JGeope ***6*** *(1), 2016, PP. 35-43*

Prediction of long-term slake durability of clay-bearing rocks

Mojtaba Heidari*, Behrouz Rafiei, Yazdan Mohebi, Vahid Rastegarian
Geology Department, Bu-Ali Sina University, Hamadan, Iran
**Corresponding author, e-mail: heidari _enggeol@yahoo.com*
(*received: 04/09/2014 ; accepted: 29/02/2016*)

Abstract

A research program was conducted on different clay-bearing rocks selected from the Ilam, Sarpol-e Zahab and Tajarak regions (Iran) to predict their slaking characteristics. The new durability apparatus (nested mesh drums) separates disintegrated particles varying from > 25.4 to < 2 mm as the drums were rotated. On the basis of the particle size distribution, the disintegration ratio (DR) was used to evaluate the rock durability. A concept was proposed to describe the rock slaking characteristics under the slake durability test cycles, by using the difference in the DR values between the adjacent (ΔDR) and backward (N^*) cycles. This allows the estimation of the rock durability as it is subjected to a larger number of test cycles, and hence the prediction of the effects of weathering processes. This prediction provides an effective approach when data are limited or inaccessible. Therefore, a new classification system is introduced for rock durability assessment. The test results show that the Gurpi-limey marls (G-2, G-3) and the Pabdeh-marly limestone (P-3) are classified as moderate to high durability rocks.

Keywords: *Clay-Bearing Rocks, Disintegration Ratio, Durability, Slaking.*

Introduction

One of the main problems in construction on clay-bearing rocks is their susceptibility to slaking or weathering upon exposure. Weathering can induce a a rapid change from an initial rock material to a soil-like one. A variety of engineering tests are employed to accurately predict the weathering behavior of rock over time and under certain climatic conditions. Most tests are designed to accelerate the normal physical weathering response of rocks under controlled laboratory conditions. The The best-known weathering test for clay-bearing rocks is the slake durability test (Francklin and Chandra, 1972). The durability behavior of these rocks is responsible for slope stability problems due to rapid slope degradation by the loss of strength of the surface material, unexpected additional settlements, and failures of embankments, long-term term loss of intact strength affecting the stability of underground openings, etc. (Hornig, 2010; Frydman Frydman *et al*., 2007; Gokceoglu *et al*., 2000; Johnston and Novello, 1994; Anagnostopoulos *et al*., 1991; Fookes *et al*., 1988; Olivier, 1979). Several investigators have attempted to correlate the durability index results of rocks with the state of weathering (Robinson and Williams, 1994; Koncagul and Santi, 1999; Oguchi and Matsukura, 1999; Oyama and Chigira, 1999; Gokceoglu *et al*., 2000; Gupta and Seshagiri, 2000; Fang and Harrison, 2001; Dhakal *et al*., 2002; Tugrul, 2004; Phienwej and Singh, 2005). The ISRM (1979) and the American Society for Testing and Materials (ASTM, 2004) suggest using the second cycle slake durability results for determining the slake durability index. During the slake durability test, conducted in accordance with ASTM procedure D-4644 (ASTM, 2004), the portion of sample retained inside the 2 mm mesh drum consists of slaked fragments of varying dimensions. The spread breakdown of the initial rock lumps during sieving in the standard tests cannot be avoided, and for the evaluation of durability purposes, a single sieve cannot give a more satisfactory index. The study presented herein aimed to develop a new methodology for incorporating the slaking characteristics of a rock into the results of slake durability test.

In the present work, a new slake durability device with nested drums was suggested and the deterioration of different clay-bearing rocks selected from different parts of Iran were predicted. Also, based on test results obtained from the new apparatus, "Disintegration Ratio" (DR) as defined by Erguler and Shakoor (2009), was calculated. By using the difference in the DR values between the adjacent (ΔDR) and the backward (N^*) cycles, we were able to develop a quantitative classification. This research is part of a mission devoted to predicting the decrease in rock durability with time owing to the weathering processes. The main aim of the present study is to predict the durability of clay-bearing rocks. The research findings can be of use for the design and analysis of rock foundations and embankments; further, they can support systems for long-term mechanical stability.

Study area and sampling

A total of 70 block samples were selected from eleven different locations in Iran. These samples were selected on the basis of published lithologic descriptions and observations of durability behavior made during exploratory sampling trips. Figure 1 shows the locations of the collected samples from the Ilam Province (in the southwest of Iran), Sarpol-e Zahab and around the city of Saveh (in the west of Iran).

Three types of samples were obtained from the Qom formation (Oligomiocene), four types from the Pabdeh formation (Paleocene) and four type from the Gurpi formation (Cretaceous) in the west of Iran (Table 1).

The clayey marls of the Qom formations are green gray in color. For certain kinds of samples, especially those with higher clay content, sampling was difficult because of their weak nature and frequent fractures. The bedding planes observed in the marls are generally closely spaced with apertures ranging from 0 to 0.5 mm. Sampling was difficult from laminated marley samples (P-2, G-1, G-4), because of their weak nature and fractures. Compacted marley limestone (P-3) and thickly bedded limey marl (G-2, G-3) are grayish in color; they are thickly bedded and have a massive appearance and a high amount of carbonate. The sample number, description, lithology, geologic name, geologic age and site description of each rock rock sample is shown in Table 1.

Table 1. General information on rock samples

Formation	Sample number	Rock type	Number of blocks sampled
Qom (Oligo-Miocene)	S–1	Clayey Marl	7
	S–2	Clayey Marl	6
	S–3	Clayey Marl	5
Pabdeh (Paleocene)	P–1	Sandy Marl	7
	P–2	Marl	5
	P–3	Marley Limestone	6
	P–4	Sandy Limey Marl	7
Gurpi (Cretaceous)	G–1	Marl	7
	G–2	Limey Marl	6
	G-3	Limey Marl	6
	G-4	Marl	6

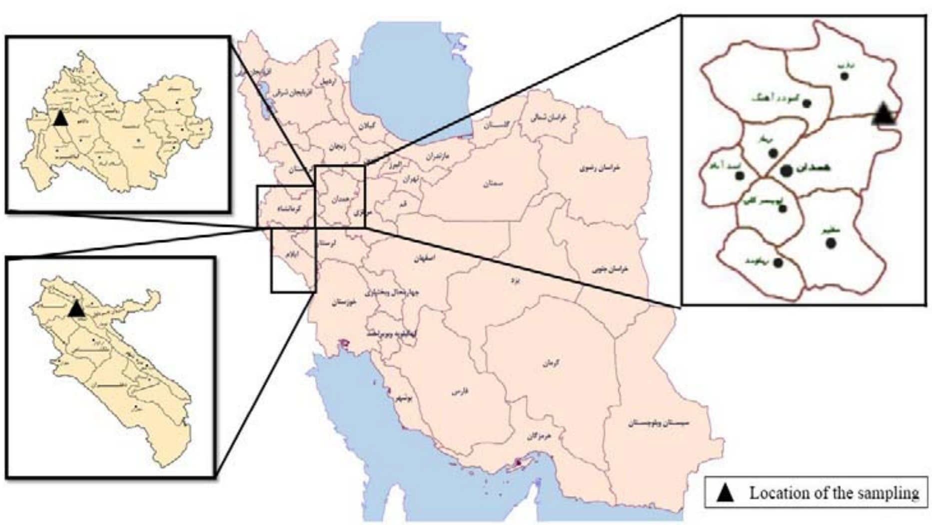

Figure 1. The samples location map

The block samples with approximate dimensions of 30 cm × 30 cm × 40 cm were extracted using a geologist's hammer and chisel from 1 m beneath the surface of exposures and from bench faces in open pit mines.

Test procedures

Certain physical and mechanical properties of rock samples such as dry density, porosity, water absorption, and Atterberg limits testing, have been performed in accordance with the standard procedures of the ASTM (1998). Point load index tests were conducted following the recommendations of ISRM (1985).The identity of clay minerals was determined using a Philips PW 1140 diffractometer with a Huber Model 631 photographic chamber (Cu kα radiation). Carbonate percentages of the samples were determined by a calcimetry test according to the ASTM standard (2004).

The durability test was conducted using a set of nested stainless steel drums of diameters 140, 180, 250, and 300 mm, which were constructed of woven-wire cloth of 25.4, 12.7, 6.35, and 2.0 mm mesh (innermost to outermost). Each cylindrical drum was 100 mm long. The main features of the trough and drum assembly are shown in Figure 2. The two end plates are rigid, with one being removable. Because the exterior of the meshes and the interior of the drums cannot be obstructed by supports, the strength of the assembly was provided by a trough that horizontally supports the drums, enabling the drums to rotate freely around a common axle and ensuring that the shape of the drums is retained during the test. The trough could be filled with water to a level of 170 mm below the axle, with a minimum clearance of 20 mm between the trough and the bottom of the last mesh. The drums were rotated by a motor capable of maintaining a speed of 20 rpm for a period of 10 min. A digital timer automatically stopped the motor after a preset time. A representative sample of 10 rock pieces was selected, with each lump weighing 40–60 g, to give a total sample weight of 450–550 g. Each lump was prepared to be roughly spherical in shape, with rounded corners. The samples were placed in clean drums and dried at 105°C for 2–6 h to a constant weight. The drums were then set to rotate for a preset time. Rotation of the drums sieved the rock lumps, separating them into size fractions; oversized grains were trapped above the drum screens, while undersized grains passed through the screens. Following the rotation period, the drums were extracted from the trough and the drum lids were removed. The retained rock samples were then dried to a constant weight at 105°C and weighed, and the weight of the retained pieces was recorded. The percentage retained was calculated for each drum by dividing the dry weight retained in each drum by the weight of the original dry samples. This separation of the samples into size fractions enables particle size distributions to be determined. After each wetting–drying cycle, the degree of disintegration was indicated by the distribution of the grain sizes.

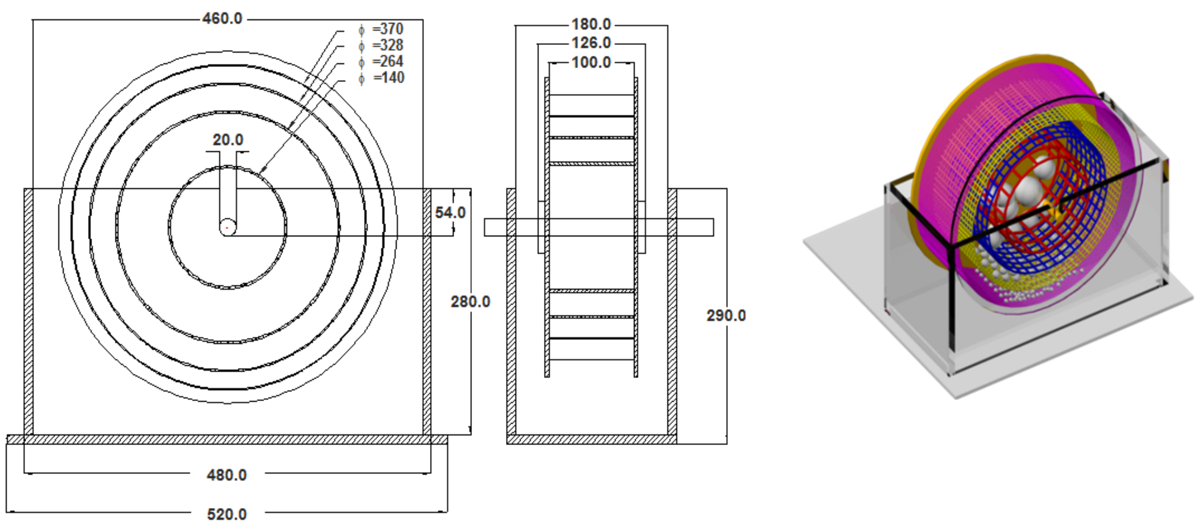

Figure 2. Nested mesh drum apparatus shown from the front (left), the side (center) and general view (right) Ø: Drums diameter (mm)

Tests results

The slake durability test results, percentage of carbonate minerals, water adsorption, dry density, and point load strength index are summarized in Table 2. The semi-quantitative estimates of the clay minerals were determined from the powder diffractograms following an external standard method developed by Gundogdu (1982). The calcium carbonate content ranged from 29% to 66.5%. High values of index durability from rock samples such as P-3 usually indicate calcareous rocks with high carbonate content. The rock samples showed low to medium plasticity. The liquid limit ranged from 20.1% to 39.2%, and the plasticity index ranged from 8.1% to 19%. The Pabdeh clayey limestone (P-3) showed the lowest water absorption. The S-3 sample had the highest water absorption. The density of the rock samples ranged from 2 to 2.67 g/cm^3. Sample S-3 showed the highest porosity (25.02%).

The slake durability test results listed in Table 3 show that the rock samples disintegrated into fragments of varying sizes after each cycle, a great number of which did not pass through the 2 mm mesh of the drum. Previous studies by Moon and Beattie (1995), Erguler (2007), and Erguler and Ulusay (2009) also showed that rock materials break into fragments of varying sizes during the second cycle of the slake durability test, and that the the fragments are much larger than the mesh of the drum. The large fragments that are retained in the drum are therefore classified as durable materials. The durability index (Id) calculated from five-cycle slake durability tests does not offer an acceptable measure of the durability of clay-bearing rocks. The standard test requires grain size analysis, which is a laborious procedure requiring a set of sieves, to describe the disintegration characteristics of the rocks after each of the five cycles. The authors believe that testing using a set of nested drums with mesh sizes of 25.4, 12.7, 6.35, and 2.0 mm provides a better indicator of the slake durability of rock samples. The modified test is an application of the method already introduced by Erguler and Shakoor (2009), who suggested that the DR should be used to define the grain size distributions, as follows:

$$DR = AC/AT \quad (1)$$

where AC is the area under the distribution curve for any fragment size and AT is the total area encompassing the range of fragment size distributions (Erguler & Shakoor, 2009). By calculating the area under the distribution curve for any grain size (AC) and the total area encompassing all grain size distribution curves (AT) of the samples tested, the DR can be determined after the selected number of wetting–drying cycles. An example of the calculation of this index after the fifth wetting– drying cycle is shown in Figure 3.

Figure 4 shows the calculated values of the DR index plotted against the number of wetting–drying cycles (N).

The DR distinguishes high-durability rocks from low-durability rocks. The index ranges from 0 to 1, with low values indicating less durable rock and high values indicating high durability. As we would expect, DR values decreased as the cycle number increased. It can be seen that the variation of the DR DR indices of the rock specimens decreased at different rates.

Table 2. Some physical and mechanical properties of the selected rock samples

SN	Is_{50}(MPa)	Id_2	$CaCO_3$ (%)	Clay (%)	PI	LL	n (%)	Iv (%)	γ_d (gr/cm^3)
S-1	1.61	94.06	27.0	41.3	9.3	27.5	16.43	13.96	2.48
S-2	1.12	95.53	42.0	38.7	13.3	30.5	12.45	10.57	2.47
S-3	1.60	85.92	29.0	49.4	18	39.2	25.02	17.68	2.45
P-1	2.25	97.50	52.0	26.9	10.2	23.6	6.83	4.32	2.54
P-2	1.92	85.87	55.0	39.7	9.3	24.5	6.59	8.59	2.63
P-3	3.12	99.35	65.0	26.5	8.1	20.1	5.50	3.11	2.67
P-4	2.83	98.40	58.0	38.8	11.8	24.6	3.17	5.46	2.61
G-1	1.72	93.82	31.0	38.9	14.7	30.8	13.10	11.45	2.47
G-2	2.08	98.87	55.0	29.6	12.8	25.4	7.91	3.76	2.56
G-3	2	99.17	66.5	25.3	8.5	20.7	2.5	3.55	2.33
G-4	0.45	76.63	47.16	34.6	19	37.5	15.85	7.05	2.00

SN: Sample Number, Is50: Point load index; Id2: Second slake durability index; PI: Plasticity index; LL: Liquid Limit; n: Porosity; Iv: Water absorption; γ_d: Dry density (gr/cm^3)

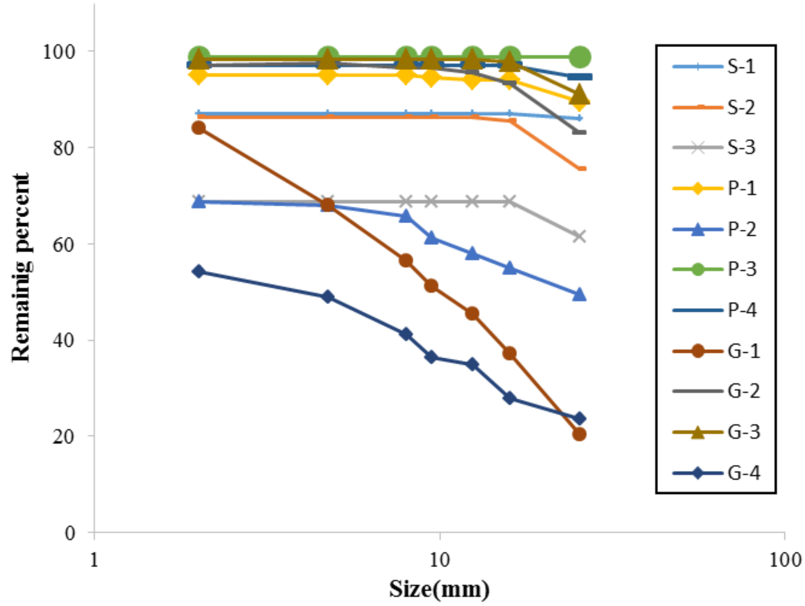

Figure 3. Grain size distribution curves for selected samples after fifth cycle test

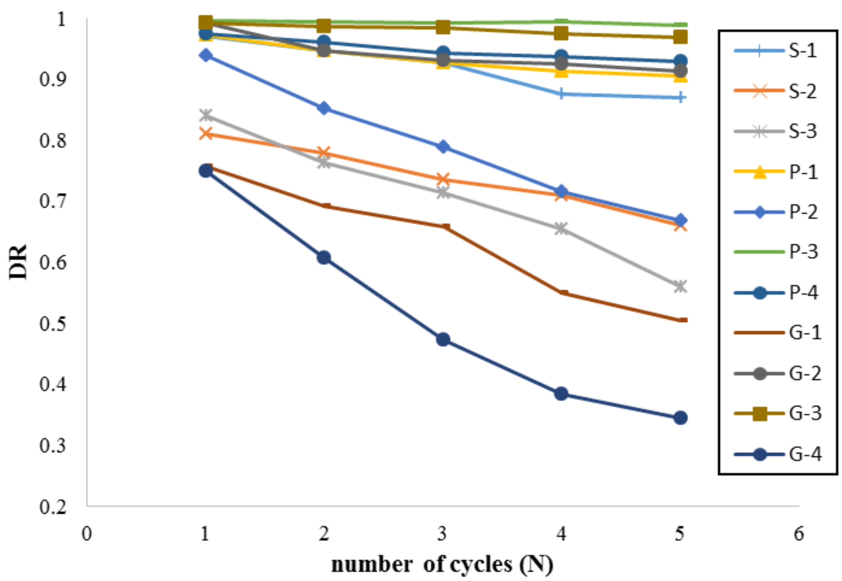

Figure 4. The DR index versus number of cycles (N)

The marl (P-2, G-1, and G-4) and clayey marl (S-1, S-2, and S-3) samples tend to degrade much quicker than the other samples. The study results show a close relation between DR and water absorption for the samples. This parameter provides a good predictor of durability, because water absorption is not only a measure of induration but it is also influenced by the presence of expandable clay minerals.The type of clay minerals is the most important parameter that affects the degradation behavior. This can be concluded by comparing the plasticity and durability indices. The sample with the highest plasticity index, G-4, shows the lowest slake durability index (Id2), and the sample with lowest plasticity index, P-3, shows the highest slake durability index. It is also noted that microfractures, high degrees of porosity, and liquid limit contribute to their low durability (Table 2). The rock samples such as S-1, P-1, P-3, P-4, G-2, and G-3 are considered to have a very high durability based on Gamble's classification (Gamble, 1971).An attempt is made here to use the results of the modified slake durability testing to predict the future condition of the rocks. A hypothesis is proposed to describe the physical characteristics of the rock fragments used in the modified slake durability test. It is assumed that all rock fragments inside the drums for each test test are identical and have non-uniform textures. The outer surface is weaker (lower strength, higher degree of weathering) than the inner matrix. This is reflected by the decrease in the rate of degradation as the number of test cycles increased.

Rock durability classification

This paper examines the value of short-term (results of slake durability tests) in the prediction of long-term deterioration. A trend line shows a trend in a laboratory data set and is typically associated with regression analysis. Creating a trend line and calculating its coefficients allows for the quantitative analysis of the underlying data and the ability to extrapolate the data for prediction purposes. Using regression analysis yields a lot more information than trend line coefficients. The rest of the information is important in understanding how well the regression line fits the data, how significant the individual coefficients are, and the significance of the regression as a whole. When using regression for prediction, we are often considering time series data, and we are aiming to predict the future.

The slake durability patterns of weak rock show that DR variation in the laboratory is opposed to that under natural conditions. The clay-bearing rocks begin to deteriorate and disintegrate at different rates after exposure to the atmosphere, leading to a greater long-term deterioration of these rocks.

The curves for samples G-1, G-4, P-2, S-3, and S-2 are concave upward. Here the decrease of the rock matrix strength from the outer surface to the inner part can be abrupt or graded, depending on the the rock type and weathering characteristics. The more abrupt the change, the more concave the DR–N curve. In the weak rock, after the first cycle slake durability test, most of the samples disintegrated. When the samples had undergone further wetting and drying cycles, the rate of fragmentation of samples was decreased.

If the proposed hypothesis is valid, it can be postulated that the weak rock fragments inside the drum tend to become stronger as they are subjected to a larger number of slake durability test cycles. As the rock fragments become stronger, the difference in the DR values between the adjacent cycles (hereafter called ΔDR) becomes smaller. ΔDR at any cycle can be represented by:

$$\Delta DR = DR\ (N) - DR\ (N+1) \qquad (2)$$

where DR (N) is the Disintegration Ratio at cycle N, and DR (N+1) is the Disintegration Ratio at cycle N+1.

In order to predict the rock durability in the future, the ΔDR are calculated for the five cycles. Figure 5 plots the ΔDR as a function of the reversed cycles, N^*. This is primarily to avoid confusion with with the original forward cycles (N) defined earlier. This reversed plotting is mainly for convenience in analyzing the test results. For example, the ΔDR that represent the difference between the DR of the first cycle and the conditions as collected is plotted at $N^*=5$. The difference between the DR values between the fourth and fifth cycles is plotted for $N^*=1$. For this new approach, while the ΔDR increases with N^*, the rock becomes weaker.

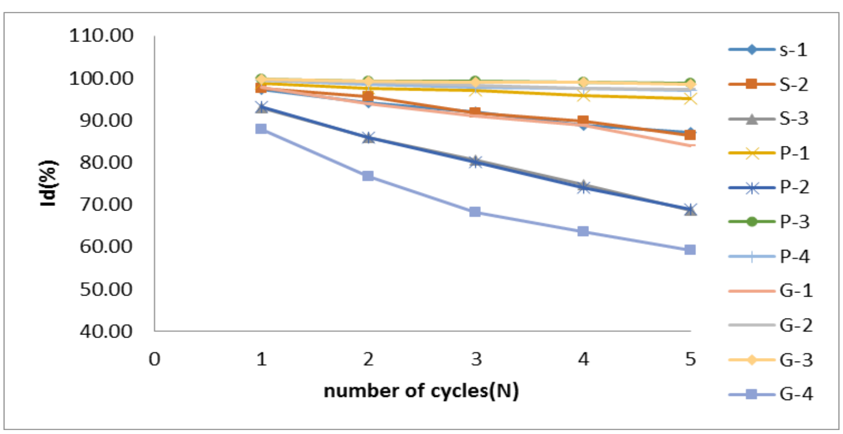

Figure 5: The Id index versus number of cycles (N)

This is similar to the actual rock degradation due to the weathering process that occurs in the in situ condition.

The ΔDR-N^* curves have a significant advantage over the conventional DR-N diagram. The new curves can show a future trend for the rock durability, as ΔDR values can be statistically projected to a larger number of test cycles than those that can be performed in the laboratory. The prediction of the ΔDR value as a function of N^* is obtained by extrapolation of the fitted curve to a higher number of N^*. In Figure 6, the ΔDR results are projected versus cycles number (N^*). Regression analyses on the 6 ΔDR values indicate that an exponential equation can best describe the variation of ΔDR with N^* for the S-2, S-3, P-1, P-2, G-1, and G-4 samples, and that a linear equation can can best describe the variation of ΔDR with N^* for the S-1, P-3, P-4, G-2, and G-3 samples. Tables 3 and 4 give summaries of the correlation coefficients for the relationship between ΔDR and N^* for each rock type.

A preliminary classification system is proposed for rock durability based on ΔDR and its projected values to any N^*, as shown in Table 4.

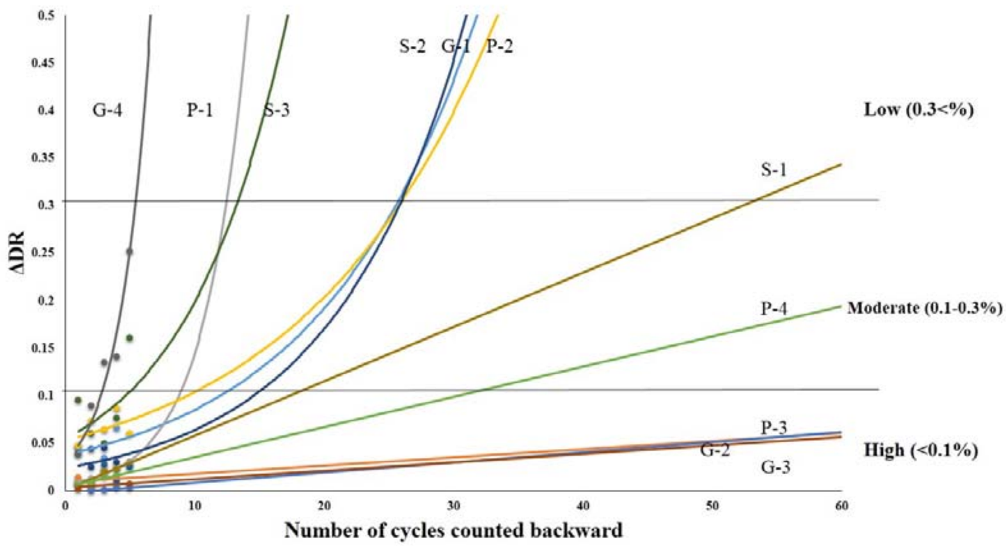

Figure 6: ΔDR as a function of N^*

Table 3. Empirical constants for exponential relationship between ΔSDI and N^*

Rock types	**$\Delta SDI = Ae^{BN^*}$**		Correlation coefficient
	A	B	
S-2	2.55	0.066	0.028
S-3	5.3	0.052	0.494
P-2	4.94	0.075	0.796
G-1	1.22	0.296	0.993
G-5	1.07	0.700	0.898

Table 4. Empirical constants for linear relationship between ΔSDI and N^*

Rock types	**$\Delta SDI = AN^* + B$**		Correlation coefficient
	A	B	
S-1	0.376	0.615	0.394
P-1	0.084	0.888	0.385
P-3	0.035	0.157	0.752
P-4	0.225	0.045	0.716
G-2	0.085	0.290	0.914
G-3	0.360	0.636	0.822
G-4	0.036	0.260	0.025

The ΔDR-N^* curves obtained from the eleven rock types tested here are compared with the new classification system (Fig. 6). For example, at N^* = 60 or below, the G-2, G-3, and P-3 samples are classified as high durability rocks. The P-4 sample is classified as moderate durability rock, and the other samples are classified as low durability rock, because their ΔDR values rapidly increased within a few cycles of N^*. It should be noted that the projection of ΔDR-N^* curves relies heavily on the number of cycles actually tested. The larger the number of tested cycles, the higher the reliability of the projected results. This agrees with the classification and conclusions drawn earlier from the results of the wet and dry SDI tests. It should be noted that the projection of ΔDR-N^* curves relies on the number of cycles actually tested.

Table 5. Proposed classification system for durability of intact rocks

Description	ΔDR(%)
High durability	< 0.1
Moderate durability	0.1-0.3
Low durability	0.3<

Conclusions

In this paper, the effect of weathering processes on the slaking of some clay-bearing rocks has been experimentally investigated. Based on a limited number of determinations at the Ilam, Sarpol-e Zahab, and Tajarak regions, the prediction technique has been employed to assess susceptibility to deterioration. Since the mechanisms causing deterioration of a weak rock subject to wetting-drying are not fully understood, an attempt has been made to assess the potential for disintegration by using the prediction technique based on a limited slake durability test carried out in in the laboratory. This appears to offer a cost-effective alternative to the full laboratory test. A preliminary classification system (Table 5) was proposed for the evaluation of the slake durability of clay-bearing rocks. In order to predict the rock durability in the future, the ΔDR are calculated for five cycles. The ΔDR values are then plotted as a function of the number of cycles counted backward. This backward cycle is denoted by N^* to avoid confusion with the original forward cycles (N) defined earlier. This backward plotting is mainly for for convenience in analyzing the test results. For this new approach, while the ΔDR increases with N^*, the clay-bearing rocks become weaker. This is similar to the actual rock degradation due to the weathering process that occurs in the in-situ condition. The new curves can show a future trend for the rock durability, as the ΔDR values can be statistically projected to a larger number of test cycles than can be performed in the laboratory.

A preliminary classification system is proposed for rock durability based on ΔDR and its projected values to any N^*. The ΔDR–N^* curves obtained from eleven rock types tested here are compared against the new classification system. In the classification system, rocks are divided into 3 classes. Durable rocks encounter a little surface slaking in the environment. Moderately durable rocks in an environment encounter considerable weakness, meaning that a number of rock properties, such as physical, mechanical or physico-chemical properties, may be affected considerably. It should be noted that the proposed classifications are an initial and basic idea. The authors maintain that additional data and studies on marls from other regions are needed to verify the proposed criteria.

References

ASTM C127., 1998. Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate.

ASTM D4644-87., 2004. Standard test method for slake durability of shale and similar weak rocks.

Anagnostopoulos, A.G., Kalteziotis, N., Tsiambaos, G.K., and Kavvadas, M. 1991. Geotechnical properties of the Corinth Canal Marls. GeotechGeolEng. 9(1): 1-26.

Brown, E.T. 1981. Rock characterization testing and monitoring ISRM suggested method, 1 stedn, Pergamon Press, Oxford, 211p

Dhakal, G., Yoneda, T., Kata, Y., and Kaneko, K. 2002. Slake durability and mineralogical properties of some pyroclastic and sedimentary rocks. Engineering Geology. 65(1): 31-45.

Erguler, Z.A. 2007. Investigation of the Effect of Water Content on Engineering Behavior of the Clay-Bearing Rocks. PhD Thesis, Hacettepe University, Geological Engineering Department (in Turkish).

Erguler, Z.A., Shakoor, A. 2009. Quantification of fragment size distribution of clay-bearing rocks after slake durability testing. Environmental and Engineering Geoscience. 15(2): 81-89.

Erguler, Z.A., Ulusay, R. 2009. Assessment of physical disintegration characteristics of clay-bearing rocks:

Disintegration index test and new durability classification chart. Engineering Geology. 105(1-2): 11-19.

Fang, Z., and Harrison, J.P. 2001. A mechanical degradation index for rock. International Journal of Rock Mechanics and Mining Sciences. 38(8):1193-1199.

Fookes, P.G., Gourley, C.S., and Ohikere, C. 1988. Rock weathering in engineering time.Q J EngGeol 21, 33-57

Francklin, J. A. Chandra, A. 1972. The slake durability test. International Journal of Rock Mechanics and Mining Sciences. 9: 325-341.

Frydman, J. A., Talesnick, M., Geffen, S., Shvarzman, A. 2007. Landslides and residual strength in marl profiles in Israel. EngGeol. 89(1-2): 36-46.

Gamble, J. C. 1971. Durability-Plasticity Classification of shales and other argillaceos rocks. Unpublished Ph.D. Thesis, University of Illinois, Urbana-Champaign, IL, 161p.

Gokceoglu, C., Ulusay, R., andSonmez, H., 2000. Factors affecting 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. EngGeo. l57(1): 215-237.

Gundogdu, N., 1982. Geological, mineralogical and geochemical investigation of the neogene aged Bigadic sedimentary basin PhD. Thesis, Haccetepe University, Ankara, Turkey, 386PP.(In Turkish).

Gupta, A.S., Seshagiri, K.R., 2000. Weathering effect on the strength and deformational behavior of crystalline rocks under uniaxial compression state.Engineering Geology. 56(3-4): 257-274.

Horing, E.D., 2010. Field and laboratory tests investigating Settlement of foundations on weathered Keuper Marl. GeotechGeolEng. 28(3): 233-240.

ISRM. 1979, Suggested method for determination of the slake durability index. International Journal of Rock Mechanics and Mining Science and Geomechanics Abstracts. 16: 154-156.

ISRM. 1985. Suggested Method for Determining Point Load Strenght. International Journal of Rock Mechanics, Mineral Sciences and Geomechanics. Abstract. 22: 51-60.

Johnston, I.W., and Nevello, E.A., 1994. Soil mechanics, rock mechanics and soft rock technology. GeotechEng. 107(1): 3-9.

Koncagul, E.C., Santi, P.M., 1999. Predicting the unconfined compressive strength of the Breathitt shale using slake durability, Shore hardness and rock structural properties. Int J Rock Mech Min. 36(2): 139-153.

Moon, V.G., Beattie, A.G., 1995. Textural and microstructural influence on the durability of Waikato coal measures mudrocks. Quarterly Journal Engineering Geology. 28: 303-312.

Oguchi, C.T., and Matsukura, Y., 1999. Effect of porosity on the increase in weathering-rind thickness of andesite gravel. Engineering Geology. 55(1-2): 77-89.

Olivier, H.J.,1979. Some aspect of the influence of mineralogy and mudrocks, Proc. 4th International Congress in Roc Mecanics. Montreux. 3: 1-8

Oyama, T., and Chigira, M., 1999. Weathering rate of mudstone and tuff on old unlined tunnel walls. Engineering Geology. 5(1-2): 15-27.

Phienwej, N., and Singh, V.K., 2005. Engineering Properties of Rocks of PhuKadung and PhraWihan Formations in Northeast Thailand. Proc. of the International Symposium-GEOINDO. KhonKaen, Thailand. 199-204.

Robinson, D.A., and Williams, R.B.G., 1994. Rock Weathering and Landform Evolution. John Wiley & Sons, Inc., New York.

Tugrul, A., 2004. The effect of weathering on pore geometry and compressive strength of selected rock types from Turkey. Engineering Geology. 75(3-4): 215-227.