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Technical note

On the reliability of the strength retention ratio for estimating the strength of weathered rocks

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ABSTRACT

This technical note examines the validity of the strength retention ratio (R_s) as a criterion for estimating the strength of weathered rocks. Although R_s has been widely used for classification purposes, it seems to significantly underestimate the strength of slightly weathered (SW) rocks. To better understand the limitations within which R_s can be used, a series of point load and slake durability tests were performed on weathered rocks of three types. The obtained correlations between the point load and slake durability indices were used as a basis to refine the current method of determining R_s. Using this new procedure, the available data from the literature were revisited, and R_s was re-calculated providing a better match between the quantitative and qualitative description of weathered rocks.

1. Introduction

Weathering of rock materials has a strong effect on the stability of rock masses. A number of studies have been performed in the past few decades to provide qualitative description of weathered rock materials and rock masses (Irfan and Dearman, 1978; Irfan and Powell, 1985; Tugrul and Gurpinar, 1997; Basu et al., 2009; Marques et al., 2010) and quantitative (Gupta and Rao, 2000, 2001; Kim et al., 2015a, 2015b) information about weathered rocks, resulting in several criteria and indices which are currently used for rock classification.

From an engineering point of view, changes in the strength of weathered rocks will be of great importance for design purposes and the prediction of long-term stability of natural and engineering structures (Tating et al., 2013). To address this issue, Gupta and Rao (2001) proposed a "strength retention ratio" (R_s) to describe the strength of weathered crystalline rocks. R_s is defined as the ratio of the uniaxial compressive strengths (or point load index) of weathered to the fresh intact rock specimens, and its value starts at 100% for fresh rocks decreasing with progressive weathering.

Although R_s has become a popular tool to classify the degree of weathering of granitic rocks (Heidari et al., 2013; Momeni et al., 2015) and rock mass (Ramamurthy, 2004), there are still some concerns regarding its use. In particular, a) the value of R_s strongly depends on the strength of fresh rocks. However, published lab data suggest that the strength of fresh rocks can vary significantly. For example, Dagdelenler et al. (2011) indicated that the unconfined compressive strength (UCS) of fresh Koprukoy granite can range from 77.1 MPa to 143.6 MPa while Baczynski (2001) reported a wide variation of point load strength index (from 1 to 3.1 MPa) for Brisbane argillite. b) In addition, R_s seems to significantly underestimate the retained strength of slightly weathered (SW) crystalline rocks. For example, for SW granites (Gupta and Rao, 2001), R_s can drop as low as 52%, which indicates a significant difference in strength between fresh and slightly weathered rocks. However, this doesn't seem to fit in the ISRM (1981) description of SW rocks which states that SW rocks "may be somewhat weaker than in its fresh conditions" (Table 1). It also contradicts the classification of

Table 1
Weathering degrees: qualitative description and ranges of slake durability index (I_{d2}).

Grade of weathering	Qualitative description (after ISRM, 1981)	I_{d2}, %
Fresh (F)	No visible sign of weathering; perhaps slight discoloration on major discontinuities surfaces	98–100
Slightly weathered (SW)	Rock may be discoloured and may be somewhat weaker than in its fresh conditions	95–98
Moderately weathered (MW)	Less than half of the rock material is decomposed and/or disintegrated to a soil.	85–95
Highly weathered (HW)	More than half of the rock material is decomposed and/or disintegrated to a soil.	60–85
Completely weathered (CW)	All rock material is decomposed and/or disintegrated to soil.	<60

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Table 2
Summary of lab data.

No.	Point load strength index, $I_{s(50)}$ (MPa)	Slake durability index, I_{d2} (%)	Weathering grade
Rock type: Sandstone			
1	1.42	99.20	F
2	1.04	98.70	F
3	1.83	98.10	F
4	1.93	97.20	SW
5	2.71	97.07	SW
6	3.90	97.00	SW
7	1.50	96.71	SW
8	2.07	96.69	SW
9	1.55	96.60	SW
10	1.64	96.30	SW
11	2.36	96.00	SW
12	1.35	95.57	SW
13	0.92	95.50	SW
14	0.66	94.18	MW
15	1.47	93.20	MW
16	0.75	92.40	MW
17	1.30	92.31	MW
18	1.34	91.71	MW
19	1.09	91.08	MW
20	1.33	91.05	MW
21	0.61	91.10	MW
22	0.84	90.70	MW
23	1.17	90.60	MW
24	0.93	90.57	MW
25	0.60	89.38	MW
26	0.86	89.00	MW
27	0.68	88.20	MW
28	1.05	87.14	MW
29	0.73	86.40	MW
30	0.57	85.60	HW
31	0.62	84.00	HW
32	0.83	83.00	HW
33	0.58	79.37	HW
34	0.50	73.51	HW
35	0.26	69.76	HW
36	0.33	69.06	HW
37	0.17	59.30	HW
38	0.10	57.40	CW
39	0.17	50.00	CW
Rock type: Shale			
40	0.99	98.38	F
41	2.26	98.06	F
42	1.67	97.86	SW
43	1.20	96.34	SW
44	1.25	96.00	SW
45	1.20	93.50	MW
46	0.86	90.57	MW
47	0.90	86.93	MW
48	0.95	83.90	HW
49	0.78	80.64	HW
50	0.58	78.50	HW
51	0.62	72.31	HW
52	0.21	64.92	HW
53	0.38	58.08	CW
54	0.19	45.15	CW
Rock type: Tuff			
55	2.40	97.80	F
56	1.40	93.20	SW
57	2.04	93.16	SW
58	0.85	81.80	HW
59	0.80	75.20	HW
60	0.28	63.70	HW
61	0.21	55.80	CW
62	0.30	48.70	CW
63	0.28	43.70	CW
64	0.18	40.30	CW
65	0.13	33.60	CW
66	0.05	24.80	CW

Note: F — fresh, SW — slightly weathered, MW — moderately weathered, HW — highly weathered, CW — completely weathered.

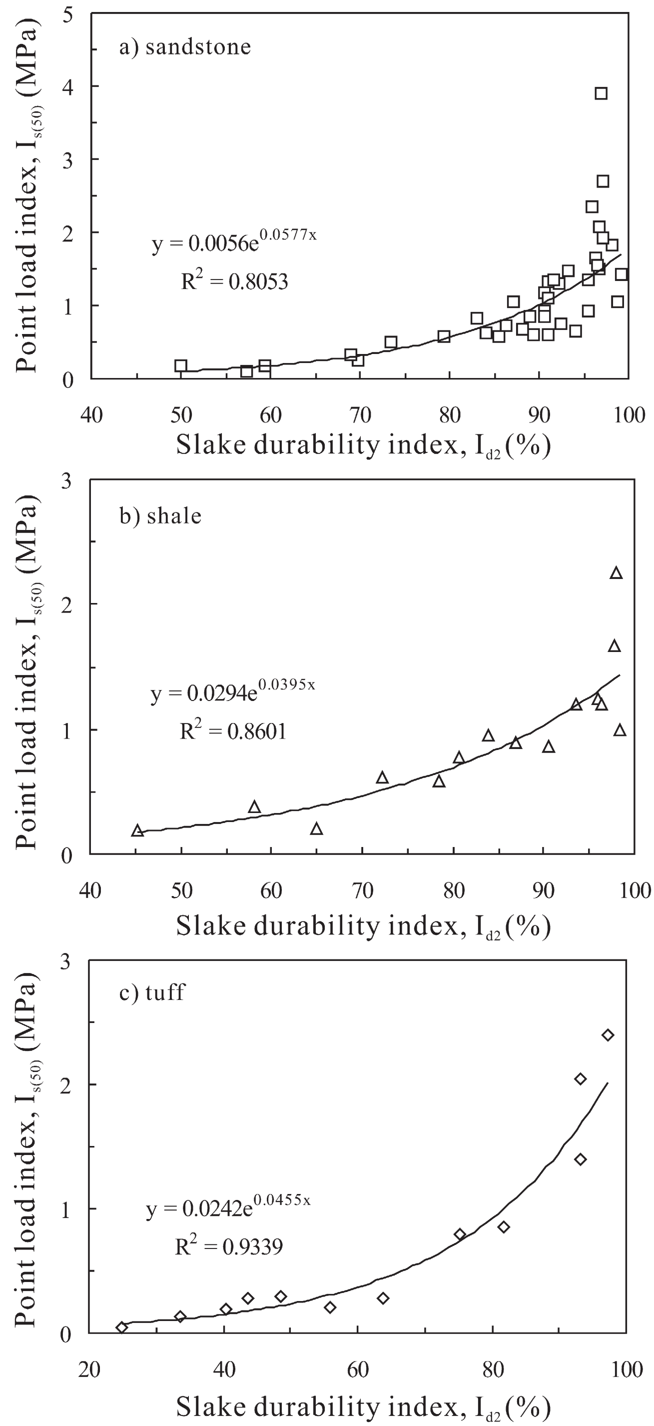

Fig. 1. Results of point load and slake durability tests obtained for sandstone (a), shale (b), and tuff (c).

SW rocks given by Australian Standard AS1726 (1993), which describes SW rocks as "little or no change of strength from fresh rock".

This study seeks to critically assess the use of R_s as an indicator of weathered rock strength. In particular, this technical note presents the data from a series of point load and slake durability tests performed on three different types of rocks from the Gold Coast area (Queensland, Australia) to establish the correlation between the rock strength and its resistance to weathering. Based on the obtained results, the use of R_s is critically analysed and some adjustments to the current procedure of determining R_s are proposed. Finally, the available literature is reviewed to discuss the use of R_s for a variety of rock types.

Table 3
Summary of previous studies on weathered rocks and determination of rock strength at $I_{d2} = 100\%$.

Source	Rock type	Test*	Data from lab tests (MPa)				Analysis using the proposed procedure			
			Fresh	SW	MW	HW	Equation**	R^2	Strength (MPa) at $I_{d2} = 100\%$	Hoek–Brown constant, m_i
Khanlari et al. (2012)	Monzogranite	UC	125.64	74.45	69.59	52.06	$UCS = 17.31e^{0.153I_{d2}}$	0.99	79.9	32
Momeni et al. (2015)	Granodiorite	UC	221.1	126.1	72.7	33.2	$UCS = 0.672e^{0.053I_{d2}}$	0.98	140.1	29
Tugrul (2004)	Sandstone	UC	52.5	35.5	19.5	7.75	$UCS = 0.088e^{0.061I_{d2}}$	0.98	40.4	17
Tugrul (2004)	Basalt	UC	111.0	84.0	40.0	14.0	$UCS = 0.074e^{0.071I_{d2}}$	0.98	96.0	25
Tugrul (2004)	Granodiorite	UC	126.5	98.5	47.0	16.0	$UCS = 0.078e^{0.0728I_{d2}}$	0.98	113.8	29
Tating et al. (2013)	Sandstone	UC	96.8	58.5	23.4	7.6	$UCS = 0.021e^{0.0807I_{d2}}$	0.96	65.9	17
Beavis et al. (1982)	Shale	PL	3.98	2.42	2.38	1.2	$PLI = 0.129e^{0.031I_{d2}}$	0.95	2.9	6
Irfan and Dearman (1978)	Granite	PL	10.0	8.75	5.75	2.5	$PLI = 0.06e^{0.0512I_{d2}}$	0.99	10.1	32
Gokceoglu et al. (2009)	Granitoid	PL	6.86	3.56	1.65	0.7	$PLI = 0.0065e^{0.0639I_{d2}}$	0.95	3.9	19
Dearman and Irfan (1978)	Granite	PL	9.0	7.2	4.7	3.0	$PLI = 0.243e^{0.0342I_{d2}}$	0.94	7.4	32
Baczynski (2001)	Argillite	PL	4.9	3.8	2.4	1.05	$PLI = 0.0233e^{0.0523I_{d2}}$	0.99	4.4	7
Baczynski (2001)	Metabasalt	PL	6.3	4.2	3.2	1.45	$PLI = 0.0577e^{0.0445I_{d2}}$	0.99	4.9	25
Marques et al. (2010)	Kinzigite	PL	2.79	1.98	0.99	0.33	$PLI = 0.0017e^{0.0722I_{d2}}$	0.98	2.3	12
This study	Sandstone	PL	2.04	0.95	0.36	0.1	$PLI = 0.003e^{0.082I_{d2}}$	0.97	1.1	17
This study	Shale	PL	1.64	1.1	0.6	0.19	$PLI = 0.001e^{0.0716I_{d2}}$	0.99	1.3	6
This study	Tuff	PL	1.95	1.4	0.6	0.2	$PLI = 0.0007e^{0.0766I_{d2}}$	0.97	1.5	13

* UC — unconfined compression, PL — point load, UCS — unconfined compressive strength, PLI — point load strength index.
** The following relationships between the qualitative description of weathering grades and I_{d2} derived from Fig. 2 were used: "SW" — $I_{d2} = 96.5\%$, "MW" — $I_{d2} = 90.0\%$, and "HW" — $I_{d2} = 72.5\%$.

2. Materials and method

A series of point load and slake durability tests were performed on 66 samples to determine the rock strength and its resistance to weathering. Three different rock types: sandstone, shale, and tuff were used. Sandstone and shale, which were a part of the Neranleigh-Fernvale beds (Willmott, 2010; Kim et al., 2013), were collected from a road cut along the Beaudesert–Nerang Road that connects the Gold Coast with the Tambourine Mountain area. Visual examination of the samples was performed using the ISRM (1981) guidelines (Table 1) to determine the degree of weathering. The weathered tuff samples were collected from a landslide site near the Tambourine Mountain. Fresh samples of tuff were collected from a slope outcrop which was located about 30 m away from the slide. The degree of weathering of all tested samples is given in Table 2.

2.1. Determination of rock strength

The point load test (Broch and Franklin, 1972) has become a popular method of testing rocks as it provides a cheap and simple way of classifying rock material strength. In addition, the results of this test can also be used to estimate the unconfined compressive strength of rocks which makes it more popular among engineers. In this work, a series of point load (PL) tests were performed on irregularly-shaped (lump) samples following AS 4133.4.1–2007 (2007). From each test, the point load strength index ($I_{s(50)}$) was obtained and used to determine the strength of rocks. The values of $I_{s(50)}$ for all tested samples are summarized in Table 2.

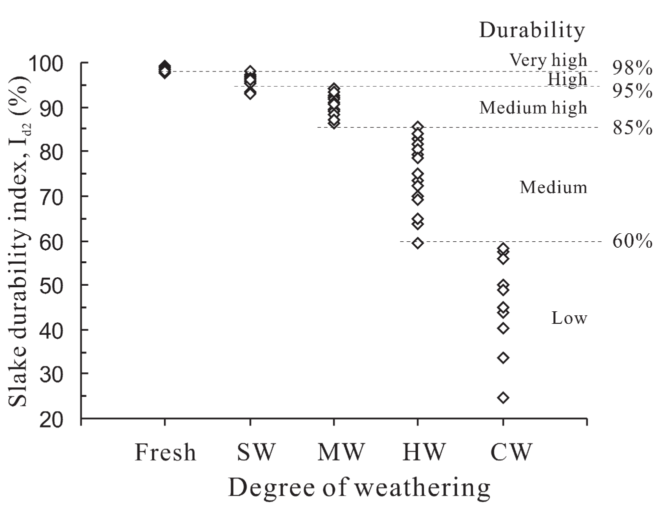

Fig. 2. Results of slake durability tests obtained for sandstone, shale and tuff with different degrees of weathering.

2.2. Slake-durability tests

To determine the rock resistance to weathering, a series of slake durability (SD) tests (Franklin and Chandra, 1972) were performed. This type of test is typically carried out to estimate the strength of rocks when there is a wide range of weak and highly weathered material. In this study, all SD tests were conducted in accordance with AS 4133.3.4–2005 (2005), and the slake durability index obtained for the second cycle (I_{d2}) was reported (Table 2).

3. Results and discussion

3.1. Test results

Results from PL and SD tests are summarized in Table 2 and plotted in Fig. 1 as $I_{s(50)}$ against I_{d2} for sandstone (a), shale (b), and tuff (c). It is evident from this figure that regardless of rock type, 1) the rock samples with higher I_{d2} tend to have higher values of $I_{s(50)}$. 2) There is a scatter of $I_{s(50)}$ values for a very narrow range of I_{d2} (95–100%). For example, for the sandstone (Fig. 1a), the $I_{s(50)}$ varied significantly from 0.6 to 3.6 MPa when $I_{d2} \geq 95\%$. 3) In contrast, the data to the left of this point ($I_{d2} < 95\%$) seem to have much less variability. Similar findings were obtained by Cargill and Shakoor (1990) and Koncagul and Santi (1999), who reported a large variation of unconfined compressive strength (UCS) for different rocks with durability greater than 94%. In fact, the available literature suggests that a variation of strength in closely related rocks is not uncommon and can be explained by a number of factors including mineral composition and microstructural features (which may not be noticeable during visual examination of rock samples). Prikryl (2001) studied microstructural aspects of strength variation in rocks and reported that even a small change in the average grain size can significantly affect the strength of rocks. Koncagul and Santi (1999) also noted the important role of microstructure in the strength of argillaceous rocks. The investigators indicated that the turbostatic microfabric of shale can result in higher UCS values compared to the skeleton microfabric.

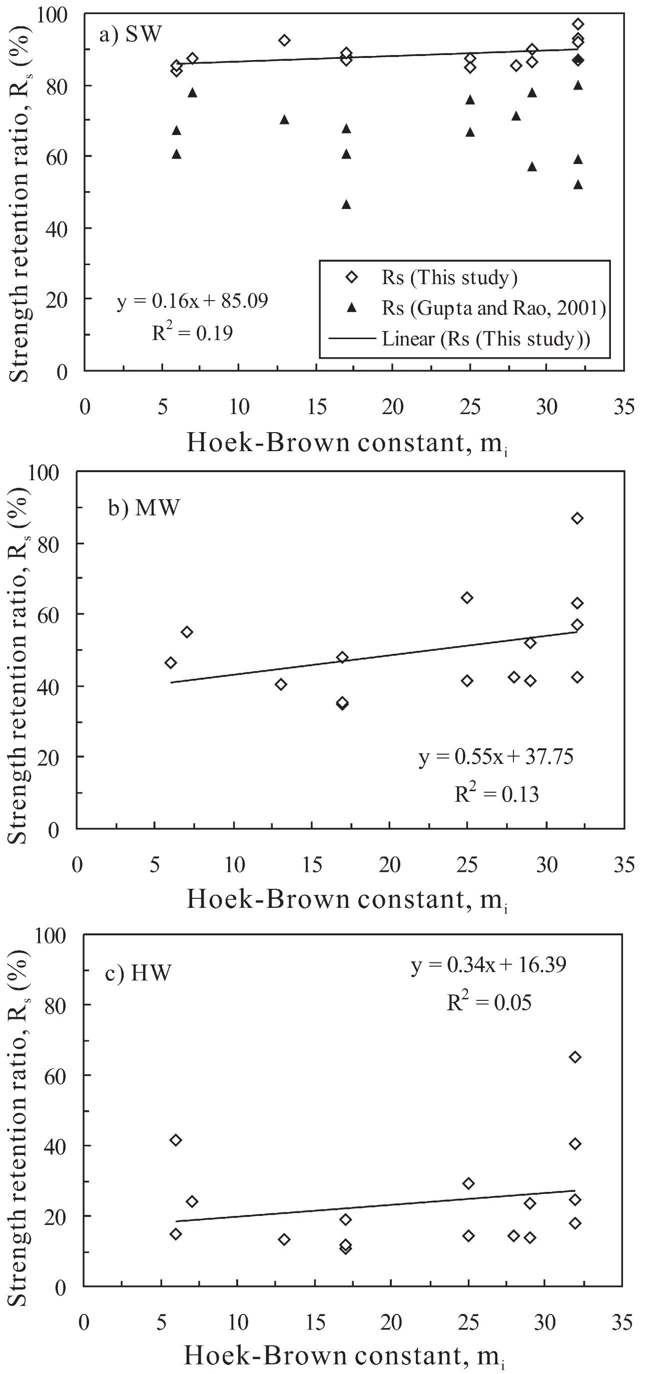

Fig. 3. Correlations between R_s and the Hoek–Brown constant (m_i) obtained using the previously published data: a) slightly weathered (SW), b) moderately weathered (MW), and c) highly weathered (HW) rocks.

This large variation of $I_{s(50)}$ at $I_{d2} \geq 95\%$ makes it rather difficult to determine the true value of $I_{s(50)}$ for fresh rocks. This study proposes to consider a much larger range of I_{d2} (45–95%), which has a much higher level of correlation ($R^2 = 0.8$–0.93) between I_{d2} and $I_{s(50)}$, and extrapolate this data to obtain the strength of fresh rock at $I_{d2} = 100\%$. To demonstrate how this procedure can be used to evaluate the strength of weathered rocks, previously published data were revisited and R_s was re-calculated and compared with the one obtained following Gupta and Rao (2001).

3.2. Analysis of published data using R_s

The data from previous studies in which the strength of rock material was determined at all levels of weathering (F, SW, MW, and HW) were summarized in Table 3. As the proposed procedure involves the use of slake durability index (I_{d2}), it was first necessary to convert the qualitative description of weathering (ISRM, 1981) into relevant values of I_{d2}. Although some attempts to establish correlations between these two rock characteristics were previously made (Lee and Freitas, 1988), it was not sufficient to define the range of I_{d2} that could match each of the weathering grades. For this reason, all of the results obtained in this study from SD tests were summarized in Fig. 2 to determine the range of I_{d2} that can be assigned to each weathering grade. It is evident from this figure that the boundaries that can be established for each weathering grade are in agreement with the durability classification for I_{d2} (Franklin and Chandra, 1972), where fresh rocks (F) are referred to as "very high" durable (I_{d2} ranges from 98–100%), SW rocks have a "high" durability to weathering (I_{d2} is in the range of 95–98%), MW rocks are linked to the "medium high" durability grade (I_{d2}: 85–95%), and HW rocks can be described as a "medium" durability to weathering (I_{d2}: 60–85%). After the range of I_{d2} was established for each weathering grade, the average value of I_{d2} was used to represent the qualitative weathering grades as follows: "SW" − $I_{d2} = 96.5\%$, "MW" − $I_{d2} = 90.0\%$, and "HW" − $I_{d2} = 72.5\%$. Then for each rock in Table 3, the relationship between I_{d2} and unconfined compressive strength (UCS) or point load strength index (PLI) was established with a high level of correlation (R^2). Using this relationship, the strength of rock at $I_{d2} = 100\%$ was calculated (Table 3) and this value was used as the fresh rock strength to obtain R_s.

The values of R_s calculated for all rocks from Table 3 are summarized in Fig. 3 for different weathering degrees: "SW" (a), "MW" (b), and "HW" (c) plotted against m_i, which is the Hoek–Brown constant selected to represent the overall strength of rocks (e.g., an increase in m_i correlates with an increase in rock strength). The average value of m_i recommended by Hoek (2007) was used for the rocks in Fig. 3. For comparisons, R_s values calculated following Gupta and Rao (2001) are also given in Fig. 3a.

Fig. 3a indicates that slightly weathered rocks tend to retain about 80–90% of the fresh rock strength (compared to the 45–80% retention of strength, according to Gupta and Rao (2001)), a range that appears to better match the qualitative description of slightly weathered rocks provided by ISRM (1981). It can also be inferred from Fig. 3a that rocks with higher m_i (harder rocks) tend to retain more strength than the rocks with lower m_i (weaker rocks). However, the coefficient of determination of this relationship is relatively low ($R^2 = 0.2$), which may suggest that "a strong rock may not always be the durable one or vice versa" (Koncagul and Santi, 1999). It is noted that average values of m_i was chosen for each rock, which may also influence the observed correlation. Similar observations can be made for moderately (Fig. 3b) and highly (Fig. 3c) weathered rocks; that is, rocks with higher m_i tend to retain more strength than the rocks with lower m_i. It is interesting to note that slightly weathered rocks can, on average, retain about 80–90% of fresh rock strength while the moderately and highly weathered rocks can retain about 40–60% and 10–20%, respectively.

4. Conclusions

In this work, a series of point load and slake durability tests were performed on three rock types to study the effect of weathering on rock strength. The main conclusions that can be drawn from this work are as follows:

- The use of R_s proposed by Gupta and Rao (2001) may lead to underestimation of the strength of slightly weathered rocks.
- The data from point load and slake durability tests revealed a high scatter of $I_{s(50)}$ values at $I_{d2} \geq 95\%$, which makes it difficult to determine accurate values of fresh rock strength.

- The range of I_{d2} for each qualitatively-defined grade of weathering was established. It was found to correlate with the durability classification of rocks.
- Analysis of the published data revealed that rocks with a higher Hoek–Brown constant (m_i) tend to retain more strength as weathering continues.

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References

Australian Standard AS 1726-1993, 1993. Geotechnical Site Investigations.
Australian Standard AS 4133.3.4–2005, 2005. Methods of testing rocks for engineering purposes. Method 3.4: Rock Swelling and Slake Durability Tests—Determination of the Slake Durability Index of Rock Samples.
Australian Standard AS 4133.4.1–2007, 2007. Method 4.1: Rock Strength Tests—Determination of Point Load Strength Index.
Baczynski, N.R., 2001. Intact rock strength of Neranleigh-Fernvale strata. Aust. Geomech. 36 (3), 9–15.
Basu, A., Celestino, T.B., Bortolucci, A.A., 2009. Evaluation of rock mechanical behaviours under uniaxial compression with reference to assessed weathering grades. Rock Mech. Rock. Eng. 42, 73–93.
Beavis, F.C., Roberts, I., Minskaya, L., 1982. Engineering aspects of weathering of low grade metapelites in an arid climatic zone. Q. J. Eng. Geol. 15, 29–45.
Broch, E., Franklin, J.A., 1972. The point load strength test. Int. J. Rock Mech. Min. Sci. 9 (3), 669–697.
Cargill, L.S., Shakoor, A., 1990. Evaluation of empirical methods for measuring the uniaxial compressive strength of rock. Int. J. Rock Mech. Min. Sci. 27 (6), 495–503.
Dagdelenler, G., Sezer, E.A., Gokceoglu, C., 2011. Some non-linear models to predict the weathering degrees of a granitic rock from physical and mechanical parameters. Expert Syst. Appl. 38, 7476–7485.
Dearman, W.R., Irfan, T.Y., 1978. Classification and index properties of weathered coarse grained granites from SW England. Proc 3rd International Congress IAEG, pp. 119–130.
Franklin, J.A., Chandra, R., 1972. The slake-durability test. Int. J. Rock Mech. Min. Sci. 9, 325–341.
Gokceoglu, C., Zorlu, K., Ceryan, S., Nefeslioglu, H.A., 2009. A comparative study on indirect determination of degree of weathering of granites from some physical and strength parameters by two soft computing techniques. Mater. Charact. 60, 1313–1327.
Gupta, A.S., Rao, K., 2000. Weathering effects on the strength and deformational behaviour of crystalline rocks under uniaxial compression state. Eng. Geol. 56, 257–274.
Gupta, A.S., Rao, K., 2001. Weathering indices and their applicability for crystalline rocks. Bull. Eng. Geol. Environ. 60, 201–221.
Heidari, M., Momeni, A.A., Naseri, F., 2013. New weathering classifications for granitic rocks based on geomechanical parameters. Eng. Geol. 166, 65–73.
Hoek, E., 2007. Practical rock engineering. https://www.rocscience.com/learning/hoek-s-corner/books.
Irfan, T.Y., Dearman, W.R., 1978. Engineering classification and index properties of a weathered granite. Bull. Int. Assoc. Eng. Geol. 17, 79–90.
Irfan, T.Y., Powell, G.E., 1985. Engineering geological investigations for pile foundation on a deeply weathered granitic rock in Hong-Kong. Bull. Int. Assoc. Eng. Geol. 32, 67–80.
ISRM, 1981. Basic geotechnical description of rock masses. Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 18, 85–110.
Khanlari, G.R., Heidari, M., Momeni, A.A., 2012. Assessment of weathering processes effect on engineering properties of alvand granitic rocks (west of Iran), based on weathering indices. Environ. Earth Sci. 67, 713–725.
Kim, D.H., Gratchev, I., Balasubramaniam, A.S., 2013. Determination of joint roughness coefficient (JRC) for slope stability analysis: a case study from the Gold Coast area, Australia. Landslides 10 (5), 657–664. http://dx.doi.org/10.1007/s10346-013-0410-8.
Kim, D.H., Gratchev, I., Balasubramaniam, A.S., 2015b. Back analysis of a natural jointed rock slope based on the photogrammetry method. Landslides 12 (1), 147–154.
Kim, H.D., Gratchev, I., Balasubramaniam, A.S., 2015a. A photogrammetric approach for stability analysis of weathered rock slopes. Geotech. Geol. Eng. 33, 443–454. http://dx.doi.org/10.1007/s10706-014-9830-z (online first).
Koncagul, E.C., Santi, P.M., 1999. Predicting the unconfined compressive strength of the Breathitt shale using slake durability, Shore hardness and rock structural properties. Int. J. Rock Mech. Min. Sci. 36, 139–153.
Lee, S.G., Freitas, M.H., 1988. Quantitative definition of highly weathered granite using the slake durability test. Geotechnique 38 (4), 635–640.
Marques, E.A., Barroso, E.V., Menezes Filho, A.P., Vargas, E.A., 2010. Weathering zones on metamorphic rocks from Rio de Janerio — physical, mineralogical and geomechanical characterization. Eng. Geol. 111, 1–18.
Momeni, A.A., Khanlari, G.P., Heidari, M., Sepahi, A.A., Bazvand, E., 2015. New weathering geological weathering classifications for granitoid rocks. Eng. Geol. 185, 43–51.
Prikryl, R., 2001. Some microstructural aspects of strength variation in rocks. Int. J. Rock Mech. Min. Sci. 38, 671–682.
Ramamurthy, T., 2004. A geo-engineering classification for rocks and rock masses. Int. J. Rock Mech. Min. Sci. 41, 89–100.
Tating, F., Hack, R., Jetten, V., 2013. Engineering aspects and time effects of rapid deterioration of sandstone in the tropical environment of Sabah, Malaysia. Eng. Geol. 159, 20–30.
Tugrul, A., 2004. The effect of weathering on pore geometry and compressive strength of selected rock types from Turkey. Eng. Geol. 75, 215–227.
Tugrul, A., Gurpinar, O., 1997. A proposed weathering classification for basalts and their engineering properties (Turkey). Bull. Int. Assoc. Eng. Geol. 55, 61–71.
Willmott, W.F., 2010. Rocks and Landscapes of the Gold Coast Hinterland Geological Society of Australia. Queensland division.