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Field Methods for Characterizing Weak Rock for Engineering

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ABSTRACT

Many classification and testing methods for shale, slaking rock, weak rock, and weathered rock have been developed. However, few of these methods are suitable for field use or are applicable to a wide range of material types. The purpose of this paper is to present a summary of recent research and analysis evaluating classification and testing methods. This summary will assist the practitioner in properly identifying problem shale and weak rock units, in adequately describing their characteristics in the field, and in selecting and performing field tests to quantify their behavior. For identification of shale and weak rock units, three increasingly site-specific tools are presented. First is a map showing occurrences of weak rock units in the United States. Second is a detailed list of suspect rock types that may appear on regional or local geologic maps. Third is a summary of engineering properties that describe weak rock units, based on a review of technical literature. Some of these properties are compressive strengths between 1 and 20 MPa, slake durability less than 90 percent, clay content greater than 15 percent, poor induration, a significant amount (50 to 75 percent) of matrix between hard blocks, or high moisture content. Methods of field description were chosen based on a review of existing methods to assess their ease of application, breadth of application, and the usefulness of the engineering properties indicated by each system. Two modified methods are presented to indicate proportion and nature of corestones and matrix, strength, influence of discontinuities, and reactivity to water. Finally, field-testing methods that estimate strength, permeability, durability, and reaction to water are identified. These include point load index, Norwegian Geotechnical Institute Rock Mass Classification, jar slake, and hammer rebound classification. Predictive equations to estimate unconfined compressive strength, slake durability, and slake index are given.

INTRODUCTION

Throughout this paper, the term “weak rock” is used to refer both to weak and weathered materials. According to Santi and Doyle (1997), weak materials are “intact, unweathered to slightly weathered materials that have low compressive strength or are highly fractured.” They defined weathered materials as “materials that show significant deterioration, particularly near the ground surface or along fractures.” Santi and Doyle (1997) also note, “although these types of materials show markedly different genetic and post-depositional histories, they both represent a range of properties intermediate to soil and rock.” This observation could lead one to group weak and weathered materials together for analysis and discussion.

In spite of the large number of classification and testing schemes for shales and other weak or weathered rock types, there exists no single accepted method for characterizing these materials. For example, researchers and practicing professionals who deal with weak rock were asked at a symposium to suggest the classification system they prefer to use. Among 10 respondents, nine different schemes were suggested (Santi and Shakoor, 1997). In an overview of classification systems, Chapman and others (1976) note that shale classification systems have fallen into three categories: systems developed by geologists emphasizing genesis, systems developed by engineers emphasizing quantitative laboratory tests, and systems developed by agencies, which prove to be limited to specific regions or applications.

In particular, field recognition and field identification of adverse properties need to be consistently addressed. Santi and Shakoor (1997) note that many common shortcomings in dealing with weak rocks stem from poor field data, lack of recognition of sensitivity to water, and underestimation of the influence of rock mass properties such as remnant bedding planes. The goal of this paper is to help reduce these shortcomings by summarizing recent research and analysis for field identification, description, and testing of weak and weathered rock materials. The content of this paper is expanded and updated from Santi (1998a).

IDENTIFICATION OF WEAK ROCK

For field identification of weak rock units, three increasingly site-specific tools are presented. The first is

Figure 1. Examples of weak rock occurrences in the conterminous United States (from Santi and Doyle, 1997). Units of small areal extent are not included because of map scale limitations. Units shown are expected to have less than 30 ft of soil cover and to be at least 10 ft thick.

a map showing locations of weak rock units in the United States. The second is a detailed list of suspect rock types that may appear on regional or local geologic maps. The third is a summary of engineering properties that describe weak rock units, based on a review of technical literature.

General Weak Rock Units

Figure 1 (from Santi and Doyle, 1997) shows generalized locations of various types of weak rock in the United States. Because of the small scale of the map, many small weak rock bodies could not be included. Likewise, karst formations were not included because their properties depend so strongly on microclimate and other local conditions (Santi and Doyle, 1997). The units shown in Figure 1 are expected to have less than 30 ft (10 m) of soil cover and to be at least 10 ft (3 m) thick. The discussion of each type of weak rock below has been summarized from Santi and Doyle (1997).

The young volcanic units shown in Figure 1 consist mostly of lava flows and ash beds in the Cascade Range,

the Snake River basalts and related tuffs, and Tertiary tuffs and volcanic breccias in the Basin and Range Province and in the Mexican Highlands. These materials are considered weak rock because of their low strength, interbedding with continental detritus, and susceptibility to weathering and alteration as a result of their young ages. Some portions may be dominated by stronger and more resistant units.

Marls and chalks are included in Figure 1 because their high calcium carbonate contents render them susceptible to dissolution, softening, or expansion in the presence of water. These materials are also often poorly consolidated, resulting in low strength. They are concentrated in the Atlantic and Gulf Coastal Plain and include the Navarro, Yorktown, and Calvert Formations; the Taylor Marl and the Austin Chalk; and the Jackson, Claiborne, Wilcox, and Midway Groups, among others.

The Tertiary conglomerates and pediments are formed from accumulations of continentally derived sediments. They contain a high percentage of easily weathered minerals such as micas and feldspars because of their

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Table 1. *Types of weak rocks (compiled with data from Santi and Doyle, 1997).*

Mineralogy or Processes Affecting	Explanation of Importance	Rock Types
Materials with high clay content	Clay minerals are very sensitive to water, have low friction angles, and are generally poorly cemented, all of which reduce material strength. Although an engineering definition of clay requires at least 50 percent clay-sized particles, clay-like behavior will be observed with a much smaller clay component.	Overconsolidated clay; cemented clayshale, shale; siltstone; mudstone, mudrock; tightly interbedded sedimentary rocks; marl; flysch; turbidite
Materials with other undesirable minerals	Other minerals may be weak or reactive to water.	Chalk; anhydrite; gypsum
Young materials	Young materials may be poorly cemented, poorly consolidated, and retain a significant component of unstable and easily weathered minerals.	Quaternary carbonates; Tertiary sedimentary rocks (conglomerate, sandstone); Tertiary volcanic rocks (some basalt, tuff, volcanic breccia); pediments
Highly weathered materials	Weathering removes cement, dissolves mineral framework, loosens cohesive bonds, creates clays, lower friction angles, yet often leaves relict planes of weakness such as joints and bedding planes. Weathering also deposits clays on fractures and separates fractures.	Saprolite; weathered igneous rocks; weathered metamorphic rocks
Metamorphosed materials	Metamorphism often produces unstable and easily weathered minerals, schistosity or other layered weakness planes, or block-in-matrix structure which is problematic for sampling and testing.	Melange; metashale
Hardened soils	These materials are often underlain by weaker soils, and they may also break down upon extended saturation.	Hardpan; caliche; laterite; tropical duracrust

proximity to the source areas. Weathering of these minerals, compounded by the poor consolidation and cementation typical of young rocks, results in low strength. These units include the White River Group, Wasatch Formation, and Castle Rock Conglomerate of the western Great Plains and Colorado Plateau provinces.

Shales and siltstones are the most widespread and frequently encountered weak rock types, as shown on Figure 1. They are commonly poorly compacted and cemented, exhibit low strength values, slake on contact with water, may experience rebound or expansion as a result of stress relief, and may be interbedded with undesirable materials

Table 2. *Summary of engineering properties of weak rock (modified from Santi and Doyle, 1997).*

Test or Property	Value or Range for Weak Rock	Reference
Compressive strength	1–20 MPa	Afrouz, 1992
Standard penetration test	50–300 blows per ft (15–90 blows per m)	White and Richardson, 1987 Sowers, 1973
Rock quality designation	<25–75 percent	Santi and Doyle, 1997
Hammer rebound	≥category 4	Santi, 1995
Seismic wave velocity	<7,000 ft per second* (2100 m/sec)	Caterpillar, 1996
Ratio of weathered matrix to unweathered blocks	>75 percent matrix	White and Richardson, 1987 Geological Society, 1995
Jar slake	≤4	Santi, 1995
Slake durability, I _d (2), ASTM D4644-87	<90 percent	Santi and Doyle, 1997 Lee and de Freitas, 1989
Free swell	>3–4 percent	Welsh and others, 1991 Underwood, 1967
Natural moisture content	>1 percent for igneous and metamorphic rocks >5–15 percent for clayey rocks	Santi and Doyle, 1997
Dearman weathering classification	≥category 4	Santi, 1995
CSIR rock mass rating (Bieniawski, 1976)	<35–60	Santi, 1995
Norwegian Geotechnical Institute “Q” rating	<2	Santi, 1995

*Lower velocities may be appropriate, depending on equipment used and degree of rock fracturing.

Table 3. *Weathering grades of weak and weathered rock (modified from Dearman, 1976; and Geological Society, 1995).*

Weathering Grade	General Description	Specific Description	
		Weathered Materials*	Weak Rock Materials†
VI — Residual soil	The rock is completely changed to a soil in which the original rock texture has been completely destroyed.	Soil derived by <i>in situ</i> weathering but retaining none of the original texture or fabric.	Residual or reworked. Matrix with occasional altered random or “apparent” lithorelicts, bedding destroyed.
V — Completely decomposed	The rock is changed to soil in which the original rock texture is (mainly) preserved.	Considerably weakened, slakes, and the original texture is apparent.	Destructured. Greatly weakened, mottled, ordered lithorelicts in matrix becoming weakened and disordered, bedding disturbed.
IV — Highly decomposed	50–100 percent soil from decomposition of the rock mass.	Large pieces can be broken by hand; does not readily slake when dry sample immersed in water.	Partially or distinctly weathered. Weakened, close fracture spacing, weathering penetrating in from fractures, brown oxidation.
III — Moderately decomposed	Up to 50 percent soil from decomposition of the rock mass.	Considerably weakened, penetrative discoloring; large pieces cannot be broken by hand.	Unweathered. Original strength, color, and fracture spacing.
II — Slightly decomposed	100 percent rock; discontinuity surfaces or rock material may be discolored.	Slight discoloration and slight weakening.	—
I — Fresh	100 percent rock; no discoloration, decomposition, or other change.	Unchanged from original state.	—

*Uniform weathered materials such as igneous and metamorphic rocks, which may show weakening and susceptibility to slaking on weathering.

†Materials that incorporate both matrix and mass features; weathering is enhanced along fractures, but most weathering occurs near the ground surface. Includes overconsolidated clays, shales, and mudstones.

Figure 2. Interpretation of S-D-R (strength-discontinuity-rate of change of strength) values from Table 4 (modified from Palicki, 1997).

such as evaporites, bentonite, or high-organic-content materials. In general, the shales and siltstones in the western United States are Cretaceous age or younger and include the Pierre, Fort Union, and Bearpaw shales, among others. The shales of the Midwest and Eastern United States are mostly Triassic age or older and include dozens of formations grouped together in Figure 1.

The mixed and interbedded rocks shown in Figure 1 include materials that could be placed in more than one category, such as marly shales, in addition to typical mixed materials, such as flysch, turbidites, and mélange. The best-known unit in this group is the Franciscan Complex in California, Nevada, and Oregon.

Saprolites are residual soils formed on deeply weathered rocks and ordinarily retain the original structure of the parent rock. The units shown in Figure 1 include phosphate clays of central Florida and extensive saprolite exposures on the Piedmont Plateau, the Atlantic Coastal Plain, the northern Pacific Coast, and portions of the Sierra Nevada and Cascade Ranges.

Rock Types for Local Recognition

Figure 1 is intended to provide a regional scale reference for various types of weak rock. Local geologic maps should be used to identify the actual types and boundaries of weak rock in an area. The rock types that are typically weak are listed in Table 1 (more detail on

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Table 4. *Corestone (C), strength (S), discontinuity (D), and rate of change of strength (R) values for weak and weathered rock (modified from Geological Society, 1995; and Palicki, 1997).*

C Value	Percent of Each Weathering Grade (Table 3)		Typical Characteristics		
1	100 percent I–III; 0 percent IV–VI		Behaves as rock; apply rock mechanics principles to mass assessment and design.		
2	>90 percent I–III; <10 percent IV–VI		Weak materials along discontinuities. Shear strength, stiffness, and permeability affected.		
3	50–90 percent I–III; 10–50 percent IV–VI		Rock framework still locked and controls strength and stiffness; matrix controls permeability.		
4	30–50 percent I–III; 50–70 percent IV–VI		Rock framework contributes to strength; matrix or weathering products control stiffness and permeability		
5	<30 percent I–III; >70 percent IV–VI		Weak grades will control behavior. Corestones may be significant for investigation and construction.		
6	0 percent I–III 100; percent IV–VI		May behave as soil although relict fabric may be still significant.		
S Value	Field Estimation				Unconf. Compr. Strength (MPa)
0	Soil extrudes between fingers when squeezed in hand				<0.04
1	Soil easily molded with fingers				0.04–0.08
2	Soil can only be molded by strong pressure of fingers				0.08–0.15
3	Soil cannot be molded by fingers				0.15–0.30
4	Soil can be indented by fingernail				0.30–0.60
5	Brittle or tough, may be broken by hand with difficulty				0.60–1.25
6	Very soft rock, material crumbles under firm blows with sharp end of a geological pick				1.25–5.0
7	Too hard to cut by hand into a cylindrical lab specimen				5.0–12.5
8	Soft rock, 5-mm indentations with sharp end of a rock pick				12.5–50
9	Hard rock, hand-held specimen can be broken with single blow of a geological hammer				50–100
10	Very hard rock, more than one blow of a geological hammer required to break specimen				>100
D Value*	Spacing		Aperture		Roughness
0	<6 mm	Very narrow	>200 mm	Wide	Polished
1	6–20 mm	Narrow	60–200 mm	Moderately wide	Slickensided
2	20–60 mm	Moderately narrow	20–60 mm	Moderately narrow	Smooth
3	60–200 mm	Moderately wide	6–20 mm	Narrow	Rough
4	200–600 mm	Wide	2–6 mm	Very narrow	Defined ridges
5	600 mm–2 m	Very wide	>0–2 mm	Extremely narrow	Small steps
6	>2 m	Extremely wide	0	Tight	Very rough
R (“Jar Slake”) Value†	Term		Description (see Figure 3)		
1	Mud		Degrades to a mud-like consistency.		
2	Flakes		Sample reduced to flakes. Original outline of sample not discernible.		
3	Chips		Chips of material fall from the sides of the sample. Sample may also be fractured. Original outline of sample is barely discernible.		
4	Fractures		Sample fractures throughout, creating a chunky appearance.		
5	Slabs		Sample parts along a few relatively planar surfaces.		
6	No reaction		No discernible effect.		

*Select the lowest “D” value from the three factors (spacing, aperture, or roughness).

†These values are based on reactions after a 30-minute soaking in distilled water.

some of these rock types, as well as several case histories, are given in Hatheway, 1997).

Rock types in Table 1 are grouped by both mineral content and post-depositional processes because both of these components contribute to weak rock behavior. Poorly behaving minerals include clays, evaporites, certain carbonates, and unstable minerals produced at high temperature and pressure (these are metamorphic minerals, such as olivine, pyroxene, amphibole, biotite, and calcium-

rich feldspar). Post-depositional processes contributing to weak rock formation include slaking or dissolution in water, weathering, poor cementation and consolidation, development of planes of weakness, and proximity to other layers with substantially different properties.

Recognition of Weak Rock by Engineering Properties

If even a small amount of laboratory or field data are

Table 5. *Engineering behavior from weathering grade (modified from Dearman et al, 1978; Krank and Watters, 1983; Lee and de Freitas, 1989; and Santi, 1995).*

Engineering Property	Fresh, I	Slightly Weathered, II	Moderately Weathered, III
Foundation conditions	Suitable for concrete and earthfill dams	Suitable for concrete and earthfill dams	Suitable for small concrete structures, earthfill dams
Excavatability	In general, blasting necessary	In general, blasting necessary	Generally blasting needed, but ripping may be possible depending upon the jointing intensity
Building material	Very durable, difficult to shape, excellent aesthetic properties, good aggregate	Very durable, but less aesthetically pleasing due to discoloration, good aggregate	Poor, subject to deterioration, not suitable as an aggregate
Slope stability (Krank and Watters, 1983)	Excellent; can stand vertically unsupported	Excellent; can stand vertically unsupported	Very good; can stand vertically unsupported, but subject to deterioration
Slope stability (Dearman, et al, 1978)	1/4:1 H:V	1/2:1 to 1:1 H:V	1:1 H:V
	Benches and surface protection structures are advisable, particularly for more highly weathered material. The presence of through-going adversely oriented structures is not taken into account.		
Tunnel support	Not required unless joints are closely spaced or adversely oriented	Not required unless joints are closely spaced or adversely oriented	Light steel sets on 0.6- to 1.2-m centers
Point load strength (MPa)	9–18	5–12.5	2–6
Schmidt hammer value (MPa)	59–62	51–56	37–48
Moisture content (percent)	0.06–0.30	0.15–0.29	0.25–0.49
Unconfined compressive strength (MPa)	125–260	100–175	60–120
Drilling RQD (percent)	75, usually 90	75, usually 90	50–75
Core recovery (percent) (NX)	90	90	90
Drilling rates (m/hour) (Diamond NX)	2–4	2–4	8–10
2½ in. percussion	5–7	8	12–15
Permeability	Low to medium	Medium to high	Medium to high
Seismic velocity (m/sec)	3050–5500	2500–4000	1500–3000
Resistivity (ohm-m)	340	240–540	180–240
	Tends to be determined by joint openness and water-table depth		

available, it may be used to help identify problematic weak rocks. While the map and rock type information presented above is useful as a general overview for a region, the engineering properties should be used for site-specific confirmation. A summary of engineering properties potentially identifying weak rock is given in Table 2.

Details on the selection of ranges and cutoff values in Table 2 are given in Santi and Doyle (1997). In general, these ranges and cutoff values recognize the influence of fractures, decreased strength, creation of weathered matrix material, and reaction to water demonstrated by weak and weathered rock materials. For example, soil-like materials will typically have strength values below the ranges shown for compressive strength, standard penetration test, rock quality designation, and hammer rebound, and rock-like materials will have values above these ranges. As intact rock weathers, seismic wave velocity drops (7,000 ft per

second [2,100 m/second] is judged to be a suitable threshold related to conventional rippability for a D9 bulldozer, according to Caterpillar, 1996). Furthermore, the volume of fine-grained weathered matrix material increases to the point that the matrix, rather than the intact rock blocks in between, controls the behavior (at approximately 75 percent matrix). Material with high reaction to water and low resistance to abrasion is considered weak (measured by low jar slake values, low slake durability, and high free swell). High natural moisture contents also indicate a high degree of weathering, fracturing, or disaggregation. Finally, weak rocks will plot toward one end of many rock classification schemes (schemes by NGI [Barton et al. 1974], Dearman [1976], and Bieniawski [1976] are suggested here). Not all of the criteria shown in Table 2 are equally diagnostic for different rock types, and some very strong rocks will

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Table 5. *Extended*

Highly Weathered, IV	Completely Weathered, V	Residual Soil, VI
Suitable for earthfill dams	Suitable for low earthfill dams	Generally unsuitable
Generally ripping and/or scraping necessary	Scraping	Scraping
Unsuitable, not usable as an aggregate	Too angular and poorly graded to serve as an aggregate by itself	Too poorly graded to be used as an aggregate by itself, but may serve as a sand filler if screened
Good; can stand vertically unsupported up to 25 feet high, greater heights should be 1:1 H:V with benches, deteriorates with time	Moderate; can stand unsupported at 1:1 H:V with benches to catch detritus	Very poor; unstable because of low cohesion, greatly influenced by ground water, best removed
1:1 to 1.5:1 H:V	1.5:1 to 2:1 H:V	1.5:1 to 2:1 H:V
	Benches and surface protection structures are advisable, particularly for more highly weathered material. The presence of through-going adversely oriented structures is not taken into account.	
Steel sets, partial lagging, 0.6- to 0.9-m centers	Heavy steel sets, complete lagging on 0.6- to 0.9-m centers. If tunneling below water table, possibility of soil flow into tunnel	Heavy steel sets, complete lagging on 0.6- to 0.9-m centers. If tunneling below water table, possibility of soil flow into tunnel
0.3–0.9	0.1–0.5	—
12–21	5–20	—
0.37–3.80	7.84–21.00	12.24–22.1
35–55	1–10	<1
0–50	0 or does not apply	0 or does not apply
15 to 70, depending on percentage of corestones	15 as sand	15 as sand
8–10	10–13	10–13
12–15	17	17
High	Medium	Low
1000–2000	500–1000	500–1000
180–240	180	180
	Tends to be determined by joint openness and water-table depth	

exhibit some properties in the weak rock range. Identification of weak rock using Table 2 should be made on the basis of more than one type of test, if possible.

FIELD DESCRIPTION OF WEAK ROCK

Santi (1997) evaluates and compares 14 different popular classification systems for weak or weathered rock and proposes modifications to enhance the applicability of some of the more useful systems. The evaluation was based on a series of 10 questions, which should be answered “yes” for the most useful systems:

1. Can it (the system) be applied in the field without special equipment?
2. Can it be used without any laboratory work?
3. Is the classification confirmed and enhanced with laboratory data?
4. Does it apply to weak rock?

5. Does it apply to weathered rock?
6. Does it apply to rock masses, considering fractures and block-in-matrix structure?
7. Does it evaluate strength?
8. Does it evaluate durability?
9. Does it suggest a range of quantitative engineering properties?
10. If not quantitative, does it suggest at least a qualitative range of engineering properties?

Although no single system addresses all the issues queried above, Santi (1997) suggests that modifications to Dearman (1976), Geological Society (1995), and Palicki (1997) may be incorporated and the systems used in tandem to provide a thorough and useful field classification system. For this paper, Santi’s (1997) system has been further modified and consolidated and is presented in Tables 3 and 4.

To apply Table 3, the user should first identify the

Table 6. *Estimates of slake durability and long-term material behavior based on the rate of change of strength (R) value (compiled with data from Santi and Higgins, 1998; and Santi, 1995).*

(R) Value ("Jar Slake" Category)	Slake Durability	Slake Index	Long-Term Treatment*
1	0–15	75–100	Soil
2	15–25	40–90	Soil
3	25–40	25–70	Very poor rock
4	40–55	5–30	Poor, yet durable rock
5	55–70	5–15	Good to fair rock
6	70–100	0–10	Good to fair rock

*"Long-term treatment" is the expected behavior of the material following long-term exposure to weathering.

material in question as "weathered materials" (materials that are moderately strong in the fresh state and that tend to weather into stronger blocks surrounded by weaker matrix materials), or as "weak materials" (materials that are moderately weak in the fresh state and that weather more homogeneously throughout the mass, but with intensity increasing near the ground surface). For weak materials, the weathering grade of the layer or depth in question can be identified (note that because of their natural weakness, even fresh "weak materials" cannot have a weathering grade higher than III). For weathered materials, the proportion of matrix and intact blocks should be estimated (e.g., "30 percent blocks and 70 percent matrix"), and the weathering grade of both components should be estimated (e.g., "matrix is grade VI and blocks are grade III").

Table 4 is used to select four different values describing the critical behavior of a weak or weathered material. The first set is used to select a corestone value (C), to gauge importance of the matrix on the overall behavior. The second set is used to estimate a strength value (S), the third set is used to select the critical aspect of discontinuities controlling the behavior (D), and the fourth set is used to measure the reactivity to water as an indication of the long-term performance of the material (the "rate of change of strength" value, R).

The S-D-R values are then carried to Figure 2 to simultaneously weigh the importance of strength, discontinuities, and changing strength. For example, consider a shale with values from Table 4 of C = not applicable, S = 5, D = 1, and R = 3. This material would plot in Region VII on Figure 2, indicating that some strength loss from slaking will occur over time, but not enough to disregard the original strength or the effects of discontinuities.

Additional engineering characteristics can be deduced using previously published correlations to the weathering grade (Table 3). Quantitative values shown in Table 5 were originally determined for weathered granite by Dearman and others (1976), Krank and Watters (1983),

Figure 3. Modified jar slake test categories and descriptions (from Santi, 1998b).

and Lee and de Freitas (1989) and also include correlations for shale and siltstone using data from Santi (1995).

Table 6 shows estimates of slake durability and long-term material behavior based on the R value from Table 4. These values are based on correlations between the field-measurable R values and the laboratory slake durability and slake index values (Santi and Higgins, 1998).

Table 7. Field estimate of permeability (modified from Lee and de Freitas, 1989; and Anonymous, 1977).

Class	Description of Absorption	Description of Discontinuities	Estimated Permeability
1	Specimen is almost impermeable, most of the water remains on the surface.	No discontinuities	$\leq 10^{-7}$ cm/second
2	Specimen is slightly permeable, some water is absorbed.	Widely to very widely spaced discontinuities (0.6 to 6 m)	10^{-5} to 10^{-7} cm/second
3	Specimen is moderately permeable, more than half of the water is absorbed.	Widely to very widely spaced discontinuities (0.6 to 6 m)	10^{-3} to 10^{-5} cm/second
4	Specimen is highly permeable, most of the water is absorbed.	Close to moderately spaced discontinuities (6 to 60 cm)	1 to 10^{-3} cm/second
5	—	Very close to extremely close spaced discontinuities (< 6 cm)	≥ 1 cm/second

FIELD TESTING OF WEAK ROCK

In addition to the estimates of engineering properties that may be made using Tables 4–6, several field tests may be correlated to laboratory tests. For example, Smith (1997) proposes a relationship between Unconfined Compressive Strength (UCS) and the field-derived Point Load Index (I_s). For stronger rock the UCS is generally 20 to 25 times the I_s (ISRM, 1985). Smith (1997) recognizes that this factor is usually less for weaker materials, so provided the test can be run successfully (that is, with the test failure plane passing through both loading platens), his data may be used to derive the following correlation (UCS and I_s are both reported in psi units):

$$UCS = 0.6638I_s^{1.5857} \quad (1)$$

$$R^2 = 0.9712 \text{ (effective for } I_s < 450)$$

Smith (1997) also suggests using flat platens over the conical platens on the point load device so that loads will be more broadly distributed and weak materials can be successfully tested.

Slake durability may also be predicted by field tests. Santi and Higgins (1998) provide the following predictive equations for second cycle slake durability, $I_d(2)$, based on tests of 100 samples of shale, siltstone, and sandy shale:

$$I_d(2) = 16.0(\text{jar slake}) - 1.7 \quad R^2 = 0.79 \quad (2)$$

$$I_d(2) = 66.5 - 3.7(Q) - 3.7(\text{hammer rebound}) + 7.2(\text{jar slake}) - 0.5(\text{slake index})$$

$$R^2 = 0.85 \quad (3)$$

where:

jar slake = rate of change of strength (R) value shown on Table 4.

Q = Norwegian Geotechnical Institute rock mass classification (Barton et al., 1974). The system integrates both block and discontinuity properties and requires estimates of number of joint sets, joint roughness, joint alteration, joint water, and a stress reduction factor.

hammer rebound = number value indicating resistance to blows from a geologic hammer (NAVFAC, 1982):

- 1 = extremely strong (many blows required to break)
- 2 = very strong (more than one blow required to break)
- 3 = strong (one moderate blow required to break)
- 4 = moderately strong (indents 1–3 mm with one blow)
- 5 = moderately weak (crumbles with one blow)
- 6 = weak (disintegrates with one blow).

slake index = weight percentage material lost through a #10 sieve after oven drying and soaking in water (Deo, 1972; Chapman et al., 1976).

Santi (1995) also provides a correlation equation to estimate one-cycle slake index in the field:

$$\text{slake index} = 106.0 - 18.6(\text{jar slake}) \quad R^2 = 0.85 \quad (4)$$

Although the jar slake test is convenient to perform in the field, the descriptions for each category are very vague, and as the test is normally performed, readings should be completed at both 30 minutes and 24 hours (Wood and Deo, 1975). This long time period reduces the test's utility as a quick field test. Santi (1998b) showed that for 50 samples classified by 13 different technicians, the 30-minute and 24-hour classifications showed no statistical difference, and the 30-minute test is sufficient. Furthermore, it was shown that by more carefully defining the test categories and providing drawings of samples in each category, included as Figure 3, the consistency between different technicians is greatly improved. Use of the jar slake method shown in Figure 3 produced an average of the standard deviations of results from each sample of 0.39. Using the original jar slake descriptions from Wood and Deo (1975) produced an average of the standard deviations of 0.57. This is a reduction in the "error" of the test by one-third.

Finally, a rough estimate of permeability of weak rock (as absorption or as a function of fracture density) may also be made in the field, using Table 7, modified from Anonymous (1977) and Lee and de Freitas (1989). The absorption test, designed for weathered granite blocks, is based on observing the penetration of a few drops of water from a dropper onto a hand specimen, over a period of one minute. The fracture density correlation is intended for rock types where the fractures dominate transport of water, such as fine-grained shales or low porosity rocks.

CONCLUSIONS

Adequate engineering of shales, weak rock, and weathered rock begins with adequate recognition of potential problems in the field. The tools presented in this paper are intended to help the practitioner recognize potential slaking and reactivity to water, low strength, expected strength loss over time, influence of strong corestones and weak matrix, and expected behavior for various engineering uses. Two field classifications are proposed. The first is a modification of Dearman's Weathering Grade to include shales and other non-granitic rocks. The second system incorporates the modified Dearman scheme and assimilates several existing systems, to indicate proportion of corestones and matrix, strength, influence of discontinuities, and reactivity to water. Finally, several tables and predictive equations will provide the user with a field estimate of unconfined compressive strength, slake durability, slake index, and permeability.

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