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ORIGINAL PAPER

Correlation between slake durability and rock properties for some carbonate rocks

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Abstract The paper reports a study to assess the relationship between slake durability indices and uniaxial compressive strength, Schmidt hardness, P-wave velocity, modulus of elasticity, effective porosity, water absorption and dry and saturated unit weight for seven types of carbonate rocks obtained from south west Turkey. It was found that the dry unit weight, saturated unit weight and Schmidt hardness gave the best relationship with first cycle slake durability ($r = 0.99$) while uniaxial compressive strength has a strong relationship with fourth cycle slake durability ($r = 0.94$). The results showed little difference in the correlation coefficients obtained after the fourth cycle. It is concluded that, for the rocks studied, the first and fourth cycles provide sufficiently good data on the durability for preliminary engineering/design works and that the second to fourth cycle results could be estimated using the first cycle slake durability index ($r = 0.99$–0.97).

Keywords Slake durability · Uniaxial compressive strength · Rock properties · Carbonates

Résumé L'article présente une étude destinée à évaluer les relations entre les indices d'altérabilité et la résistance à la compression simple, la dureté de Schmidt, la vitesse des ondes P, le module d'élasticité, la porosité efficace, l'absorption d'eau et les poids spécifiques sec et saturé pour sept types de roches carbonatées du sud-ouest de la Turquie. Le poids spécifique sec, le poids spécifique saturé et la dureté de Schmidt des roches donnent la meilleure corrélation avec Id_1 ($r = 0{,}99$) tandis que la résistance à la compression simple présente une forte corrélation avec Id_4 ($r = 0{,}94$). Les résultats ont montré une faible différence de coefficients de corrélation obtenus après le quatrième cycle dans l'essai d'altérabilité. Il est conclu que, pour les roches étudiées, les Id_1 et Id_4 fournissent des données suffisamment bonnes sur l'altérabilité pour des études d'ingénierie préliminaires et que les indices Id_2 à Id_4 pourraient être estimés en utilisant le premier cycle de l'essai d'altérabilité ($r = 0{,}99$ à $0{,}97$).

Mots clés Essai d'altérabilité · Résistance à la compression simple · Propriété des roches · Carbonates

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Introduction

Slake durability of rocks is an important parameter when investigating the engineering behavior of a rock mass (Franklin and Chandra 1972; Onodera et al. 1974; Crosta 1998; Koncagul and Santi 1999; Gokceoglu et al. 2000; Dhakal et al. 2002; Singh et al. 2005), especially weak and soluble rocks such as shale, clay-bearing rocks, travertine and weak limestones, as it represents the degradability. In most of the previous studies and standards, the slake durability assessment of rock is based on the second cycle of the test, although some researchers (Taylor 1988; Moon and Beattie 1995; Ulusay et al. 1995; Bell et al. 1997; Gokceoglu et al. 2000; Yagiz and Akyol 2008; Yagiz 2010) recognize the need to carry out further cycles. Ulusay et al. (1995) carried out a five cycle slake durability test on marly spoil pile material and samples obtained from waste benches in open cast coal mines. They stated that as the number of cycles increases, the slake durability index decreases. Bell et al. (1997) studied several British coal mine wastes and stated that three cycle testing was a better way of assessing the durability of rocks such as sandstone and mudstone. Tugrul and Zarif (1999) stated that the mineralogical composition of the matrix in rocks provides the most direct control on the durability; however textural and fabric characteristics seem to be more important than grain mineralogy for the durability of sandstone. Gokceoglu et al. (2000) evaluated the factors affecting the durability of weak and clay-bearing rocks together with the influence of wetting and drying cycles on durability and noted a strong correlation with the presence of expansive clay minerals. They reported the best correlations between slake durability index and UCS were obtained after the fourth cycle. Sharma and Singh (2008) tested various rocks, including sandstone, basalt, mica schist, coal and shale, to assess the relationship between slake durability index and UCS, impact strength, Schmidt hammer and P-wave velocity. Dhakal et al. (2002) observed that mineralogy has a significant effect, with slake durability decreasing with increasing degree of weathering. Gupta and Ahmed (2007) stated that fine grained limestone is more susceptible to degradation than coarse grained and carbonate rocks, particularly in acidic environments.

In this paper, the relationships between the wetting/drying cycle and UCS, Schmidt hardness, P-wave velocity, modulus of elasticity, effective porosity, water absorption and both dry and saturated unit weight of various carbonate rocks have been investigated.

Rock sampling

Four types of travertine and three types of limestone were collected from south west Turkey (Fig. 1). The most common travertine types quarried in the Denizli basin are:

(a) Shrub type travertine, represented by small bush-like growths is a common deposit on horizontal and sub horizontal surfaces;
(b) Crystalline crust (onyx) commonly forms as a result of rapid precipitation due to fast flowing water on a smooth slope;
(c) Reed travertine, deposited in marsh pools, mounds and channels, and
(d) Noche—as a compact sub-unit of reed travertine.

The three limestones studied were:

(a) Dark dolomitic limestone of Eocene age which outcrops around Bozkurt village, Denizli.
(b) White limestone of Eocene age which outcrops in the village of Elmali, Antalya.
(c) Beige crystalline limestone of Jurassic age quarried in the village of Korkuteli, Antalya.

Fig. 1 Location of the sampling sites in southwestern Turkey

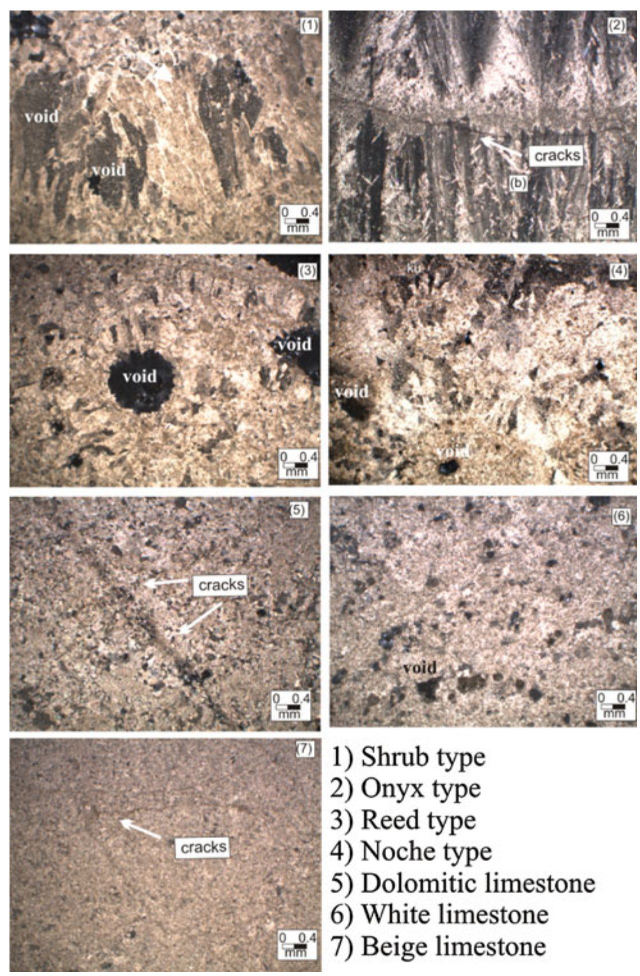

Fig. 2 Studied rock units, cross polarized under optical microscope (×10)

Block samples (300 × 250 × 300 mm) were obtained from quarries in the cities of Denizli and Antalya and their surroundings.

Mineralogical studies

Thin sections were used to investigate the texture and mineralogical composition of studied carbonate rocks.

(a) The shrub type travertine has micritic layers while 3–16 mm thick shrub layers are light cream in colour with crystals ranging from 5 to 10 μm (Fig. 2-1).
(b) The crystalline crust type has a micrite/sparite cement and calcite crystals some 10 μm wide and 100–200 μm long (Yagiz 2009). This travertine is usually dense, crudely fibrous and composed of elongated calcite feathers developed perpendicular to the depositional surface (Fig. 2-2).
(c) The reed travertine has moulds of reed and coarse grass. It has a sparite/calcite cement, grain sizes from fine to medium and crystal size ranging from 20 to 150 μm in diameter (Ozkul et al. 2002) and a higher organic content and porosity than the other travertines (Fig. 2-3).
(d) The noche type travertine, a sub-unit of the reed type, has a sparite/calcite cement and crystal sizes >20 μm in diameter. It is dense and dark brown colored with relatively low porosity (Fig. 2-4).
(e) The dolomitic limestone has sparite/micrite cement and a grain size ranging from medium to coarse (Fig. 2-5). It has random microcracks which have be infilled with calcite, such that the rock is weaker than anticipated.
(f) The white limestone is fine grained with sparite/calcite cement. This soft rock has no visible fissures or cracks but water absorption is relatively high (Fig. 2-6).
(g) The beige limestone has medium to coarse grains in a sparite/calcite cement (Fig. 2-7). It has some micro cracks and joints infilled with calcite, reducing the strength of the rock.

Rock testing methods

Uniaxial compressive strength, slake durability index, Schmidt hardness (N), P-wave velocity (V_p), modulus of elasticity (E), effective porosity (n'), water absorption by

Table 1 Descriptive statistical distribution of performed tests results for studied rock units

Rock type	γ_{dry} (kN/m^3)	γ_{sat} (kN/m^3)	N (–)	UCS (MPa)	V_p (km/s)	E (GPa)	n' (%)	w (%)	Id_2 (%)
Shrub type	24.27 ± 0.22	24.40 ± 0.25	45 ± 4	61 ± 20	4.8 ± 0.12	43 ± 7	1.35 ± 0.46	0.55 ± 0.19	98.91 ± 0.10
Onyx type	26.63 ± 0.46	26.84 ± 0.38	51 ± 3	58 ± 15	4.7 ± 0.19	44 ± 5	2.05 ± 0.88	0.76 ± 0.34	99.24 ± 0.07
Reed type	23.18 ± 0.56	23.36 ± 0.54	39 ± 5	41 ± 17	4.5 ± 0.11	35 ± 6	1.89 ± 0.50	0.80 ± 0.22	98.55 ± 0.14
Noche type	23.73 ± 0.48	23.88 ± 0.42	47 ± 3	64 ± 11	5.0 ± 0.08	44 ± 3	1.59 ± 0.89	0.66 ± 0.38	98.87 ± 0.12
Dolomitic limestone	27.26 ± 0.34	27.32 ± 0.32	53 ± 2	92 ± 33	4.9 ± 0.29	52 ± 12	0.60 ± 0.27	0.22 ± 0.10	99.65 ± 0.06
White lime	22.67 ± 0.98	23.62 ± 0.78	41 ± 4	32 ± 4	3.8 ± 0.41	22 ± 5	9.70 ± 2.20	4.24 ± 1.14	98.49 ± 0.25
Beige lime	26.31 ± 0.08	26.32 ± 0.08	54 ± 2	82 ± 28	5.0 ± 0.17	46 ± 4	0.16 ± 0.10	0.06 ± 0.04	99.43 ± 0.04

w water absorption by weight

Table 2 Summary of averaged slake durability indices with standard deviation for rock units

	Shrub travertine	Onyx travertine	Reed travertine	Noche travertine	Dolomitic limestone	White limestone	Beige limestone
Id_1	99.23 ± 0.08	99.53 ± 0.04	98.94 ± 0.12	99.25 ± 0.11	99.73 ± 0.06	99.00 ± 0.15	99.62 ± 0.03
Id_2	98.91 ± 0.10	99.24 ± 0.07	98.55 ± 0.14	98.87 ± 0.12	99.65 ± 0.06	98.49 ± 0.25	99.43 ± 0.04
Id_3	98.57 ± 0.11	99.05 ± 0.09	98.23 ± 0.16	98.59 ± 0.13	99.56 ± 0.06	98.03 ± 0.33	99.29 ± 0.07
Id_4	98.34 ± 0.12	98.86 ± 0.10	97.95 ± 0.19	98.32 ± 0.16	99.50 ± 0.07	97.62 ± 0.40	99.13 ± 0.05
Id_5	98.09 ± 0.13	98.69 ± 0.13	97.66 ± 0.23	98.09 ± 0.17	99.43 ± 0.07	97.26 ± 0.45	99.00 ± 0.06
Id_6	97.89 ± 0.15	98.55 ± 0.15	97.44 ± 0.25	97.88 ± 0.19	99.36 ± 0.08	96.97 ± 0.52	98.89 ± 0.08
Id_7	97.71 ± 0.18	98.41 ± 0.16	97.24 ± 0.26	97.69 ± 0.17	99.31 ± 0.08	96.63 ± 0.61	98.80 ± 0.08
Id_8	97.54 ± 0.19	98.28 ± 0.17	97.05 ± 0.28	97.51 ± 0.17	99.24 ± 0.08	96.36 ± 0.68	98.70 ± 0.11
Id_9	97.36 ± 0.20	98.15 ± 0.19	96.86 ± 0.29	97.37 ± 0.18	99.19 ± 0.09	96.06 ± 0.74	98.60 ± 0.12
Id_{10}	97.20 ± 0.22	98.05 ± 0.21	96.67 ± 0.30	97.18 ± 0.19	99.15 ± 0.09	95.79 ± 0.80	98.53 ± 0.13

$\bar{x} \pm$ SD refers to average values and standard deviation, respectively

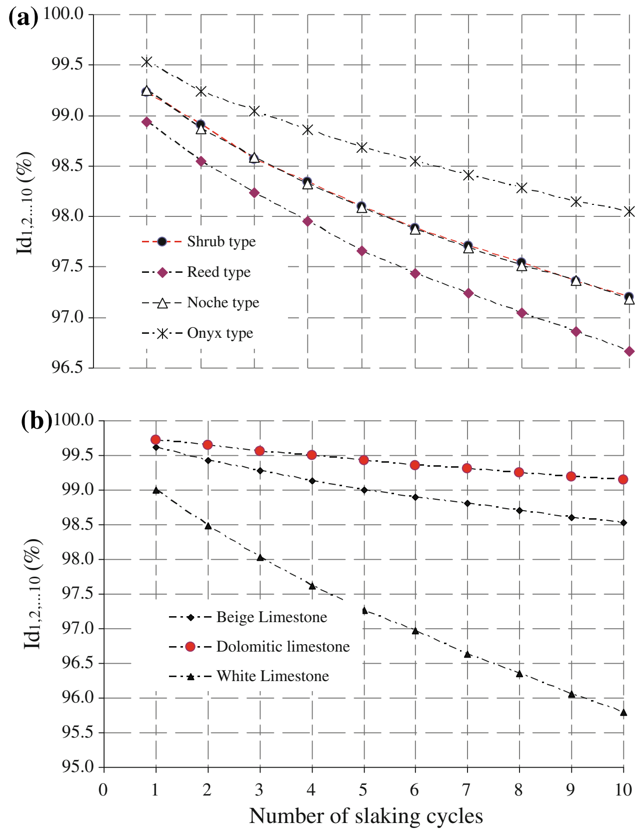

Fig. 3 Comparison of slake durability indices obtained from **a** four types of travertine and **b** three types of limestone

weight (w) and dry (γ_{dry}) and saturated (γ_{sat}) unit weight were determined on ten samples from each rock type. The results are given in Table 1 as average values and standard deviations.

The UCS tests were performed in accordance with EN1926 (European Norms 2000) which requires the cubic samples to have approximate dimensions of 70 × 70 × 70 mm; the uniaxial load is applied perpendicular to the bedding/layers with a loading rate of 0.5–1 MPa. Any sample which failed on cracks, weathered zones or other weakness planes was excluded. For the Schmidt hardness tests, an L-type Schmidt hammer was held vertically downwards on the cubic specimen and an impact energy of 0.735 Nm applied following ISRM (1981). P-wave, E, w, n', γ_{dry} and γ_{sat} were also established following ISRM (1981).

Slake durability testing (Franklin and Chandra 1972) was undertaken on ten samples of each rock type for ten cycles. The average results and standard deviations are tabulated in Table 2 and shown graphically in Fig. 3.

Regression analysis

One of the commonly accepted methods of investigating empirical relationships between rock properties is simple/multiple regression analysis. However, a large quantity of data is essential to determine meaningful correlations between the variables and to establish relevant predictive equations. In this research, linear ($y = ax + b$) and non-linear ($y = ax^b$) regression analyses were undertaken between the slake durability indices and measured rock properties. In addition, exponential ($y = ae^x$) and logarithmic ($y = a + \ln x$) relationships between the variables were also attempted to develop the most reliable empirical equations. The best correlations between the parameters were generally obtained via linear regression analysis using a statistical package (SPSS 2002) with 95% confidence (see Table 3). It was found that after the fourth cycle of wetting/drying, the increment on the coefficient of correlation between the rock properties (i.e., UCS, E, V_p, n' and w) and slake durability indices is not significant and can be ignored (Fig. 4). The relationships between the relevant rock properties and four-cycle slake durability index are given in Figs. 5, 6, 7, 8 and 9. The highest correlation coefficient was obtained between the first-cycle slake durability index and the index properties including N, γ_{dry} and γ_{sat} of rock (Figs. 10, 11, 12).

Table 3 Distribution of correlation coefficient (r) between slake durability indices and relevant rock properties for ten cycles

r	Id_1	Id_2	Id_3	Id_4	Id_5	Id_6	Id_7	Id_8	Id_9	Id_{10}	Relations
N	0.99	0.96	0.95	0.94	0.94	0.93	0.93	0.92	0.92	0.92	Linear
UCS	0.90	0.93	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.94	Linear
V_p	0.65	0.69	0.71	0.73	0.73	0.73	0.75	0.75	0.76	0.76	Linear
E	0.81	0.85	0.87	0.89	0.89	0.89	0.90	0.90	0.91	0.91	Linear
γ_{dry}	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.96	0.96	Linear
γ_{sat}	0.96	0.95	0.94	0.93	0.93	0.93	0.92	0.92	0.91	0.91	Linear
n'	0.72	0.76	0.78	0.79	0.79	0.79	0.80	0.81	0.81	0.81	Power
w	0.74	0.79	0.81	0.81	0.81	0.82	0.83	0.83	0.83	0.83	Power

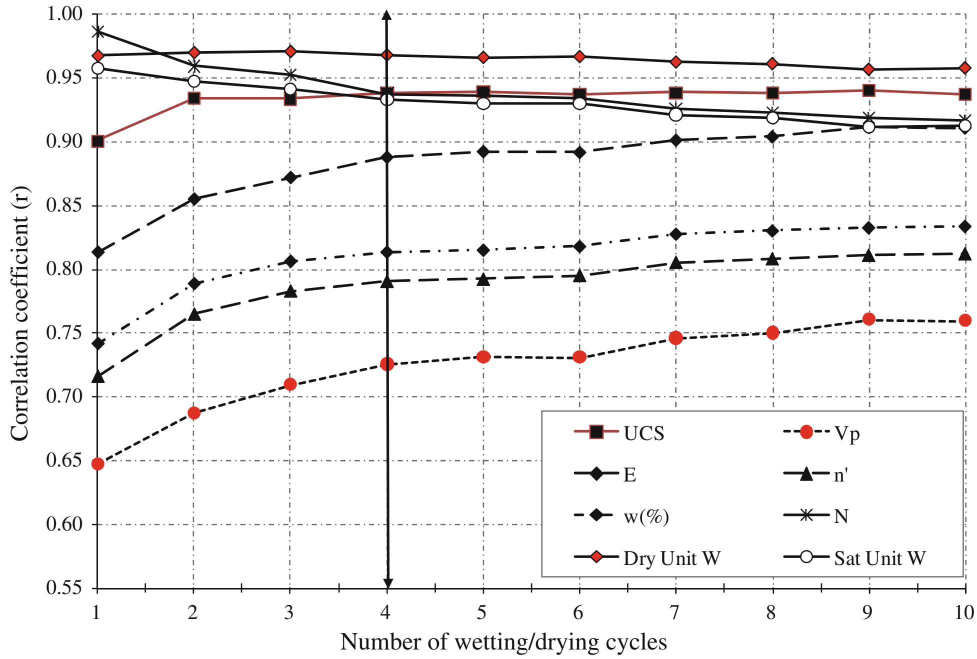

Fig. 4 Relationships between the wetting/drying cycles and different rock properties

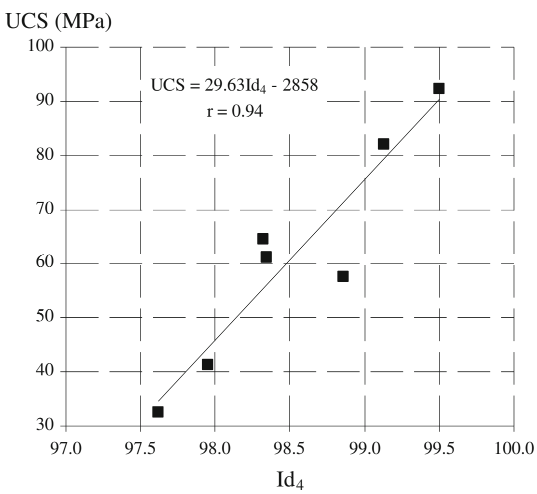

Fig. 5 Relationship between the UCS and Id_4

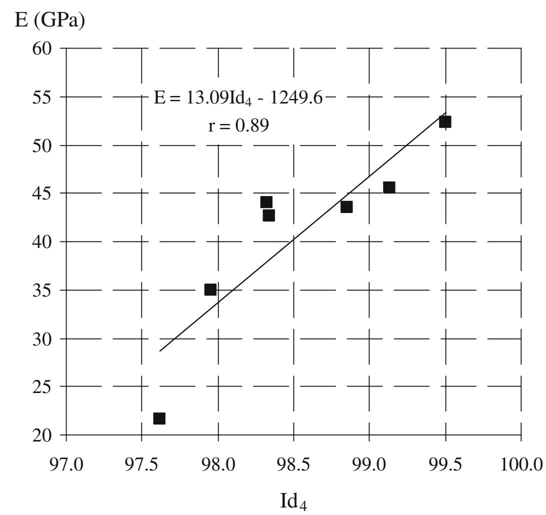

Fig. 6 Relationship between the *E* and Id_4

In order to shorten the test duration, an attempt was made to empirically predict the Id_2 through Id_5 values directly from the Id_1 value (Table 4). This table also shows the results of the *t* test and *F* test which confirm the relationship between the variables is significant. With correlation coefficients of 0.99 and 0.97, respectively, the empirical relationships proposed for the first-cycle slake durability index (Id_1) and both Id_2 and Id_4 are sufficiently good to be used in the early stages of rock engineering and design works.

Conclusions

In this study, the relationships between the slake durability indices and UCS, *E*, V_p, modulus of elasticity,

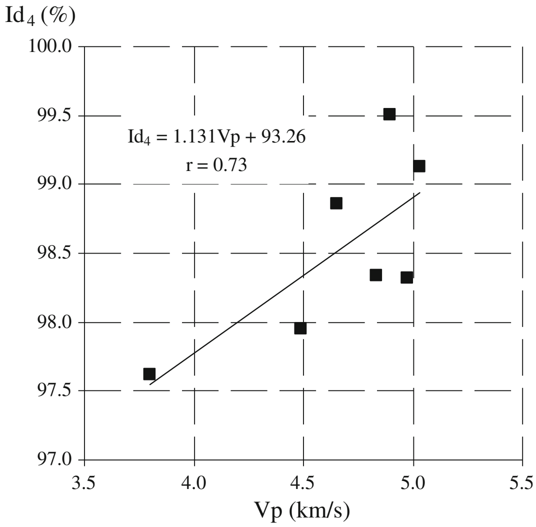

Fig. 7 Relationship between the V_p and Id_4

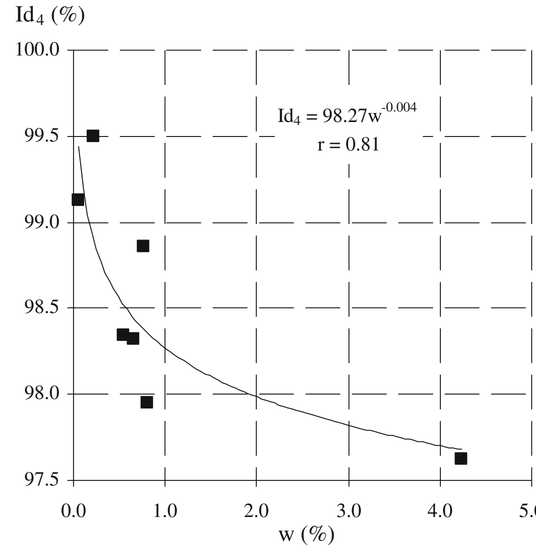

Fig. 9 Relationship between the water absorption by weight and Id_4

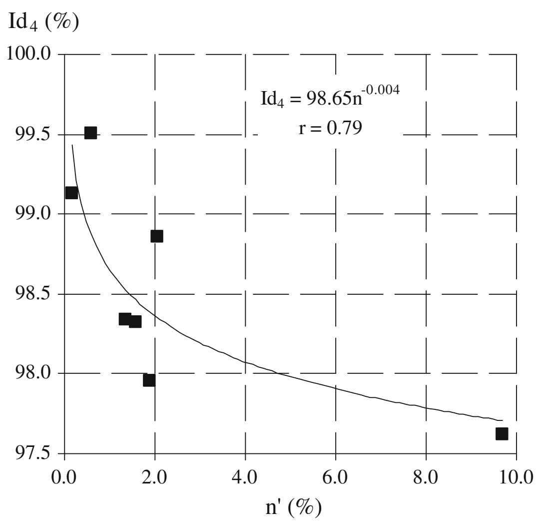

Fig. 8 Relationship between the effective porosity and Id_4

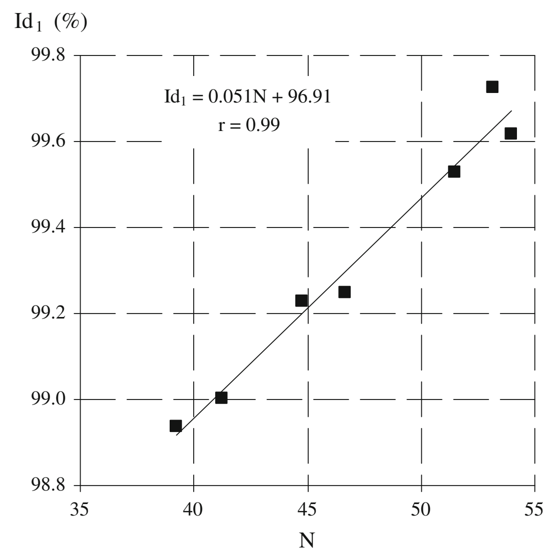

Fig. 10 Relationship between the *N* and Id_1

Schmidt hardness, effective porosity, water absorption by weight and the dry and saturated unit weight of seven types of carbonate rocks have been investigated. The dry unit weight, saturated unit weight and Schmidt hardness of carbonate rock give the best relationship with Id_1 ($r = 0.99$, 0.97 and 0.96, respectively). For Id_4, the highest correlation coefficients were found with UCS ($r = 0.94$) and it is recommended four cycles of the slake durability test rather than two are used for soluble rocks.

It was also found that after four cycles of wetting/drying, the correlation obtained between the slake durability indices and P-wave velocity, elasticity modulus, effective porosity and water absorption does not change significantly. Further, for carbonate rocks Id_2–Id_4 could be estimated using the first cycle slake durability index ($r = 0.99$–0.97).

Whilst only a limited number of tests were undertaken on specific rock types, the study has shown that the results can be useful in the early stage of a project.

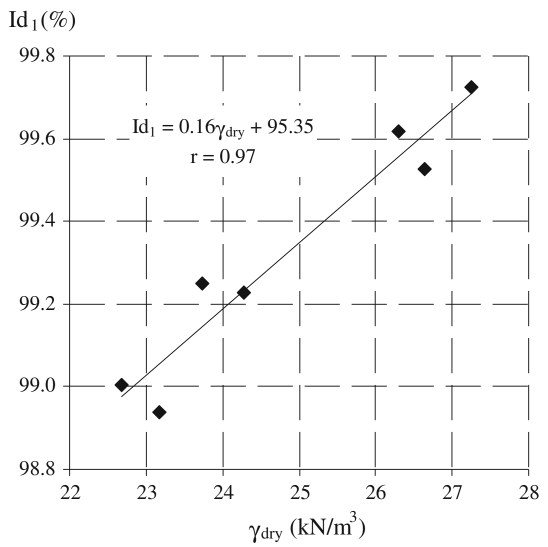

Fig. 11 Relationship between the dry unit weight and Id_1

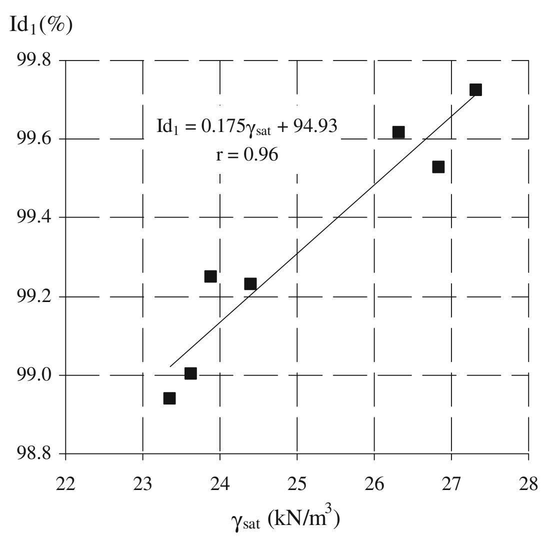

Fig. 12 Relationship between the saturated unit weight and Id_1

Table 4 The functional relationships for predicting the slake durability indices from the Id_1

Equations	*r*	*t* test	*F* test	$p < 0.05$
$Id_2 = 1.430Id_1 - 42.97$	0.99	16.37	268.07	0.000
$Id_3 = 1.814Id_1 - 81.39$	0.98	12.31	151.54	0.000
$Id_4 = 2.129Id_1 - 112.98$	0.97	9.81	96.24	0.000
$Id_5 = 2.441Id_1 - 144.11$	0.97	9.49	90.05	0.000

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