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ORIGINAL PAPER

Classification and modification of slake durability test for different types of rocks

Timur Ersöz[1] · Tamer Topal[2]

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Abstract

Rocks exposed to atmospheric conditions are subjected to weathering processes driven by numerous factors especially precipitation. The slaking behavior attributed to water-induced weathering particularly affects rocks containing pore spaces, fractures, and joints. This study aims to improve the slake durability test and propose a new classification method that is consistent with field conditions. The configured discard method (CDM), which incorporates the discard method (DM) to calculate the retaining weights after wet-dry cycles, is introduced. In this method, specimens are fully saturated in a vacuum chamber to approximate field conditions. The DM excludes discarded fragments by simulating rock mass detachment and result in a new equation and classification table based on two wet-dry cycles, Schmidt rebound hammer, point load index test, and effective porosity. In the study, 86 rock slopes across Turkey were investigated and different rock types were considered for the development of the equations, tables, and classification scheme. Significant differences are observed in comparisons with the standard method (SM), emphasizing the need to improve the methodology. An equation, combination of strength and porosity, is presented to provide a better correlation with slake durability. The study presents a new classification system based on CDM considering site performance and rock-specific parameters. The method was validated through tests, incorporating a new drum design with slot-type meshes, and showed higher accuracy compared to SM. Furthermore, the consistency of CDM with field observations and comparison with previous studies provides a more realistic representation of slake durability, underlining its reliability and potential for wider application.

Keywords Clay-bearing rock · Disintegration · Rock strength · Slaking · Slake durability test

Introduction

Rocks exposed to atmospheric conditions are affected by several weathering agents. These can be listed as rainfall, freezing and thawing, wind, and some biological effects. Rocks containing pore spaces, micro to macro fractures, joints, bedding planes, faults, and other similar discontinuities are prone to weathering due to temperature differences, wetting-drying, freezing-thawing, and chemistry of solutions absorbed. In general, the main cause of weathering of a rock is water, which is directly related to drying and wetting, freezing and thawing, and precipitation. Disintegration, breaking up, or weakening of a rock material which is exposed to water is explained by slaking phenomenon (Morgenstern and Eigenbrod 1974; Nettleton 1974). This can be explained as a rock material getting wet, absorbing water into its structure and eventually breaking the bonds between clay minerals or widening the fractures. Subsequently, shrinkage takes place as the opposite effect of the drying of the saturated material. The cycles of these activities cause the material to disintegrate. This phenomenon is observed more in clay-bearing rocks which are affected easier due to their weak structures. It is known that 2/3 of the stratigraphic column (Blatt 1982) and 1/3 of the total land area (Franklin 1983) are represented by the mudrocks. These fine-grained siliciclastic sedimentary rocks containing more than 50% clastic grains smaller than 0.06 mm in diameter (Blatt et al. 1980) can be classified as siltstones, shales, mudstones, and claystones. Not only mudrocks, but also marl and slate contain clay particles that can be affected by water intrusion. Natural exposures of these materials are open to weathering conditions, air, water, and physical disturbances. Also, these clay-bearing materials are poorly

✉ Timur Ersöz
ersoztimur23@gmail.com

1 Graduate School of Science and Technology, Niigata University, 9502181 Niigata, Japan

2 Department of Geological Engineering, METU, Ankara 06800, Turkey

understood in terms of their engineering properties so that they may cause slope stability problems and embankment failures. Therefore, many laboratory tests like wet-dry test (Phillbrick 1950), ultrasonic degradation test (Gipson 1963), slake durability test (Franklin and Chandra 1972), rate of slaking test (Morgenstern and Eigenbrod 1974), Washington degradation test (Reidenouer et al. 1974), modified soundness test (Wood and Deo 1975), jar slake test (Wood and Deo 1975), simple slake test (Stollar 1976), freeze-thaw test (RILEM 1980), and salt crystallization test (RILEM 1980) were developed. These tests were used by many scientists to determine the slaking conditions of the materials by assigning durability values. The classification developed by Gamble (1971) introduces the ranges for retaining percentages of the materials after slaking. ISRM (1981) suggested method for slake durability index test adopts Gamble's classification chart to assess the durability of the rocks against slaking. Even though this classification is widely used, scientists tend to improve their tests to obtain accurate results. In addition, there are many examples in the literature showing that the results do not match the real conditions in the field (Hopkins and Deen 1984; Dick and Shakoor 1992; Topal and Doyuran 1997; Heidari et al. 2018; Fereidooni and Khajevand 2018; Selen et al. 2020). Assigning inaccurate values to the slopes, embankments and dam reservoir areas, which are severely influenced by wet-dry cycles, can have unintended consequences and affect both the structure itself and human life.

The main purpose of this study is to improve the methodology of testing for slake durability and to introduce a new classification system that can accurately reflect the actual performance of various rocks. This real effort involved a modification of the approach to slake durability by considering additional parameters such as strength and effective porosity in order to better reflect field conditions. Subsequently, the configured discard method (CDM) was developed to determine the slake durability of rock masses. The discard method (DM) was applied to calculate retaining weights after each wet-dry cycle, providing a more rigorous estimate. This innovative method involves fully saturating the samples in a vacuum chamber to accelerate degradation and to simulate field conditions during testing. In order to simulate realistic scenarios where fragments break away from the rock mass, the weighing process deliberately excludes fragments discarded from each piece under the discard method (DM). The research paper presents a new equation and classification table that utilizes two wet-dry cycles, point load index test, Schmidt rebound hammer, and effective porosity data to estimate the slake durability of various rock types. In order to better understand the exact conditions of the rocks, a comprehensive investigation of 86 rock slopes in various regions including Ankara, Zonguldak, Karabük, Bolu, Çankırı, Kastamonu, and Bilecik was carried out in this study. This detailed analysis was used to develop the equations, graphs, and description tables. A variety of rock types were sampled to provide a representative cross-section for the study, including andesite, flysch, basalt, conglomerate, granite, granodiorite, graywacke, limestone, marl, mudstone, sandstone, shale, siltstone, and tuff.

Theoretical background

Slaking is defined as crumbling and disintegration of earth materials exposed to air or moisture, breaking up of dried clay when saturated with water due to either compression of entrapped air by inwardly migrating capillary water or progressive swelling of the outer layers (American Geological Institute 1962), resistance of a rock sample to weakening and disintegration resulting from a cycle of drying and wetting (Franklin and Chandra 1972), disintegration of rocks by water immersion (Nettleton 1974), or disintegration of mudstones upon alternate drying and wetting cycles (Morgenstern and Eigenbrod 1974). As the definition suggests, the main factors affecting the slaking behavior are clay-bearing rocks and presence of water. Also, wet-dry cycles play an important role by changing the material volume, affecting the structure and breaking up the bonds of clay minerals by swelling and shrinking. The three fundamental concepts of slaking can be listed as material, mechanism, and time.

Many kinds of slaking can be listed but the major types are indicated as slaking to inherent grain size, chip slaking, and slab or block slaking (Andrews et al. 1980). Slaking to inherent grain size occurs in the destruction of the matrix and the formation of a sediment mass of fine-grained particles. This mode of slaking generally occurs in a time period ranging from a few days to several years which is generally observed in mudstones and sometimes sandstones. Chip slaking is way different than slaking to inherent grain size in terms of destruction. This kind of slaking generally occurs as thin slabs in dimensions of 0.6 to 2 cm in width and 2.5 to 15 cm in length. Further slaking of these thin slabs is not usual but generally stable. Slaking starts from the planes of weaknesses that cannot be observed from the fresh rock materials in the field. The existence of contrasting mineralogy such as aggregation of mica flakes was found to be a reliable indicator of chip slaking. As the mode of failure implies, this type of slaking can be observed in shales and siltstones and sometimes in thin bedded sandstones. Lastly, slab or block slaking occurs as thick slabs or equidimensional blocks in sizes ranging from 7.5 to 180 cm. Degradation initiates along natural or blasting-induced fractures. Once they are broken into blocks, they are considered to be resistant to further breakdown. Sandstones and limestones can show this type of slaking behavior. If rocks undergo more than one type of slaking, it generally starts from chip slaking to inherent grain size. Time required for slaking under such cases can be changed from instantaneous to less than 6 months (Perry and Andrews 1982).

Many slaking tests have been developed to assess the behavior of the materials. The most popular one among them is slake durability index test (Franklin and Chandra 1972; ISRM 1981). Slake durability test was first introduced by Chandra in 1970 as a one-cycle test. It was later developed to a two-cycle wet-dry test by Gamble in 1971. Later, Franklin and Chandra (1972) developed the test again as two cycles according to its final state. Slake durability test is conducted with an equipment containing an engine, two drums, and two pools. The engine has the capability of rotating the drums 20 rpm in one direction. Two identical drums have 2-mm mesh with 1-mm steel wire thickness. They are located at both ends of the engine and are submerged in pools of water up to a certain height. The slaking fluid is recommended as tap water at 20°C to a level 20 mm below the drum axis (ISRM 1981). In the beginning of the test, 450–550 g of test material is chosen to be put into the drums. It is usually desirable that each piece of material is around 50 g. It is suggested that the sharp edges of the rocks are rounded before the test to avoid any biased results. Before starting the test, materials are put into oven at 105°C for 24 h to obtain dry weights. The drums are rotated for 10 min to complete one test cycle. After 10 min, samples are put into oven again at 105°C for 24 h and the dry unit weights are measured. The same procedure is applied for the 2nd cycle. According to the initial and the retaining weights in the drums after 1st and 2nd cycles, slake durability index values Id_1 and Id_2 are obtained, respectively. The main idea of this test is determining the retaining weights in the drums after two wetting and drying cycles. In order to classify durability, Gamble (1971) presented a classification table based on the retaining weight percentages of the specimens after first and second cycles (Table 1). Parameters affecting the behavior of the samples can be listed as testing fluid, sample shapes, test equipment properties, wet dry cycle durations, number of wet-dry cycles, and sample properties such as effective porosity, permeability, and swelling.

After the presentation of the slake durability index test, many researchers have continued to develop this test until today. The researchers examined the effect of parameters such as the nature of the water used, number of cycles, rotation durations, drying temperatures, properties of clay minerals, and sample shapes. Although the test was originally designed using tap water, distilled water (Moriwaki and Mitchell 1977) and water with different pH values (Kayabali et al. 2006) were used to investigate the slaking behavior of different minerals in the rocks. Similarly, many researchers studied the effect of change of number of cycles and rotation durations (Hopkins and Deen 1984; Richardson and Long 1987; Taylor 1988; Dick and Shakoor 1992; Dick et al. 1994; Moon and Beattie 1995; Tuğrul and Zarif 1998; Gökçeoğlu et al. 2000; Kolay and Kayabali 2006; Ankara et al. 2015; Fereidooni and Khajevand 2018; Selen et al. 2020). Russell (1982) and Selen et al. (2020) suggested using different drying temperatures between the cycles. Clay mineral types (Moon and Beattie 1995) and material roundness (Kolay and Kayabali 2006; Ankara et al. 2015) are also found to be effective on the slaking of materials. Koncagul and Santi (1999) used a correlation between UCS and Id_2. Another correlation was used to obtain Id_2 considering P-wave velocity (Sharma and Singh 2006). Santi and Higgins (1998) and Santi (2006) used jar slake test, Schmidt hammer rebound test, and Id_2 to find slake durability index of shales. Erguler and Shakoor (2009) developed a new technique to assess disintegration of rocks and adopted this parameter into equations to estimate Id_2 values. They used different sieve sizes to develop disintegration ratio of the rocks considering the area obtained from fragment size distribution curves. Moradian et al. (2010) reveal that slake durability is correlated with effective porosity, density, P-wave velocity, and UCS. According to their results, the most significant correlation is found to be effective porosity and P-wave velocity with slake durability index. In their research, Kolay et al. (2010) used neural network to predict Id_2 by using fractional dimension of the samples, point load strength index, and dry unit weight. Yang et al. (2023) proposed the relationship between electric resistivity of the carbonaceous rocks and slake durability index.

There are many parameters that affect the slake durability of a material. These include testing fluid, sample shapes, test equipment properties, wet-dry cycle durations, number of wet-dry cycles, and some sample properties like strength, effective porosity, permeability, and swelling. Slake durability test comprises all these parameters to assign the index value of a material. Researchers worked on these parameters to obtain most accurate results indicating the field conditions. There have been many attempts to change the number of wet-dry cycles to approach the values reflecting field conditions. In general, cycles have been increased up to three and four (Taylor 1988; Moon and Beattie 1995; Tuğrul and Zarif 1998; Gökçeoğlu et al. 2000) and in some cases ten (Ankara et al. 2015; Zhang et al. 2024) and even up to 15 cycles (Jamshidi and Sedaghatnia 2023). In some studies, durations of the cycles were also increased (Hopkins and Deen 1984). Sample properties like effective porosity, permeability, and swelling are not considered in the standard test. The only parameter considered apart from retaining weight is plasticity of the samples. Furthermore, no rock

Table 1 Gamble's slake durability classification (Gamble 1971)

Group name	Id_1	Id_2
Very high durability	> 99	> 98
High durability	98–99	95–98
Medium high durability	95–98	85–95
Medium durability	85–95	60–85
Low durability	60–85	30–60
Very low durability	< 60	< 30

type or clay content values are considered while assessing the durability of a material. The mesh size (2 mm) also poses a problem, as large particles cannot pass through the sieve even if they are completely degraded in the drum. Another issue concerns the shape of the slaked particle. Some types of rocks can be slaked into inherent grains, while others can show chip slaking. Moreover, slaking can also occur on the plane of weaknesses of rocks that are disintegrated into thin slabs, which cannot pass from the 2 mm mesh. There are many studies in the literature that exceed the cycles proposed by the original method (Taylor 1988; Moon and Beattie 1995; Tuğrul and Zarif 1998; Gökçeoğlu et al. 2000; Ankara et al. 2015; Selen et al. 2020), while durability classification introduced by Gamble (1971) classifies the slaking values up to Id_2 (two wet-dry cycles). Therefore, cycles exceeding original method cannot be classified in terms of durability in a proper way. Also, durability classes are not described to reflect to field conditions.

Materials and methods

Material properties

Materials of this study composed of a diverse range of rock types obtained from various regions: Ankara, Zonguldak, Karabük, Bolu, Çankırı, Kastamonu, and Bilecik in Turkey. The rock types sampled are intended to enable a comprehensive coverage of the study, including andesite, flysch, basalt, conglomerate, granite, granodiorite, greywacke, limestone, marl, mudstone, mudstone, sandstone, shale, siltstone, and tuff. Samples and their locations were chosen for their extensive prevalence in natural exposures and their susceptibility to weathering, thereby qualifying them for the slake durability tests. Properties of the sampled rocks are summarized in Table 2. Hand specimens collected from the field were used in order to obtain point load index and effective porosity values of different kind of rocks. Point load test was conducted on ten irregular shaped samples for each sample location. Effective porosity was obtained by using vacuum chamber. L-type Schmidt hammer rebound test was conducted with a minimum distance of 10 cm from the nearest joint and perpendicular to the inclined surface of the road cut.

Methodology

This study consists of several steps in the improvement of the slake durability test. In the first phase, a slake durability classification table was developed based on field observations. While creating the table, characteristics such as rock dimensions, weathering degree, and rock type were used and the classification was made according to the field observations of the authors. The strength and porosity properties of the rocks collected from the field were then analyzed in the laboratory and in situ. The rocks were also prepared for use in slake durability testing. In the next phase, the discard method (DM) was developed specifically for this study. As a side alternative to the DM, two different slot type mesh drums were also developed (Fig. 1). In order to improve the effect of the DM to slaking, a slake durability classification chart was then developed by combining strength and porosity properties with DM and using the slake durability classification table obtained from field observations. Lastly, this chart was validated with control groups.

Table 2 Schmidt hammer rebound, point load, and effective porosity of the samples

	Schmidt hammer rebound	Point load (Is50 MPa)	Effective porosity (%)	Number of sample
Andesite	34	6.54	4.35	3
	±7	±0.29	±0.44	
Basalt	34	4.97	9.49	5
	±12	±3.28	±2.85	
Conglomerate	20	0.57	14.11	1
	-	-	-	
Flysch	39	4.31	4.91	8
	±11	±1.76	±2.85	
Granite	10	0.87	4.76	2
	±0	±0.82	±2.82	
Granodiorite	26	0.71	3.27	2
	±3	±0.24	±1.02	
Greywacke	23	0.84	6.23	1
	-	-	-	
Limestone	35	2.66	8.11	12
	±14	±0.81	±2.15	
Marl	21	3.04	9.55	19
	±11	±1.97	±5.18	
Mudstone	10	1.25	14.13	4
	±0	±0.77	±4.44	
Sandstone	28	2.29	10.48	26
	±10	±1.42	±4.19	
Shale	29	3.90	3.50	1
	-	-	-	
Siltsone	31	6.40	7.30	1
	-	-	-	
Tuff	16	0.29	13.00	1
	-	-	-	

Slake durability classification table

Gamble's (1971) slake durability classification table was designed based on percentage retained in the drums after

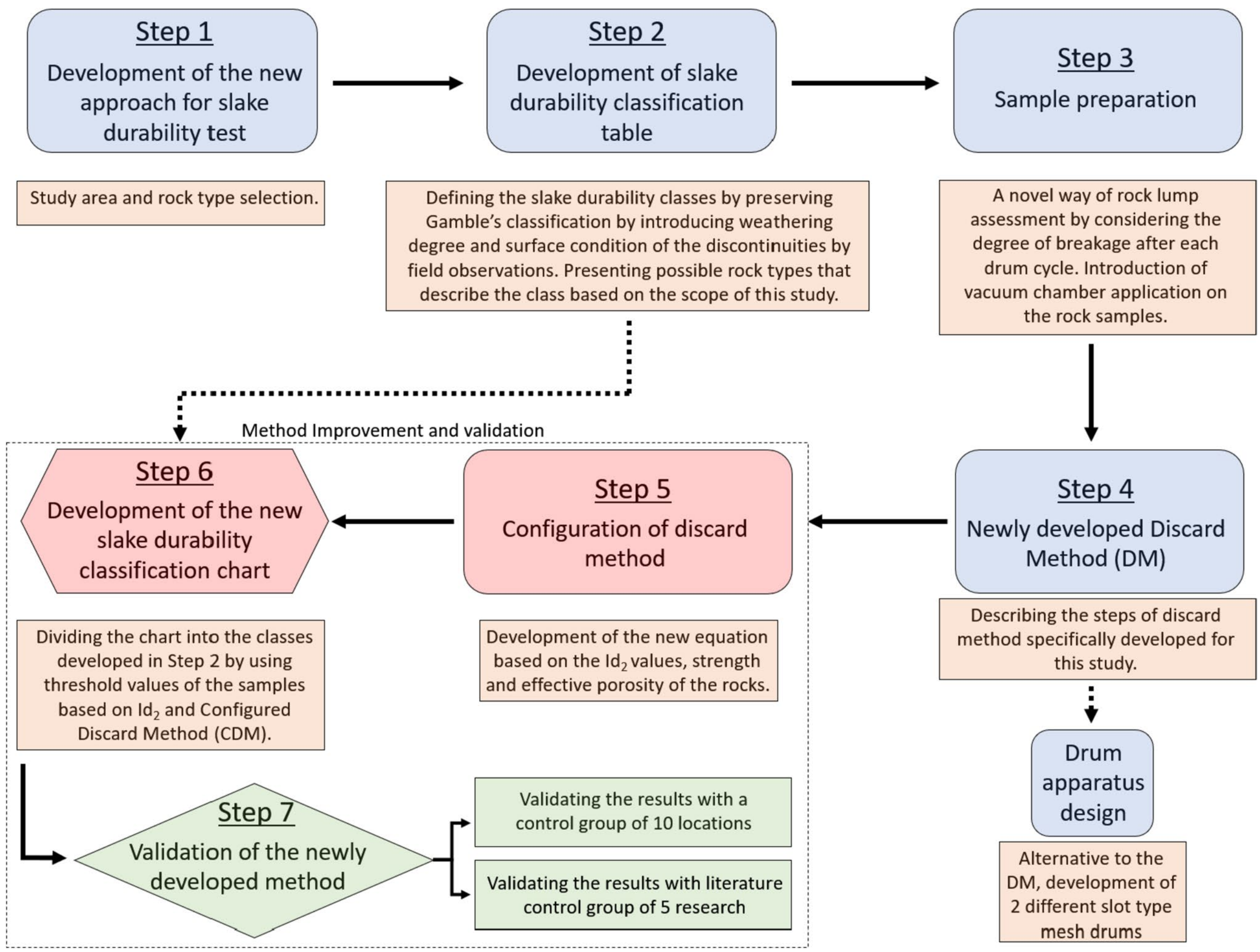

Fig. 1 Development procedure of the new slake durability system

first and second dry-wet cycles. Six classes presented in the table define the rocks based on their durability against slaking. The lack of field reflections of the classes in the table can cause subjectivity among researchers. In order to prevent this and to facilitate the use and objectivity of the new method developed in this study, a descriptive classification table is presented (Table 3). The main aim of this table is to add definitions to Gamble's (1971) slake durability classes to better understand the condition of the rocks in the field by observations. The definitions in the table, which the authors decided in the line with their field observations, are considered in six categories in order to remain in the line with Gamble (1971). This table is created based on the rock types used in this study and field observations. The structural features and appearances of the rock masses in the outcrops are highlighted. Eighty-six rock slopes were investigated in the field to create this complete definition table including the features like weathering degree, block size, and type of the rocks.

Strength and effective porosity features of the rocks

Strength and effective porosity play significant roles on material slaking. Low strength and high effective porosity both reduce the durability of rocks. In addition, weak and porous rocks are prone to weathering, which eventually further reduces strength and increases effective porosity. Therefore, the link between a rock's slake durability and its weathering potential is inevitable. Rocks with high porosity allow water to penetrate into the pores and cause the rock to become easily saturated with water, leading to decrease in its strength and subsequent disintegration. Many researchers in the literature have considered increasing the number of cycles or the duration of the experiment when implementing or developing the slake durability test, because the two cycles of 10 min used in the standard method (SM) proposed by ISRM (1981) (slake durability index test) do not accurately reflect the field conditions. In the interest of time-saving and adhering to a method that is as familiar as possible to the users, the new method developed in this study

Table 3 Slake durability classification table

Class	Definition
Very high durability	Completely durable rock body. None or very small fallen or broken blocks from the outcrop. Slight surface staining or fresh appearance. Original conditions of the discontinuities are preserved. Strong basalt, andesite, granite or limestones.
High durability	Very small, small, or medium blocks fallen or broken from the outcrop. Slight surface staining. Original conditions of the discontinuities are preserved up to certain degree. Strong basalt, andesite, limestone, silicified sandstone, or siltstone. None or minor amount of material accumulated at the toe of the slope.
Medium high durability	Very small, small, medium, or large blocks fallen or broken from the outcrop. Surface staining and degradation due to weathering can be observed. Original condition of the discontinuities and surface of the body is disturbed. Moderately strong limestone, sandstone, or marl. Minor amount of material accumulated at the toe of the slope.
Medium durability	Very small, small, medium, or large blocks fallen or broken from the outcrop. Moderately or highly weathered rock body can be observed. Some discontinuities cannot be traced. Secondary apertures are created due to degradation. Moderately strong sandstone, limestone, marl, or flysch. Minor to major amount of material accumulated at the toe of the slope.
Low durability	Very small or small blocks fallen or broken from the outcrop and accumulated at the toe of the slope. Undercutting can be observed. Moderately or highly weathered rock body. Many discontinuities cannot be traced. Secondary apertures are created due to degradation. Weaker rocks are completely weathered for flysch or alternating rocks. Moderately weak to weak limestone, sandstone, marl, flysch, conglomerate, tuff, and highly altered granite or basalt. Major amount of material accumulated at the toe of the slope.
Very low durability	Very small or small blocks fallen or broken from the outcrop and accumulated at the toe of the slope. Highly or completely weathered rock body. Most of the discontinuities cannot be traced. Secondary apertures are created due to degradation. Weaker rocks are completely weathered for flysch or alternating rocks. Weak to very weak sandstone, mudstone, flysch, or highly altered granite. The amount of accumulated material dominates the appearance of the slope.

was conducted under saturated conditions while determining the strength parameters in order to obtain results close to field conditions. The same principle was applied to determine the effective porosity and the results were obtained by using a vacuum chamber.

The strength of the materials used in this study are determined in two ways: under laboratory conditions by using point load index test and by using L-type Schmidt rebound hammer in the field. Unlike uniaxial compressive strength, point load index test can also be applied to irregular specimens, allowing the user to easily determine the rock strength. Ten irregular shaped specimens representing each road cut were used in this test. The average values of the test results were assigned as the point load strength of each road cut. L-type Schmidt rebound hammer was conducted in the field on slope surfaces which enables simple measurements to be taken from many points in the rock mass, which provides accurate results by giving the strength of the rock in natural conditions. And this test eliminates the use of hand specimens, which can be collected from the most convenient locations and give biased results. It also offers fast results without the need to prepare specially shaped hand specimens. The application point of the experiment should be at least 10 cm away from the nearest joint and perpendicular to the sloping surface of the road cut. The porosity values of the samples were determined using a vacuum chamber and averaged over 10 samples of each road cut.

Sample preparation for slake durability test

The new method adopts to eliminate fragments that break off from the original lump. Therefore, visual inspection between cycles plays an important role. As suggested by SM, ten irregular samples of almost identical size were prepared, totaling about 500 g. To facilitate the lump tracking, it is highly recommended to photograph and number each lump before each test cycle. The slaking process can take from days to several years under natural conditions, depending on the material and type of slaking. Laboratory tests aim to shorten these times and provide fast and accurate results. Since the main factor in the slake durability test is that water penetrates the rock and causes degradation, it is important to accelerate this process. Therefore, the samples are kept in a vacuum chamber between drying in an oven and drum rotation.

Discard method (DM)

Originally, the percentage of weight retained is calculated by the particles remaining in the drum after two test cycles. Even if all particles are fragmented, if they are larger than 2 mm, the Id_n value is calculated as 100% according to the standard formula. In this study, a new approach called discard method (DM) is introduced. The logic behind this method is that materials detached from the mail block are discarded regardless of their size. The main reason for developing such an approach is to reflect the in situ assessment of a rock. The loss of weight or volume of a rock mass can be detected by broken pieces deposited at the edge or bottom of an outcrop/slope. Based on this, the pieces that break off from the original lumps are excluded from the weighing calculations. The same logic is built to be applied on the slake durability of materials. In this method, the same steps are followed with the original slake durability index test with some modifications. Other procedures specified in the SM must be applied to obtain the best result reflecting the field conditions. The modified steps are listed as follows:

- The samples used in the test must be photographed and numbered (ten samples with a total weight of about 500 g is the best configuration) before applying any step of the experiment. After each cycle (starting from $t = 0$), the orientation and numbering of the rocks photographed before a cycle must be kept the same and photographed

Fig. 2 Samples before (above) and after (below) two cycles of slake durability test. Pieces marked in red are excluded from the calculation because they are smaller in mass than the original lump

again. This helps the user to understand the loss of material from an original lump, even if it is retained in the drum after the cycle.

- Different than the suggested test technique (ISRM 1981), the samples must be soaked in the vacuum chamber between oven dry and drum rotation in order to accelerate the disintegration processes.
- Any broken piece smaller in weight than the original lump must be identified and discarded from the weighing (Fig. 2).
- If more than half of a lump is broken into pieces, the whole lump must be discarded from the weighing (Fig. 3).

Drum apparatus design

The drums used in SM have 2-mm openings which do not allow the broken particles to fall into the pool. Therefore, a drum apparatus with different slot type mesh sizes, 5 mm × 40 mm and 10 mm × 40 mm, was developed in order to approach DM results (Fig. 4). These drums are designed to be used as an alternative to DM which allows a less complicated approach to estimate the slake durability without considering the steps listed in DM. Instead of using round or square openings, slot type openings were chosen to help

Fig. 3 Samples completely discarded after two cycles of slake durability test. Lump numbers 5 and 7 are discarded from weighing since more than half of its original weight is lost. Thick marked pieces of lump 1 and 4 are included (having weight more than half of the original lump); however, cross-marked pieces are discarded (having weight less than half of the original lump)

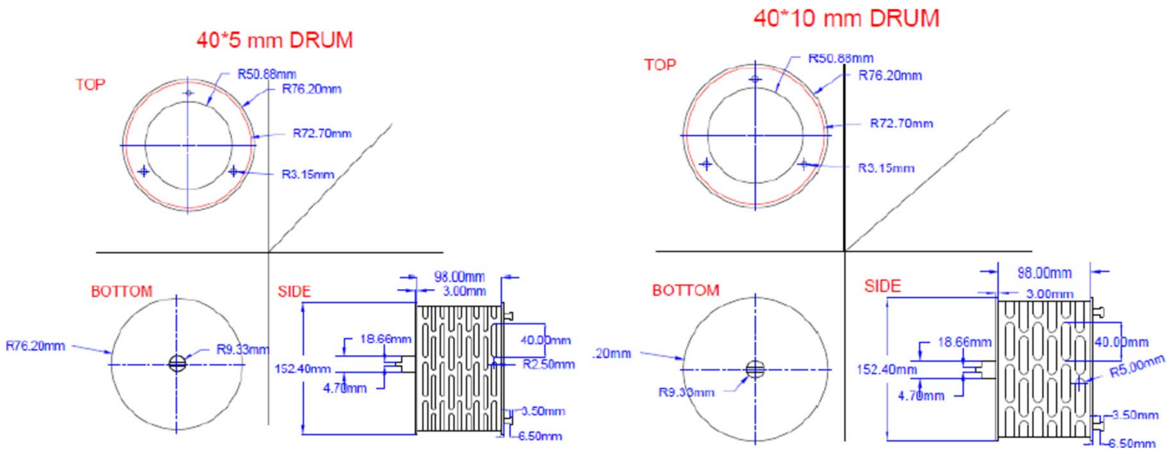

Fig. 4 Dimensions of slot type openings drum apparatus design with top, bottom and side views (40 × 5 mm drum on the left, 40 × 10 mm drum on the right)

remove both round/sub-round and flat type particles during drum rotation. The only difference of the original test apparatus and new design is the mesh section. The dimensions of the other parts are the same as with the original apparatus. Two pieces of each drum set have been made with stainless steel, having the same weight with the original drums (Fig. 5). Since the weight and size are similar to the original ones, engine limits are not pushed.

Development of the new slake durability classification chart

The DM developed for this study is used to calculate Id_2 values. In addition to the slake durability value obtained as a result of this 2nd cycle, properties such as strength and porosity that affect rock durability also have a certain level of influence on the slake durability of the rock. For this reason, the DM method has been configured by using saturated point load, Schmidt hammer, and effective porosity parameters to classify the slake durability of the rocks as a result of the proposed new experiment. The main purpose of the configuration process was to correlate the field observations with the results obtained from the experiment. The weighted coefficient of each parameter was found by using indirect methods. Each coefficient found by random iterative testing was continuously varied in order to classify the rocks accurately and finally fixed values were reached.

Validation of the newly developed method

An additional set of ten rock slopes was analyzed in order to validate the new proposed method. Moreover, five research consisting of 56 samples examining different rock types were reviewed (Pasamehmetoglu 1981; Topal and Doyuran 1997;

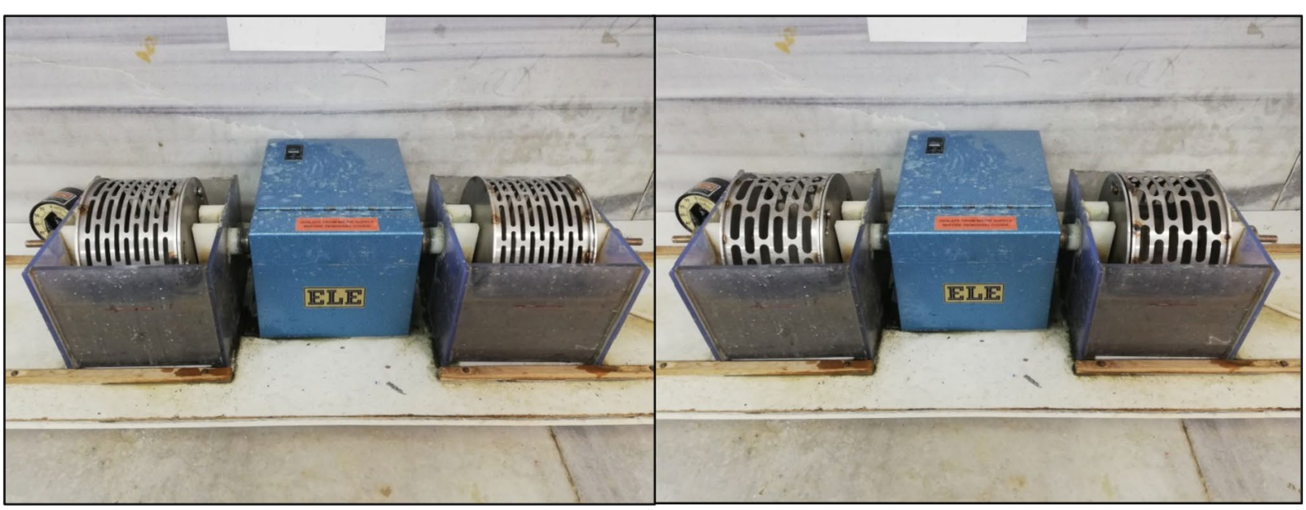

Fig. 5 Slot type opening drums integrated into the slake durability index test device

Table 4 Rock type, strength, and porosity features of collected samples and literature-derived samples

	Name	Rock type	Schmidt rebound hammer	Saturated point load strength index (Is50 MPa)	Effective Porosity (%)		Name	Rock type	Schmidt rebound hammer	Saturated point load strength index (Is50 MPa)	Effective porosity (%)
Collected samples group	TT-01	Mudstone	10	0.69	30.37	Literature-derived samples group	Pasa-Kizil3	Andesite	30	1.82	17.21
	TT-02	Mudstone	10	0.72	21.95		Pasa-Kizil4	Andesite	20	0.68	20.85
	TT-03	Mudstone	34	0.79	25.24		Pasa-Gol1	Andesite	61	5.18	9.00
	TT-04	Mudstone	10	0.30	39.16		Pasa-Gol2	Andesite	50	2.85	14.31
	TT-05	Mudstone	10	0.40	39.11		Pasa-Gol3	Andesite	28	1.08	19.16
	TT-06	Mudstone	18	2.07	22.72		Pasa-Gol4	Andesite	25	0.71	21.46
	TT-07	Flysch	48	6.50	9.55		Pasa-Kos1	Andesite	54	2.90	10.16
	TT-08	Flysch	60	1.44	9.87		Pasa-Kos2	Andesite	40	2.55	11.18
	TT-09	Flysch	40	0.99	13.96		Pasa-Kos3	Andesite	30	1.57	14.69
	TT-10	Sandstone	15	0.08	25.21		Pasa-Kos4	Andesite	22	0.55	17.92
Literature-derived samples group	TT-VD-1997	Tuff	27	0.13	38.29		Pasa-Cubuk1	Andesite	50	4.51	2.22
	Heidari-S1	Marl	19	1.61	16.43		Pasa-Cubuk2	Andesite	47	3.34	4.62
	Heidari-S2	Marl	18	1.12	12.45		Pasa-Cubuk3	Andesite	34	2.35	5.66
	Heidari-S3	Marl	19	1.60	25.02		Pasa-Cubuk4	Andesite	23	0.55	8.50
	Heidari-P1	Sandy Marl	21	2.25	6.83		TT-BS-2003 W	Tuff	16	0.25	38.82
	Heidari-P2	Marl	20	1.92	6.59		TT-BS-2003P	Tuff	33	0.78	33.48
	Heidari-P3	Marly Limestone	23	3.12	5.50		AG-1990 W	Tuff	14	0.24	28.30
	Heidari-P4	Sandy Limey Marl	22	2.83	3.17		AG-1990P	Tuff	24	0.75	24.20
	Heidari-G1	Marl	19	1.72	13.10		Binal 1998 W	Tuff	18	0.40	33.10
	Heidari-G2	Limey Marl	20	2.08	7.91		Binal 1998P	Tuff	33	1.20	29.10
	Heidari-Ag1	Marl	18	0.88	22.78		BE-Ekinli	Tuff	48	1.40	23.91
	Heidari-Ag2	Marl	17	0.47	22.05		BE-AlabeyliY	Tuff	46	2.31	28.17
	Heidari-Ag3	Clayey Siltstone	17	0.70	19.40		BE-AlabeyliW	Tuff	42	1.81	24.93
	Heidari-Ag4	Clayey Siltstone	17	0.71	16.67		BE-Pusatli	Tuff	48	1.57	34.84
	Heidari-Ag5	Marl	16	0.32	28.67		BE-Komurkoy	Tuff	28	1.82	31.71
	Heidari-Ag6	Clayey Siltstone	18	1.19	7.28		BE-Kurukop	Tuff	56	2.37	22.04
	Heidari-Ag7	Marl	20	1.87	10.52		BE-KamberG	Tuff	38	1.16	30.72
	Heidari-Ag8	Clayey Siltstone	18	1.01	16.76		BE-KamberB	Tuff	38	0.84	35.88
	Heidari-Ag9	Clayey Siltstone	18	0.87	11.63		BE-KamberY	Tuff	45	1.28	32.13
	Heidari-Ag10	Clayey Siltstone	22	2.89	5.68		BE-Gesi	Tuff	45	1.11	28.99
	Heidari-Ag11	Clayey Siltstone	22	2.79	8.32		BE-Incesu	Tuff	48	0.95	21.78
	Pasa-Kizil1	Andesite	52	4.15	4.63		BE-SevıncG	Tuff	32	0.47	21.23
	Pasa-Kizil2	Andesite	42	2.35	11.19		BE-SevıncP	Tuff	35	0.66	28.99

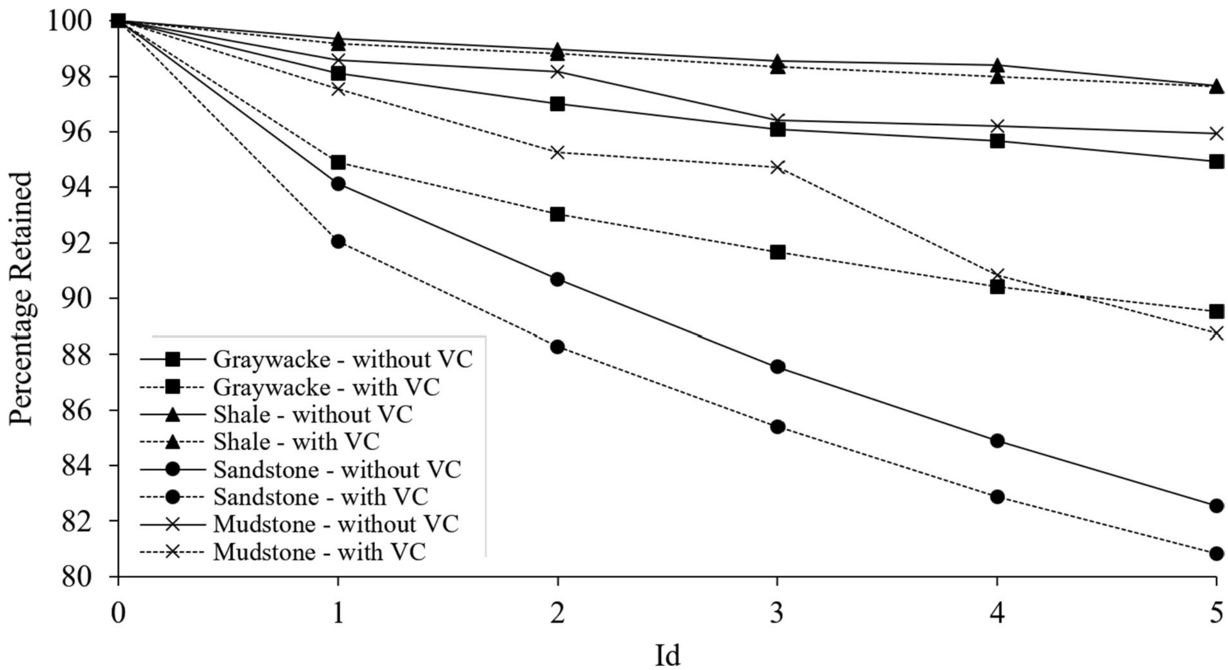

Fig. 6 Percentage retained of different rock types with and without vacuum chamber (VC) application before each cycle

developed parameter, which is a combination of these three parameters, and Id_2 (Fig. 9). In this context, weighted coefficients of 0.85, 0.1, and 0.05 were assigned to the saturated point load strength index, Schmidt hammer rebound, and effective porosity values, considering their effects on slake durability. Since the units of each parameter are completely different, additional coefficients were also assigned to equalize their position on the same axis (Eq. 1).

$$CDM = [(P \times (-3)) + 65 \times 0.05] + [S \times 0.1] + [a \times SPL \times 6 \times 0.85] \quad (1)$$

where *CDM* is the configured discard method, *P* is the effective porosity (%), *S* is the Schmidt hammer rebound value, *SPL* is the saturated point load strength index (MPa), and *a* is the coefficient constant.

Here it should be noted that the values assigned to the parameters are obtained by trial and error to best fit the relationship between CDM and Id_2.

As the effective porosity increases, slake durability decreases as the specimen absorbs more water, leading to a higher degree of degradation. On the other hand, strength is directly proportional to the slake durability, as low strength values can lead to further material degradation. Therefore, the effective porosity values are inverted by a negative constant value in Eq. 1. In addition, another coefficient "a" is inserted in the equation which has the relation with Id_2 and saturated point load strength index. The value is developed to categorize the durability classes based on the field conditions of the rocks. As per the other constants in the equation, "a" is derived by indirect methods, i.e., random iterative testing, to obtain the highest possible correlation between CDM and Id_2.

If		a
$Id_2 \geq 98$	SPL≥4,5	1,0
	SPL<4,5	2,0
$98 > ıd_2 \geq 92{,}5$	SPL≥4,5	0,7
	4,5>SPL≥3,5	1,0
	3,5>SPL≥2,0	1,5
	SPL<2,0	2,5
$92{,}5 > ıd_2 > 90$	SPL≥4,5	0,5
	4,5>SPL≥3,5	0,7
	3,5>SPL≥1,0	1,5
	SPL<1,0	4,0
$90 \geq Id_2$	SPL≥4,5	0,2
	4,5>SPL≥1,0	0,7
	SPL<1,0	2,0

The main approach in creating the constant "a" is to maximize the correlation of Fig. 9, i.e., Id_2 and CDM, to determine the boundaries between the classes more accurately. For this reason, this constant was determined by indirect methods by assigning various values to different Id_2 values and the

Table 5 Average Id_2 of rock samples with or without application of vacuum chamber

	Without vacuum chamber	With vacuum chamber	Number of samples
Andesite	99.07	98.83	3
Basalt	98.42	96.59	5
Conglomerate	99.26	68.09	1
Flysch	98.61	83.71	8
Granite	99.10	48.19	2
Granodiorite	97.81	80.80	2
Greywacke	97.00	63.64	1
Limestone	98.47	91.97	12
Marl	96.04	88.16	19
Mudstone	98.16	95.26	4
Sandstone	97.79	83.75	26
Shale	98.97	92.36	1
Siltsone	99.52	99.20	1
Tuff	98.83	72.03	1

Topal and Sozmen 2003; Ertas Deniz 2016; Heidari et al. 2018) (Table 4). As many different rock types as possible, samples with a wide range of strength and effective porosity values were selected and compiled for validation of the newly developed method. The rock types of the samples consist of marl, limestone, siltstone, andesite, tuff, mudstone, sandstone, and flysch.

Results

Vacuum chamber application and DM-SM difference

The differences between experiments with and without a vacuum chamber for different rock types show that water penetrates further into the rock and accelerates the disintegration when a vacuum chamber is used (Table 5). Regardless of rock type, average Id_2 values are lower when using a vacuum chamber. As can be seen in slake durability tests increased up to five cycles, Id values show lower results in all conditions when using vacuum chamber (Fig. 6).

Id_2 values obtained by SM and DM are compared and categorized based on Gamble classification system (Table 6) to reveal the dramatic differences between two methods. Regardless of the cycle number, DM shows lower values than SM (Fig. 7). These differences reflect the fact that DM accelerates the disintegration of rock materials without any additional cycles or waiting time during the procedure.

Relationship between strength and porosity parameters with slake durability is assessed (Fig. 8) by regression analyses. The results indicate that the maximum correlation coefficient was obtained from the analysis between saturated point load strength index tests with Id_2. On the contrary, effective porosity reveals the lowest relation. In addition, DM shows better correlations than SM in terms of effective porosity and strength of the rocks (Table 7). In consequence, the correlation coefficients suggest that a certain relationship between each parameter and Id_2 can be established using DM instead of SM, but the combination of parameters is expected to present higher values with Id_2.

Configuration of discard method

Since the combination of porosity and strength effects on slake durability of a rock is undeniable, a configuration on the data is developed based on these parameters in order to obtain better relationships. Considering the DM correlation coefficients of the parameters, the highest correlation is obtained from the saturated point load strength index. Schmidt hammer rebound and effective porosity follow this parameter in a decreasing manner (Table 7). In this regard, certain coefficients have been assigned to each value based on their correlation coefficients against slake durability by indirect methods. Several attempts were made to obtain the highest possible correlation coefficient by performing regression analyses between the newly

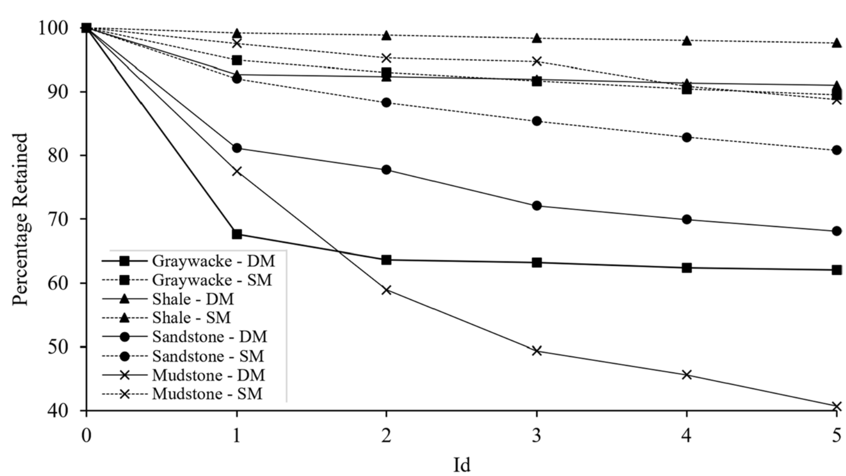

Fig. 7 Percentage retained of different rock types with standard method (SM) and discard method (DM) (DM with solid lines, SM with dashed lines)

Table 6 Id_2 classification based on SM and DM

	Id_2					Id_2					Id_2					Id_2			
Rock type	SM	DM	SM	DM	Rock type	SM	DM	SM	DM	Rock type	SM	DM	SM	DM	Rock type	SM	DM	SM	DM
Andesite	99.12	98.72	V.High	V.High	Limestone	97.89	97.86	High	High	Marl	95.81	87.55	High	M.High	Sandstone	98.73	81.21	V.High	Medium
Andesite	98.96	98.18	V.High	V.High	Limestone	98.69	85.95	V.High	M.High	Marl	99.25	90.98	V.High	M.High	Sandstone	98.37	96.83	V.High	High
Andesite	99.57	99.12	V.High	V.High	Limestone	97.64	91.09	High	M.High	Marl	98.91	90.65	V.High	M.High	Sandstone	96.51	95.50	High	High
Flysch	98.90	91.28	V.High	M.High	Limestone	97.84	91.29	High	M.High	Marl	98.84	90.58	V.High	M.High	Sandstone	99.71	31.18	V.High	Low
Flysch	98.69	88.94	V.High	M.High	Limestone	99.24	92.69	V.High	M.High	Marl	98.67	90.41	V.High	M.High	Sandstone	97.59	81.09	High	Medium
Flysch	97.82	63.30	High	Medium	Limestone	98.47	91.92	V.High	M.High	Marl	94.72	86.46	M.High	M.High	Sandstone	96.66	80.16	High	Medium
Flysch	99.28	84.87	V.High	Medium	Limestone	99.16	92.61	V.High	M.High	Marl	91.82	83.56	M.High	Medium	Sandstone	98.73	82.24	V.High	Medium
Flysch	98.54	82.01	V.High	Medium	Limestone	98.08	81.04	V.High	Medium	Marl	91.18	82.92	M.High	Medium	Sandstone	98.10	81.60	V.High	Medium
Flysch	97.97	76.54	High	Medium	Limestone	98.49	98.16	V.High	V.High	Marl	69.49	61.23	Medium	Medium	Sandstone	98.76	82.26	V.High	Medium
Flysch	98.57	89.63	V.High	M.High	Limestone	98.96	98.85	V.High	V.High	Marl	98.42	97.45	V.High	High	Sandstone	98.37	81.87	V.High	Medium
Flysch	99.08	93.08	V.High	M.High	Limestone	98.64	98.13	V.High	V.High	Mudstone	94.64	80.80	M.High	Medium	Sandstone	98.53	82.03	V.High	Medium
Basalt	97.78	97.35	High	High	Limestone	98.87	92.32	V.High	M.High	Mudstone	97.79	89.10	High	M.High	Sandstone	97.87	81.37	High	Medium
Basalt	100.00	98.02	V.High	V.High	Marl	96.81	91.29	High	M.High	Mudstone	97.81	35.12	High	Low	Sandstone	95.20	87.26	High	M.High
Basalt	100.00	99.06	V.High	V.High	Marl	98.16	89.13	V.High	M.High	Mudstone	95.26	58.88	High	Low	Sandstone	94.89	92.97	M.High	M.High
Basalt	98.26	93.73	V.High	M.High	Marl	98.83	88.70	V.High	M.High	Sandstone	99.30	93.14	V.High	M.High	Sandstone	97.66	89.78	High	M.High
Basalt	98.99	91.85	V.High	M.High	Marl	97.46	86.98	High	M.High	Sandstone	100.00	98.74	V.High	V.High	Sandstone	98.76	98.11	V.High	V.High
Conglomerate	99.26	68.09	V.High	Medium	Marl	98.94	92.79	V.High	M.High	Sandstone	98.96	79.11	V.High	Medium	Sandstone	96.45	96.06	High	High
Granite	99.25	74.82	V.High	Medium	Marl	99.37	91.11	V.High	M.High	Sandstone	99.50	86.59	V.High	M.High	Sandstone	91.55	90.70	M.High	M.High
Granite	98.94	21.57	V.High	V.Low	Marl	99.20	90.93	V.High	M.High	Sandstone	96.66	91.57	High	M.High	Shale	98.97	92.36	V.High	M.High
Granodiorite	96.07	70.35	High	Medium	Marl	99.51	91.24	V.High	M.High	Sandstone	97.59	61.16	High	Medium	Siltstone	99.52	99.20	V.High	V.High
Granodiorite	99.56	91.25	V.High	M.High	Marl	99.37	91.11	V.High	M.High	Sandstone	98.94	83.89	V.High	Medium	Tuff	98.83	72.03	V.High	Medium
Greywacke	97.00	63.64	High	Medium						Sandstone	99.09	82.21	V.High	Medium					

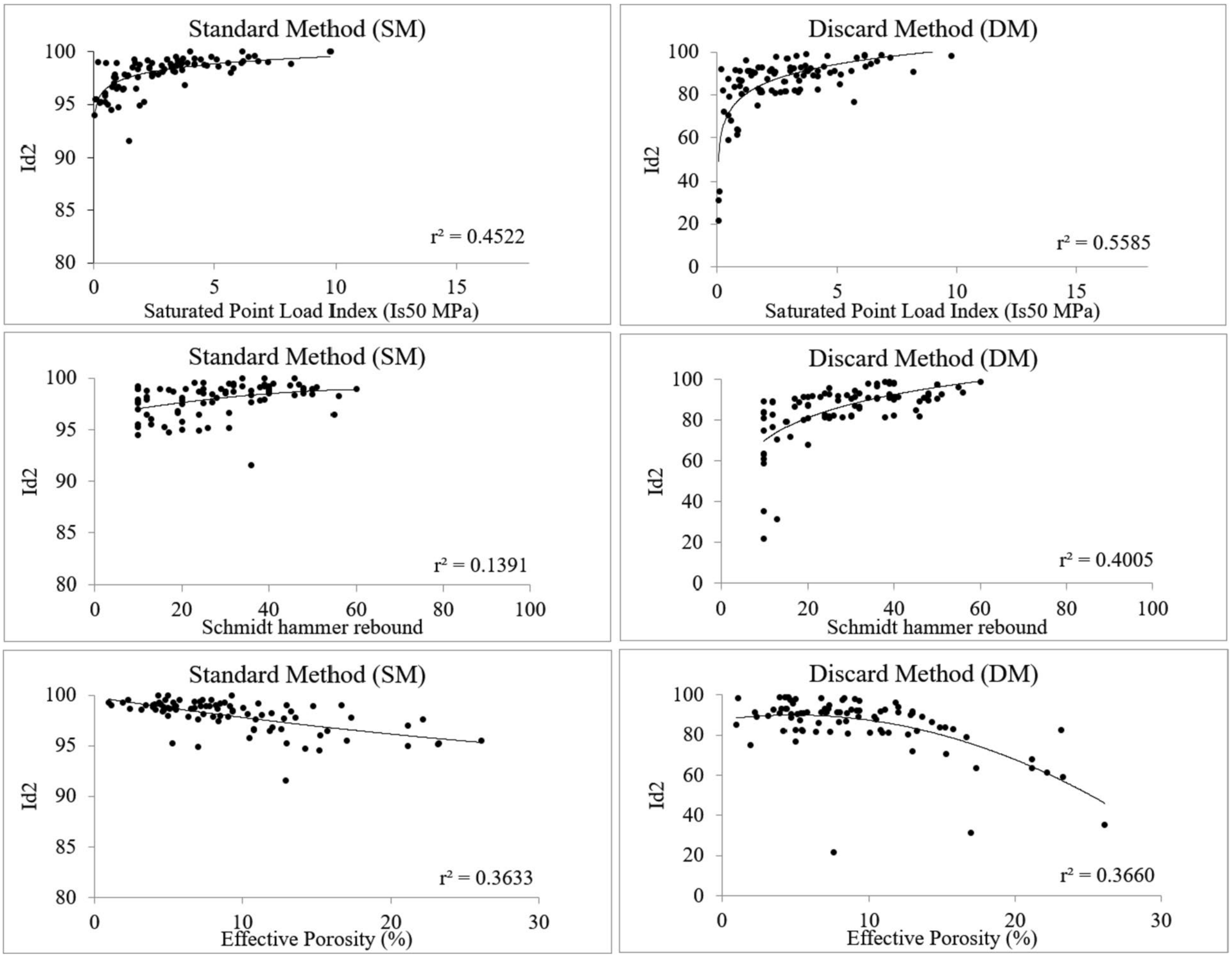

Fig. 8 Relationship of Id_2 and effective porosity, Schmidt rebound hammer, and saturated point load strength index with standard method (SM) and discard method (DM)

highest possible correlation between these two parameters was achieved. Afterwards, the best fit was tuned by shifting upwards and the upper bound of the classification was determined (Fig. 10). Subsequently, the rock classes were categorized according to Table 3 obtained from field observations and the class boundaries were determined accordingly. Classification ranges were determined within certain threshold values of Id_2 and CDM. Therefore, field observations were used as a basis for constructing the chart and then the effects of Id_2, strength, and effective porosity were added.

Table 7 Correlation coefficients of effective porosity, Schmidt hammer, and saturated point load against Id_2 based on standard method (SM) and discard method (DM)

	SM (r^2)	DM (r^2)
Effective porosity	0.3633	0.3660
Schmidt hammer rebound	0.1391	0.4005
Saturated point load strength index	0.4522	0.5585

New slake durability classification chart

Higher CDM and higher Id plotted on the graph (Fig. 9)indicate higher durability against slaking. SM for the slake durability index test uses Gamble's (1971) classification system to categorize materials. In this concept, there are six classes with certain ranges for Id_1 and Id_2 (Table 1). The new classification system was developed based on these classes, CDM and Id_2 (Fig. 10). Durability categories are divided according to the field performance of the rocks. Field observations of the rock slopes are based on the weathering rates and individual observations of several engineers, which reduces bias in the data (Table 3). The upper threshold of the categories is drawn by adhering to the best fit obtained using the relationship between CDM and Id_2, and upward-tuned according to the 86 rock slopes monitored in this study.

In this new concept, Gamble's (1971) categorization is directly adopted; however, the ranges are changed. For example, even if the percentage retained weight is very high, it is considered that the material can be assigned to more flexible

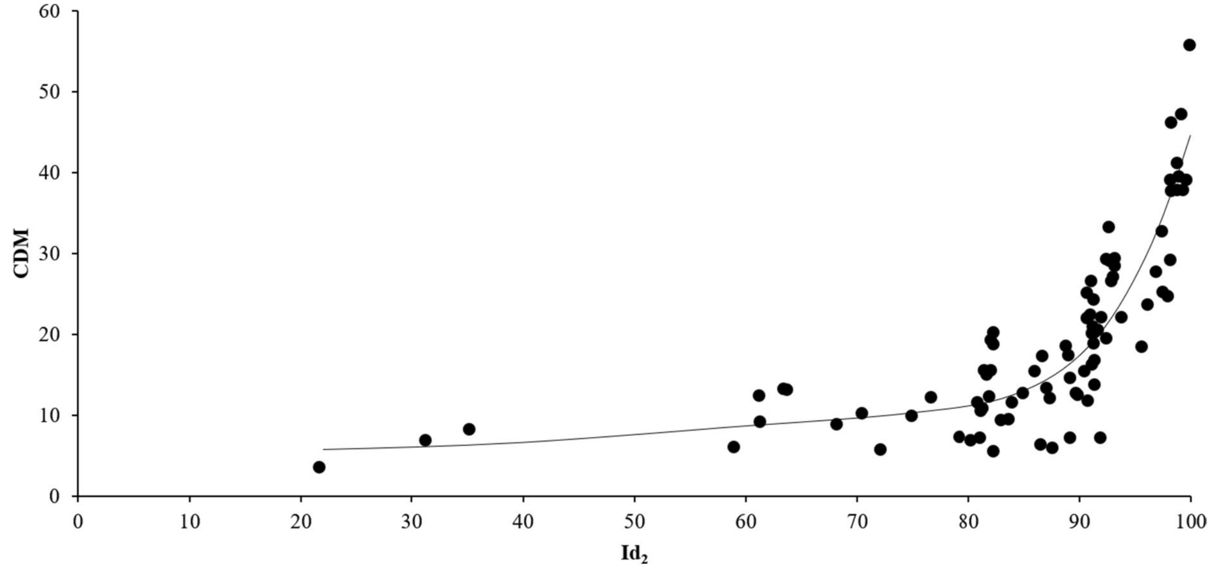

Fig. 9 Plot of the samples calculated by configured discard method (CDM) based on Id_2

categories based on properties such as strength and effective porosity rather than a single category. Also, the upper bounds of low and very low durability have shifted towards higher percentages, starting from around 85% and 65%, respectively.

Category regions are indicated and divided with solid lines (Fig. 10). The categories divided by dashed lines above the upper bound of the arc suggest some misleading results. These regions have been added to the chart to help users assign appropriate categories based on their results. It is recommended to repeat all calculations resulting in these zones. The upper left part of the chart is marked N/A (not applicable) because it is inaccessible and the materials may yield completely wrong and irrelevant results. The dashed line between very low (VL) and low (L) zones indicate CDM = 1.5. Values below this indicate extremely low strength and high effective porosity, which can be treated as VL. However, since

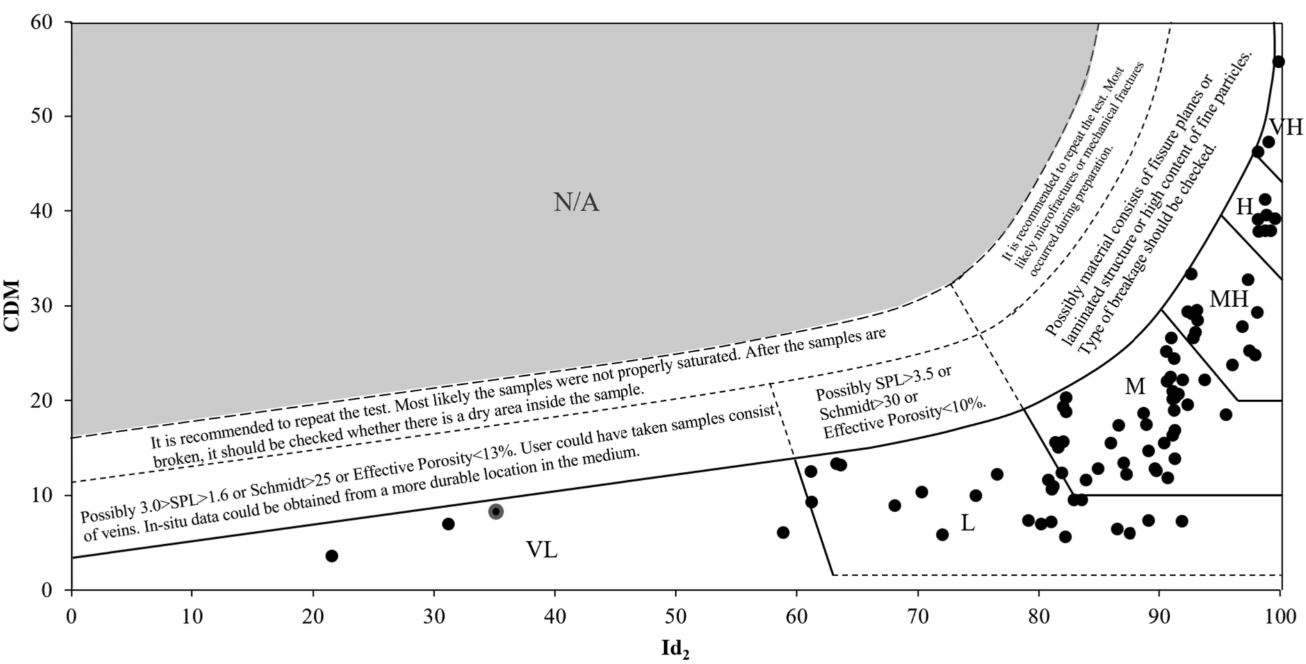

Fig. 10 Slake durability classification chart (VH, very high; H, high; MH, medium high; M, medium; L, low; VL, very low durability. Blue circled point indicates the case study result)

the authors did not encounter such low CDM values in their experiments, this dashed line is left as a guide for possible future results. The summarized whole procedure and the flow chart of this newly proposed method is presented in Fig. 11.

Effect of drum apparatus design on slake durability estimation

Comparison between SM and DM shows dramatic differences between each method. Discarding the broken parts from the experiment allows more accurate results to be predicted. Different samples are tested with SM, DM, 5×40 mm, and 10×40 mm drum sets. The Id_2 values obtained from each method evaluated with CDM (Table 8). The most coherent results are obtained by DM. The dramatic difference between CDM and Franklin and Chandra (1972) (SM) can be observed at first glance. The results obtained from drum designs show lower (more realistic) values compared to SM. However, these values are still high considering the actual field conditions. Drum design having 10×40 mm slots shows the closest results with DM. Even though these results are one or two categories higher than field observations and DM, 10×40 mm slots drum design can be used to approach more realistic results instead of SM.

Validation of the newly developed method

Collected samples group

Ten more samples were tested to verify the CDM (Fig. 12). Results obtained from the control group samples and field observations show good agreement. CDM is 90% coherent with field observations (Table 9). The only difference between CDM and field condition was observed at slope TT-07. According to the field observations, this slope is considered to be highly durable. The difference arises because the samples are collected in weaker parts of the slope. It is comprehensible to get biased samples from the slope as it is easier to extract from such a massive mass. The modified Id_2 values obtained by applying DM shown in Table 9 have two zero values (TT-04 and TT05). The test results on these two specimens showed that neither material was observed

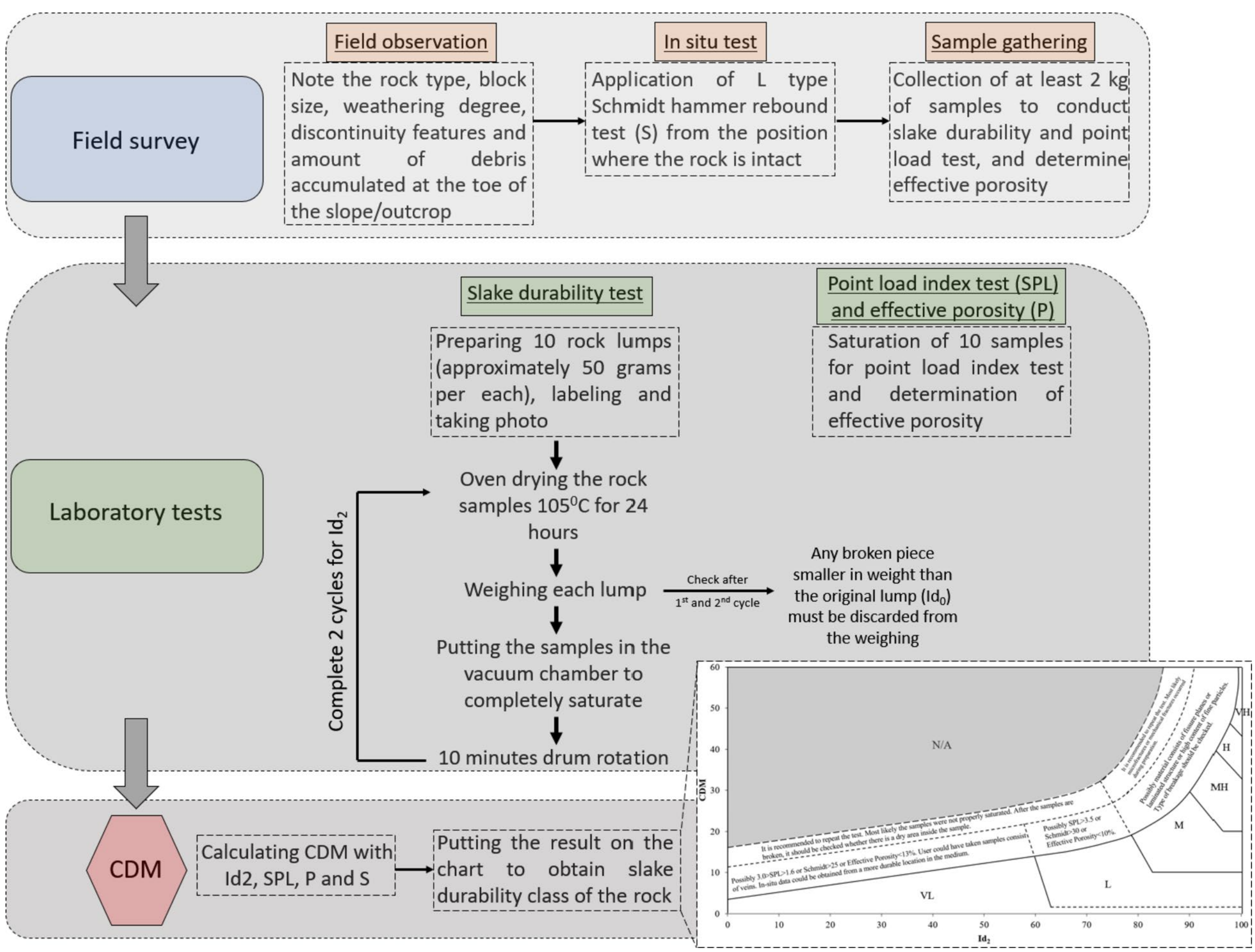

Fig. 11 Flow chart of the newly proposed method

Table 8 Durability classes of different methods and drum designs for the tested samples

	Sample name	Method	Id2	Durability
Franklin and Chandra 1972	GLST	SM	98.08	V.High
	HGMD-1		97.00	High
	HGMD-2		98.47	V.High
	BMD-1		97.81	High
	BMD-2		95.26	High
CDM	GLST	5×40 mm drum	96.58	M.High
	HGMD-1		94.64	Medium
	HGMD-2		98.10	Medium
	BMD-1		94.77	Medium
	BMD-2		77.42	Low
	GLST	10×40 mm drum	93.89	Medium
	HGMD-1		86.71	Medium
	HGMD-2		97.79	Medium
	BMD-1		94.23	Medium
	BMD-2		64.68	Low
	GLST	DM	81.04	Low
	HGMD-1		80.80	Low
	HGMD-2		89.10	Low
	BMD-1		35.12	V.Low
	BMD-2		58.88	V.Low

to be as intact as at the beginning of the test ($t = 0$) (Fig. 13). Therefore, their Id_2 values according to DM are zero. The Id_2 values according to SM, on the other hand, are 86.66% (medium high) and 30.13% (low) for TT-04 and TT-05, respectively. According to CDM, durability classes are automatically very low, since their DM Id_2 values are zero.

Literature-derived samples group

In order to validate the CDM, five different research papers (Pasamehmetoglu 1981; Topal and Doyuran 1997; Topal and Sozmen 2003; Ertas Deniz 2016; Heidari et al. 2018) examining different rock types were reviewed. Fifty-six samples were assessed by CDM and the results of the studies were compared with the new findings. According to the results, CDM generally shows lower classes than the findings by the researchers. The important part should be noted that the Id_2 values shown in Table 10 are obtained by standard method by each researcher. This means that these values do not reflect the exact values of CDM. According to all researchers except Heidari et al. (2018), the classes shown in Table 10 are lower and not consistent with field observations. Therefore, even when using standard method Id_2 values, the CDM works and correlates better with field observations than the original method proposed by Franklin and Chandra (1972). Heidari et al. (2018), on the other hand, obtained the classes shown in Table 10 with their approach and divided classification method into five instead of six classes. Their approach shows better consistency than the suggested method considering the field conditions. The differences between their approach and this study are most probably due to Id_2 estimation variations and classification differences. Therefore, minor classification differences are considered to be acceptable. There is only one dramatic difference between Heidari et al. (2018) and CDM which is sample S3. Considering 20 samples used in their study, 5% difference could be accepted as very tolerable.

Case study

A mudstone rock slope about 15 m high in the vicinity of Alci village in Ankara, Turkey, is presented as an example (Fig. 14). According to the newly developed slake durability classification chart (Table 3), which was developed specifically for this study, the outcrop was classified as very low regardless of any feature other than visual observations. The untraceable discontinuities, secondary openings due to degradation, and especially the accumulated debris dominating the slope appearance facilitated the determination of this classification.

Mineral composition analyses resulting in X-ray diffraction (XRD) patterns reveal the presence of montmorillonite minerals, which are considered to have high swelling capacity (Fig. 15). Schmidt hammer rebound, saturated point load strength index, and effective porosity values are obtained as 10, 0.68 MPa, and 19.24%, respectively. Schmidt hammer in situ test is applied to the most suitable part of the slope, considering the minimum 10 cm distance from the closest joint, and the position where the rock is intact.

The result of the two-cycle slake durability test (Id_2) according to SM is 97.81%. On the other hand, when DM was used, the result was 35.12% (Table 11). Here, lumps 1, 3, 4, 5, 7, and 9 were eliminated according to DM because their retained percentages were less than 50%, i.e., more than half of the lump was broken (Fig. 16). Moreover, as DM pointed out, broken pieces are discarded from the experiment even if they are retained in the drum. Then, CDM is calculated as 8.3 with the input parameters. The parameter "a" is determined as 2, since Id_2 obtained from DM is less than 90% and saturated point load strength index is less than 1 MPa.

According to SM, results indicate the slake durability as high (97.81%). On the other hand, this rock slope is in the category of very low durability based on CDM (Fig. 10), same as the field observations. In addition, the very low durability behavior is compatible with presence of montmorillonite mineral, which is a good indicator of the swelling potential of this rock and tends to degrade easily when immersed in water. Only DM application (35.12%) indicates low durability according to Gamble's classification.

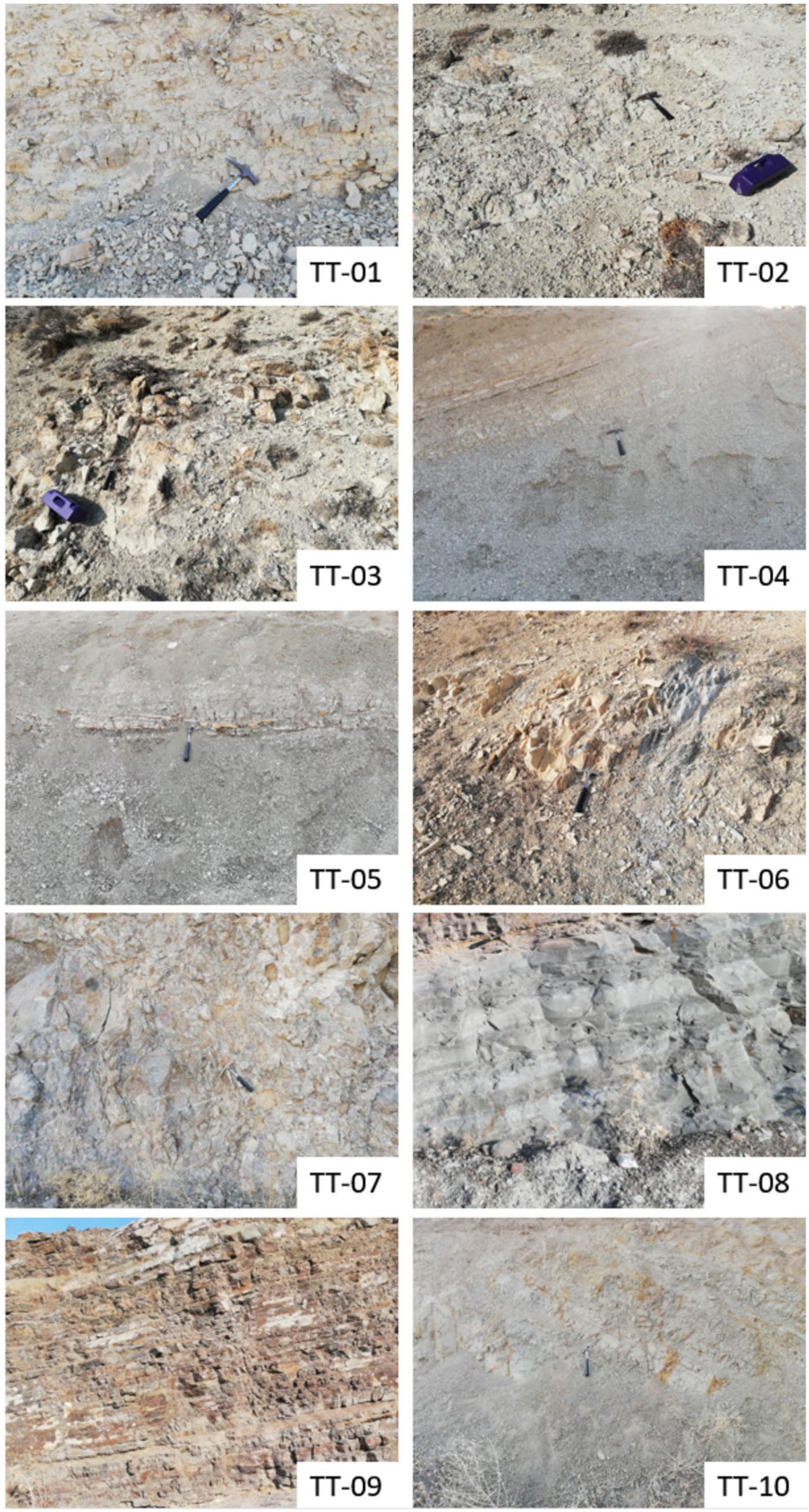

Fig. 12 Outcrop photos of control group samples

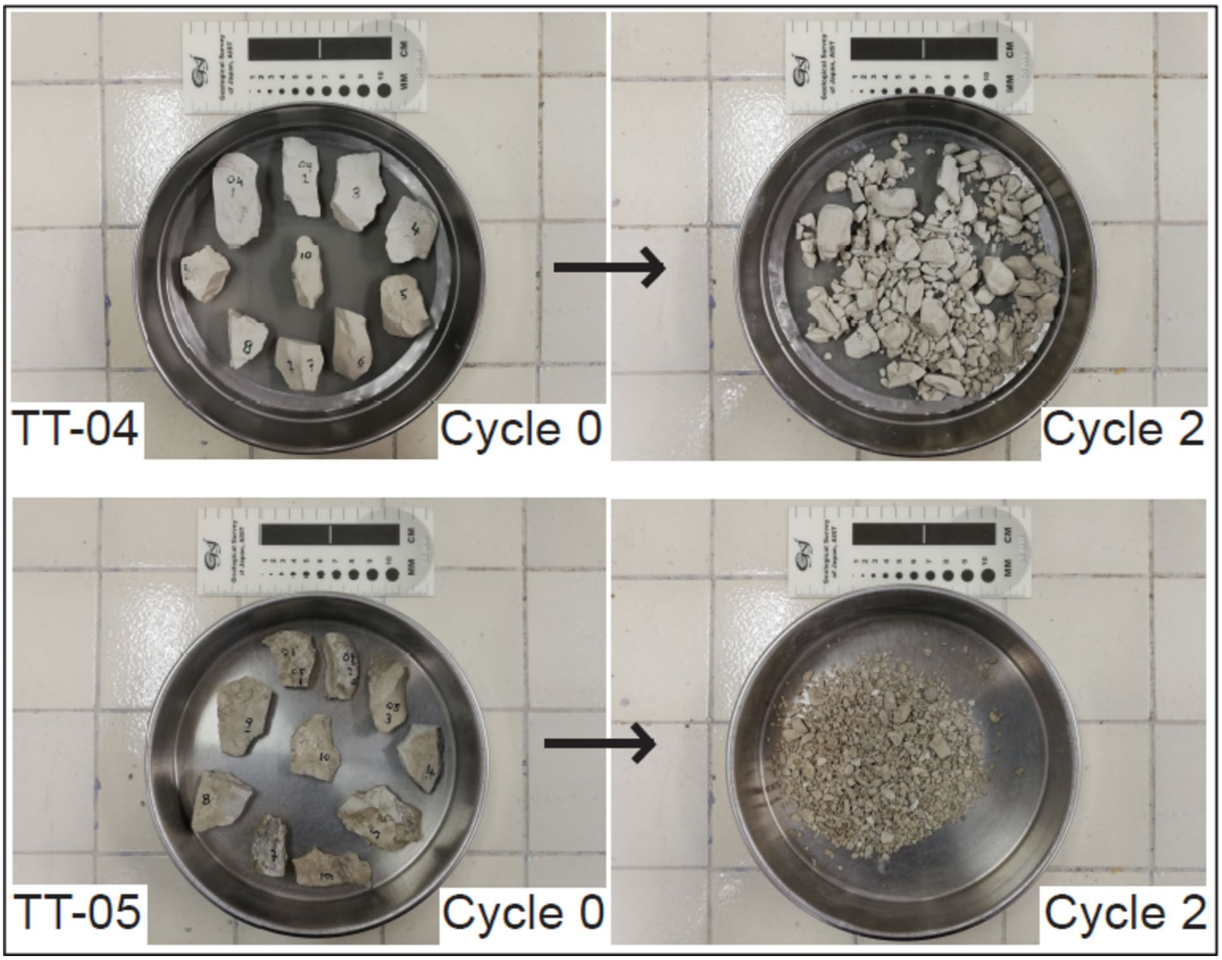

Fig. 13 TT-04 and TT-05 sample conditions before and after slake durability test

However, CDM predicts better results than DM by assigning input parameters such as Schmidt hammer rebound, point load strength index, and effective porosity.

Discussions

New approach to slake durability analysis provides a user-friendly equation, chart, and definition table to assess the

Table 9 Collected samples group summary table

CDM result	Rock type	Name	Id_2	Schmidt	Saturated point load strength index (MPa)	Effective porosity (%)	CDM
Low	Mudstone	TT-01	94.75	10	0.69	30.37	8.49
Low	Mudstone	TT-02	77.04	10	0.72	21.95	8.30
Medium	Mudstone	TT-03	95.38	34	0.79	25.24	12.93
Very low	Mudstone	TT-04	0.00	10	0.30	39.16	1.44
Very low	Mudstone	TT-05	0.00	10	0.40	39.11	2.46
M.High	Mudstone	TT-06	98.87	18	2.07	22.72	22.76
M.High	Flysch	TT-07	93.91	48	6.50	9.55	29.82
M.High	Flysch	TT-08	96.19	60	1.44	9.87	26.13
Medium	Flysch	TT-09	79.71	40	0.99	13.96	15.25
Very low	Sandstone	TT-10	7.92	15	0.08	25.21	1.78

Table 10 Literature-derived samples group and CDM data

	Researcher classification	CDM classification	Rock type	Sample name	Id_2^*	Schmidt	Saturated point load	Effective porosity	CDM
TT-VD	Medium	Low	Tuff	TT-VD-1997	84.00	27	0.13	38.29	1.53
Heidari	M.High	Medium	Marl	Heidari-S1	94.06	19	1.61	16.43	23.21
	High	Medium	Marl	Heidari-S2	95.53	18	1.12	12.45	17.46
	M.High	Low	Marl	Heidari-S3	85.92	19	1.60	25.02	7.11
	High	M.High	Sandy marl	Heidari-P1	97.50	21	2.25	6.83	21.54
	M.High	Medium	Marl	Heidari-P2	85.87	20	1.92	6.59	11.12
	V.High	High	Marly limestone	Heidari-P3	99.35	23	3.12	5.50	36.55
	V.High	M.High	Sandy limey marl	Heidari-P4	98.40	22	2.83	3.17	33.84
	M.High	Medium	Marl	Heidari-G1	93.82	19	1.72	13.10	20.73
	V.High	M.High	Limey marl	Heidari-G2	98.87	20	2.08	7.91	25.28
	Medium	Low	Marl	Heidari-Ag1	70.62	18	0.88	22.78	10.61
	Medium	Low	Marl	Heidari-Ag2	61.88	17	0.47	22.05	6.44
	Medium	Low	Clayey siltstone	Heidari-Ag3	84.21	17	0.70	19.40	9.18
	High	Medium	Clayey siltstone	Heidari-Ag4	95.43	17	0.71	16.67	11.50
	Medium	V.Low	Marl	Heidari-Ag5	61.61	16	0.32	28.67	3.81
	V.High	M.High	Clayey siltstone	Heidari-Ag6	98.04	18	1.19	7.28	23.03
	V.High	M.High	Marl	Heidari-Ag7	98.46	20	1.87	10.52	22.75
	M.High	Medium	Clayey siltstone	Heidari-Ag8	94.24	18	1.01	16.76	15.41
	M.High	Medium	Clayey siltstone	Heidari-Ag9	90.42	18	0.87	11.63	21.05
	V.High	M.High	Clayey siltstone	Heidari-Ag10	98.69	22	2.89	5.68	34.08
	V.High	M.High	Clayey siltstone	Heidari-Ag11	98.72	22	2.79	8.32	32.66
Pasa	V.High	V.High	Andesite	Pasa-Kizil1	98.30	52	4.15	4.63	50.09
	High	M.High	Andesite	Pasa-Kizil2	97.70	42	2.35	11.19	23.75
	High	M.High	Andesite	Pasa-Kizil3	96.50	30	1.82	17.21	26.87
	M.High	Low	Andesite	Pasa-Kizil4	85.50	20	0.68	20.85	9.06
	High	M.High	Andesite	Pasa-Gol1	97.30	61	5.18	9.00	26.49
	High	M.High	Andesite	Pasa-Gol2	95.80	50	2.85	14.31	27.91
	High	Medium	Andesite	Pasa-Gol3	95.40	28	1.08	19.16	16.95
	High	Medium	Andesite	Pasa-Gol4	95.60	25	0,71	21.46	11.58
	High	M.High	Andesite	Pasa-Kos1	97.40	54	2.90	10.16	29.31
	High	M.High	Andesite	Pasa-Kos2	97.20	40	2.55	11.18	25.08
	M.High	Medium	Andesite	Pasa-Kos3	90.50	30	1.57	14.69	16.06
	Medium	Low	Andesite	Pasa-Kos4	85.10	22	0.55	17.92	8.37
	V.High	M.High	Andesite	Pasa-Cubuk1	98.20	50	4.51	2.22	30.92
	High	M.High	Andesite	Pasa-Cubuk2	96.60	47	3.34	4.62	32.81
	M.High	Medium	Andesite	Pasa-Cubuk3	88.60	34	2.35	5.66	14.19
	Medium	Low	Andesite	Pasa-Cubuk4	80.20	23	0.55	8.50	9.89
TT-BS	M.High	Low	Tuff	TT-BS-2003 W	91.00	16	0.25	38.82	4.12
	High	Medium	Tuff	TT-BS-2003P	96.00	33	0.78	33.48	11.47
	M.High	Low	Tuff	AG-1990 W	92.20	14	0.24	28.30	5.30
	High	Medium	Tuff	AG-1990P	96.80	24	0.75	24.20	11.58
	M.High	Low	Tuff	Binal 1998 W	87.00	18	0.40	33.10	4.16
	High	Medium	Tuff	Binal 1998P	95.50	33	1.20	29.10	17.49

Table 10 (continued)

	Researcher classification	CDM classification	Rock type	Sample name	Id_2^*	Schmidt	Saturated point load	Effective porosity	CDM
Deniz	High	M.High	Tuff	BE-Ekinli	97.00	48	1.40	23.91	22.31
	High	M.High	Tuff	BE-AlabeyliY	96.00	46	2.31	28.17	21.30
	M.High	M.High	Tuff	BE-AlabeyliW	93.00	42	1.81	24.93	26.79
	High	M.High	Tuff	BE-Pusatli	97.00	48	1.57	34.84	22.84
	M.High	M.High	Tuff	BE-Komurkoy	94.00	28	1.82	31.71	24.50
	High	M.High	Tuff	BE-Kurukop	95.00	56	2.37	22.04	23.67
	High	Medium	Tuff	BE-KamberG	96.00	38	1.16	30.72	17.23
	M.High	Medium	Tuff	BE-KamberB	94.00	38	0.84	35.88	12.38
	High	Medium	Tuff	BE-KamberY	97.00	45	1.28	32.13	19.25
	M.High	Medium	Tuff	BE-Gesi	92.00	45	1.11	28.99	11.89
	High	Medium	Tuff	BE-Incesu	95.00	48	0.95	21.78	16.90
	M.High	Medium	Tuff	BE-SevıncG	92.00	32	0.47	21.23	12.85
	High	Medium	Tuff	BE-SevıncP	96.00	35	0.66	28.99	10.82

TT-VD: Topal and Doyuran (1997), Heidari: Heidari et al. (2018), Pasa: Pasamehmetoglu et al. (1981), TT-BS: Topal and Sozmen (2003), Deniz: Ertas Deniz (2016). *Id_2 values are standard method (SM) values suggested by Franklin and Chandra (1972)

condition of a rock mass. This approach includes parameters such as Schmidt hammer rebound, saturated point load strength index, and effective porosity values to better define the field performance of the rocks. This new approach follows the DM which adopts the natural behavior of rock slopes instead of considering SM.

SM can present data within 2 days considering the wet/dry cycles. Although new parameters have been added to this new classification, 2 days is still enough time to determine them. Effective porosity and saturated point load strength index values can be obtained around 4–5 h. Therefore, by adding a few new parameters that are easy to obtain, this new approach can provide more accurate results and deliver solutions in the same time as the standard method.

An important observation is that durability of the samples decreases dramatically in the first cycle and this dramatic decrease slows down immediately afterwards. The weight loss is usually observed immediately after drum rotation. The weight loss in the oven-dried samples is very small compared to wetting and the frictional effect due to drum rotation. Therefore, the major impact is observed upon wetting. The reason why the first cycle showed dramatic weight loss can be explained due to presence of microfractures in the specimens. The greywacke used in this study shows a large number of microfractures in the specimens prior to the application of any slake durability test. However, the same specimens show a limited amount of fracture after two cycles (Fig. 17), indicating that fracture-free specimens tend to be more resistant to slake durability.

The newly proposed method has been validated based on the descriptions presented in Table 3. Definitions of each durability class have been prepared by the field observations, based on surface conditions, weathering degrees, block sizes, and amount of accumulated debris. The descriptions of the classes are proposed in this study by adhering the categories suggested by Gamble (1971). Even though the suggested categories were divided based on the Id values obtained from the laboratory tests, the definitions were lacking and a comparison between field and laboratory performance of the rocks has not been established. Therefore, in this study, the descriptions are based on the experience of the authors from the field observations of nearly 100 rock slopes. This newly proposed method fills the missing part of the system, basically in an explanatory way the denotations of classes. Since this is a newly proposed method based on laboratory experiments and field observations, new addition of data would increase the accuracy of the system by improving the link between field and laboratory performances of the rocks individually. In this study, while developing the CDM table, classification limits were set in accordance with the field conditions mentioned in Table 3. In other words, field observations were used to construct the CDM and the boundaries between the classes were determined accordingly. When determining the boundaries, the lower boundary of each class with the lowest durability was taken into consideration. In this context, the CDM accurately reflects the site conditions identified in this study.

In line with the use of the vacuum chamber, which is critical for the study, the variation of the samples over five cycles is presented in Fig. 6 in comparison with the results obtained without the vacuum chamber. As mentioned in the sample preparation

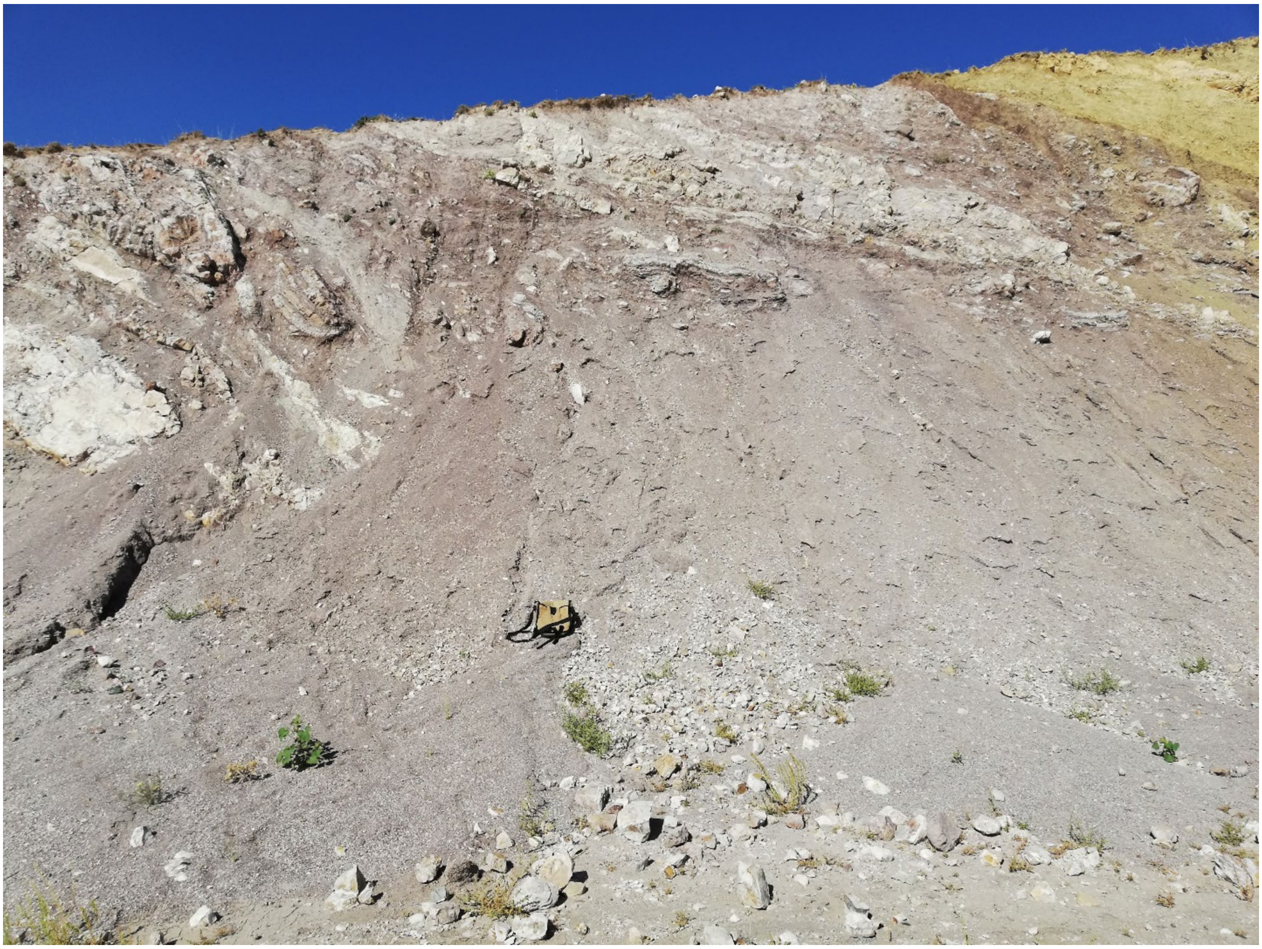

Fig. 14 Case study outcrop photo

section, the vacuum chamber was preferred in order to allow the rocks to reach the field conditions more quickly, and lower Ids were obtained than the tests performed without the vacuum chamber. The reason for this is explained as the rock material is completely saturated and becomes more easily disintegrated. As a result of the experiments, the effect of the vacuum chamber was noticeable more clearly in coarse particle materials, such as sandstone and greywacke, while it was relatively less in fine particle materials. When the Id_2 values obtained by using the standard method are analyzed, the difference between coarse particle materials with and without vacuum chamber is about 3%, while this difference is about 1% in fine particle materials. Although the effect of the vacuum chamber does not appear as a big difference in the standard method, it is seen that the same materials show larger percentage differences when the discard method is used. In the case of coarser materials, the difference was more than 5%, whereas in the case of finer materials, differences of more than 2% were observed. This proves that the use of the vacuum chamber, when combined with the DM developed in this study, can make enough difference to change the slaking class of the material.

In the experiments using vacuum chamber, the average values of SM and DM Id_2 are 97.72% and 85.33%, respectively. From these results alone, it can be seen that SM values are in the high durability class and DM values are in the medium high durability class on average, which are close to the upper part of the class limit for SM and close to the lower limit for DM (Table 6). Again, when the Id_2 values for SM and DM are analyzed according to rock classes, it is seen that there are not very large differences between igneous and sedimentary rock. The igneous and sedimentary rock values for SM are 98.87% and 97.51%, respectively, while these values are 85.08% and 85.38% for DM. When the related values are considered, no clear difference can be observed between the rock classes, while it is observed that DM makes a clear difference in the cases of fine and coarse material. Considering the average Id_2 values obtained when DM is used, the value of fine materials is 89.30%, while this value is 80.98% for coarse materials. In other words, it is observed that DM does not make a difference between the rock classes examined in this study, but when coarse and fine materials are considered, it reveals clear distinctions.

The significant differences between the CDM and the SM examined in this study are particularly large due to the fact that the latter classifies even materials that are almost completely degraded under field conditions into very high and high durability classes (Table 12). The number of rock slopes in the very high class obtained with SM was 56, while this number dramatically decreased to 3 in CDM (Fig. 18). As mentioned before, the SM's experimental procedure is relatively overestimated due to the fact that the material is perceived as if the material has not degraded at all, even though it has completely disintegrated but remains within the 2-mm mesh drum. On the other hand, with the CDM procedure, the newly added discard procedure removes the degraded material from the weight measurement process at the end of the cycle. This means that, as can be observed in field conditions, fragments that break off from the bedrock accumulate as debris. Therefore, although SM cannot accurately simulate a highly degraded material, CDM can present it much closer to field conditions via the discard method and rock strength and effective porosity parameters. The classification of a material as very high slaking when a rock material can crumble in the hand even with the application of finger stress is another indication that SM yields overestimated results. Since the material cannot fall from the drum into the pool even though it is broken into small pieces, it appears as if the material has lost almost no weight in the weighing process. In fact, this causes the materials that should be included in the lower class under field conditions to be placed in much higher classes. As can be seen in Table 3, rock block dimensions, discontinuity frequency, and surface conditions, which are considered in the classification process, are not fully met in the SM. The use of vacuum chambers, another significant difference between CDM and SM, provides substantial results in terms of predicting the future conditions of the rock levels of the classifications. While rock materials are included in the high durability classes as defined by SM, when all samples are considered and divided into igneous and sedimentary, or fine and coarse, the conditions of the materials in the future are actually much better predicted and in line with the definitions presented in Table 3. SM shows a decreasing trend when all rocks are considered, while CDM shows a right-skewed normal distribution. In particular, sedimentary rocks used in the study and coarse materials with accelerated saturation by the vacuum chamber indicate lower durability classes.

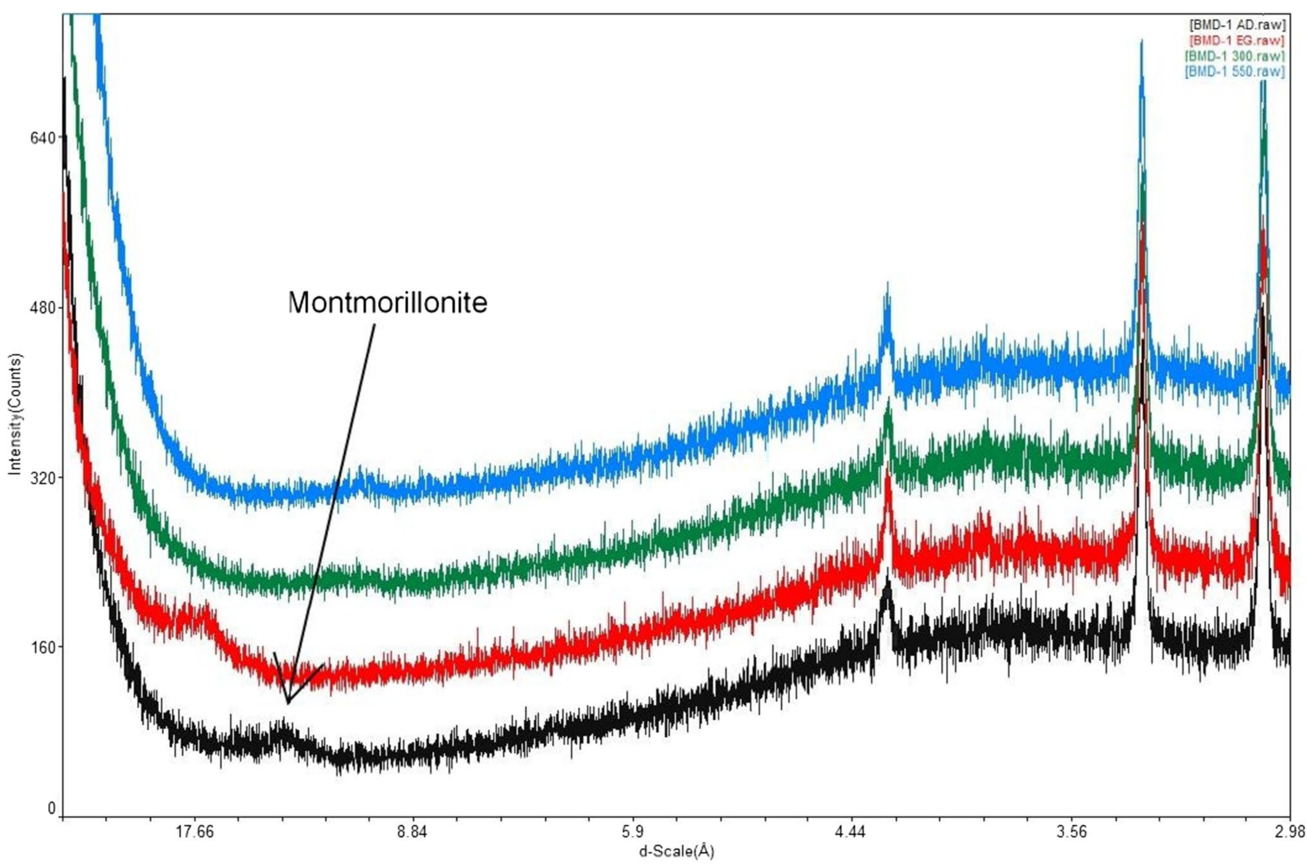

Fig. 15 XRD pattern from oriented clay fraction. Air-dried-treated (black), ethylene glycol-treated (red), 300 °C-treated (green), and 550 °C-treated (blue) sample shows small amount of montmorillonite mineral

Fig. 16 Samples before (above) and after (below) two cycles of slake durability test of the case study. Lumps 1, 3, 4, 5, 7, and 9 are discarded from weighing. Lumps 3, 4, and 9 are broken into many pieces shown by dashed circles. Lumps 1, 5, and 7 are broken into either 3 or 4 pieces each having less than half of the original lump weight. Lumps 2, 6, 8, and 10 are included in the calculations since they lost less than half of the original lump by weight

Limitations of CDM

The tables and charts developed in this study are derived solely from data collected in the field. In order to obtain a comprehensive result, 86 rock slopes were rigorously surveyed in homogenous ranges covering the central and northwestern regions of Turkey. The study area displays a variety of climatic conditions, the central part of which is characterized by a relatively arid climate, while the northern and western parts are subject to rainy influences. These differences in climate were deliberately included in the classification to account for varying weathering conditions. In spite of the absence of extreme tropical rainfall, the rock slopes in this study still provide a valuable dataset for studying slake durability under particular climatic effects.

Table 11 Slake durability analyses with standard method (SM) and discard method (DM) of the case study

		Id_0	1st cycle (Id_1)				2nd cycle (Id_2)			
		Initial Weight (grams)	Weight (grams)		Percentage retained		Weight (grams)		Percentage retained	
		M_{Dry}	SM	DM	SM	DM	SM	DM	SM	DM
	Total	353.10	348.53	303.28	98.71	85.89	345,35	124.01	**97.81**	**35.12**
Lump	1	36.36	NA	35.98	NA	98.95	NA	15.78	NA	43.40
	2	41.75		38.47		92.14		38.09		91.23
	3	33.97		29.49		86.81		14.04		41.33
	4	20.56		12.56		61.09		2.19		10.65
	5	39.35		22.80		57.94		9.92		25.21
	6	47.28		46.97		99.34		29.56		62.52
	7	39.35		26.07		66.25		15.18		38.58
	8	35.02		34.79		99.34		33.05		94.37
	9	27.70		26.14		94.37		7.47		26.97
	10	31.87		29.95		93.98		23.31		73.14

Metamorphic rocks are not included in the 14 rock types analyzed in this study. Although weak metamorphic rocks are prone to slaking, the CDM may not be the most appropriate tool to classify this rock type. Cognizant of this limitation, the classification system in this study focusses on sedimentary rocks, which account for 85% of the rock types analyzed. This intentional prioritization increases the accuracy of the results in accordance with the predominant geological composition in the study area.

It is particularly important to mention that the validation of this new system was primarily based on the control group of 86 rock slopes used in the study. Unfortunately, owing to the novelty of the discard method, it is difficult to make a direct comparison with the available literature. The fact that the discard method has not been previously adopted limits the extent to which the methodology can be cross-validated. Nevertheless, the description table based on the 86 rock slopes and the CDM still stands open to future updates. This framework allows modifications to be carried out to the class boundaries, allowing the classification system to remain responsive to evolving insights and advances in the field.

Conclusion

Considering the limitations and shortcomings of standard method, the critical issue of accurately evaluating the slake durability of rock masses is addressed within the scope of this study. This research highlights the essential role of water in weathering of rocks and stresses the importance of understanding the engineering properties of clay-bearing rocks. The originality of this paper lies in the development of configured discard method (CDM) as an improvised technique for determining slake durability of

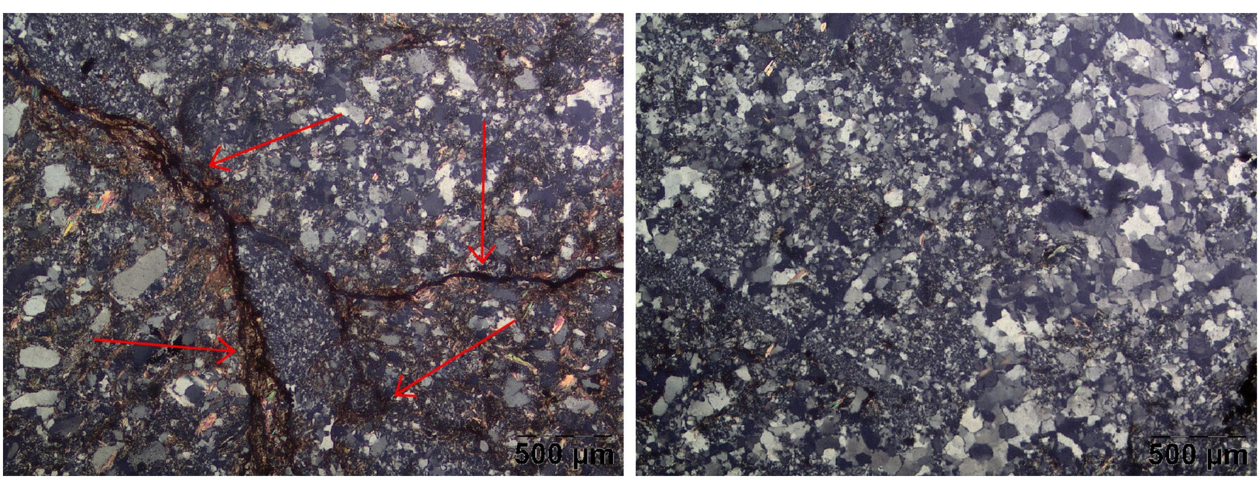

Fig. 17 Fractures in the samples before (left) slake durability test and after (right) 2nd cycle. The micro-fractures from end to end vanished after slake durability cycles

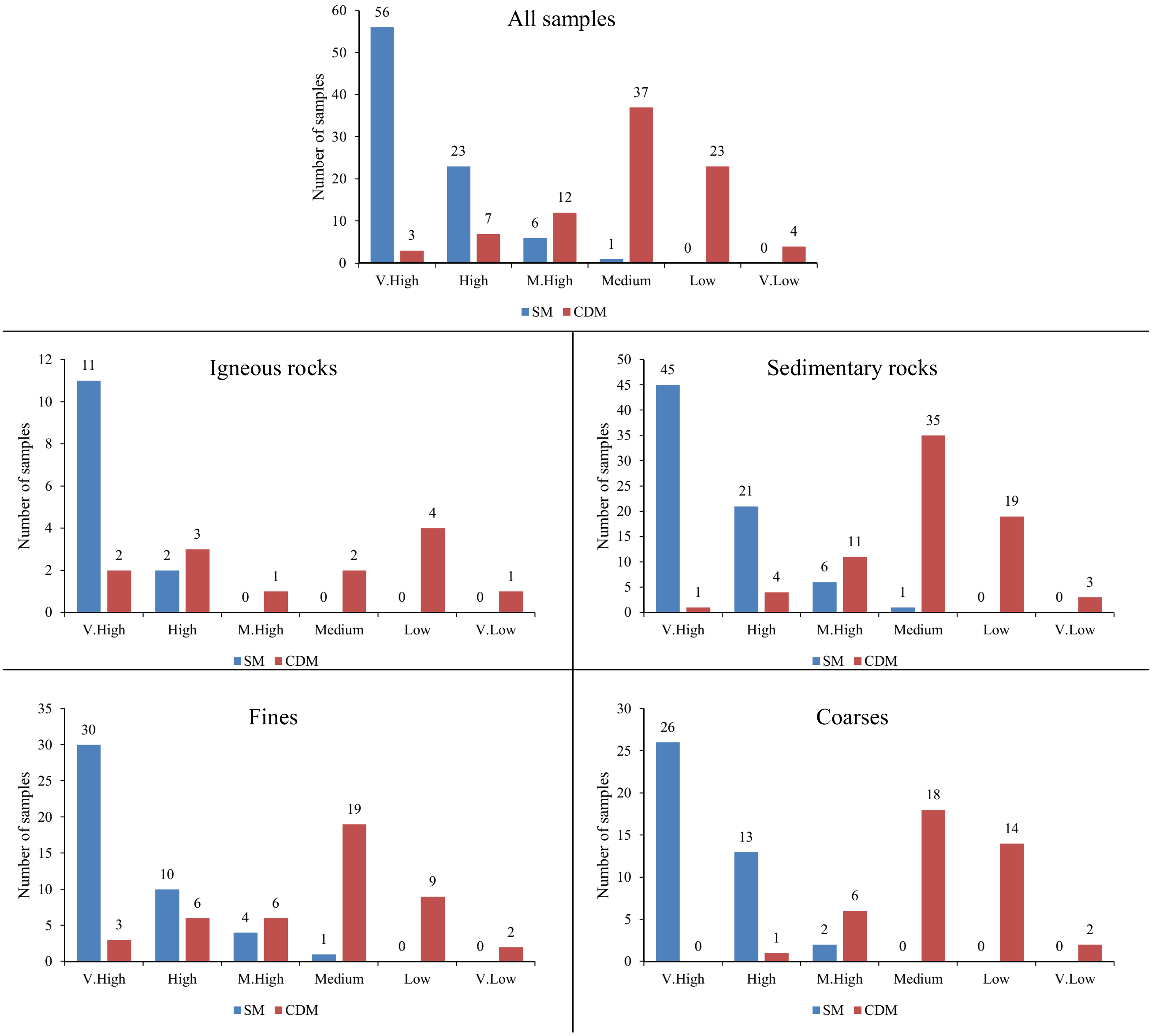

Fig. 18 The distribution of the samples according to SM and CDM analyses (numbers on the bars indicate the number of samples)

rocks. Differing from the standard method (SM), the CDM simulates a more realistic in situ evaluation of rocks by introducing modifications such as the use of vacuum chamber before drum rotations to accelerate degradation and removal of broken pieces from weighing calculations. The main findings from the study show that the CDM yielded lower values of slake durability relative to the SM, suggesting that this represents more extensive fragmentation of rock materials. Furthermore, results of correlation analyses show the significant role of effective porosity and strength on slake durability, confirming the importance of these factors in understanding rock weathering performance. The classification chart developed on the basis o the CDM brings a new classification system that considers effective porosity, strength, and most importantly field performance. The classification moves away from strict percentage-based characterization, enabling a more sophisticated evaluation of rocks based on their unique features. Field verifications and comparisons with other studies support the efficacy of CDM in ensuring more realistic and coherent results. The outcomes of this research are particularly important for geotechnical engineering and infrastructure development. Proper judgements of shear strength are crucial for predicting the stability of slopes, embankments, and dam reservoir areas where weathering conditions significantly affect the performance of structures. The suggested CDM provides a more robust and site-specific approach, thereby minimizing the risk of assigning false to the rocks and ultimately reducing the potential negative impacts on structures and human safety. While the CDM introduced in this research marks a

Table 12 Durability classes obtained from SM and CDM

Rock type	SM	CDM	Rock type	SM	CDM
Andesite	V.High	High	Marl	High	Low
Andesite	V.High	High	Marl	V.High	Medium
Andesite	V.High	High	Marl	V.High	Medium
Flysch	V.High	Medium	Marl	V.High	Medium
Flysch	V.High	Medium	Marl	V.High	Medium
Flysch	High	Low	Marl	M.High	Low
Flysch	V.High	Medium	Marl	M.High	Low
Flysch	V.High	Medium	Marl	M.High	Low
Flysch	High	Low	Marl	Medium	Low
Flysch	V.High	Medium	Marl	V.High	M.High
Flysch	V.High	M.High	Mudstone	M.High	Low
Basalt	High	M.High	Mudstone	High	Low
Basalt	V.High	V.High	Mudstone	High	V.Low
Basalt	V.High	V.High	Mudstone	High	V.Low
Basalt	V.High	Medium	Sandstone	V.High	M.High
Basalt	V.High	Low	Sandstone	V.High	High
Conglomerate	V.High	Low	Sandstone	V.High	Low
Granite	V.High	Low	Sandstone	V.High	Medium
Granite	V.High	V.Low	Sandstone	High	Medium
Granodiorite	High	Low	Sandstone	High	Low
Granodiorite	V.High	Medium	Sandstone	V.High	Medium
Greywacke	High	Low	Sandstone	V.High	Low
Limestone	High	M.High	Sandstone	V.High	Low
Limestone	V.High	Medium	Sandstone	V.High	M.High
Limestone	High	Medium	Sandstone	High	Medium
Limestone	High	Medium	Sandstone	V.High	V.Low
Limestone	V.High	M.High	Sandstone	High	Low
Limestone	V.High	Medium	Sandstone	High	Low
Limestone	V.High	M.High	Sandstone	V.High	Medium
Limestone	V.High	M.High	Sandstone	V.High	Medium
Limestone	V.High	Low	Sandstone	V.High	Medium
Limestone	V.High	V.High	Sandstone	V.High	Low
Limestone	V.High	High	Sandstone	V.High	Medium
Limestone	V.High	High	Sandstone	High	Medium
Marl	High	Medium	Sandstone	High	Medium
Marl	V.High	Medium	Sandstone	M.High	M.High
Marl	V.High	Medium	Sandstone	High	Medium
Marl	High	Medium	Sandstone	V.High	M.High
Marl	V.High	Medium	Sandstone	High	Medium
Marl	V.High	Medium	Sandstone	M.High	M.High
Marl	V.High	Medium	Shale	V.High	Medium
Marl	V.High	Medium	Siltstone	V.High	High
Marl	V.High	Medium	Tuff	V.High	Low

substantial advance in the assessment of slake durability, it is essential to recognize its current limitations and to accept the potential for further development in the future. The conclusions derived from this study are based on a limited sample size and a variety of rock types and therefore the method could potentially benefit from further refinement and validation across a wider range of materials.

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Declarations

Competing interests The authors declare no competing interests.

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