86                | 2.02                   | 3.96         | 8.8            | 0.1                        | 1.87 | 2.03 | 2.22 |
| Max                |            | 2.28                | 2.4                    | 8.54         | 15.89          | 0.19                       | 2.25 | 2.34 | 2.49 |
| Mean               |            | 2.16                | 2.27                   | 5.25         | 11.02          | 0.13                       | 2.11 | 2.22 | 2.36 |

6. Slake durability test
Franklin and Chandra (1972) proposed the slake durability test to predict the potential deterioration of rocks under wet condition [1]. This test is the most commonly used and reliable one and is recommended by the International Society of Rock Mechanics [34] and the American Society for Testing and Materials [35]. Various durability classifications such as those by Gamble (1971), Franklin and Chandra (1972), Franklin (1983), Johnson and DeGraff (1988) were developed based on the tests [1, 10, 36, 37]. Most previous researchers have assessed the durability of rocks based the L_2, although, for clay-bearing rocks particularly, other investigators, e.g. Taylor, 1988, Bell et al., 1997 were of the opinion that the two-cycle slake durability testing did not provide an acceptable indication of the durability [6, 38, 39]. Some clay minerals expand with hydration and cause double layer repulsion force and negative pore pressure.
in slaking mechanisms. In these rocks more water carrying dissolved ions enters through the open structure leading to expansion and destruction of the crystal lattice [40].

In this study, to assess the effects of various geoenvironmental conditions on the three different sets of carbonate rocks (from Rus, Dammam and Asmari Formations) under various pH levels 2, 4, 6, 8, 10, 12 and 14, the slake durability test was carried out on the representative samples from each set (Figure 5).

![Figure 5](image)

Figure 5. Tested rock lumps after first (a,c) and second cycle (d,f) at pH = 2.

7. Results and discussions

Most of samples indicate a consistent pattern between SDI and the slake fluid at different pH levels. However, there are variations for different types of limestone at different pH level. This may be related to the nature of the rocks such as fractures, types of filling materials, interior cavities, etc. There is a decreasing trend of slake durability index with increasing pH levels, from acidic to alkali environment. For higher amount of slaking at lower pH the SDI variations appear to be due to different proportions of calcite and dolomite. CaCO₃ is main source of calcite and dolomite and it is highly affected by an acidic geoenvironmental condition (see Figure 6a-g). Singh et al. (2006) showed that the dissolution of CaCO₃ is quick while the acid attacks the free charged particles that generally binds the CO₃ [41].

Thin sections and the SEM studies prove that some partial influence of slaking fluid has been recognized on samples tested in different pH levels due to the components and textures of the sample, such as filling materials, porosity, permeability and etc. and interaction with the slaking fluid. The XRD results show that all samples are nearly pure calcite with some minor and trace components, and there is no remarkable change in crystallinity of limestone samples, either slaked or non-slaked.
Figure 6. The results of the first and second cycle slake durability tests ($I_{d1}$ and $I_{d2}$) carried out on seven samples of limestone from Rus, Dammam and Asmari Formations.
Based on the durability classification (Franklin and Chandra, 1972), all of the studied limestone samples are classified in very high and extremely high categories after two cycles (I\textsubscript{d1} and I\textsubscript{d2}). Among the three different types of limestone, Asmari Formation, sample 5, has the lowest SDI (94.91%) at 2 pH level after the second cycle (I\textsubscript{d2}) (Figure 6e). This could be related to high values in water absorption (w\textsubscript{a}), porosity (n) and void ratio (e) compared to the other samples (Table 1). In some cases, the slake durability index at pH level of 6, 10 and 14 was recorded as 100% after the first cycle (I\textsubscript{d1}) for both Rus and Dammam Formation (Figure 6a, b, c, e and g). This confirms that the SDIs (I\textsubscript{d1} and I\textsubscript{d2}) for limestone tested under various pH levels (acidic and alkali environment) are mainly controlled by mineralogical composition and texture of rocks, rather than slaking fluid.

The relationship between mean slake durability index, I\textsubscript{d1} and I\textsubscript{d2} and various pH levels for three different limestone sets is shown in Figure 8. The mean slake durability index of limestone from the Dammam and Rus Formation are very close to each other and all of them, including some limestone from the Asmari Formation, exhibit extremely high durability (Figure 7). However, other limestone samples from the Asmari Formation have the lowest durability (Figure 7). This could be due to its high index properties of water absorption (w\textsubscript{a}), porosity (n) and void ratio (e) compared to the other two limestones (Table 1) apart from limited effects of especially acidic environment, low pH level, on CaCO\textsubscript{3} which is the main component of dolomite and calcite. Hence, this may show that textural features of rocks have a higher role to regulate the degradability of these rocks than the different pH levels.

![Figure 7](image.png)

**Figure 7.** The relationship between the mean slake durability index, I\textsubscript{d1} and I\textsubscript{d2} and pH.

8. Conclusions

This study was mainly focused on the degradability of limestone from Asmari, Rus and Dammam Formations under different pH levels of 2, 4, 6, 8, 10, 12 and 14. The results clearly indicate that the degradability of rocks is highly controlled by mineralogical composition and textural features of limestone. On the other hand, the impact of slaking fluid in the degradability of limestone is very limited due to chemical reaction of CaCO\textsubscript{3} with especially lower pH level acidic fluid, which reduce the bonding strength between grains.

Through knowing and correctly estimating the degradability behavior of carbonate rocks under various geoenvironmental conditions, acidic and alkali, through detailed laboratory studies, vital information for engineering and environmental projects in the targeted area will certainly be provided. The information will also minimize unnecessary survey for stability problems, reduce costs associated with any kind of engineering applications, mitigate any possible causality and reduce loss of property today and in the future.
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References
[1] J. A. Franklin, and A. Chandra, “The slake-durability test,” International Journal of Rock Mechanics and Mining Sciences, 9, pp. 325–341, 1972.
[2] J. G. Rodrigues, “Physical characterization and assessment of rock durability through index properties,” NATO ASI Ser. Ed. Applied Sciences, 200, 7-34, 1991.
[3] V. Moon, “Microstructural controls on geomechanical behaviour of ignimbrite,” Engineering Geology, 35, pp. 7-34, 1993.
[4] Z. Papadopoulos, E. Kolaiti, and N. Mourtzas, “The effects of crystal size on geotechnical properties of Neogene gypsum in Cret,” Quarterly Journal of Engineering Geology, 27, pp. 267–273, 1994.
[5] J. C. Dick, and A. Shakoor, “Characterization durability of mud rocks for slope stability purposes,” Geological Society of America, Review in Engineering Geology, 65, pp. 31–45, 1995.
[6] C. Gokceoglu, R. Ulusay, and H. Sonmez, “Factor effecting the durability of selected weak and clay bearing rocks from Turkey, with particular emphasis on the influence of the number of drying and wetting cycles,” Engineering Geology, 57, pp. 215–237, 2000.
[7] I. Yilmaz, and E. Karacan, “Slake durability and its effect on the doline formation in the gypsum,” Environmental Geology, 47, pp. 1010-1016, 2005.
[8] E. Kolay, and K. Kayabali, “Investigation of effect of aggregate shape and roughness on the slake durability index using the fractal dimension approach,” Engineering Geology, 86, pp. 271–284, 2006.
[9] V. Grupta, and I. Ahmed, “The effect of pH of water and mineralogical properties on the slake durability (degradability) of different rocks from the Lesser Himalaya, India,” Engineering Geology, 95, pp. 79–94, 2007.
[10] R. B. Johnson, and J. V. DeGraff, Principles of Engineering Geology. Wiley, New York, 497 pp., 1988.
[11] H. Cetin, H. Laman, and A. Ertunc, “Settlement and slaking problems in the world’s fourth largest rock-fill dam, the Ataturk Dam, in Turkey,” Engineering Geology, 56 (3–4), pp. 225–242, 2000.
[12] G. Dhakal, T., Yoneda, M. Kato, and K. Kaneko, “Slake durability and mineral properties of some pyroclastic and sedimentary rocks,” Engineering Geology, 65, pp. 31–45, 2002.
[13] J. C. Dick, and A. Shakoor, “Lithological controls of mud rock durability,” Quarterly Journal of Engineering Geology, 25, pp. 31–46, 1992.
[14] F. G. Bell, D. C. Entwisle, and M. G. “Culshaw, A geotechnical survey of some British coal measures mudstones, with particular emphasis on durability,” Engineering Geology, 46, pp. 115–129, 1997.
[15] R. K. Taylor, “Coal Measures mud rocks: composition, classification and weathering processes,” Quarterly Journal of Engineering Geology, 21, pp. 85–99, 1988.
[16] R. Ulusay, F. Arikan, M. F. Yoleri, and D. Caglan, “Engineering geological characterization of coal mine waste material and an evaluation in the context of back-analysis of spoil pile instabilities in a strip mine SW Turkey,” Engineering Geology, 40, 77–101, 1995.
[17] V. G. Moon, and A. G. Beattie, “Textural and microstructural influences on the durability of Waikato coal measures mud rocks,” Quarterly Journal of Engineering Geology, 28, pp. 303–312, 1995.
[18] S. Idress, A. Khattab, and H. M. S. Othman, “Durability of limestone used in building,” Al-
Rafidain Engineering, 21, pp. 1-14, 2012.

[19] H. Arman, M. El Tokhi, O. Abdelghany, B. Mahmoud, and M. Abu Saima, “Slake durability test on Lower Oligocene limestones from Al Ain City, United Arab Emirates,” Journal of Earth Science and Climate Change, 7 (6), pp. 1-4, 2016.

[20] A. Abd El Aal, and S. Kahraman, “Estimating of durability aspects of Al Masjid Al-Haram marble, Makkah city, Saudi Arabia,” Geotechnical and Geological Engineering, 35 (6), pp. 2763-2779, 2017.

[21] S. Yagiz, “The effect of pH of the testing liquid on the degradability of carbonate rocks,” Geotechnical and Geological Engineering, First Online, January 23, 2018.

[22] H. Arman, W. Hashem, O. Abdelghany, and A. Aldahan, “On the accuracy of the in situ Schmidt hammer tests on carbonate rocks,” In: Kwasniewski, M. & Lydzba, D. (eds) Proceedings of Eurock 2013 – Rock Mechanics for Resources, Energy and Environment – The 2013 ISRM International Symposium, Wroclaw, Poland, 23–26 September, CRC Press/Balkema, Taylor & Francis Group, London, pp. 189–193, 2013a.

[23] W. Hashem, O, Abdelghany, A. El Saiy, A Murat, S. Hussein, A. Gabr, H. Baker, and Al Aldahan, “Structural and stratigraphic parameters as tools for the geozoning project of Al Ain city, UAE,” In: Proceedings of the Second International Conference on Engineering Geophysics, Al Ain, United Arab Emirates, 24–27 November, EG39, pp. 242–245, 2013.

[24] O. Abdelghany, M. Abu Saima, H. Arman, and A. Fowler, “Gysiferous bedrocks and soils of Abu Dhabi and their implications for engineering geozoning,” In: Proceedings of the Third International Conference on Engineering Geophysics, Al Ain, United Arab Emirates, 15–18 November, EG36, pp. 156–159, 2015.

[25] M. Sirat, I. S. Al-Aasm, S. Morad, A. Aldahan, O. Al-Jallad, A. Ceriani, D. Morad, H. Mansurbeg, and A. Al-Suwaidi, “Saddle dolomite and calcite cements as records of fluid flow during basin evolution: Paleogene carbonates, United Arab Emirates,” Marine and Petroleum Geology, 74, pp. 1–21, 2016.

[26] M. Warrak, “Origin of Hafit structure: implication for timing the Tertiary deformation in the northern Oman Mountains,” GeoArabia, 12, pp. 803-818, 1996.

[27] M. A. Noweir, “Back-thrust origin of the Hafit structure, northern Oman Mountains front, United Arab Emirates,” GeoArabia, 5, pp. 215-228, 2000.

[28] M. Styles, R. Ellison, S. Arkley, Q. G. Crowley, A. Farrant, K. M. Goodenough, J. McKervey, T. Pharaoh, E. Phillips, D. Schofield, R. J. Thomas, “The geology and geophysics of the United Arab Emirates,” Volume 2, Geology. Ministry of Energy, Abu Dhabi, 2016.

[29] H. Arman, W. Hashem, O. Abdelghany, and A. Aldahan, “Evaluation of laboratory Schmidt hammer tests on carbonate rocks,” In: Proceedings of the Second International Conference on Engineering Geophysics, Al Ain, United Arab Emirates, 24–27 November, EG37, pp. 234–237, 2013b.

[30] H. Arman, W. Hashem, E. M. Tokhi, O. Abdelghany, and E. A. Saiy, “Petrographical and geomechanical properties of the Lower Oligocene limestones from Al Ain City, United Arab Emirates,” Arabian Journal for Science and Engineering, 39(1), pp. 261-271, 2014.

[31] H. Arman, W. Hashem, O. Abdelghany, and A. Aldahan, “Effects of lithofacies and environment on in situ and laboratory Schmidt hammer tests: a case study of carbonate rocks,” Quarterly Journal of Engineering Geology and Hydrogeology, May 2017, Vol. 50, No: 2, pp. 179-186, doi:10.1144/qjegh2016-049, 2017.

[32] R. J. Dunham, “Classification of carbonate rocks according to depositional texture,” In: Ham, W. E. (ed.): Classification of carbonate rocks. AAPG Bulletin Memoir, 1, pp. 108-121, 1962.

[33] R. L. Folk, “Practical classification of limestone,” AAPG Bulletin, 43, pp. 1-38, 1959.

[34] ISRM, “ISRM suggested methods: rock characterization, testing and monitoring,” In: Brown, E.T. (Ed.), Pergamon Press, London. 211 pp, 1981.

[35] ASTM D4644-08, “Standard test method for slake durability of shales and similar rocks,” 1-4. 2008.
[36] J. C. Gamble, “Durability-plasticity classification of shales and other argillaceous rocks,” Ph. D. Dissertation, University of Illinois, 1971.

[37] J. A. Franklin, “Evaluation of shales for construction projects: An Ontario shale rating system,” Report RR 229, Research and Development Branch, Ministry of Transportation and Research, Toronto, 1983.

[38] R. K. Taylor, “Coal measures mud rocks: composition, classification and weathering processes,” Quarterly Journal of Engineering Geology, 21, pp. 85–99, 1988.

[39] F. G. Bell, D. C. Entwisle, and M. G. Culshaw, “A geotechnical survey of some British coal measures mudstones, with particular emphasis on durability,” Engineering Geology, 46, pp. 115–129, 1997.

[40] E.C. Koncagul, and P.M. Santi, “Predicting the unconfined compressive strength of the Breathitt shale using slake durability, Shore hardness and rock structural properties,” International Journal of Rock mechanics and Mining Sciences, 36, 139–153, 1999.

[41] T. N. Singh, P. K. Sharma, and M. Khandelwal, “Effect of pH on the Physico-mechanical properties of marble,” Bulletin of Engineering Geology and the Environment, 66 (1), 81–87, 2006.