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Investigation of the effect of aggregate shape and surface roughness on the slake durability index using the fractal dimension approach

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Abstract

Argillaceous rocks cover about one thirds of the earth's surface. The major engineering problems encountered with weak- to medium-strength argillaceous rocks could be slaking, erosion, slope stability, settlement, and reduction in strength. One of the key properties for classifying and determining the behavior of such rocks is the slake durability. The concept of slake durability index (SDI) has been the subject of numerous researches in which a number of factors affecting the numerical value of SDI were investigated. In this regard, this paper approaches the matter by evaluating the effects of overall shape and surface roughness of the testing material on the outcome of slake durability indices.

For the purpose, different types of rocks (marl, clayey limestone, tuff, sandstone, weathered granite) were broken into chunks and were intentionally shaped as angular, subangular, and rounded and tested for slake durability. Before testing the aggregate pieces of each rock type, their surface roughness was determined by using the fractal dimension. Despite the variation of final values of SDI test results (values of I_d), the rounded aggregate groups plot relatively in a narrow range, but a greater scatter was obtained for the angular and subangular aggregate groups. The best results can be obtained when using the well rounded samples having the lowest fractal values. An attempt was made to analytically link the surface roughness with the I_d parameter and an empirical relationship was proposed. A chart for various fractal values of surface roughness to use as a guide for slake durability tests is also proposed. The method proposed herein becomes efficient when well rounded aggregates are not available. In such condition, the approximate fractal value for the surface roughness profile of the testing aggregates could be obtained from the proposed chart and be plugged into the empirical relation to obtain the corrected I_d value. The results presented herein represent the particular rock types used in this study and care should be taken when applying these methods to different type of rocks.

Keywords: Argillaceous rock; Fractal dimension; Slake durability; Surface roughness

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1. Introduction

Argillaceous rocks are found at and near the surface of the earth owing to the geological processes such as deposition and weathering and cover about one thirds of the earth's surface. It was reported that rocks containing large ratios of clay content (e.g., claystone, shale, marl, siltstone) covers a significant portion of the stratigraphic column (e.g., Franklin and Chandra, 1972; Blatt, 1982; Dick et al., 1994). Thus, it is often inevitable to work with the clayey rocks during geotechnical activities.

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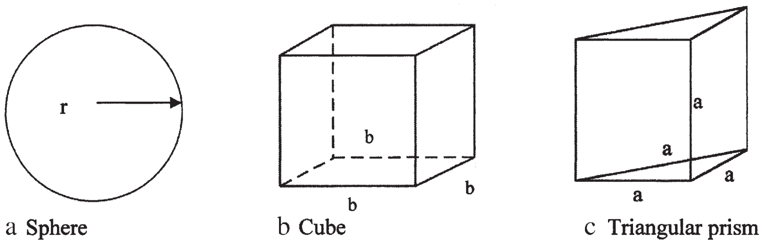

Fig. 1. Geometrical shapes used for surface area calculation.

The rocks containing high-plasticity clays may swell, shrink, and slake. The outcome of such effects could lead to the rapid weathering of exposed rocks which causes slope stability problems, failure of earthfills as well as reduction strength with rocks exposed to air in underground openings (Gokceoglu et al., 2000).

The slake durability is an important property for rock materials and rock masses (Franklin and Chandra, 1972; Rodrigues, 1991; Dick and Shakoor, 1995; Gokceoglu et al., 2000; Dhakal et al., 2002; Dhakal et al., 2004; Yilmaz and Karacan, 2005; Singh et al., 2005). One of the major problems arising during construction of engineering structures in clayey rocks results from rapid weathering. The susceptibility of such rocks to weathering and the degree of weathering could be determined using some slake durability parameters such as the slake durability index. This is an important engineering property for rocks such as mudstone, marl, ignimbrite, weakly cemented conglomerate and siltstone (Gokceoglu et al., 2000). The concept of slake durability has also been used to study the weathering processes of granitic rocks (Lee and Freitas, 1988; Zhao et al., 1994). Slake durability index (I_{d2}) was also included in the modified rock mass rating (M-RMR) and became an efficient tool for design practices on rock masses (Unal, 1996). Some researchers (e.g., Koncagül and Santi, 1998; Gokceoglu et al., 2000) used the slake durability index to establish a relationship with the uniaxial compressive strength.

Introduced by Chandra (1970) and later improved by Franklin and Chandra (1972), the slake durability test was proposed as a standard test for rocks by ISRM (1981) and also became an ASTM standard in 1990.

It was reported that the results of slake durability test are susceptible to the porosity and permeability of the rocks tested, nature of the testing fluid, resistance of rocks against swelling and disintegration, the shape of sample pieces placed in the testing drum, properties of testing equipment, conditions of sample storing, and the number of wetting–drying cycles (Franklin and Chandra, 1972). Tests omitting any of the factors listed above would lead to erroneous results.

One of the basic requirements of the slake durability test (ISRM, 1981; ASTM, 1990) is nearly spherical chunks with truncated corners, each having a mass between 40 to 60 g. Nevertheless, preparation of nearly spherical samples could be time consuming or sometimes be very difficult. Slake durability depends on many factors such as rock type, degree of weathering, grain size, mineralogical composition, and structural/textural properties. For this reason, during preparation of aggregates satisfying the standards of the test, such requirements usually are not given sufficient care. Thus, the results are thought to overestimate the value of true slake durability index which may readily cause the change of the slaking class of a rock from one to another.

There are two reasons for the severe influence of aggregate shape and surface roughness on the slake durability index. One is, depending on the degree of surface roughness, the attrition among sample pieces as well as with the inner surface of the drum increases the abrasive stresses which results into more disintegration of sample pieces. The other is, rough surface of aggregate creates more surface area. As the aggregates lose sphericity and gain higher amplitudes of asperities, the surface area exposed to testing fluid increases resulting more interaction with the fluid. In order to demonstrate this effect, the objects of the same volume but different geometrical shapes can be compared as illustrated in Fig. 1. For this, the volumes are equalled at the first step:

$$V_{\text{sphere}} = V_{\text{cube}} = V_{\text{tr.prism}} \Rightarrow 4.19r^3 = b^3 = 0.43a^3 \quad (1)$$

Because the areas are quadratic expressions, it would be convenient to raise each term to the power 2/3 such that:

$$2.6r^2 = b^2 = 0.57a^2 \quad (2)$$

Rearranging in terms of b^2 would give:

$$r^2 = 0.38b^2 \text{ and } a^2 = 1.75b^2 \quad (3)$$

The surface areas of the three figures are as follows:

$$A_{\text{sphere}} = 4\pi r^2 \qquad A_{\text{cube}} = 6b^2 \qquad A_{\text{tri.prism}} = 3.87a^2 \quad (4)$$

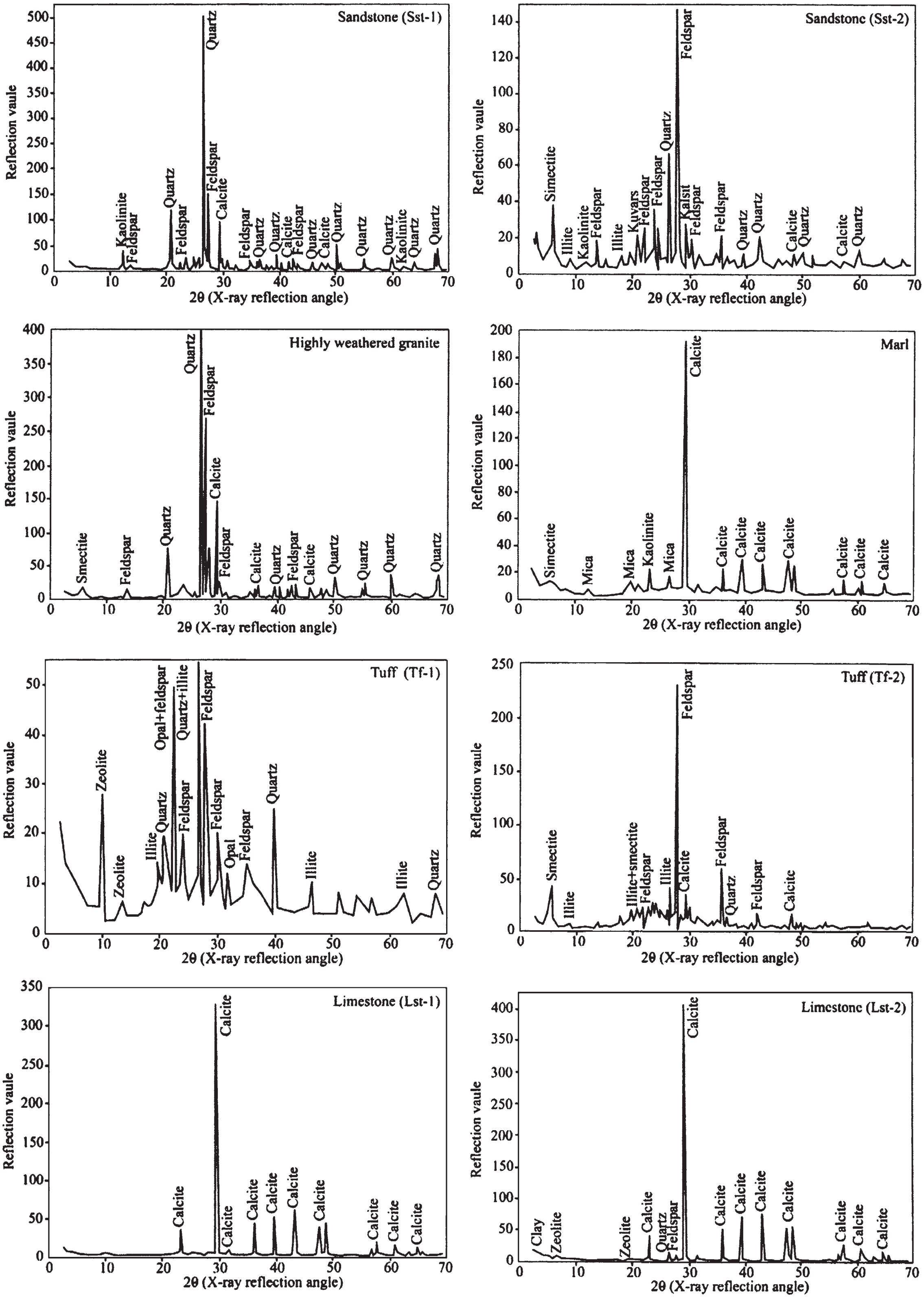

Fig. 2. Results of XRD analyses for the rock samples used in the study.

Table 1
Summary of the XRD analyses in terms of mineralogical composition (from most abundant to the least)

Rock type	Mineralogical composition
Arkose arenite (Sst-1)	Quartz, feldspar, calcite, clay
Lithic arenite (Sst-2)	Fragments of andesite and basalt, feldspar, quartz, clay
Weathered granite (WG)	Feldspar, quartz, calcite, clay
Lithic tuff (Tf-1)	Fragments of andesite and basalt, quartz, opal, feldspar, clay
Ignimbrite (Tf-2)	Fragments of andesite, feldspar, clay, quartz
Marl (M)	Calcite, clay
Limestone (Lst-1)	Calcite, clay, fossil
Limestone (Lst-2)	Calcite, clay, fossil

Writing the r^2 and a^2 terms in terms of b^2 would yield the following areas in the ascending order:

$$A_{\text{sphere}} = 4.83b^2 < A_{\text{cube}} = 6b^2 < A_{\text{tri.prism}} = 6.78b^2 \tag{5}$$

The mathematical expression written above clearly indicates an increase in the surface area as the geometrical shape departs from the ideal sphere.

This study aims to investigate the effects of shape and surface roughness and shape of aggregates used in slake durability tests on the slake durability index using the concept of fractal dimension. Empirical relationships were sought between the fractal dimension representing the surface roughness plus the shape and slake durability index. Primary factors such as density as well as point load index and the secondary factors like mineralogical, textural, and structural features were combined in the analyses so as to link the two concepts mentioned above.

2. Materials and methods

2.1. Rock samples

The rock materials used in this study include the following types of clayey rocks: clayey limestone (Lst-1 and Lst-2), marl (M), clayey sandstone (Sst-1 and Sst-2), tuff (Tf-1 and Tf-2), and weathered granite (WG). Although sample collection did not depend on a certain geographical location, samples are mostly from fresh exposures on highway cuts. During sampling, preferences were given for homogeneity and to collect ample amount of material. A series of XRD analysis (model: PW-3710 and Cu tube) were also performed in order to clarify the mineralogical composition of the tested materials. The output of those analyses are presented in Fig. 2. A summary of the results are also provided through Table 1. The first group of sandstone samples (Sst-1) is medium-grained; white to gray; consisting of quartz, feldspar, calcite, and clay with carbonate cementing material and are classified as arkose–arenite. The second group of sandstone samples (Sst-2) is greenish; has medium-grained andesitic–basaltic rock fragments, feldspar, and quartz with clay cementing material and are classified as arenite. The third group consists of highly weathered medium-grained granite (WG) with major mineral composition of feldspar, quartz, calcite minerals, and clay. The fourth group (Tf-1) is tuff; with range of colors and thinly bedded. Mineral composition consists of andesite–basalt fragments, quartz, amorphous silica, feldspar, and clay. This group of rock was classified as lithic tuff. The fifth group of testing material is also tuff (Tf-2). This clastic rock consists of obsidian and pumice fragments; is gray and

Table 2
Dry density and point load strength of rocks used in slake durability tests

Rock type	Dry density, ρ_d (g/cm^3)			Point load strength, $I_{s(50)}$(MPa)		
	Max	Min	Mean	Max	Min	Mean
Sst-1	2.72	2.47	2.6	5.43	3.75	4.54
Sst-2	2.64	2.21	2.37	4.43	3.16	3.57
WG	2.88	2.61	2.71	4.11	1.95	3.34
Tf-1	2.09	1.96	2.05	1.26	0.99	1.08
Tf-2	1.45	1.30	1.40	1.67	1.38	1.51
M	2.20	1.87	2.02	3.85	2.19	3.21
Lst-1	2.30	2.23	2.27	5.11	3.72	4.69
Lst-2	2.31	2.10	2.24	4.54	2.03	3.42

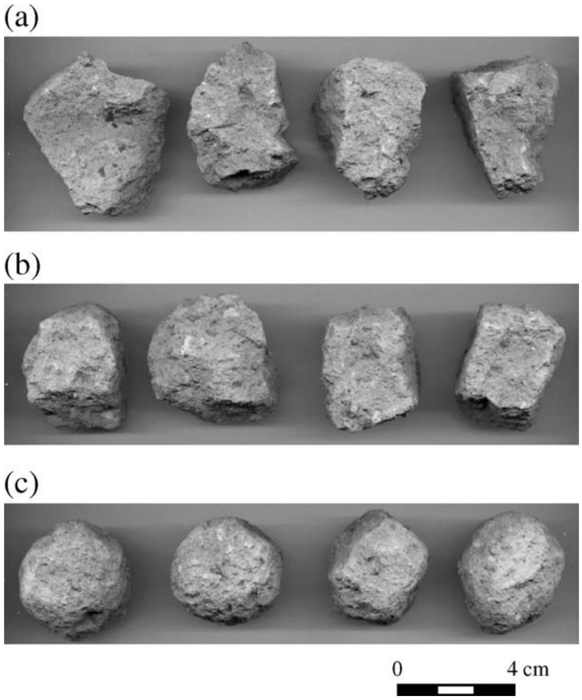

Fig. 3. A general view of the angular (a), subangular (b), and rounded aggregates (c) prepared for the test.

pink, and was classified as ignimbrite tuff. The sixth group of testing material is marl (M). It is homogeneous light green and consists of calcite and clay (smectite, kaolinite, and some mica). The seventh group of testing material is clayey limestone (Lst-1), white to light gray and is of bio-micritic type. The vugs are filled with calcite and occasionally by clay minerals. The eighth group of testing material is also limestone (Lst-2), white to light gray. XRD analyses show that it contains calcite, clay, and large amount of fossil fragments.

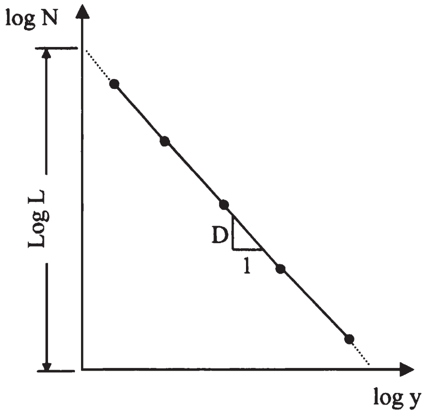

Fig. 4. The Hausdorf and Besitovitch graph (Mandelbrot, 1983).

2.2. Methodology

Before using in slake durability tests, the dry densities and point load strengths of rock samples were determined

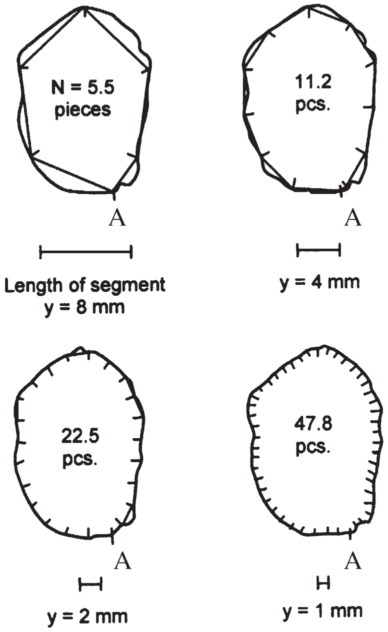

Fig. 5. Segmentation of the aggregate profile using the segment of fixed lengths (Vallejo, 1994).

Table 3
Fractal dimension evaluation of the aggregate profile given Fig. 5 (Vallejo, 1994)

Segment length y (mm)	Number of segments N	Total length of perimeter $L=Ny$ (mm)	Fractal dimension D
1	47.8	47.8	1.0462
2	22.5	45.0	
3	11.2	44.8	
4	5.5	44.0	

according to ISRM (1981) standards. For dry densities, 5 samples were tested for each rock group. Ten samples of each rock groups were tested for point load strength. The results are given in Table 2.

In order to obtain testing aggregates of 40 to 60 g in mass, sharpened special hammers, pocket knife, and sandpaper were used. Angular (AN), subangular (SA) and rounded (RN) aggregates were prepared for each of the eight groups of rocks. A general view of the prepared specimens is shown in Fig. 3. Although slake durability tests are performed using two wetting and drying cycles, four wetting and drying cycles were also conducted in this study so as to analyze the effect of increasing number of wetting and drying cycles.

In order to quantify the angularity and surface roughness, the concept of "fractal dimension" was employed. Introduced by Mandelbrot in 1967, the concept was developed to numerically define the borders of irregular shapes such as the borders of states, lakes, islands, etc.

Fig. 6. Digitization of an aggregate profile to evaluate through a computer code.

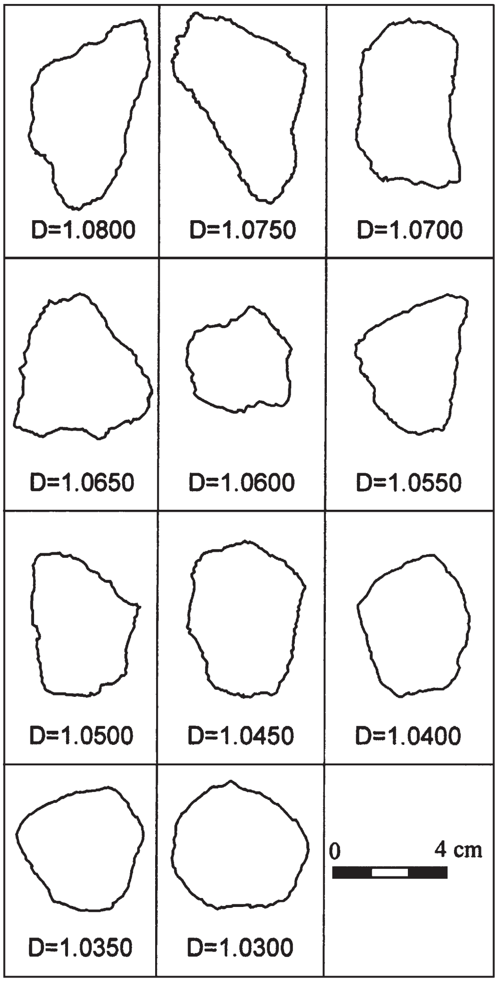

Fig. 7. The fractal dimension of some profiles computed from the fractal programme.

Initially, the application of the concept of fractal dimension (D) was for the determination of a shoreline (Mandelbrot, 1967) where the shoreline was divided into the fixed lengths (y) and linked the number of these fixed lengths (N) through the following relationship:

$$L = Ny \tag{6}$$

where L is the total length of the shoreline. Plotting of N versus y in a log–log diagram (Fig. 4) would yield a slope, D, which is called as Hausdorff and Besicovitch dimension. Using the relationship in Fig. 4, Mandelbrot (1983) proposed an expression as follows:

$$L = Ny^D \tag{7}$$

Carr and Warnier (1987) redefined this equation as follows:

$$\log N = \log L - D \log y \tag{8}$$

An application of the fractal dimension concept to the slake durability test was carried out by Vallejo (1994) by comparing the fractal dimensions of the aggregates before and after the experiment. A review of the definition of the Vallejo's work would be considered beneficial, for the current research.

Table 4
Statistical properties of rock groups with respect to fractal dimension

Rock type	Shape	Fractal dimension			
		$D_{\min}$	$D_{\max}$	D_{avg}	Standard deviation
Sst-1	AN1	1.027	1.080	1.044	0.009
	AN2	1.024	1.081	1.042	0.010
	SA1	1.027	1.072	1.037	0.008
	SA1	1.024	1.052	1.037	0.007
	RN1	1.021	1.046	1.032	0.006
	RN2	1.020	1.045	1.030	0.005
Sst-2	AN1	1.028	1.078	1.050	0.012
	AN2	1.029	1.084	1.048	0.012
	SA1	1.025	1.053	1.036	0.006
	SA1	1.027	1.062	1.040	0.007
	RN1	1.021	1.047	1.033	0.005
	RN2	1.022	1.050	1.035	0.006
WG	AN1	1.025	1.067	1.043	0.009
	AN2	1.030	1.119	1.052	0.020
	SA1	1.025	1.062	1.039	0.009
	SA1	1.023	1.059	1.037	0.009
	RN1	1.021	1.041	1.029	0.004
	RN2	1.024	1.054	1.033	0.007
Tf-1	AN1	1.029	1.104	1.050	0.019
	AN2	1.027	1.092	1.050	0.015
	SA1	1.022	1.054	1.037	0.007
	SA1	1.022	1.055	1.038	0.008
	RN1	1.020	1.038	1.027	0.004
	RN2	1.021	1.038	1.027	0.004
Tf-2	AN1	1.024	1.080	1.047	0.014
	AN2	1.025	1.067	1.042	0.011
	SA1	1.023	1.039	1.031	0.004
	SA1	1.024	1.055	1.033	0.007
	RN1	1.019	1.033	1.024	0.003
	RN2	1.021	1.034	1.027	0.004
M	AN1	1.025	1.054	1.038	0.007
	AN2	1.023	1.068	1.038	0.009
	SA1	1.020	1.047	1.031	0.005
	SA1	1.023	1.046	1.032	0.006
	RN1	1.019	1.032	1.024	0.003
	RN2	1.020	1.036	1.024	0.003
Lst-1	AN1	1.026	1.075	1.039	0.010
	AN2	1.024	1.072	1.041	0.011
	SA1	1.024	1.055	1.033	0.007
	SA1	1.020	1.039	1.030	0.004
	RN1	1.016	1.033	1.023	0.003
	RN2	1.018	1.037	1.026	0.004
Lst-2	AN1	1.026	1.093	1.041	0.011
	AN2	1.022	1.082	1.041	0.013
	SA1	1.026	1.059	1.036	0.006
	SA1	1.023	1.053	1.034	0.006
	RN1	1.017	1.035	1.025	0.003
	RN2	1.020	1.041	1.027	0.004

Table 5
Slake durability indices corresponding to wetting/drying cycles along with their corresponding average fractal dimensions

Rock type	Shape	Slake durability index (%)				
		I_{d1}	I_{d2}	I_{d3}	I_{d4}	($D_{\mathrm{avg.}}$)
Sst-1	RN1	95.90	93.46	91.43	89.58	1.032
	RN2	94.63	91.13	88.24	85.68	1.030
	SA1	94.03	90.58	86.95	83.75	1.037
	SA1	93.87	90.37	87.44	84.94	1.037
	AN1	91.28	86.10	81.83	78.09	1.044
	AN2	89.91	83.27	78.08	73.00	1.042
Sst-2	RN1	96.92	94.52	92.03	90.10	1.033
	RN2	96.13	93.85	91.15	89.14	1.035
	SA1	96.33	93.87	91.07	89.18	1.036
	SA1	95.71	93.42	90.69	88.84	1.040
	AN1	93.45	87.63	82.02	78.34	1.050
	AN2	94.51	90.26	86.68	84.08	1.048
WG	RN1	95.23	91.82	88.93	86.63	1.029
	RN2	93.89	90.04	86.87	84.32	1.033
	SA1	78.09	66.03	58.59	53.55	1.039
	SA1	85.48	75.68	66.82	61.66	1.037
	AN1	87.24	79.78	73.95	70.21	1.043
	AN2	82.97	73.33	66.44	62.26	1.052
Tf-1	RN1	84.06	71.15	60.05	51.96	1.027
	RN2	82.83	69.42	57.32	46.02	1.027
	SA1	83.49	64.20	53.23	43.90	1.037
	SA1	83.38	64.79	53.67	45.72	1.038
	AN1	76.94	55.67	41.35	31.26	1.050
	AN2	78.97	62.45	47.75	36.77	1.050
Tf-2	RN1	83.26	66.84	47.78	33.61	1.024
	RN2	83.02	62.92	45.53	31.71	1.027
	SA1	78.65	52.11	34.27	25.45	1.031
	SA1	76.31	54.76	30.37	19.49	1.033
	AN1	69.71	40.78	23.73	16.70	1.047
	AN2	70.87	44.30	30.74	22.55	1.042
M	RN1	94.03	89.93	85.98	82.98	1.024
	RN2	94.24	90.48	86.64	83.68	1.024
	SA1	92.91	88.78	84.35	80.83	1.031
	SA1	93.20	88.69	84.30	80.67	1.032
	AN1	92.76	87.37	82.29	78.36	1.038
	AN2	90.30	86.82	81.46	77.43	1.038
Lst-1	RN1	97.58	96.14	95.02	93.92	1.023
	RN2	98.72	96.25	95.63	93.74	1.026
	SA1	95.39	90.40	88.72	82.99	1.033
	SA1	97.04	92.03	90.86	87.12	1.030
	AN1	98.61	94.66	94.31	90.37	1.039
	AN2	96.75	94.81	93.37	91.89	1.041
Lst-2	RN1	96.64	93.06	90.21	86.96	1.025
	RN2	97.24	91.38	86.90	84.43	1.027
	SA1	87.58	84.17	81.68	79.58	1.036
	SA1	95.51	90.94	87.29	84.34	1.034
	AN1	85.31	82.23	79.57	77.62	1.041
	AN2	92.74	89.18	86.27	84.18	1.041

Table 6
The variation of slake durability indices of angular aggregates of different rock types and the number of wetting/drying cycles

The number of wetting/drying cycles	Rock type	Variation of slake durability index with angularity of aggregates (%)
1	Sst-1	6.76
	Sst-2	3.47
	WG	12.26
	Tf-1	7.12
	Tf-2	13.55
	M	3.94
	Lst-1	3.33
	Lst-2	11.33
2	Sst-1	10.19
	Sst-2	6.89
	WG	18.49
	Tf-1	15.48
	Tf-2	26.05
	M	3.66
	Lst-1	5.85
	Lst-2	10.83
3	Sst-1	13.35
	Sst-2	10.01
	WG	22.49
	Tf-1	18.70
	Tf-2	24.05
	M	5.18
	Lst-1	6.91
	Lst-2	10.64
4	Sst-1	16.58
	Sst-2	11.76
	WG	24.37
	Tf-1	20.70
	Tf-2	16.91
	M	6.25
	Lst-1	10.93
	Lst-2	9.34

Variation of I_d values related to rock type, number of wetting/drying cycles, and angularity.

In order to determine the fractal dimension of the aggregates, the perimeter (or profile) needs to be obtained first. Then, having a pair of compasses with a fixed step length, the selected profile is systematically marked by starting a certain point. For this, the keen leg of the compasses is placed right at the starting point and the marker leg marks a small notch on the profile. Following this, the keen leg is removed to the marked point and the second notch is marked and the process is repeated until the whole perimeter is covered. At the end, the total number of steps is determined (Fig. 5). As would be expected, as the segment length decreases, the number of steps increases proportionally. The results of this process using four different segment lengths are presented in Table 3.

According to Mandelbrot (1977) and Turcotte (1992), the logarithmic relationship between the length and the number of segments indicates a fractal dimension for the profile of an aggregate specimen. The absolute value of the slope of the reverse linear relationship indicates the fractal dimension (D) of the specimen's profile. As the angularity and the amplitude of surface roughness increase, so does the fractal dimension. With the aid of the following expression, fractal dimension of a profile can be readily explored:

$$D = -\frac{\sum(\log_{10}(N)\log_{10}(y)) - (\sum\log_{10}(N)\sum\log_{10}(y))/J}{\sum(\log_{10}(y))^2 - (\sum\log_{10}(y))^2/J} \tag{9}$$

where J is the "number of segments of different lengths" considered for the computation of fractal dimension.

It would certainly be complicated to calculate the fractal dimensions of a parametric study requiring several thousands of aggregates. To do this in a more practical way, the perimeter profile of each aggregate was determined via scanning procedure. Because an aggregate is a three dimensional object and the shape of the perimeter depends on the position of the aggregate that is placed on the scanner, each aggregate specimen was scanned four times for different positions. These four files were then transferred to a program called Didger (Golden Software, 2000) to determine the perimeter of the scanned object as a polygon with different length of segments (Fig. 6). The x, y Cartesian coordinates of the points constituting the polygon were thus obtained. These files were then used as input data for the computer code FRAKTAL (Kolay and Kayabali, 2005) for calculating the fractal dimension of each of the four profiles corresponding to single aggregate. The average of the four values of the computed fractal dimensions (D_{avg}) was taken to represent the fractal dimension of an individual specimen. Working with the precision as high as 0.1-mm step lengths, the algorithm of the computer program is as follows:

- The program reads the x and y coordinates of the closed polygon and computes the linear lengths between the adjacent two points.
- By summing up these lengths, the perimeter of a polygon (L) is determined.
- In order to determine the segment lengths (y) to be used in the analyses, the perimeter (is) divided by 10, 20, 30, 40, and 50. The meaning of this, 5 different segment lengths [which correspond to J in Eq. (9)] is used throughout the study. Depending upon the irregularity of the aggregates, it might be better to vary 'J' number to reflect more accuracy than assigning one number to all shapes of aggregate pieces.

- The lines connecting two adjacent points within the polygon is divided into pieces of 0.1-mm lengths and new coordinates are assigned to those points.
- The number of pieces making up the polygon is thus computed using each of five different segment lengths. At the end of the process, five pairs of data are obtained as five different segment lengths (y) versus five different number of pieces of lines (N) corresponding to each of those segment lengths.
- Using the method of least squares [Eq. (9)], the program computes the fractal dimension of a single polygon representing one of the four perimeters of an individual specimen.
- The program prints the results on the screen in the following order: the segment lengths (y), the corresponding number of pieces of lines (N), and the fractal dimension (D).
- The program provides only one fractal dimension at each run.

Aggregate shapes are usually defined qualitatively (e.g., Powers, 1953; Pettijohn, 1957; Barret, 1980; Clayton et al., 1995; Boggs, 1995) which would be inappropriate to involve into some analytical evaluations in disciplines such as engineering geology, rock mechanics, and sedimentology. Therefore, a chart presented in Fig. 7 would serve as a guide for quantitative description of grain and aggregate shapes.

In order to better represent the relationship between the surface roughness and slake durability index through the fractal dimension approach, six groups of aggregates were prepared for each of the eight group of rocks listed earlier. Out of the six groups, two stands for angular aggregates (AN-1 and AN-2), two is for subangular (SA-1 and SA-2) and the remaining two are for the rounded group (RN-1 and RN-2). As per the requirement of 10 pieces of aggregates in the slake durability test, six groups of aggregate for one kind of rock accumulates 60 pieces of aggregates. Because the determination of fractal dimension of an individual specimen required four scanning operations, a total of 240 scanning operations were performed for a single rock type. Thus, a total of 480 pieces of aggregates were prepared for eight group of rocks and about 2000 scanning operations were performed. Eventually, 480 fractal dimension values were obtained for eight group of rocks with different shapes.

For a meaningful relationship between independent and dependent variables, simple and multiple regression analyses were performed for linear, nonlinear, exponential and logarithmic functions with the help of statistical software packages. A program called SPSS (Statistical Package for Social Science; SPSS Inc., 1998) was used to link the I_{d2} values with the fractal dimension values. The I_{d2} values were considered as dependent variables whereas the fractal dimension, dry density, and point load strength as independent variables. The statistical

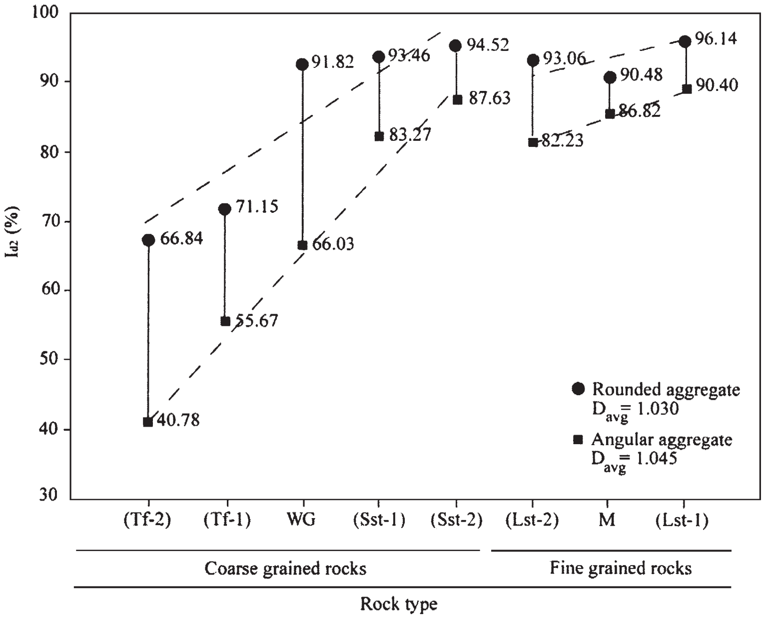

Fig. 8. Effect of surface roughness on I_{d2} values in fine and coarse grained rocks.

Table 7
Empirical relationships between the I_d values and fractal dimension values of the rock groups used in the study

The number of wetting/drying cycles	Rock type	Regression equation	Coefficient of correlation (*r*)
1	Sst-1	$I_{d1}=-367.59D+474.42$	−0.88
	Sst-2	$I_{d1}=-174.31D+276.89$	−0.97
	WG	$I_{d1}=-522.13D+629.56$	−0.65
	Tf-1	$I_{d1}=-367.59D+474.42$	−0.88
	Tf-2	$I_{d1}=-639.85D+738.48$	−0.98
	M	$I_{d1}=-192.4D+291.34$	−0.83
	Lst-1	$I_{d1}=-31.328D+129.67$	−0.18
	Lst-2	$I_{d1}=-535.82D+646.65$	−0.75
2	Sst-1	$I_{d2}=-594.05D+705.11$	−0.85
	Sst-2	$I_{d2}=-360D+466.85$	−0.95
	WG	$I_{d2}=-783.28D+893.15$	−0.64
	Tf-1	$I_{d2}=-594.05D+705.11$	−0.85
	Tf-2	$I_{d2}=-1100D+1190.9$	−0.96
	M	$I_{d2}=-229.45D+325.33$	−0.98
	Lst-1	$I_{d2}=-79.724D+176.31$	−0.24
	Lst-2	$I_{d2}=-455.42D+559.49$	−0.73
3	Sst-1	$I_{d3}=-768.76D+882.77$	−0.85
	Sst-2	$I_{d3}=-499.85D+609.05$	−0.93
	WG	$I_{d3}=-944.95D+1055.3$	−0.64
	Tf-1	$I_{d3}=-768.76D+882.77$	−0.85
	Tf-2	$I_{d3}=-944.82D+1012.2$	−0.90
	M	$I_{d3}=-326.45D+420.86$	−0.98
	Lst-1	$I_{d3}=-83.217D+178.85$	−0.22
	Lst-2	$I_{d3}=-403.35D+502.46$	−0.71
4	Sst-1	$I_{d4}=-937.56D+1054.6$	−0.84
	Sst-2	$I_{d4}=-585.08D+695.4$	−0.92
	WG	$I_{d4}=-1019.3D+1128.7$	−0.63
	Tf-1	$I_{d4}=-937.56D+1054.6$	−0.84
	Tf-2	$I_{d4}=-645.49D+692.27$	−0.86
	M	$I_{d4}=-401.19D+494.44$	−0.99
	Lst-1	$I_{d4}=-154.93D+249.87$	−0.26
	Lst-2	$I_{d4}=-343.71D+438.31$	−0.68

analyses were performed for each rock type as well as for all rock groups.

3. Results and discussion

The dry densities and point load strengths of rocks used in this study are given in Table 2. Table 4 shows the minimum, maximum, and the mean values of the fractal dimensions and their standard deviation for eight rock groups each having six subgroups. In Table 5, the average fractal dimension values of 8×6=48 groups of rocks with the number of slake durability test cycles are presented. The evaluation of these results using certain statistical methods are as follows.

3.1. Empirical relationships between fractal dimensions and slake durability index

The comparative examination of the I_d values for all group of rocks reveals that the variation of slake durability indices for the rounded aggregates (RN-1 and RN-2) is relatively low as compared to those for the angular (AN-1 and AN-2) and subangular (SA-1 and SA-2) aggregates. Goodman (1989) stated that an index property is considered to be useful only if it could give approximately the same results as the test is repeated. In this regard, only the rounded aggregates could be used for the slake durability tests for reliable results.

The variation between the lower and upper extremes of the slake durability indices ranges from 3 to 26% (Table 6) for the losses between the first and fourth wetting/drying cycles of different group of aggregate shapes. In order to illustrate this effect, the eight group of rocks are classified as fine grained and coarse grained and the variation of slake durability indices for only two cycles (I_{d2}) are plotted for different rock groups as shown in Fig. 8. Close examination of Fig. 8 reveals that

Table 8
The empirical relationships between dry density (ρ_d), point load strength [$I_{s(50)}$], and I_{d2} for coarse- and fine-grained rock groups

Rock type	The parameter compared	Regression equation	
Coarse grained	ρ_d–$I_{s(50)}$	$\rho_d=0.2389I_{s(50)}+1.5347$	$R^2=0.48$
	I_{d2}–ρ_d	$I_{d2}=29.003e^{0.4116\rho d}$	$R^2=0.63$
	I_{d2}–$I_{s(50)}$	$I_{d2}=10.4841I_{s(50)}+44.5$	$R^2=0.64$
Fine grained	ρ_d–$I_{s(50)}$	$\rho_d=0.063I_{s(50)}+1.9369$	$R^2=0.17$
	I_{d2}–ρ_d	$I_{d2}=110.59\mathrm{Ln}(\rho_d)+2.4638$	$R^2=0.55$
	I_{d2}–$I_{s(50)}$	$I_{d2}=39.177\mathrm{Ln}(I_{s(50)})+36.402$	$R^2=0.53$

R^2=coefficient of determination

the rocks of lower slake durability resistance are more prone to the variation with aggregate shape and surface roughness. This is particularly true for rocks with the I_{d2} values ranging from 40 to 80%. For example, the I_{d2} values of one of the tuff groups (Tf-2) are 40.8% and 66.8% for the angular and rounded aggregate groups, respectively, whereas the I_{d2} values of marl is 86.8% and 90.5% for the angular and rounded aggregate groups, respectively.

The empirical relationships between the I_d values and the fractal dimensions of rock groups are presented in Table 7 for different number of wetting/drying cycles. From this table, it can be observed that as the number of wetting/drying cycles increases, the absolute value of the correlation coefficient decreases. This can be attributed to the fact that, as the number of wetting/drying cycles increases, the effect of the shape and surface roughness of aggregates on the slake durability indices decreases. At the end of the first and second cycles, the sharp edges of the aggregates get rounded and their behavior resembles somewhat to that of rounded ones. That is to say, as the number of cycles increased and the aggregates get rounded, the loss of their masses decreases in further cycles. Generally, such effect is significantly high at the first and the second cycles.

The examination of Tables 6 and 7 and Fig. 8 reveals that the effect of angularity and surface roughness on the I_d values is more distinct and consistent for the medium to coarse grained rocks. However, the effect on the fine grained rocks is rather different because of the heterogeneities especially in the clayey limestones. Despite the great effort during the preparation of clayey limestone aggregates, the changes with the ratios of clay, calcite, dolomite, and fossil contents may have contributed to the uncertainties arising in the I_d results. Such effect is true for the other fine grained rocks as well.

Table 9
Summary of correlations between the point load strengths and dry densities

Rock type	Angularity	Coefficient of correlation	
		$r(I_{d2}-I_{s(50)})$	$r(I_{d2}-\rho_d)$
Coarse grained	RN	0.92	0.89
	SA	0.84	0.72
	AN	0.86	0.88
Fine grained	RN	0.96	0.81
	SA	0.54	0.19
	AN	0.86	0.42

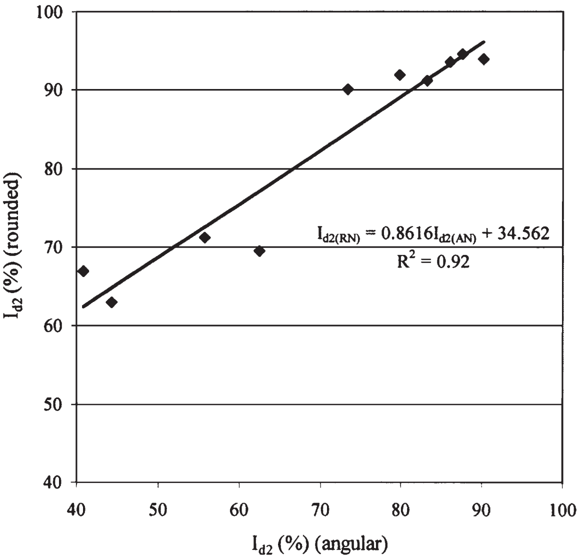

Fig. 9. The relationship between the I_{d2} values of the rounded and angular aggregates of the coarse grained group.

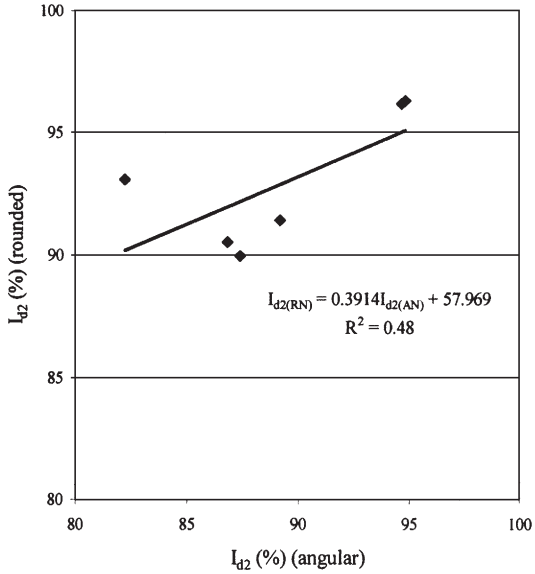

Fig. 10. The relationship between the I_{d2} values of the rounded and angular aggregates of the fine grained group.

Table 10
The functional relationships for predicting I_{d2}, I_{d3}, and I_{d4} directly from the I_{d1} values

Rock type	Regression equation	Coefficent of determination (R^2)
Coarse grained	$I_{d2}=1.9833I_{d1}-96.531$	0.96
	$I_{d3}=2.6344I_{d1}-161.77$	0.94
	$I_{d4}=2.9844I_{d1}-198.07$	0.90
Fine grained	$I_{d2}=31.456e^{0.0112Id1}$	0.92
	$I_{d3}=24.132e^{0.0136Id1}$	0.85
	$I_{d4}=22.778e^{0.0139Id1}$	0.69

This is also one of the reason for handling the rock groups according to their grain sizes.

3.2. General statistical evaluations

Strength of rocks is closely related to their mineralogical composition as well as their structural/textural properties. Density of a rock has a close relationship with its mineralogical composition. As the clay content of rocks increases, their densities, strengths and slake durability resistances decrease.

Because the density and strength are two fundamental index properties of rocks, attempts to establish empirical relationships between slake durability index and fractal dimension representing the aggregate shape and surface roughness include these two parameters as both dependent and independent variables. The results are given in Table 8 for all rock types combined. While comparing the relationships between strength, density, and slake durability resistance for coarse- and fine-grained rocks, it was observed that the relationships for rounded aggregates of the coarse-grained rock group yield usually higher values of correlation coefficients (Table 9). As the surface roughness increases, the values of correlation coefficients for the angular and subangular aggregates either fall or show fluctuations.

Table 11
A summary of the multiple regression analyses for coarse grained rocks

Parameter	Coefficient	Standard dev.	*t* values	Factor of significance
Constant	603.48	121.891	4.951	0.000
D	−685.805	120.542	−5689	0.000
ρ_d	74.38	9.308	7.992	0.000
$I_{s(50)}$	80.28	11.008	7.293	0.000
$\rho_d * I_{s(50)}$	−30.77	4.549	−6.764	0.000

Model
$I_{d2}=I_{s(50)}*80.28+\rho_d*74.38-D*685.805-\rho_d*I_{s(50)}*30.77+603.48$ ($R^2=0.92$)

Table 12
A summary of the multiple regression analyses for fine grained rocks

Parameter	Coefficient	Standard dev.	*t* values	Factor of significance
Constant	342.908	94.354	3.634	0.002
D	−258.373	91.189	−2.833	0.013
$I_{s(50)}$	3.78	0.871	4.338	0.001

Model
$I_{d2}=I_{s(50)}*3.780-D*258.373+342.908$ ($R^2=0.65$)

It was mentioned earlier that (Franklin and Chandra, 1972; ISRM, 1981; ASTM, 1990) the slake durability experiments require the use of rounded aggregates but it has not been the case in practice owing to the time consuming nature of the sample preparation procedure. This study shows that the slake durability indices of some rock type vary greatly with the variation in the shape of the test sample prepared. Figs. 9 and 10 show the relationships between I_{d2} values obtained using the rounded specimens and those using the angular aggregates for the coarse-grained and fine-grained rocks, respectively. A close relationship can be observed between I_{d2} value of rounded and angular aggregates of coarse grained rock. However, the relationship is relatively less prominent in aggregate of fine grained rocks.

Some researchers (e.g., Martin, 1986; Ulusay et al., 1995; Gokceoglu and Aksoy, 2000) proclaim that the slake durability tests would be more meaningful when using the results of four cycles instead of two. The slake durability test requires that the aggregates need to be oven-dried at 105 °C for 2 and 6 h after each cycle. Total hours required for large number of cycles renders this index test rather impractical. In order to shorten the duration and thus to empirically predict the I_{d2}, I_{d3} and I_{d4} values from directly I_{d1} value, some functional relationships were sought between the slake durability indices for different number of wetting/drying cycles. The results are listed in Table 10.

A close look to the Table 10 reveals that, the empirical relationships for the coarse-grained rocks are more prominent, which is similar to the previous comparison.

For the multiple regression analyses, the I_{d2} values were considered to be dependent variable whereas the D, $I_{s(50)}$ and ρ_d values were taken as independent variables. In addition, the impact of dual interactions between the independent variables (e.g., $D*I_{s(50)}$, $D*\rho_d$, $I_{s(50)}*\rho_d$) on the models to be constituted was investigated.

By using the computer code SPSS, it is possible to determine confidence interval of the model, the value of

R^2, and the degree of impact of the parameters utilized in the model. The factor of significance being lower than 0.05 (for the confidence interval of 95%) means that the model is statistically meaningful and the effect of parameters is significant. When examining the effect of a factor or the interaction for the model, the other factors and the interactions are excluded so that the effect of a certain factor as well as the statistical meaning of the model can be investigated.

The final regression models showing the interrelationships between the slake durability indices are given in Tables 11 and 12 for the coarse- and fine-grained rock groups, respectively. Also given in these tables is the surface roughness in terms of fractal dimensions along with the two other fundamental rock indices. In these models, the I_{d2} values are used as dependent variables while D, $I_{s(50)}$, and ρ_d values are independent ones. Further, the effects of the dual interactions between the independent variables (i.e., $D*I_{s(50)}$, $D*\rho_d$, $I_{s(50)}*\rho_d$) were also evaluated. Therefore, the model constructed for the coarse grained rocks is statistically meaningful and the density, strength and dual interactions have a significant effect for the model. However, the effect of density and dual interactions are insignificant for the model constructed for fine-grained rocks, and only meaningful relationship can be established between D and the strength [i.e., $I_{s(50)}$].

4. Conclusions and recommendations

Following conclusions were derived from this research:

1) The investigation of the effects of the surface roughness and aggregate shape on the slake durability of low- to medium-strength argillaceous rocks reveals that variations in the slake durability index for two cycles (I_{d2}) as high as 26% might develop for the same type of rock depending on the specimen preparation method.
2) When considering the limits of the classes of slake durability index of rocks, this high level of variation with the I_{d2} value may readily shift the class of any rock from one to another.
3) The experiments conducted on different rock type and shape of aggregate suggest that the best and the most consistent results are achieved when using the rounded specimens as indicated by the standards. In order for a parameter to be considered as an index property, it must give approximately the same results when repeated (Goodman, 1989). Thus, the results of slake durability tests should be considered meaningful only when performed using the rounded aggregates.
4) The rocks with lower slake durability indices are more susceptible to the variations with the aggregate shape and surface roughness. This is particularly true for those rocks having I_{d2} values between 40 to 80%. Thus, more attention must be paid when preparing the specimens of low strength materials than that of higher strength.
5) As implied by the correlation coefficient for the equation given below, there is a strong statistical relationship between the slake durability indices of angular aggregates [$I_{d2(AN)}$] and rounded aggregates, especially for the coarse grained rocks. Thus, the deviations in the slake durability index when using the angular aggregates would be eliminated by using the following equation:

$$I_{d2(RN)} = 0.86161 I_{d2(AN)} + 34.562 \times (R^2 = 0.92) \qquad (10)$$

6) Dry density and point load strength show greater degree of consistence when correlated with the I_{d2} values of the rounded group of coarse-grained rocks. However, such statement cannot be made for the fine grained rocks of this study.
7) The mean value of the fractal dimension (D) for all the rounded aggregates of eight group of rocks is approximately 1.030. Fig. 7 is presented to use as a guide for the rough definition of the fractal dimension of a specimen's shape in two dimensions.
8) The empirical relationship between the slake durability index and the fractal dimension representing the aggregate angularity or roundness, dry density, and the point load strength for the coarse grained rocks used in this study is as follows:

$$I_{d2} = I_{s(50)}80.28 + \rho_d 74.38 - D685.805 - \rho_d * I_{s(50)}30.77 + 603.48 \qquad (R^2 = 0.65) \qquad (11)$$

The present study did not cover all rocks that could be tested for slake durability and therefore care should be taken when considering the empirical relationships presented herein. The model presented here could be developed and put in a more general form by covering as many rock types as possible.

Although the results obtained this way would be somewhat conservative and put the designer on the safe side, it is better to utilize the most appropriate test results for such purposes. The greater variations of I_{d2} values emerging from mostly the use of angular and rough specimens may also lead to mistakes when indirectly predicting such parameters as the uniaxial compressive strength (σ_c), the point load strength [$I_{s(50)}$], and rock mass rating (RMR) from the empirical relationships utilizing the slake durability index.

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References

ASTM, 1990. Standard test method for slake durability of shales and similar weak rocks (D4644). Annual Book of ASTM Standards, vol. 4. 08. ASTM, Philadelphia, PA, pp. 863–865.

Barret, P.J., 1980. The shape of rock particles, a critical review. Sedimentology 27, 291–303.

Blatt, H., 1982. Sedimentary Petrology. W.H. Freeman and Company, San Francisco, CA. 564 pp.

Boggs, J.R., 1995. Principles of Sedimentology and Stratigraphy, 2nd ed. Prentice Hall, USA.

Carr, J.R., Warnier, J.B., 1987. Rock mass characterization using fractal dimension, Rock Mech. Proc. 28th US Symp. on Rock Mech. Tuscan, Arizona. Balkema, Rotterdam, pp. 73–80.

Chandra, R., 1970. Slake durability test for rocks. Unpublished M.S. thesis, Department of Mining, Imperial Collage, England.

Clayton, C.R.I., Matthews, M.C., Simons, N.E., 1995. Site Investigation. Blackwell Science Ltd., USA.

Dhakal, G.P., Yoneda, T., Kato, M., Kaneko, K., 2002. Slake durability and mineralogical properties of some pyroclastic and sedimentary rocks. Engineering Geology 65 (2002), 31–45.

Dhakal, G.P., Kodama, J., Yoneda, T., Neaupane, K.M., Goto, T., 2004. Durability characteristics of some assorted rocks. Journal of Cold Regions Engineering (2004) 18 (3), 110–122.

Dick, J.A., Shakoor, A., 1995. Characterizing durability of mud rocks for slope stability purposes. Geological Society of America, Reviews in Engineering Geology X, 121–130.

Dick, J.A., Shakoor, A., Wells, N., 1994. A geological approach toward developing a mudrock-durability classification system. Canadian Geotechnical Journal 34, 17–27.

Franklin, J.A., Chandra, R., 1972. The slake durability test. International Journal of Rock Mechanics and Mining Sciences 9, 325–341.

Gokceoglu, C., Aksoy, H., 2000. New approaches to the characterization of clay-bearing, densily jointed and weak rock masses. Engineering Geology 58, 1–38.

Gokceoglu, C., Ulusay, R., Sonmez, H., 2000. 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 (2000), 215–237.

Golden Software, 2000. Didger 2.0. Golden Software Inc., USA.

Goodman, R.E., 1989. Rock Mechanics, 2nd ed. John Wiley and Sons, USA.

ISRM, 1981. In: Brown, E.T. (Ed.), ISRM Suggested Methods: Rock Characterization, Testing and Monitoring. Pergamon Press, London. 211 pp.

Kolay, E. and Kayabali, K., 2005. Use of fractal dimension method for determining the angularity and surface roughness of aggregates: Yerbilimleri, (26)2, 49-61.

Koncagül, E., Santi, P.M., 1998. 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 (1999), 139–153.

Lee, S.G., Freitas, M.H., 1988. Quantitative definition of highly weathered granite using the slake durability test. Technical note. Geotechnique 38 (4), 635–640.

Mandelbrot, B.B., 1967. How long is the coast of Great Britain: statistical self similarity and the fractional dimension. Science 156, 636–638.

Mandelbrot, B.B., 1977. Fractals: Forms, Chance and Dimension. W.H. Freeman, San Francisco.

Mandelbrot, B.B., 1983. The Fractal Geometry of Nature. W.H. Freeman, New York. 468 pp.

Martin, R.P., 1986. Use of index tests for engineering assessment of weathered rocks. In: Proc. 5th. Int. Cong. of IAEG, Buenos Aires, 433–460.

Pettijohn, F.J., 1957. Sedimentary Rocks. Harper Brothers. Inc., New York.

Powers, M.C., 1953. A new roundness scale for sedimentary particles. Journal of Sedimentary Petrology 23, 117–119.

Rodrigues, J.G., 1991. Physical characterization and assessment of rock durability through index properties. NATO ASI Ser. E. Applied Sci., vol. 200, pp. 7–34.

Singh, T.N., Verma, A.K., Singh, V., Sahu, A., 2005. Slake durability study of shaly rock and its predictions. Environmental Geology (2005) 47, 246–253.

SPSS, 1998. Statistical Package for Social Sciences. SPSS Inc., USA.

Turcotte, D.L., 1992. Fractal and Chaos in Geology and Geophysics. Cambridge University Press, Cambridge, England.

Ulusay, R., Arikan, F., Yoleri, M.F., Caglayan, D., 1995. Engieering geological characterization of coal mine waste material and evaluation in the context of back analysis of spoil pile instabilities in a strip mine SW Turkey. Engineering Geology 40, 77–101.

Unal, E., 1996. Modified rock mass classification: M-RMR system. Milestones in Rock Engineering, The Bieniawsky Jubilee Collection. A. A. Balkema, Rotterdam.

Vallejo, L.E., 1994. Fractal analysis of the slake durability test. Canadian Geotechnical Journal 31, 1994.

Yilmaz, I., Karacan, E., 2005. Slaking durability and its effect on the Doline formation in the gypsum. Environmental Geology (2005) 47, 1010–1016.

Zhao, J., Broms, B.B., Zhou, Y., Choa, V., 1994. A study of the weathering of the Bukit Timah Granite. Part A: Review, Field Observations and Geophysical Survey. Bulletin of the International Association of Engineering Geology, Paris, vol. 49.