Geological and Engineering Classification Systems of Mudrocks

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ABSTRACT: Mudrocks are a diverse group of very fine-grained argillaceous sedimentary rocks that are frequently encountered in most types of engineering projects. Upon excavation, the release of overburden stress and changes in the moisture content may cause certain apparently well indurated mudrocks to slake, producing a soil-like material. Because many mudrocks are nondurable, they have gained a reputation as problematic soft rocks. Geologists and engineers are confronted with the problem of selecting adequate parameters for accurately evaluating engineering behavior of mudrocks. The use of a single parameter (e.g. grain-size) is never considered to be enough and a combination of several parameters are normally preferred for the classification of mudrocks. Compressive strength, slake durability index, plasticity characteristics, swelling potential, absorption and density are some of the parameters that had been used by several investigators in the past. In order to overcome this problem, considerable research attention has recently been devoted to the use of geological properties (grain size, clay content and clay composition, texture, fracture frequency, degree of lamination, etc.) in conjunction with the engineering characteristics for classification purposes. This paper describes the origin and occurrence of mudrocks, and their different types of classification tests and systems.

CONTENTS

1. Introduction

Mudrocks which include shales, mudstones, siltstones and claystones are defined as fine to very fine-grained silici-clastic sediments or sedimentary rocks (Grainger, 1984). They account for approximately two-thirds of the strategraphic column (Blatt, 1982) and one-third of the total land area (Franklin, 1983). Many of the mudrocks that are commonly encountered in engineering projects exhibit deterioration, swelling and shrinking phenomena due to low durability to weathering and exposure to changes in their moisture content, which results in slope stability problems, ground heave and embankment failures, and subsequently damage and distress to structures. Expansive mudrocks swell when given access to water and shrink when they dry out. The problems associated with expansive mudrocks are worldwide, occurring in several countries mainly in arid and semi-arid regions in Australia, Asia, Middle East, Africa, Europe, United States of America and South America.

The cost of damage and repair to structures affected by expansive mudrocks and soils are alarming. In the United States alone, the annual losses are between $6 billion and $11 billion in damages to houses, buildings, roads, etc. (Nuhfer, 1994). The cost of repair to buildings and light structures in the United Kingdom has been estimated at $100 million per annum (Williams *et al*., 1985).

The classification of mudrocks presents an important problem due to their wide range of engineering geological characteristics (Gamble, 1971). Although several mudrock classification schemes have been proposed (Underwood, 1967; Morgenstern and Eigenbrod, 1974; Olivier, 1976, Potter *et al*., 1980; Taylor and Spears, 1981; Grainger, 1984; Taylor, 1988), none have gained general acceptance. This lack of acceptance may be attributed to the fact that classifications do not take into account the geological and engineering properties in their entirety and are based on very few classification parameters. Also the laboratory/field tests used for the classification purposes inheret some degree of uncertainty which is not accounted for while classifying mudrocks. The classifications are also considered to be of limited use because they are developed using a small number of samples representing a limited variety of mudrocks.

The aim of this paper is not to suggest a new classification system but to provide a condensed critical review of existing geological and engineering classifications of mudrocks. It includes origin, mineralogical composition, geological and engineering classifications, and some applications of mudrocks.

2. Origin and Occurrence of Mudrocks

Mudrocks are formed under depositional environmental conditions in which fine sediment is abundant and water energy is sufficiently low to allow suspension settling of fine silt and clay. They are particularly characteristic of marine environments adjacent to major continents at places where the sea floor lies below

storm wave base levels (Potter *et al*., 1980). In addition, mudrocks can form in lakes and in quiet-water parts of rivers and in lagoonal, tidal-flat, and deltaic environments (Boggs, 1987).

Mudrocks are by far the most abundant type of sedimentary rocks. This is because of the fine-grained silici-clastic products of weathering which greatly exceed coarser particles. Mudrocks commonly occur interbedded with sandstones and limestones in units ranging in thickness from a few millimeters to tens of metres. Some varieties of mudrocks (e.g. shales) are found to be hundreds of metres thick with widespread areal extent (Boggs, 1987).

3.   Geological Terminology

The term "mudrock" generally refers to fine-grained sedimentary rocks and includes shales, mudstones, claystones and siltstones. However, there is a lack of agreement among researchers on the classification of fine-grained sedimentary rocks due to their wide range of geological and engineering characteristics. The main sources of ambiguities are:

(a) The term "shale" can be used in a restricted sense as a fissile or laminated rock, (Tourtelot, 1960). It has also been used as a group name for all fine-grained sedimentary rocks by many authors, (Grainger, 1984).

(b) The use of the term "mudrock" in engineering geology to encompass argillaceous engineering "rocks" as opposed to clay "soils", (De Freitas, 1981; Taylor and Spears, 1981).

(c) There is a lack of agreement on both the grain size definition and grain size distribution for siltstones, mudstones and claystones.

To avoid this confusion, it is suggested that the term "Mudrock" be used as a general group name and the term "Shale" be restricted to the fissile or laminated rocks, (Ingram, 1953; Blatt *et al*., 1972; Spears, 1980; Taylor and Spears, 1981). Therefore, the terms "Mudstone", "Siltstone" and "Claystone" should be restricted to non-fissile rocks (Clark, 1954).

Grainger (1984) proposed a broad definition which includes all fine-grained soils and considers grain size, mineral composition, texture and compressive strength. Mudrock is defined as fine to very fine-grained silici-clastic sediment or sedimentary rock. Further, the descriptive terms of this definition have been quantitatively defined as shown in Figure 1.

Since natural materials encountered in practice are borderline and difficult to classify as either "hard soil" or "soft rock", it is suggested that a broad definition of mudrocks is used and includes engineering clay soils. This preference is supported by the fact that a competent mudstone at surface may well behave like a clay in a deep mining situation. The inclusion of clay soils in the definition of mudrocks has been previously suggested by Taylor and Spears (1981) and Grainger (1984).

4.   Mudrock Classifications

Mudrocks may be classified into different types based on their geological and engineering properties. The identification of the most useful and relevant index rock properties is of prime importance, as description of lithology alone can lead to gross errors, (Olivier, 1979). Some of the other prerequisites for rock classification are mentioned by Franklin (1970) and Bieniawski (1974a). They suggested that classification should be:

1. Based on measurable parameters which can be determined by relevant tests quickly and cheaply in the field.
2. Involve only rapid testing techniques which are able to cope with a large number of routine samples.
3. Testing techniques should be simple enough to be carried out by semi-skilled field laboratory staff.
4. The range of test results values should allow for a sufficient power of discrimination when applied to various test samples.
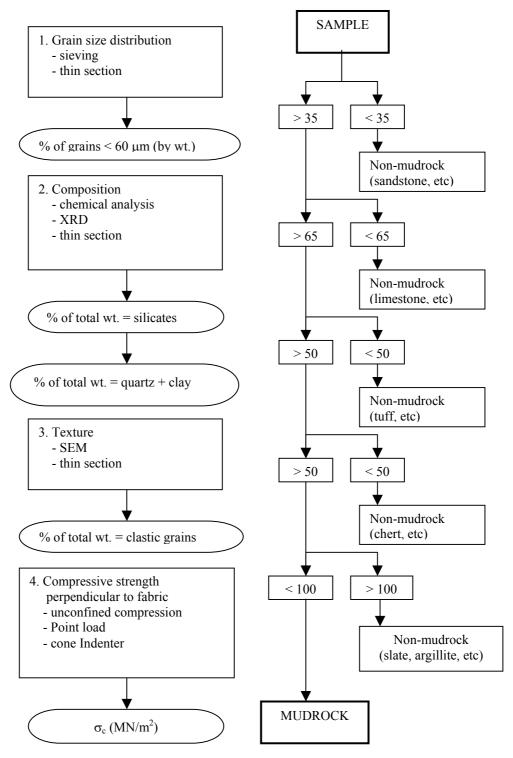
SAMPLE

1. Grain size distribution
   - sieving
   - thin section

> 35

< 35

Non-mudrock
(sandstone, etc)

% of grains < 60 μm (by wt.)

2. Composition
   - chemical analysis
   - XRD
   - thin section

> 65

< 65

Non-mudrock
(limestone, etc)

% of total wt. = silicates

% of total wt. = quartz + clay

> 50

< 50

Non-mudrock
(tuff, etc)

3. Texture
   - SEM
   - thin section

> 50

< 50

Non-mudrock
(chert, etc)

% of total wt. = clastic grains

4. Compressive strength
   perpendicular to fabric
   - unconfined compression
   - Point load
   - cone Indenter

< 100

> 100

Non-mudrock
(slate, argillite, etc)

σ_c (MN/m^2)

MUDROCK

Figure 1. The definition of mudrock (Grainger, 1984).

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Keeping in mind the above mentioned recommendations, classification based on geological properties such as grain size and mineralogy are reviewed here. Similarly, engineering index properties worth considering are strength, durability, swelling and plasticity characteristics. Since geological properties control the engineering behaviour of rocks, (Vutukuri *et al*., 1974; Tsidzi, 1990), they are discussed first.

4.1 Grain Size Classifications

Grain size is an important parameter in the classification of mudrocks. Purnell and Netterberg (1975) presented Table 1 summarizing some of the commonly used geologic classifications. Table 1 was extended to cover the classification proposed by Pettijohn (1975). The classifications differ mainly in the use of the group term. The classifications of Ingram (1953), Pettijohn (1957), and Blatt et al. (1972) use mudrock as the group term, whereas those of Twenhofel (1939) and Pettijohn (1975) use mudstone and argillaceous sediment, respectively.

Grain size classification requires the determination of clay size fraction which is normally done by carrying out a grain size distribution analysis. The procedure is described in British Standard 1377 (1990) and in D-422 (ASTM, 1990) and involves wet sieving and hydrometer analysis. For indurated mudrocks, samples have to disaggregated first by cycles of wetting and drying as crushing will break the original clay minerals (Spears, 1980). Poorly indurated mudrocks may disaggregate after one or two cycles, whereas well indurated mudrocks may require up to eight cycles (Dick et al., 1994).

Table 1. Some geological classifications of mudrocks[1] (Purnell and Netterberg 1975).

Particle Size Definition	Particle Size Distribution	Field Identification	Non-Indurated	Indurated [2]		After Incipient Meta-morphism	Group Term	Author
				None-Fissile	Fissile			
Silt 0.004-0.06 mm Clay < 0.004 mm	> 50% silt > 50% clay		Silt + water Clay = mud	Siltstone Claystone	Shale	Argillite[3]	mudstone	Twenhofel (1939)
Silt 0.002-0.02 mm Clay 0.002 mm	Silt > clay Clay > silt Unknown or unspecified		Silt + water Clay = mud	Siltstone Claystone Mudstone	Silt-shale Clay-shale Mud-shale	Argillite?	mudrock	Ingram (1953) & Pettijohn (1957)
Silt[4] > 0.01 mm Silt > 0.004 mm Clay < 0.004 mm			Silt + water Clay = mud	Siltstone Mudstone	Shale		Argillaceous sediments	Pettijohn (1975)
Silt 0.004-0.06 mm	> 2/3 silt	Abundant silt visible with hand lens		Siltstone	Silt-shale			Blatt et al. (1972) .
	1/3 – 2/3 silt	Feels gritty when chewed	Silt + water Clay = mud	Mudstone	Mud-shale	Argillite	mudrock	
Clay 0.004 mm	> 2/3 clay	Feels smooth when chewed		Claystone	Clay-shale			

Notes: (1) Mudrock : sedimentary rock composed of at least 50% silt plus clay, with no restriction as to their relative amounts or as to the breaking characteristics (Ingram 1953).
(2) An indurated material is strictly only one which does not slake (disintegrate) in air or water.
(3) An argillite is a rock indurated by slight metamorphism to a material between a mudrock proper and a slate. The term is generally used for rock which is none-fissile (Clark 1954), but if fissile, does not yet possess the slaty cleavage of a slate.
(4) The particle size of > 0.01 mm is used for the definition of siltstone.

4.2 Mineralogical Classifications

The mineralogical composition of mudrocks plays an important role in their behavior, particularly the "soil-like" mudrocks. Without a thorough understanding of the mineralogical composition, engineering

behavior of mudrock can neither be fully appreciated nor accurately predicted, (Taylor and Spears, 1981). In the case of siltstones and coarse mudstones, non-clay minerals such quartz, calcite, dolomite, etc. form a major proportion of the total minerals present in the material. In claystones, fine mudstones, shales and stiff clays, clay minerals such as montmorillonite, kaolinite, illite and chlorite are normally abundant. Pettijohn (1957) indicated that generally, the average mudrock contains one-third quartz, one-third clay and mica like minerals and one-third other minerals such as carbonates and iron oxides. Based on the geological history, climate and weathering processes, the mineralogical composition of mudrocks may vary from one locality to another. However, the engineering behavior of mudrocks not only depend on the amount of clay minerals but also on the types of minerals present (Jeremic, 1981).

Most of the construction problems associated with expansive mudrocks reported in the literature (Al-Rawas *et al*., 1998) were attributed to the presence of montmorillonite, which is well known as the most "active" clay mineral. In general, older sediments contain less montmorillonite and more illite and chlorite than the younger and are therefore likely to be less problematic. Clay minerals are formed by the alteration of the primary rock minerals due to complex processes. In silica rich rocks and minerals in which calcium and magnesium cations are present, under climatic conditions in which evaporation exceeds precipitation, pH is high and leaching conditions are favorable for the formation of montmorillonite (smectite group). On the other hand, in rocks and minerals in which alumina is abundant, magnesium and calcium cations are absent, and in areas where rainfall is relatively high and drainage is good, conditions favor the formation of kaolinite, (Tourtelot, 1973).

The classification of sediments and sedimentary rocks are based on a triangular diagrams whose apices are sand, silt and clay. In case of mudrocks, depending upon the effectiveness of dispersing techniques, concentration can be biased toward clay or silt categories (Picard, 1971). Also, Spears (1980) notes that the actual grain size analysis can be time consuming for indurated mudrocks where difficulty in disaggregation of the rock may not reveal the real percentage of clay size fraction.

Spears (1980) proposed a classification based on quartz content (Table 2) in which mudrocks are categorized into two groups based on whether a rock is fissile or non-fissile. Fissile mudrocks group encompasses flaggy siltstone and shale types, whereas non-fissile mudrocks group encompasses massive siltstone and mudstones types. Siltstones are recognized as containing > 40 % quartz.

Table 2. Proposed classification based on quartz percantage (Spears, 1980).

Quartz percentage	Mudrocks	
	Fissile	Non-fissile
> 40% quartz	Flaggy siltstone	Massive siltstone
30-40% quartz	Very coarse shale	Very coarse mudstone
20-30% quartz	Coarse shale	Coarse mudstone
10-20% quartz	Fine shale	Fine mudstone
< 10% quartz	Very fine shale	Very fine mudstone

Spears (1980) recommends the determination of quartz content directly rather than indirectly through the grain size. In the laboratory, chemical dissoultion or X-ray diffraction methods can be adopted. Mudrocks in the field can be compared with standard rocks of known quartz content (by using hand lens and naked eye), sense of touch, and other physical properties such as hardness.

4.3 Strength Classifications

Strength is one of the important index parameters used for the engineering classification of mudrocks. Several researchers, (Deere and Miller, 1966; Underwood, 1967; Morgenstern and Eigenbrod, 1974; Anon, 1977; Grainger, 1984), developed classification systems based on strength.

Deere and Miller (1966) proposed a scheme based on a plot of the uniaxial compression strength (UCS) and tangent modulus of deformation. The scheme divides the strength of mudrocks into four zones: *very low* (UCS < 25 MN/m^2), *low* (UCS 25-50 MN/m^2), *medium* (UCS 50-100 MN/m^2) and *high* (UCS > 100 MN/m^2). Similarly, the UCS values of as low as 0.17 MN/m^2 for weak mudrocks and as high as 103 MN/m^2 for well cemented mudrocks are reported by Underwood (1967).

Morgenstern and Eigenbrod (1974) conducted strength softening tests on 14 different mudrocks. They classified mudrocks into mudstones, hard clays, stiff clays, and medium clays.

Another classification system based on uniaxial compression strength (UCS) was proposed by the United Kingdom Geological Society Working Party Report (Anon, 1977). The system classifies mudrocks into four classes: a *very soft rock* (UCS < 40 kN/m^2), a *very weak rock* or *hard soil* (UCS 0.6-1.25 MN/m^2), a *weak rock* (UCS 1.25-100 MN/m^2) and a *very strong rock* (UCS > 100 MN/m^2). Grainger (1984) proposed yet another mudrock classification based on the uniaxial compressive strength values. The UCS values of 0.6 MN/m^2, 3.6 MN/m^2, and 100 MN/m^2 were proposed as boundaries between fine-grained soil like mudrocks, non-indurated mudrocks, and indurated mudrocks, respectively.

4.4 Testing Procedures

Depending upon the type of mudrock, different strength test procedures have been recommended. For very weak mudrocks (or clayey soils), Grainger (1984) recommends the straightforward undrained triaxial method of compression testing as specified by Morgenstern and Eigenbrod (1974). However for stronger indurated mudrocks, the uniaxial compression strength (UCS) is suggested.

The choice of uniaxial compressive strength (UCS) for mudrock classification is based on the fact the UCS is the most widely used design parameter in rock engineering. It has been used in most rock mass classification systems for engineering purposes, (Bieniawski, 1973; Barton *et al.*, 1974; Laubscher, 1977), and is an important parameter in rock mass strength criterion, (Hoek and Brown, 1980). The uniaxial compressive strength is also used in estimating workability of rock, (Franklin *et al.*, 1971; Wood, 1972), evaluating the use of rock as a construction material, and predicting the utilization possibilities of a tunnel boring machine (Jenni and Balissat, 1979). According to a survey reported by Bieniawski (1974b), mining engineers request the Uniaxial Compressive Strength more often than any other rock material property.

The procedure for the Uniaxial Compressive Strength Test has been standardized by both the International Society for Rock Mechanics (ISRM) and the American Society for Testing and Materials (ASTM) Designation D-2938-71a. The mudrock core sample of length twice the diameter ratio is tested in an uniaxial testing machine.

Although, the procedure to determine UCS by using UCS testing machine is simple, it requires sophisticated laboratory equipment and meticulously prepared rock cores of specific dimensions. These rock cores are not always available. Also, loosely cemented, poorly indurated, and highly laminated mudrocks disintegrate during drilling process, making it almost impossible to obtain core samples even with special drilling techniques. As a result, determination of compressive strength by standard procedures tends to be expensive, time consuming, tedious, and sometimes impossible. The problem is further compounded by the fact that mudrocks disintegrate during the drilling process making it almost impossible to obtain core samples even with special drilling techniques. This limitation lured the researchers (Olivier, 1976; Grainger, 1984) to recommend point load testing for the indirect determination of uniaxial compressive strength.

The Point Load Test measures the point load index (Is) which is multiplied by a conversion factor "k" in order to obtain the uniaxial compressive strength of a rock. This k value not only depends on the rock type but also on the sample size and shape. The widely accepted k value for most rocks is 24 for 54 mm diameter core (Broch and Franklin, 1972). However, for mudrocks, k values of as low as 8 to as high as 35 are reported (Carter and Sneddon, 1977, Norbury 1986).

Cheema (1993) performed point load tests on cube-shaped pieces of different mudrock samples. The procedure involved cutting first 15 to 20 pieces of each mudrock sample by a thin-bladed rocksaw, and then, testing by using a Point Load Tester. They followed the procedure as described by Broch and Franklin

(1972). However, because of the penetration of cones in the soft mudrocks, the distance in between the platens (D) was measured after the penetration and was used while calculating the point load index. Cheema (1993) calculated the point load index (Is) by the following formula:

$$Is = P/D^2$$

where P is the applied load and D is the distance between the platens after penetration.

The mudrock classifications based on the compressive strength by Deere and Miller (1966) and the United Kingdom Geological Society Working Party Report (Anon, 1977) systems are of limited value because their use of the compressive strength as the sole classification parameter and therefore, they are unable to differentiate between rocks of variable durability.

4.5 Durability Classifications

Durability is a property that indicates the ability of mudrocks to withstand disintegration due to weathering. Durability can be evaluated by the slake durability index test (Franklin and Chandra, 1972), the rate of slaking test (Morgenstern and Eigenbrod, 1974), the modified soundness test (Wood and Deo, 1975) and the simple slake test (Stollar, 1976). However, the slake durability index test is the most widely used test (Dick *et al.*, 1994).
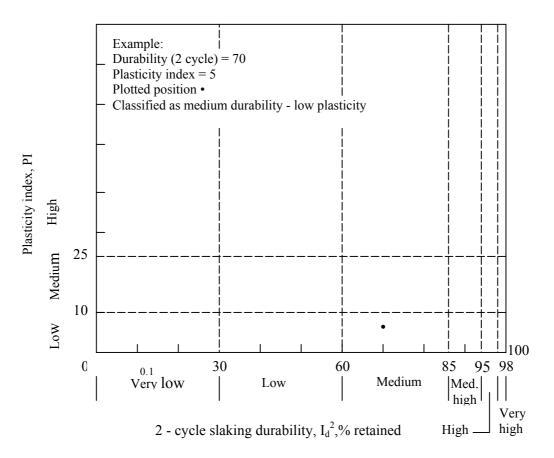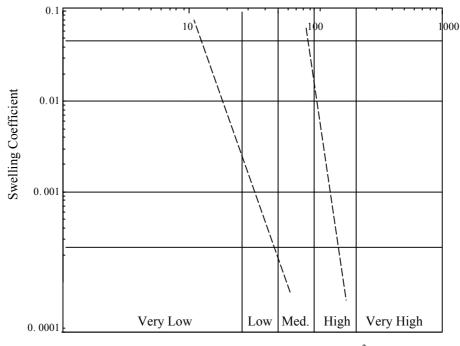

Figure 2. Durability-plasticity chart of Gamble (1971).

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Several classification systems were developed to assess the durability behavior of mudrocks. Gamble (1971) developed a durability-plasticity chart (Figure 2) for mudrocks based on two-cycle slake durability tests. The chart divides durability into six classes: *very low*, *low*, *medium*, *medium high*, *high* and *very high*. Taylor and Spears (1981) suggested the adoption of Gamble's (1971) classification for less indurated types of mudrocks. Morgenstern and Eigenbrod (1974) developed a durability classification system based on liquid limit and rate of slaking values.

Olivier (1979) developed a classification system based on a plot of the swelling coefficient (free swelling from an oven-dry to a saturated condition) against uniaxial compressive strength (Figure 3). The system recognizes six rock durability classes: *excellent* (class A), *good* (class B), *fair* (class C), *moderately poor* (class D), *poor* (class E) and *very poor* (class F). The system is particularly relevant to compacted and weakly cemented rocks. The major limitations of the system are the heterogeneous sedimentary rock masses and the variation of strength and free swelling properties of the rock material. Taylor and Spears (1981) indicated that Olivier's (1979) classification seems to be a promising approach for moderately strong to very strong mudrock types.

Figure 3 . Durability classification of Olivier (1979)

Strohm (1980) developed a durability classification system for highway embankment design based on lithologic characteristics, durability tests and field performance of mudrocks used in the construction of highways in the United States. Franklin (1983) proposed a quantitative rating system based on second-cycle slake durability index (Id_2), plasticity index (PI), and point load strength index (Is_{50}).

Grainger (1984) developed a classification scheme based on strength and durability, (Figure 4), which recognized three classes of mudrocks: soil-like mudrocks, non - durable mudrocks and durable mudrocks. A compressive strength of 0.6 MN/m^2 is taken to be the upper limit of soil-like mudrocks. A non-durable rock has a compressive strength of 0.6-3.6 MN/m^2 or 3.6-100 MN/m^2 and a slake durability less than 90%.
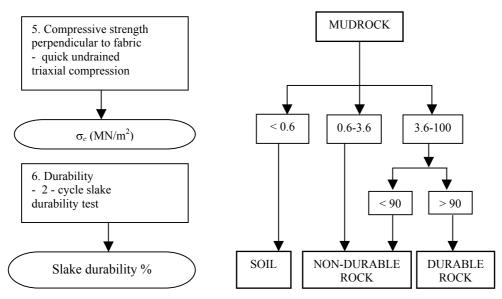
Figure 4. The classification of mudrock by strength and durability (Grainger, 1984).

A compressive strength of 3.6-100 MN/m^2 and a slake durability greater than 90% is recommended for a durable rock. Grainger's (1984) classification has the advantage of using both strength and durability, however, it lacks the description of the quality of mudrocks. Further, the compressive strength of 0.6 MN/m^2 proposed by Grainger's (1984) system as the upper limit of soil-like mudrocks is markedly lower than its equivalent proposed by the Working Party Report (Anon, 1977). Further classifications by Grainger (1984) using the quartz content, (determined by XRD analysis), and the flakiness ratio for the classification of non-durable and durable mudrocks are shown in Figures 5 and 6 respectively.

Dick et al. (1994) proposed a new durability classification based on lithologic characteristics, (Table 3), in which durability is classified into three classes: low, medium and high. The second-cycle slake durability index (Id$_2$) was used as a measure of the durability, whereas clay content, clay-mineral composition, texture, microfracture frequency, absorption, adsorption, dry density, void ratio, and Atterberg limits were used to characterize mudrock lithology. The classification requires an initial geologic classification of mudrocks into claystones, mudstones, shales, etc. using the Potter et al. (1980) before the use of the system. According to this classification, all claystones and mudstones with slickensided features have low durability, (Id$_2$ < 50%), whereas mudstones characterized by the presence of rough-surfaced microfractures, shales and siltstones have low, (Id$_2$ < 50%), to high, (Id$_2$ > 85%), durability.

Table 3. Mudrock-durability classification system based on lithologic characteristics (Dick et al. 1994).

Durability	Clay-stone	Mudstone		Shale	Combined Siltstone-siltshale	Argillite
		Slicken-sided	Imf (micro-fractures/cm)	Absorption (%)	Absorption(%)	
High: Id$_2$ > 85%	NA	NA	< 0.4	< 5.5	< 5	All
Medium: 50 < Id$_2$ < 85%	NA	NA	0.8-0.4	10-5.5	9.5-5	NA
Low: Id$_2$ < 50%	All	All	> 0.8	> 10	>9.5	NA

Figure 5

10. Composition
   - XRD analysis

% of total wt. = quartz

11. Anisotropy
   - fragment dimensions

flakiness ratio c/b

NON-DURABLE MUDROCK

< 20 | 20-40 | > 40

< 2/3 | < 2/3 | < 2/3 | > 2/3

NONDURABLE CLAYSTONE | SILTY CLAYSHALE | NON-DURABLE SILTSTONE

CLAYSHALE | NON-DURABLE MUDSTONE

Figure 5: The classification of non-durable mudrock (Grainger, 1984).

Figure 6

12. Composition
   - XRD analysis

% of total wt. = quartz

13. Anisotropy
   - point load
   - cone Indenter

Max. strength /min. strength

DURABLE MUDROCK

< 20 | 20-40 | > 40

< 2 | > 2 | > 2 | < 2

DURABLE CLAYSTONE | SILTY SHALE | DURABLE SILTSTONE
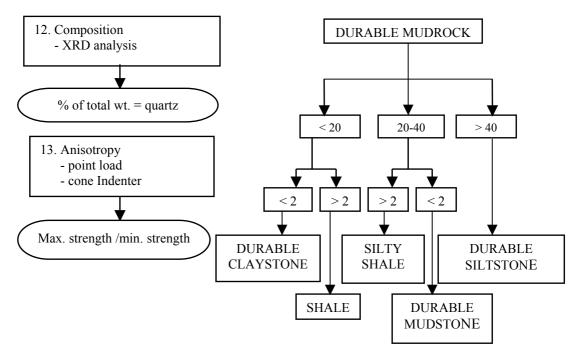
SHALE | DURABLE MUDSTONE

Figure 6. The classification of durable mudrock (Grainger, 1984).

4.6 Swelling Potential Classifications

The first step in dealing with expansive sediments or sedimentary rocks is to identify their capacity for volume change. Once rocks have been identified as expansive, a quantitative characterization of their swelling potential is necessary for design predictions. Unfortunately, there is no standard definition of the term swelling potential, available in the literature, (Holtz, 1959; Seed *et al*., 1962; Snethen, 1979). Further, there is no standard swelling potential test, and therefore, it is difficult to make reliable comparisons between results from different sources. The swelling potential of a soil or a rock can be simply defined as a measure of its ability to swell or the pressure required to prevent swelling.

Table 4. Shrinkage limit and linear shrinkage guide to potential expansion (after Altmeyer, 1955).

Shrinkage limit as a percentage	Linear shrinkage as a percentage	Degree of expansion
<10	>8	Critical
10-12	5-8	Marginal
>12	0-5	Noncritical

Table 5. Data for making estimates of probable volume change for expansive soils (after Holtz and Gibbs, 1956).

Data from Index Tests*			Probable expansion (% total volume change)	Degree of expansion
Colloid Content (% minus 0.001 mm)	Plasticity index (%)	Shrinkage limit (%)		
>28	>35	<11	>30	Very high
20-31	25-41	7-12	20-30	High
13-23	15-28	10-16	10-20	Medium
<15	<18	>15	<10	Low

* Based on vertical loading of 1.0 psi

Table 6. Degree of expansion based on percent passing no. 200 sieve, liquid limit and standard penetration resistance (after Chen, 1965).

Laboratory and Field Data*			Probable expansion (% total volume change)	Degree of expansion
Percent passing No. 200 sieve	Liquid limit (%)	Standard penetration resistance (Blows/ft)		
>95	>60	>30	>10	Very high
60-95	40-60	20-30	3-10	High
30-60	30-40	10-20	1-5	Medium
<30	<30	<10	<1	Low

* Based on loading of 1000 psf.

Table 7. Swelling potential classification based on plasticity index (after Chen, 1988).

Swelling potential	Plasticity index (%)
low	0-15
Medium	10-35
High	20-55
Very high	35 and above

Atterberg limits, clay content and activity are widely used for indirect quantification of mudrocks swell potential. Many classifications systems provide qualitative assessment of the degree of expansion such as low, medium, high and very high, or noncritical, marginal and critical. Altmeyer (1955) developed a criteria based on shrinkage limit and linear shrinkage as given in Table 4. However, recent research failed to show conclusive evidence of the correlation between swelling potential and shrinkage limit (Chen, 1988). Holtz and Gibbs (1956) proposed a classification system based on Atterberg limits and clay content as shown in Table 5. Chen (1965) developed a classification based on percent passing the No. 200 sieve size, liquid limit and standard penetration resistance (Table 6). He also developed a criteria for the estimation of swelling potential based on plasticity index alone as given in Table 7, (Chen, 1988).

Seed *et al*. (1962) established a relationship between the percentage of clay sizes, activity and swelling potential (Figure 7) based on tests done on clays compacted to maximum density at optimum water content according to the American Association of State Highway Officials (AASHTO). Raman (1967) proposed a classification for the degree of expansion based on plasticity index and shrinkage index (Table 8). Dakshanamurthy and Raman (1973) proposed a classification scheme based on liquid limit alone (Table 9). Van der Merwe (1975) developed a chart for determining expansiveness of soils, (Figure 8), based on plasticity index and clay content.
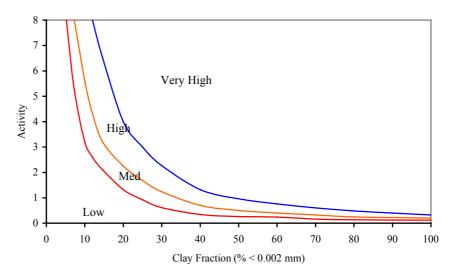

Figure 7. Swelling potential classification (Seed *et al* ., 1962).

Table 8. Degree of expansion classification based on plasticity index and shrinkage index (after Raman, 1967).

Plasticity index (%)	Shrinkage index (%)	Degree of expansion
<12	<15	Low
12-23	15-30	Medium
23-32	30-40	High
>32	>40	Very high

Table 9. Swelling potential classification based on liquid limit (after Dakshnaamurthy and Raman, 1973).

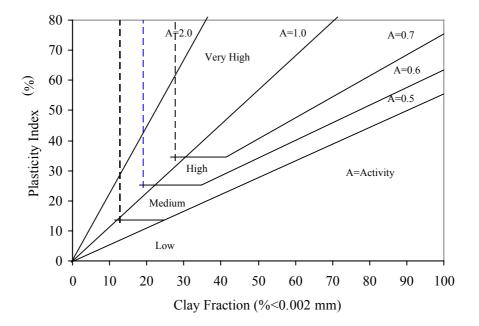| Swelling potential	Liquid limit (%)
None	0-20
Low	20-35
Medium	35-50
High	50-70
Very high	70-90
Extra high	>90

Figure 8. Swelling potential classification (After Van der Merwe, 1975).

Researchers have attempted to evaluate the various classifications available in the literature. Snethen *et al.* (1977) evaluated seventeen classification methods for predicting swelling potential. They found liquid limit and plasticity index are the best indicators of swelling potential along with natural conditions and environment. Therefore, they developed a classification scheme for swelling potential based on liquid limit

and plasticity index and in situ soil suction as an indicator of natural conditions and environment, (Table 10).

Table 10. Degree of expansion based on liquid limit, plasticity index, and in situ suction (after Snethen *et al.*, 1977).

Liquid limit (%)	Plasticity index (%)	Soil Suction *	Potential swell	Potential swell classification
>60	>35	>4	>1.5	High
50-60	25-35	1.5-4	0.5-1.5	Marginal
<50	<25	<1.5	<0.5	Low

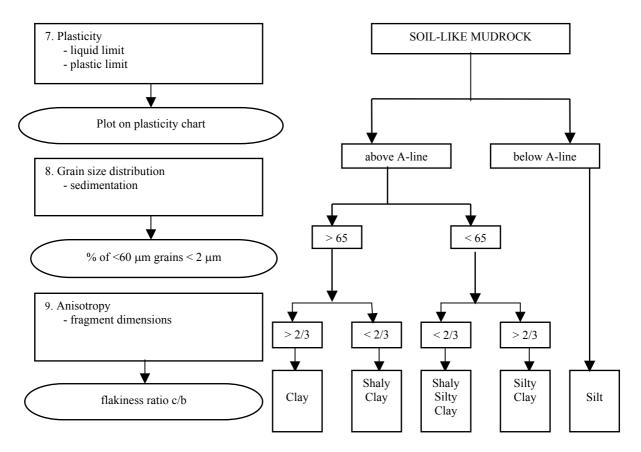*   Soil suction at natural moisture content.

Figure 9. The classification of soil-like mudrock (Grainger, 1984).

It should be noted that the above classification systems were developed based on test results of various types of soils and rocks from different parts of the world which were tested under different testing conditions. Therefore, each system might be applicable to only certain types of materials under specific conditions and might not be applicable to others. The index properties can be used as indicators of soils and

rocks swell potential, but the reliance on such empirical systems can be misleading. Nelson and Miller (1992) indicated that the use of such systems has led to overly conservative construction in some places and inadequate construction in others. Prediction testing and analysis are needed to provide reliable information on which to base design decisions.

Various methods have been reported in the literature for the measurement of soils and rocks swelling potential. The most common methods include the swell-consolidation method, loaded-swell method and constant volume method, which utilize the one-dimensional consolidation oedometer (Jennings and Knight, 1957; Komornik, and David, 1969; Al-Rawas 1999). Other methods for estimating swelling potential use soil suction (McKeen and Hamberg, 1981). These methods include tensiometers, axis translation, filter paper, thermocouple psychrometers and thermal matric potential sensors. Nelson and Miller (1992) provided good summary of common methods in use for estimating soils and rocks swelling potential.

4.7 Soil-Like Mudrocks Classifications

Grainger (1984) developed a classification system for soil-like mudrocks based on plasticity, grain size and anisotropy (Figure 9). The system is a modification to the plasticity chart (Casagrande, 1948) incorporating the percentage of clay fraction (< 2 μm) and the flakiness ratio (shortest dimension divided by the intermediate dimension). The advantage of the system is that it classifies clays into different types.

5.   Conclusions and Summary

The term "Mudrocks" refers to a group of fine to very fine argillaceous sedimentary rocks. These rocks commonly occur interbedded with sandstones and limestones in units ranging in thickness from a few millimeters to several meters. Clay minerals such as montmorillonite greatly influence the behaviour of certain mudrocks (i.e. mudstones and shales) causing swelling and shrinking problems. Therefore, qualitative and/or quantitative characterization of clay minerals is important in the study of mudrocks.

Several mudrocks classifications were reported in the literature based on different parameters including grain size distribution, mineralogical composition, strength, durability and swelling potential. Some of these classifications involve simple and inexpensive tests such as grain size distribution and plasticity tests while others are expensive, sophisticated and time consuming such mineralogical tests. The choice of a particular test depends primarily on the quality of samples. The use of a single parameter in the classification may not give a reliable characterization of the material and therefore it is recommended whenever possible to use a combination of classification parameters.

For the evaluation of mudrocks, it is recommended to initially perform basic geotechnical engineering tests such as Atterberg limits, clay content, activity, etc. Based on the results of these tests and the quality of samples, further tests can be performed. Strength, durability and swelling tests should be performed for full characterization of mudrocks. Classifications of mudrocks based on these tests should be veiwed simultaneously for assessing the actual behaviour of mudrocks.

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