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Review

Laboratory Testing and Classification of Mudrocks: A Review

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Abstract: Mudrocks are fine-grained clay-rich rocks that comprise different lithotypes forming more than 60% of all sedimentary rocks, and thus, they occur frequently in engineering projects either as natural ground or as made ground. These rocks may display a range of engineering behaviours controlled mostly by their composition and structural features. Due to rapid breakdown and susceptibility to volume changes, they may cause problems both during and after construction. Research into the susceptibility of mudrocks to breakdown aims to predict problematic behaviour and provide guidance for avoiding or mitigating these effects. Low-durability materials that disintegrate during sampling and testing can be especially difficult to assess. The paper reviews laboratory techniques for mudrock characterization as well as describes geological and engineering geological classification schemes generally used to describe and classify these materials. The value of some of the tests and determinations in the evaluation of a series of mudrock data taken from the literature is presented.

Keywords: mudrocks; laboratory tests; geological classifications; engineering geological classifications; durability

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1. Introduction

In spite of constituting more than 60% of all sedimentary rocks [1], mudrocks have been less studied than other sedimentary rock types, such as sandstones or limestones [2]. This is attributed to them being encountered in a weathered condition at surface exposures, and furthermore, they are fine-grained materials with a complex composition that needs specific laboratory analysis for their determination [2–4].

The term mudrock is used to define fine-grained sedimentary rocks constituted by more than 50% of siliciclastic grains less than 63 μm in size [5] that are typically composed of over 90% clay minerals, quartz, and feldspar. Often clay minerals will make up about 60% of the total. Carbonates may occur as grains or cement; other non-detrital minor constituents, including pyrite and organic matter, and iron-bearing compounds that are important as pigmenting agents [1,4,5] may also be present.

Fabric and grain size are the most important textural features of mudrocks. Fabric characterizes the geometric arrangement of the particles, which is influenced by the environmental conditions prevailing during sedimentation and by post-depositional loading-unloading history. A common fabric type consisting of clay flakes arranged parallel to bedding (fabric lamination) imparts fissility to the rock. This feature, which may be enhanced by weathering processes, results in the tendency of the material to split along weak surfaces parallel to the stratification. The percentages of clay size (2 μm) and silt size (63 μm) fractions present in mudrocks constitute the criteria to differentiate the mudrock lithotypes, such as claystone, mudstone, and siltstone (see Figure 1) [6].

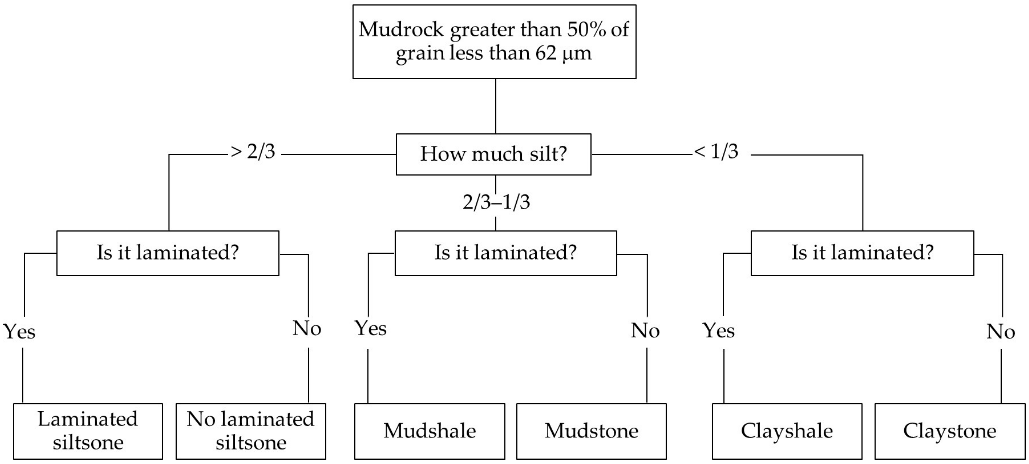


Figure 1. Lundegard and Samuels's classification of mudrock.

Stratification is a common structural feature of mudrocks which is termed bedding or laminae, where the later applies for layering thinner than 10 mm [1]. Although there is no generally accepted geological classification of mudrock, stratification and grain size are the two parameters most widely adopted in the schemes used.

Several genetic factors, including composition, induration degree, and post-depositional diagenetic changes, strongly influence the engineering properties of mudrock, particularly plasticity, strength, deformability, swelling, and durability/slaking behaviour [7,8]. The increase in burial depth and the accompanying enhancement of diagenetic bonding produce a stronger, more brittle, and more durable material. On the other hand, the removal of overburden and weathering processes results in the release of strain energy and the weakening of diagenetic bonding.

The engineering properties of mudrocks can be determined by performing appropriate laboratory tests, according to whether the material displays rock- or soil-like characteristics. However, due to the sensitivity of clay-rich materials to changes in stress and moisture content, the processes of sampling and preparation for testing may have a serious impact on the results these reveal. A particular issue is that tests may only be performed on the more durable materials, which will impart an over-estimated view of mudrock geotechnical performance in civil engineering works [9].

Laboratory techniques for mudrock characterization and geological and engineering geological classification schemes are reviewed in this paper using mudrock data taken from the literature to illustrate the value of some of the tests and classification schemes to evaluate the durability of mudrocks.

2. Laboratory Testing of Mudrocks

Laboratory testing provides mineralogical, textural, chemical, and geotechnical data for mudrock samples which, together with the information gathered by geological and structural fieldwork, underpin rock mass behaviour assessment [10]. Laboratory studies should be carefully planned since, as noted above, low-durable materials may disintegrate during sampling and preparation for testing. An additional factor is that many laboratory characterization techniques involve expensive instruments and are time-consuming procedures, which discourages their use in routine investigations. The relative merits of different methods of characterization are reviewed in the following section.

2.1. Mineralogical, Textural, and Chemical Characterization

2.1.1. Polarizing Microscopy

Polarizing microscopy may be used to study the mineralogy and texture of sand-sized and silt-sized constituents of mudrocks, including features such as cross-bedding, particle shape, segregation and orientations, micro-lamination, and cementation/bonding.

Figure 2 shows microphotographs in crossed polars of mudrocks from Abadia Beds (Lower Kimmeridgian—Portugal). Crossed polars refer to the use of polarized light to assist in the identification of the different mineral constituents.

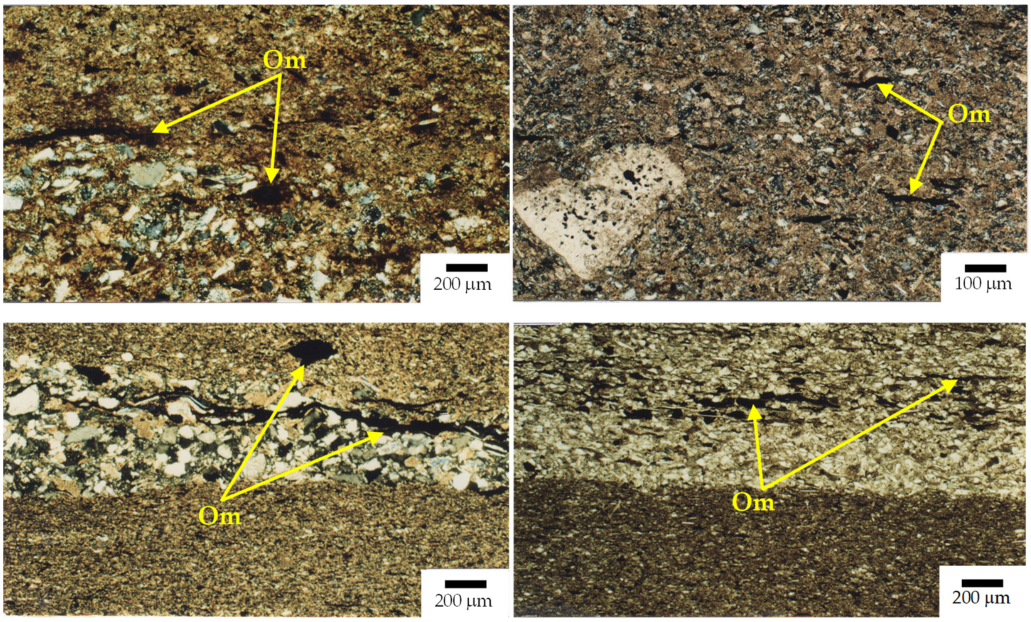


Figure 2. Massive siltstone (**upper left**), massive mudstone (**upper right**), micro-laminated siltstone (**lower left**), micro-laminated mudstone (**lower right**), from Abadia Beds, Lower Kimmeridgian, Portugal; (Om) organic matter.

The process of preparation of the slide for microscope examination entails cutting a thin slice of the rock, which is then polished using fine-grinding carborundum power and attached with resin to a glass slide. The thickness of the slice is then reduced to 30 µm by grinding the surface; thus, only rocks can be examined using this technique. Weak rocks can be stabilized by casting them into a resin block before the slice is cut. This whole process is technically demanding, and the use of the microscope for the identification and description of textural features is a skilled operation. As the identification of the mineral components depends on the transmission of light through the grain, due to their small size, it is not possible to discern individual clay grains in thin sections. Also, the slice of rock is only approximately 2 by 1 cm in area, so only small-scale features can be studied.

Figure 2 shows both massive and laminated siltstone and mudstone. Massive mudrocks (upper microphotographs) are partly cemented and show partly oriented fabric with detrital and matrix carbonates. Laminated mudrocks (lower microphotographs) show coarser and fine lamina. The former consists mainly of rounded and sub-angular grains of quartz (white and grey), some fragments, and inter-granular cementing calcite (brightly coloured) with strands and pieces of organic material (black). The finer parts contain small grains of calcite and quartz, and there may be clay minerals, intergranular calcite cement, and fragments of organic matter. Much of the ground mass of the finer parts of the slide is too small for the grains to be identified. These mudrocks would easily split along the silty laminae due to the presence of weak organic material; however, the resulting fragments would probably be strong as the calcite cement would resist particle separation.

2.1.2. Scanning Electron Microscopy

Both mineralogical and textural aspects of mudrocks may be studied by scanning electron microscopy (SEM). Secondary electron images (SEI) are used to study textural features, including fabric, shape, and size of the grains and pore space geometry. Backscattered electron (BEI) images are useful in distinguishing minerals phases as they provide atomic number contrast. The mineralogy of grains can be identified by their visual appearance or the chemical composition of grains which may be determined by an energy-dispersive X-ray analysis system (EDS) joined to SEM. The data obtained allow the role of a specific mineral phase and/or the association between mineral phases to be determined within the mudrock fabric being analysed. As the area viewed is less than 1 mm across, it is not possible to identify textural features using SEM. Figure 3 shows BEI images with the identification of minerals phases present in both siltstones and mudstone samples from Abadia Beds (Lower Kimmeridgian—Portugal).

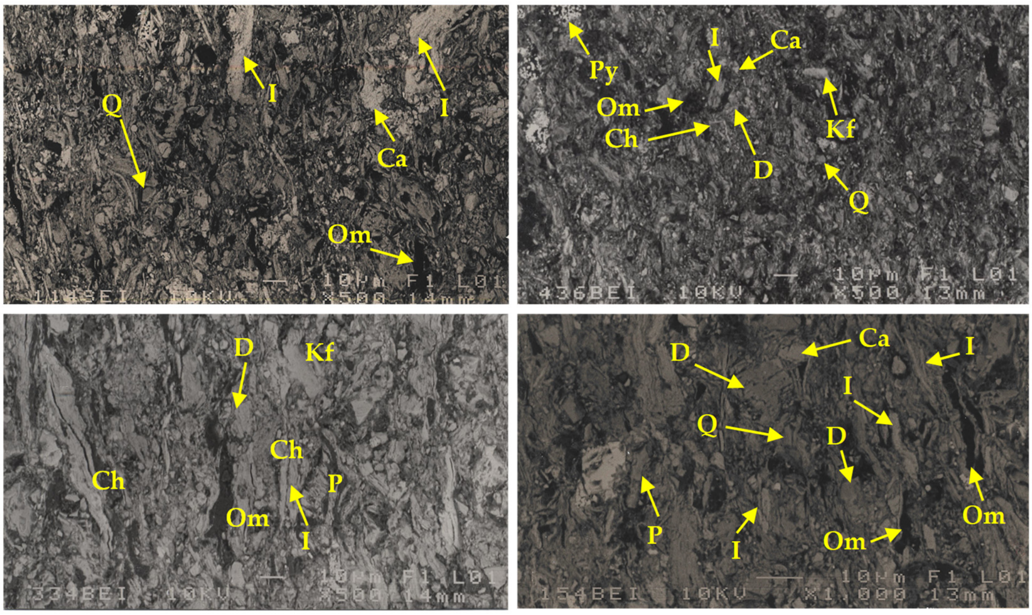


Figure 3. Massive siltstone (**upper left**), massive mudstone (**upper right**), micro-laminated siltstone (**lower left**), micro-laminated mudstone (**lower right**), from Abadia Beds, Lower Kimmeridgian, Portugal; (Q) quartz, (Fk) K-feldspar, (P) plagioclase, (Ca) calcite, (D) dolomite, (I) illite/mica, (Ch) chlorite, (Py) pyrite and (Om) organic matter.

Figure 3 shows that massive siltstone (upper left) and micro-laminated siltstone (lower left) have frequent grain-to-grain contacts with a moderate amount of matrix carbonates, which would imply a stronger mudrock. Massive mudstone (upper right of Figure 3) and micro-laminated mudstone (lower right of Figure 3) show a low amount of intergranular cement that, with the presence of clay minerals, would imply a mudrock with a low resistance to breakdown. This and the presence of pyrite in massive mudstone would tend to reduce its resistance to weathering action, as the acid produced by the oxidation of pyrite will attack the calcite cement, and expansive gypsum may be formed as a result. The partial orientation of particles would impart anisotropy to the rock, which would also result in lowered durability.

2.1.3. X-ray Diffraction

Although both optical and SE microscopy may facilitate the identification of the mineralogical composition of mudrocks, neither method provides a quantitative analysis. The mineral phases of mudrocks are usually determined by X-ray diffraction, which can return both qualitative and semi-quantitative determinations. The soil or rock is ground to a fine powder and mounted randomly oriented on a slide that is exposed to a beam of X-rays. The spectrum of X-rays reflected from the minerals in the sample is used to identify the different mineral phases present in the rock. Identification of clay minerals is assisted by subjecting the sample to pre-treatments, including separation of the <2 µm fraction, glycolation, heating, and creating particle alignment by depositing a slurry on to a slide. These are procedures that facilitate the identification of expandable clay minerals and the differentiation of kaolinite from chlorite.

X-ray diffraction requires the use of sophisticated analytical hardware, specialised software to interpret the X-ray spectrum by an adequately trained operator. The equipment must be calibrated to perform quantitative analyses.

Figure 4 shows the relationship between the total of expandable clay minerals and the total of clay minerals for Portuguese, UK, US, and Indonesian mudrocks. US mudrocks range from Palaeozoic to Mesozoic in age and show, in general, lesser contents of expandable clay minerals than mudrocks from other regions. Portuguese and UK mudrocks are Jurassic in age and show that the former contains a slightly greater amount of swelling clay minerals, making them more prone to breakdown. Indonesian mudrocks are from Late Miocene–Pliocene, and they define the upper limit of materials with higher amounts of swelling clay minerals. These data also demonstrate a tendency for older, more mature mudrocks to contain lower amounts of swelling clay minerals.

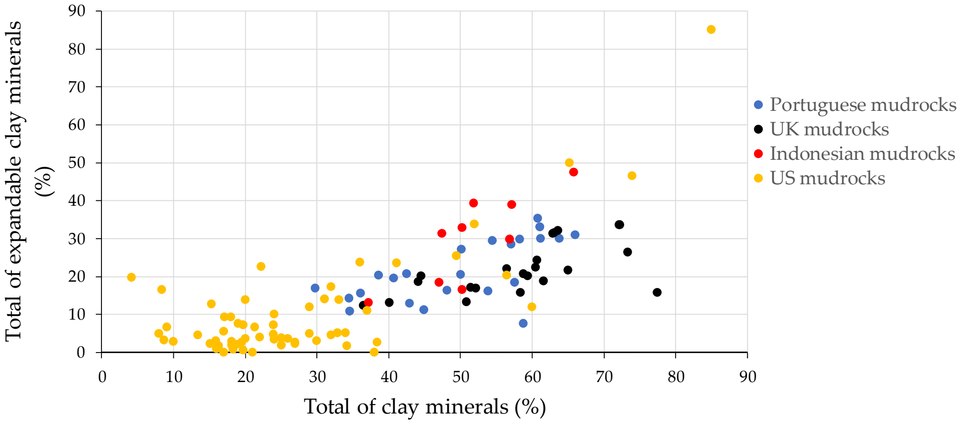


Figure 4. Relationship between the total of expandable clay minerals and the total of clay minerals for mudrocks from different regions (Portuguese mudrock data from Jeremias [11]; UK mudrock data from Campbell [12]; Indonesian mudrocks data from Sadisun et al. [13]; US mudrock data from Dick and Shakoor [14] and Shakoor and Gautam [15].

Figure 5 shows the relationships between the total resistate fraction composed of quartz and feldspar and the total carbonates: mainly calcite and dolomite. It can be seen that the resistate fraction is higher in Portuguese mudrocks than in UK mudrocks, which have greater amounts of carbonates imparting a more indurated/durable state of those rocks. Indonesian mudrocks have relatively moderate amounts of carbonates.

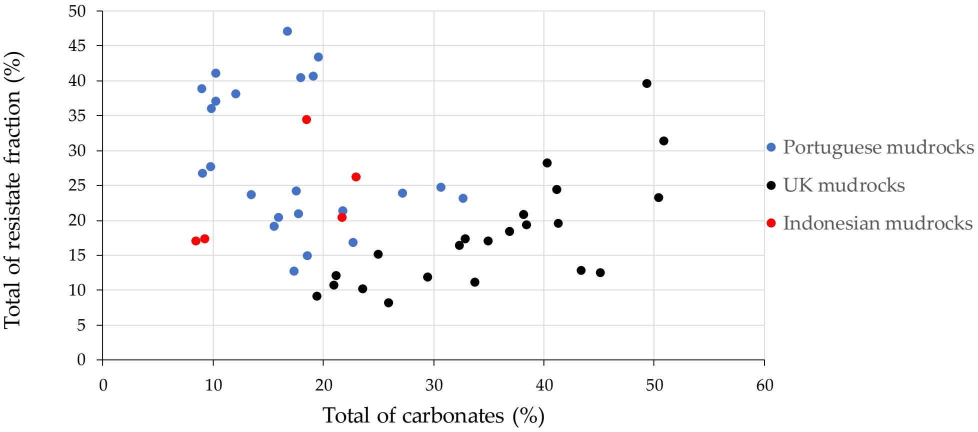


Figure 5. Relationship between the total resistate fraction (quartz + feldspar) and the total of carbonates (calcite + dolomite) for mudrocks from different regions (Portuguese mudrock data from Jeremias [11]; UK mudrock data from Campbell [12]; Indonesian mudrocks data from Sadisun et al. [13].

2.1.4. Porosimetry

Mercury intrusion porosimetry (MIP) and gas intrusion (BET) are used to determine effective porosity, pore distribution, surface porosity, and particle size of small intact samples of mudrocks. The characterization of those microtextural features is important as they are closely related to breakdown processes developed in mudrocks. Specialised equipment is used for the determinations.

2.1.5. Chemical Analyses

Several techniques, including wet chemical, Inductively Coupled Plasma Atomic Absorption Spectrometry (ICP-AAS), Atomic Absorption (AA), or X-ray Fluorescence (XRF) methods, may be used to determine bulk chemical analysis for both major and trace elements present in mudrocks (see BS1377-3:2018, [16]). Among those, XRF in which a powdered sample of the rock or soil is analysed, is a rapid procedure providing analysis of most mudrock components. However, chemical data have limited value in weathering assessment as only small changes in chemical composition accompany physical weathering processes if these predominate.

The amount of pyrite present in a mudrock sample can be determined by determining the total sulphur content by High-Temperature Combustion and then treating a sample with acid to remove any acid-soluble sulphur and analysing the resulting solution using ICP atomic emission spectroscopy or other means. In most geological materials, gypsum is the acid-soluble sulphur compound and pyrite is the only acid-insoluble sulphur compound, so the amount of pyrite can be calculated from the difference between total sulphur and acid-soluble sulphur. Some sulphur is usually present in organic material, so unless a correction is made, this method will slightly over-estimate the pyrite content. Jurassic UK mudrocks studied by Campbell [12] have pyrite contents between about 7 and 13%, whereas Portuguese mudrocks of this age usually display percentages smaller than 2% [11].

The carbonate and organic carbon present may also be determined. To determine the organic carbon present, the sample is first treated with acid to remove any carbonate present and then analysed using a High-Temperature Combustion analyser. The analyser is also used to determine the total carbon content of an untreated sample and the carbonate content is then calculated from the difference between these values.

2.2. Identification Test

2.2.1. Density and Porosity

Density and total and effective porosity may be determined by several testing procedures provided by the International Society for Rock Mechanics (ISRM) [17]. Alternative methods, such as mercury porosimetry, are used on samples that disintegrate under vacuum saturation. Table 1 shows dry density values for Palaeozoic and Mesozoic mudrocks from North America, for Cretaceous to Pliocene Iranian mudrocks, and for Portuguese Jurassic mudrocks. Claystones have dry density values less than the other lithotypes, and Portuguese and Iranian mudrocks show dry density values lower than US mudrocks, implying a more indurated state for the latter.

2.2.2. Natural Water Content

The natural water content gives valuable information concerning the presence of hydrophilic compounds in rock, particularly clay minerals. Thus clay-rich mudrocks, especially those containing swelling species, have relatively high natural water contents. Water absorption and water adsorption contents are, respectively, determined by conducting immersion tests and exposure of samples of rock fragments to specific moisture conditions [17].

2.2.3. Particle Size and Atterberg Limits

Prior disaggregation of the material is necessary for the determination of particle size distribution [18] and Atterberg limits [19]. Methods of disaggregation include alternate wetting and drying, the use of acids or chemical dispersing agents, and mechanical crushing. However, inter-particle bonding in mudrocks may prevent the disaggregation of the material into individual particles, in which case the values obtained in these tests are highly dependent on the effectiveness of the disaggregation procedure. Table 1 shows that claystone has higher percentages of material finer than 2 µm, which are similar to those of Iranian mudstones, whereas siltstones and siltshales usually display lower values. It can also be seen that US and Portuguese mudrocks have similar percentages of material finer than 2 µm.

Plasticity index values shown in Table 1 are higher for claystones showing the controlling influence of mineralogy. They are also significantly greater for Portuguese mudrocks indicating the presence of larger amounts of swelling clay minerals. These values will have been determined using standard methods entailing the use of distilled or deionised water. However, the ions present in natural ground waters may result in changes to clay minerals, especially swelling clay minerals, that affect the plasticity and strength of the materials. For example, Steward and Cripps [20] found that the residual angle of shearing resistance of mudstone of Carboniferous age was reduced by between 5 and 10% by the presence of sodium ions in the pore water and that the value increased by a similar amount when potassium was present, compared with the value for distilled water.

Table 1. Mean values of dry density, percentage of material finer than 2 µm and plasticity index of Portuguese and North American and Iranian mudrocks.

	Claystone	**Mudstone**	**Clayshale/Mudshale**	**Combined Siltstone–Siltshale**
Dry density (Mg.m^{-3})	– 2.25(b) 2.33(c) –	2.38(a) 2.42(b) 2.54(c) 2.29(e)	2.39(a) 2.52(b) 2.49(c) –	2.31(a) 2.39(b) 2.49(c) 2.34(e)
Percent < 2 µm	– 47.8(c) 52.2(d) –	25.8(a) 25.2(c) 26.8(d) 44.6(e)	20.8(a) 17.0(c) 22.2(d) –	17.2(a) 21.2(c) 12.8(d) 12.9(e)
Plasticity index (%)	– 23.1(c) 29.1(d) –	18.7(a) 7.2(c) 10.7(d) 15.6(e)	15.7(a) 6.0(c) 10.5(d) –	15.3(a) 5.8(c) 10.2(d) 7.1(e)

Portuguese mudrock data from (a) Jeremias [11]; North American mudrock data from (b) Dick et al. [21], (c) Shakoor and Gautam [15], (d) Dick and Shakoor [14]; Iranian mudrock data from (e) Heidari et al. [22].

2.2.4. Methylene Blue Adsorption

The methylene blue adsorption spot test may be used to evaluate the hydrophilic surface characteristics of the clay minerals and, thus, their capacity to retain water. Methylene blue is not adsorbed by inert minerals and thus may be used as a routine test to assess the swelling clay component in a powdered rock sample [23].

2.3. Strength and Deformability

2.3.1. Uniaxial Compressive Strength Tests

Uniaxial compressive strength procedures are given by ISRM [24] and ASTM [25]. The preparation of cylindrical or prismatic specimens for the test comprises the major drawback of this test in mudrock, especially material containing laminations that hamper the preparation of specimens with dimensions suitable for the test. The tests also entail drying the specimens, which may cause them to become damaged. Taking into account these difficulties, Koncagül and Santi [26] proposed the use of slake durability (see Section 2.5) to estimate uniaxial compressive strength, especially of weak rocks which are sensitive to damage during specimen preparation. Mudrock strength anisotropy is important as anistropic materials tend to break up more easily than isotropic ones due to stresses induced by weathering processes. Anisotropy can be evaluated by varying the direction of loading in uniaxial compressive tests. However, difficulties arise with preparing test specimens aligned parallel and perpendicular to the bedding.

Ranges of values of uniaxial compressive strength for mudrocks from Portugal, the UK, and the US are provided in Table 2.

2.3.2. Tensile Strength Tests

Testing procedures for tensile strength are given in ISRM [27], but preparing samples and applying tensile forces to specimens are very challenging, so often diametral compression (Brazilian) tests are carried out. However, particularly on massive mudrocks, as diametral testing pre-determines the specimen failure surface, they give higher values than direct tensile strength tests.

2.3.3. Point Load Test

The point load strength test procedure is described in ISRM [28]. Although the damage to specimens is caused by coring or cutting equipment, the test is most suitable for testing indurated strong mudrock types. It is not appropriate for weak or weathered materials. Poor results are obtained for irregular block mudrock samples with an axial distance smaller than 25 mm. Equidimensional lumps tested with loading direction perpendicular to stratification or weakness planes provide the most consistent results. However, for mudrock strength, anisotropy assessments with loading directions normal and parallel to bedding must be carried out. For mudrock studies, it is recommended that a site-specific correlation factor is determined. Some point load strength values for UK and Iranian mudrocks are given in Table 2.

2.3.4. Schmidt Rebound Test-Hammer

The testing procedures for the Schmidt rebound test hammer are given by ISRM [29]. This equipment is mostly used for field testing of rock outcrops, but it is also used for laboratory testing on core and/or block samples. Determinations of rebound number using an N19 Schmidt rebound test hammer for UK mudstones are provided by Carter and Sneddon [30] (Table 2), and correlations between rebound number and uniaxial compressive strength are proposed; nevertheless, for mudrocks, it is recommended that a site-specific correlation factor is determined.

2.3.5. National Coal Board Cone Indenter (NCB)

The National Coal Board (NCB) cone intender [31] was developed to determine the strength of rock chips not greater than 12 × 12 × 6 mm in size (Figure 6), where the testing procedures are provided by the National Coal Board, UK [31]. It is a portable device that does not require elaborate specimen preparation. It is very suitable for testing thinly bedded or fractured mudrock fragments that would break up during the preparation of specimens for uniaxial compression tests. In the test, a steel cone is driven against the rock fragment until the deflection values of the steel beam reach 0.635 mm (standard test) or 0.23 mm (soft rock test). The cone penetration values correlate with uniaxial compressive strength, but the determination of a site-specific correlation factor is recommended, and this requires carrying out parallel uniaxial compression tests. The test is suitable for the determination of the intrinsic strength of thinly bedded or laminated mudrocks.

Figure 7 shows the correlation between uniaxial compressive strength and cone indenter number values obtained for Portuguese Jurassic mudrocks [11]. It can be seen that weathered materials display a random trend between the uniaxial compressive strength values and the cone indenter data, being, accordingly, excluded from the correlations presented in Figure 7. The R^2 values calculated without the data for the weathered samples are significantly higher (R^2 = 0.88 for $\sigma_c/CI_{(0.23)}$ and R^2 = 0.86 for $\sigma_c/CI_{(0.635)}$), and the equations determined by the least-squares method with intercept equal to zero are presented in Figure 7. A better correlation is obtained for both parameters.

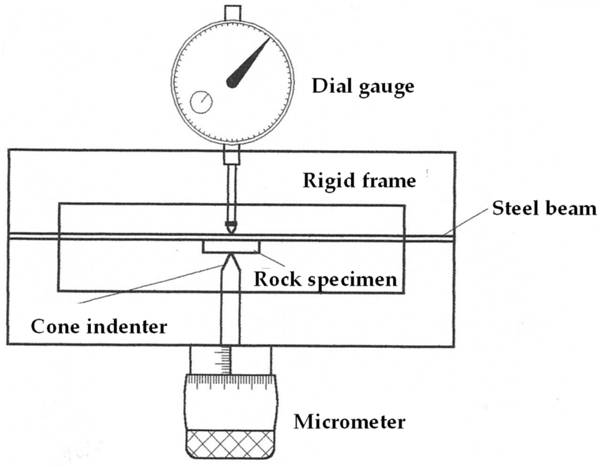


Figure 6. Diagrammatic illustration of NCB cone indenter.

Table 2. Range of values of strength and deformability for mudrocks from different regions.

	Claystone	**Mudstone**	**Clayshale/Mudshale**	**Combined Siltstone-Siltshale**
Uniaxial compressive strength (MPa)	–	13.6–26.0(a)	8.1–27.6(a)	12.9–23.4(a)
	—	25.7–45.4(b)	–	–
	–	3.4–128(c)	–	–
	15–70(e)	15–113(e)	13–72(e)	35–214(e)
Deformation modulus—secant modulus (GPa)	–	1.41 *(a)	–	1.17 *(a)
	–	5–50(c)	–	–
Point load strength (MPa)	–	1.22–2.67(b)	–	–
	–	0.21–7.2(c)	–	–
	–	0.75–0.86(d)	–	–
	–	0.32–1.72(f)	–	0.70–2.89(f)
Rebound Number (type N19 Schmidt hammer)	–	20–27(d)	–	–

Portuguese mudrock data from (a) Jeremias [11], UK mudrock data from (b) Bell [32], (c) Czerewko and Cripps [33], and (d) Carter and Sneddon [30]; North American mudrock data from (e) Sarman et al. [34]; Iranian mudrock data from (f) Heidari et al. [22]; * single value.

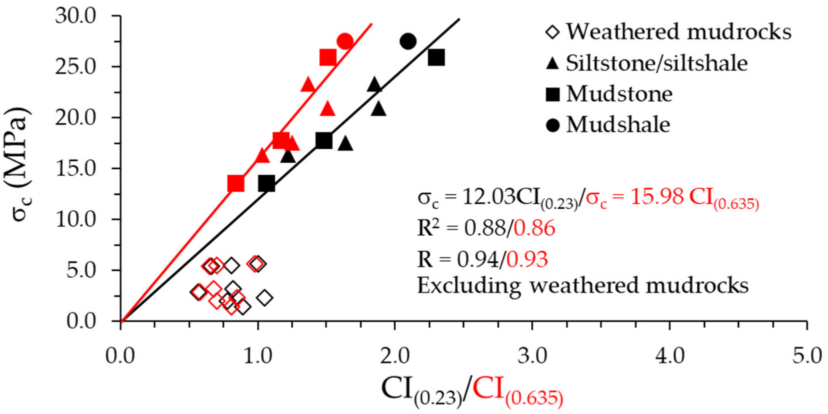
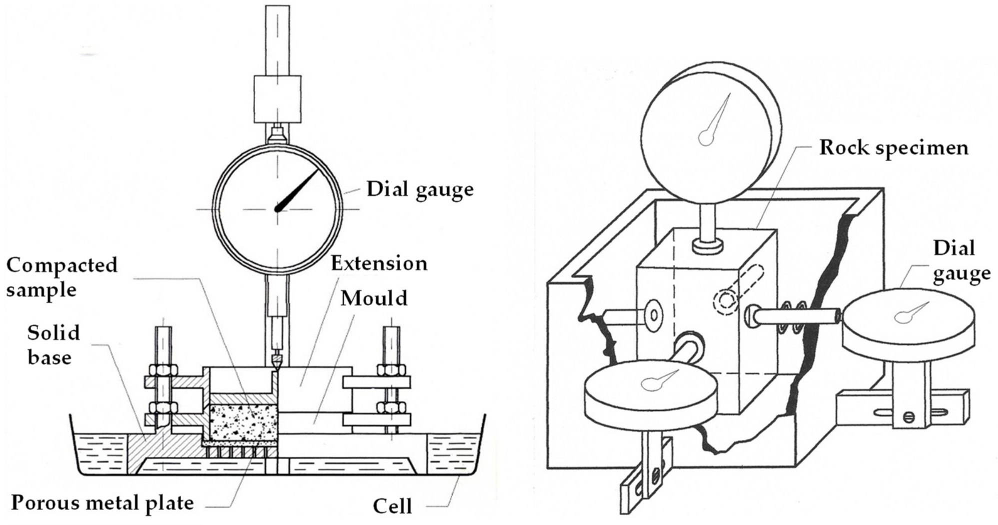


Figure 7. Correlation obtained for Portuguese Jurassic mudrocks between uniaxial compressive strength and both cone indenter number values measured according to the standard (red) ($CI_{(0.635)}$) and soft rock (black) ($CI_{(0.23)}$) methods [11].

2.4. Swelling

2.4.1. Swelling Strain

Axial swelling strain tests on radially confined remoulded specimens performed following the National Laboratory for Civil Engineering (LNEC) test standard E- 200 [35] provide data about the swelling of the mineralogical constituents of the material in the presence of water. The apparatus is illustrated in Figure 8a, where the sample consists of two 15 mm thick compacted layers of dry disaggregated material passing a #40 ASTM (425 µm) sieve. The compaction is performed using a specific plunger applying a force of 0.5 MPa. A micrometer dial gauge reading of 0.01 mm is used to record swelling strain resulting from immersion in water over a test time of 48 h.



(a) **(b)**

Figure 8. Diagrammatic illustrations of the apparatus used to measure swelling strain [11]: (**a**) on radially confined remoulded specimens; (**b**) on rock specimens.

Uniaxial and triaxial swelling strain test procedures for intact rock specimens using the apparatus shown in Figure 8b are given by ISRM [17]. One of the orthogonal axes is perpendicular to the bedding or parting in the rock. The test specimens consist of pre-cut cubes of approximately 30 mm side lengths, and they are mounted with the z-axis normal to the bedding. Micrometer dial gauges reading to 0.001 mm record swelling strain due to immersion in water during a standard test time of 48 h or until swelling has ceased. Problems arise with cutting the cubes in weak and low-durability materials.

ISRM [36] provides a method for testing argillaceous rocks suitable to determine axial and radial free swelling strains using an unconfined disc-shaped specimen. The tests can also be carried out on irregular specimens. Total radial strain at the end of the test is measured with a flexible stainless-steel band calibrated at 0.1 mm intervals, which is attached to the specimen.

Powder swelling tests aim to evaluate the mineralogical control of swelling without the influence of the texture of the rock. A graduated glass cylinder is used to measure the change in sample volume after distilled water has been added to the dry powder.

Table 3 shows swelling strain data for mudrock from different regions where US samples display much higher values of volumetric strain than UK and Portuguese mudrocks.

Table 3. Range of values of swelling strain and swelling pressure for mudrocks from different regions.

	Claystone	Mudstone	Clayshale/Mudshale	Combined Siltstone-Siltshale
Axial swelling strain on remoulded specimens (%)	–	13.2–19.4(a)	12.2–16.0(a)	10.1–18.0(a)
Uniaxial swelling strain on intact specimens (%)	– –	2.8–11.6(a) 0.6–7.8(c)	2.0–9.9(a) –	1.7–16.7(a) –
Volumetric strain (%)	– – 11.6–68.9(d)	3.5–12.3(a) 0.28–3.12(c) 0.1–54.2(d)	2.7–12.3(a) – 0.2–25.8(d)	3.7–29.7(a) – 0.3–17.8(d)
Swelling pressure (MPa)	– 0.03–8.24(d)	0.54–1.06 = (b) $1.10–1.62_{\perp}$ (b) 0.05–5.75(d)	– 0.01–2.57(d)	– 0.16–2.72(d)

Portuguese mudrock data from (a) Jeremias [11] and (b) Jeremias [37]; UK mudrock data from (c) Czerewko and Cripps [33]; North American mudrock data from (d) Sarman et al. [34].

2.4.2. Swelling Stress

Swelling stress–strain test procedures are provided by ISRM [36], which require that the applied force is increased during the test to prevent the specimen from increasing in volume during the test. The apparatus described by Jeremias [11] consists of a rigid frame and an electrical load cell, as shown in Figure 9. The swelling stress developed under conditions of zero volume change on Portuguese mudrock samples of Cretaceous age is shown in Figure 10 [37]. It can be seen that axial swelling stress developed in rock specimens perpendicular to bedding over time is greater than in specimens cut parallel to stratification and has a behaviour typical of brittle material with an asymptotic path after a peak value. In specimens cut parallel to bedding, behaviour typical of soft material is recorded with maximum swelling stress reached in an asymptotic path without passing a peak value. Accordingly, a maximum axial swelling stress of 1.1 MPa was recorded for this material, which means that in engineering applications, a back stress equal to or greater than this must be applied to balance it. Oedometer test equipment may be used to determine swelling strain and stress of remoulded and undisturbed soil-like mudrock samples.

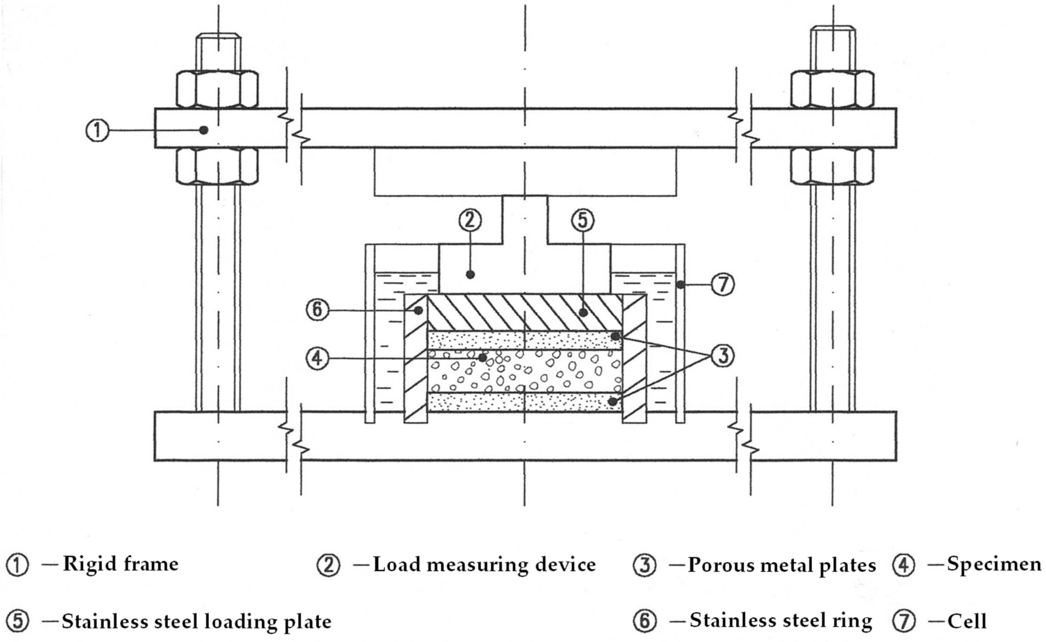


Figure 9. Apparatus for measuring the axial swelling stress of an undisturbed radially confined rock specimen [11].

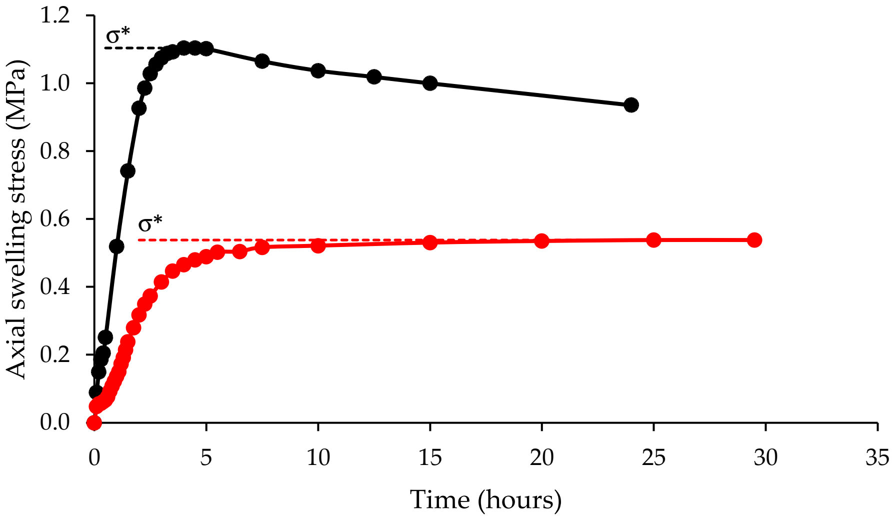


Figure 10. Axial swelling pressure versus time plots of Cretaceous Portuguese mudrocks measured perpendicular (black) and parallel (red) to bedding [37]. $\sigma*$ —Maximum axial swelling stress.

ISRM [36] provides a suggested method to evaluate the axial swelling stress developed as a result of the release of axial swelling strain. The objective of this test is to measure the swelling strain necessary to lower the swelling stress from its maximum value to one suitable for the design in the specific application.

2.5. Durability

2.5.1. Ageing Tests

Natural exposure and ageing tests provide means of mudrock durability assessment. Details of the long-term disintegration behaviour of mudrocks subjected to natural exposure tests are given by Shakoor and Gautam [15]. In ageing tests, a specific weathering process is reproduced, of which the most common are cyclic wetting and drying, freezing and thawing, and soundness tests. Although these tests are used in research studies, they are very time-consuming and not commonly used in routine investigations.

2.5.2. Slake Durability Test

Mudrock durability assessment in routine studies is usually based on slaking due to cyclic wetting and drying and mechanical disturbance evaluated using the slake durability test apparatus proposed by Franklin and Chandra [38]. This test was further recommended by ISRM [17] and standardized by ASTM [39]. The two-cycle slaking durability index (I_{d2}) has been adopted in several classification schemes for mudrock durability assessment. For the test, 10 equidimensional dried rock lumps, each 40–60 g mass, are placed in a cylindrical drum formed out of 2 mm mesh that is rotated on a horizontal axis while partly submerged in a water bath. The amount of sample retained in the drum after 200 rotations is collected, dried, and expressed as a percentage of the original dry mass of the sample. In the standard two-cycle test, after the first cycle, the sample is dried and then subjected to a second cycle of 200 rotations, but to enhance the sensitivity of the test, more cycles may be performed with 200 rotations or with a higher number of rotations. The material can then be ranked visually according to the scale given in Table 4.

In low-durability materials, useful information about the breakdown process can be obtained by analysing the particle size of the less than 2 mm material. For strongly anisotropic weaker mudrocks, it can be difficult to prepare the requisite equidimensional lumps, which results in a tendency to test only the stronger, more durable material in the sample. Figure 11 shows the greater than 2 mm sized remains of a mudrock sample after a slake durability test comprising three dynamic cycles of 200 + 200 + 600 rotations, together with the grain size curve of the material finer than 2 mm.

Table 4. Descriptive scheme for material retained in drum during the slake durability test [11].

A—Description of break-down of retained fraction after testing (I_{d3}—1000 rotations)	A.1—Minor breakdown—Less than 25% of the fragments have been reduced in size by half of their initial size (approximately between 30 to 40 mm)
	A.2—Moderate breakdown—Approximately 25% to 50% of the fragments are reduced by as much as half their initial size.
	A.3—High breakdown—More than half of the fragments have been reduced by more than 50% of their initial size.
	A.4—Extremely high breakdown—At least 75% of the fragments either totally disintegrated or the fragments were between 5 and 15 mm in size.
B—Descriptions of fragment shapes after testing (I_{d3}—1000 rotations)	B.1—Rounded—The fragments retained a relatively equant shape.
	B.2—Almond shaped—Most fragments had a flattened surface.
	B.3—Platy—The fragments were thin plates that had either angular or rounded edges.

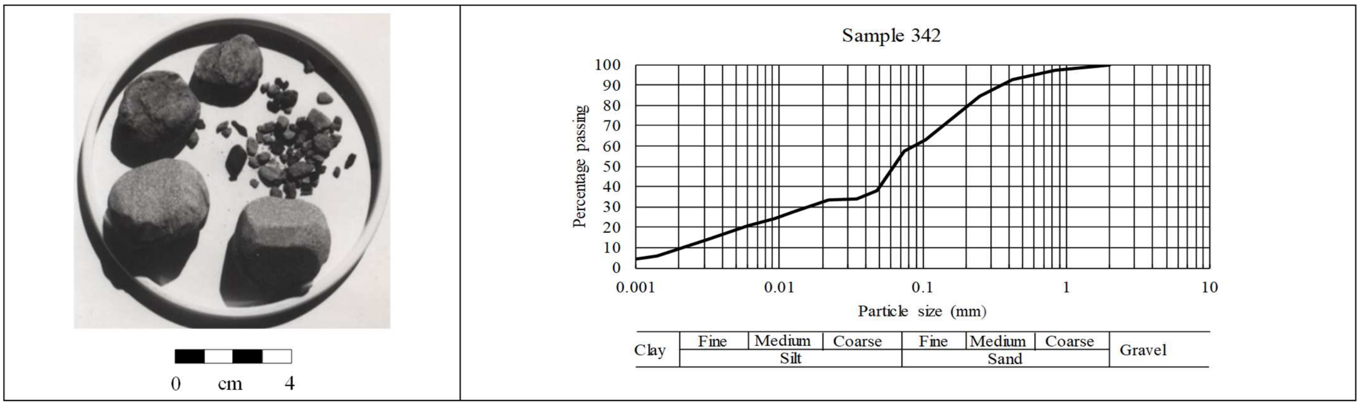


Figure 11. Result of slake durability test on sample of siltstone, with an I_{d2} value of 34.2% (durability class low) and an I_{d3} value of 26.5%. **Left**: >2 mm fragments retained in the drum after 1000 rotations. **Right**: particle size distribution plot for the <2 mm fraction from the water bath after 1000 rotations.

These results show that the sample consists of a heterogeneous mix of strong and weak layers such that in the test, most of the weak material disintegrated during the first 2 cycles (400 rotations), and an I_{d2} value of 34.2% was recorded. The stronger parts sustained little breakdown after 1000 rotations, as shown by the remaining >2 mm material, and an I_{d3} value of 26.5% was achieved. The size distribution plot for the <2 mm fraction from the water bath after 1000 rotations show that clay-plus silt-sized (0.002–0.06 mm) particles predominate.

The results presented in Figure 11 show a main drawback to this test, which is the tendency of some rocks to break down into fragments bigger than 2 mm, thus overestimating their durability. To overcome this difficulty, Erguler and Shakoor [40] proposed a method that quantifies the fragment size distribution of the slaked material in terms of the 'disintegration ratio' defined as the ratio of the area under the fragment size distribution curve to the total area encompassing the curve. An advantage advocated by those researchers in characterising the disintegration ratio is that it assists not only with the assessment of the durability of the material but also with the manner of disintegration of mudrocks of varying durability.

Table 5 shows slake durability standard two-cycle test data for mudrocks ranging in age from Palaeozoic to Pliocene from Portugal, the UK, the US, and Iran. Despite the variability of the data, a general trend in which claystones are more prone to breakdown and siltstone/siltshale are more durable emerges.

An approach in which the durability of mudrocks without carrying out laboratory tests is proposed by Singh et al. [41] using an artificial neural network model. The authors demonstrate that the predicted values for a set of mudrock samples are very close to those achieved from standard slake durability testing.

Table 5. Slake durability standard two-cycle test data for mudrocks ranging in age from Palaeozoic to Pliocene from Portugal, UK, US, and Iran.

	Claystone	**Mudstone**	**Clayshale/Mudshale**	**Combined Siltstone-Siltshale**
Slake durability standard two-cycle test (I_{d2})	–	42.3–92.3(a)	74.5–92.7(a)	34.3–90.6(a)
	–	80.0–96.0(b)	–	–
	1.0–50.0(c)	3.0–93.0(c)	36.0–97.0(c)	25.0–79.0(c)
	–	0.6–7.3(d)	29.7–47.0(d)	96.2–98.7(d)
	0.2–24.7(e)	4.0–90.5(e)	0.2–97.8(e)	6.1–98.9(e)
	3.0–83.8(f)	2.0–96.3(f)	45.5–97.2(f)	96.1–98.9(f)
	1.5–80.1(g)	3.4–95.2(g)	28.0–99.0(g)	86.9–99.2(g)
	–	61.6–95.5(h)	–	84.2–98.7(h)

Portuguese mudrock data from (a) Jeremias [11]; UK mudrock data from (b) Bell [32]; North American mudrock data from (c) Dick and Shakoor [14], (d) Shakoor and Rodgers [42], (e) Sarman et al. [34], (f) Erguler and Shakoor [40] and (g) Shakoor and Gautam [15]; (h) Iranian mudrock data from Heidari et al. [22].

2.5.3. Static Slake Test

The static slake test consists of one cycle in which an oven-dried 40–50 mm sized cube of rock in which one face is perpendicular to the bedding, is immersed in water, and its behaviour is observed at specific times over a period of 24 h (Table 6).

Table 6. Static slaking classification [43].

1—Total specimen disintegration; water muddy to quite muddy; disintegration into a pile of soil-like debris, i.e., a high proportion of sub-gravel-sized debris and some fine to medium gravel-sized fragments.
2—Partial to total disintegration; water muddy to quite muddy; the slaked debris generally consists of a pile of angular gravel-sized shards or blocky fragments, and occasionally with free-standing fragments of the original specimen block.
3—High degree of specimen deterioration; water muddy; fractures extremely closely spaced (2–6 mm) and generally open (>2 mm), usually parallel to bedding with occasionally crossed fractures; only a partial specimen shape retained, usually the specimen has split into a few free-standing blocks, with up to 50% of slaking.
4—Moderate to high specimen deterioration; water muddy; fractures extremely closely spaced (2–10 mm) and generally open (1–4 mm), generally parallel to bedding, usually with up to 25% slaking; the specimen may have split into a few free-standing blocks.
5—Moderate specimen deterioration; water muddy; fractures extremely closely spaced (5–10 mm) and generally hairline to (≤2 mm) open, usually with up to 10% slaking of the specimen consisting of gravel-sized fragments and shards.
6—Slight specimen deterioration; water muddy; fractures extremely closely spaced (10–20 mm) and generally hairline (≤1 mm) open, usually parallel to bedding with up to 5% slaking, usually from the specimen corners.
7—No notable specimen deterioration; water clean or slightly muddy; development of occasional hairline fractures, usually bedding fractures or parallel to bedding; air bubbles generally emitted from these fractures.
8—No visible sign of specimen deterioration; water clean; air bubbles may be emitted from the sample.

Several classification schemes have been proposed [43–46] to categorise the slaking behaviour of mudrocks. Santi [47] linked static slake categories to the types of slaking observed and proposed a six-category classification providing a standard visual basis for distinguishing between degrees of chip or fracture formation. Accordingly, category 1 refers to degradation to a mud-like consistency, and categories 2 and 3, respectively, describe the formation of flakes and chips. Categories 4 and 5 describe the formation of fractures and slabs, and category 6 is applied when no reaction is observed.

Table 6 integrates the proposals of Santi’s work [47], which describes the formation of fractures in lesser disintegration stages and the formation of chips and flakes in higher deterioration stages. However, some slaking in the categories linked to the formation of fracture(s) is included in this proposed unified approach in Table 6.

A quantitative index can be derived by expressing the mass of material greater than 2 mm after one or more wet–dry slaking cycles as a percentage of the mass of the original sample.

2.6. Compaction Tests

In this context, compaction tests are used to study the change of grading between uncompacted and compacted material, which reflects the breakdown of the particles during the compaction process. Several procedures have been proposed for this mudrock degradability assessment, but the test given by NF P94-066 [48] is one of the most used. In this test, degradability is expressed as the ratio between D_{10} determined in the initial grading curve for the sample and of D_{10} obtained in the grading curve after sample compaction with one hundred blows with a standard Proctor hammer using a CBR mould. Ratios higher than 7 express materials are prone to breakdown.

3. Mudrock Classifications

3.1. Geological Classifications

The descriptive schemes used for mudrock geological classification are based on features with some genetic significance. Table 7 shows the guidance given by Czerewko and Cripps [33] for the description of mudrock key features. Colour, mineralogy, fossil content, fracture type, and induration state are descriptive modifiers that complement the root names for a better mudrock characterization.

Table 7. Guide to the description of mudrock features [33].

Attribute	Descriptive Adjectives
Induration	Enables decision on description as soil or rock. If resistant to slaking in water and hard, it is rock; if susceptible to slaking in water, deformable, and ‘earthy consistency, it is soil. Strength depends on moisture state; dry sediment is stronger than wet, and rock strength varies with moisture content; sampling may impair strength.
Strength	Strength is designated based on the degree of induration. For soil, use field consistency values based on manual assessment, e.g., stiff; when shear strength measurements are made, use strength terms, e.g., high strength. For rock, a definition based principally on manual field assessment using geological hammer and knife may be confirmed with UCS measurement: indurated mudrocks range from extremely weak to medium strong; metamudrocks are stronger depending on weathering.
Structure	Standard terms for beds, laminae, and parting are provided by Potter et al. [1]. Include description of lithology and textural inter-relationship, as complex features may be present with structured strata such as ‘thin beds of cross bedded’ mudstone.

Table 7. *Cont.*

Attribute	Descriptive Adjectives
Colour	Use Munsell colour chart for consistency. Important for correlation; likely environment of formation and indication of likely behaviour of material, i.e., red colour—likely formation under oxidizing continental environment. Most important to mudrocks is relationship between colour on the Fe^{3+}/Fe^{2+} ratio. A decrease in this ratio gives an increase in colour from red → green → grey (more Fe^{2+} indicates the presence of pyrite). Organic carbon controls colour: <0.2–0.3%C = light-grey to olive grey; 0.3–0.5%C = mid-grey; >0.5%C = dark-grey to black.
Accessory minerals	Calcareous (slightly to very, based on level of effervescence when assessed with HCl, carbonaceous, dolomitic, ferruginous, glauconitic, gypsiferous, pyritic, micaceous, sideritic, phosphatic.
Rock name	See classification of Figure 1.
Additional information	Presence of fossils—record type (generic such as bivalve and retain for identification), abundance, condition, orientation. Inclusions—nodules (with mineral type and details); gravel, sand, silt partings or pockets, etc.
State of weathering	Alteration seen as distinct discoloration, significant strength reduction to discontinuities, and presence of lithorelicts (note orientation).
Fractures	Use ISO 14689:2017 standard terms and procedures [49]. For rock supplements with details such as nature of fragmentation, e.g., conchoidal, hackly, brittle, splintery, slabby, fissile.

Full engineering descriptions of the intrinsic condition and mass properties using descriptive adjectives provided in ISO standards [49–51].

Texture (grain size) and structure are the most helpful geological properties for describing and classifying mudrocks. Texture describes the relationships between the silt- and clay-sized fractions in mudrock. The structure is characterized by fissility and stratification. Fissility is defined as the character of the rock being prone to separate along lamination or bedding planes. Stratification reflects the vertical changes in composition, colour, and/or fabric that occur in sedimentary sequences. In laminations, this occurs at a spacing of less than 10 mm, whereas bedding is thicker than this. Weathering processes tend greatly to enhance fissility such that some mudrocks are prone to split into very thin layers along planar weakness surfaces. Accordingly, as a classification factor, its utility is limited to superficial rocks as it is absent at depth [6]. Geological classifications of mudrock (containing more than 50% of particles of silt- and/or clay-sized) based on grain size and fissility underpin the first approach to classification of these rocks, as proposed by several authors [5,52–54].

Stratification as either laminae (<10 mm) or bedding (>10 mm) is a natural classification factor to distinguish between bedded massive mudrocks and laminated mudrocks [1]. Thus, for classification purposes, the suffix '-stone' is used for bedded rocks, whilst the suffix '-shale' is attached if laminae are present. However, based on the work of Grainger [55], Czerewko and Cripps [33] proposed the use of the terms fissile and non-fissile for mudrock based on flakiness index (ratio of short to intermediate dimensions) and strength anisotropy (ratio of highest to lowest strengths). Accordingly, fissile mudrock possesses a flakiness index value greater than 2/3 and strength anisotropy of 2 or more.

Following Potter et al.'s [1] classification criteria, Lundegrad and Samuels [6] advocated that laminated mudrocks with a percentage of silt less than 67% should be classified as 'shale', whereas rocks with a silt-sized fraction greater than this should be designated as siltstone, as shown in Figure 1. Based on Potter et al.'s [1] classification, Dick and Shakoor [14] and Dick et al. [21] recommended a boundary at 50% of clay to distinguish between mudstones and claystones as this reflects a change in the breakdown behaviour of mudrocks.

Several classifications have used the quartz or quartz plus feldspar percentages as criteria to distinguish between the different lithotypes of mudrocks [11,33,55–57]. Boundaries were defined at 20% to differentiate between claystone and mudstone, at 40% to separate mudstone from siltstone, and at 60% to divide siltstone from sandstone. Quartz and quartz plus feldspar percentages may be determined by chemical and XRD procedures, and a correction factor must be applied to mudrocks with a carbonate content greater than 5% to account for the effect of dilution. Field criteria to distinguish mudrock lithotypes are provided in Table 8.

Table 8. Geological classification for mudrocks [11].

Quartz + Feldspar Content [1]	**Field Criteria**	**Non-Indurated** [2]	**Indurated** [2]	
			Massive	**Laminated**
>60%	Grains recognized by naked eye or with hand lens	Sand	Sandstone	NA
40–60%	Abundant silt visible with hand lens	Silt	Siltstone	Laminated Siltstone
20–40%	Slightly granular to the touch	Mud	Mudstone	Laminated Mudstone
<20%	Smooth to the touch	Clay	Claystone	Laminated Claystone

[1] Quartz + feldspar content classes adapted from Spears [56], Grainger [55], and Taylor [57]; [2] Rocks with more than 10% of carbonates have the term calcareous before the root name; NA—Not applicable.

Table 9 shows the rock classification presented in ISO 14689:2017 [49], which delineates rock-like mudrocks as fine-grained clay-bearing rocks with quartz and feldspar grains less than 0.063 mm in size. The table includes the terms argillaceous, which means containing clay minerals, and lutaceous, which implies a material containing fine grains of silt- and/or clay-sized material. In accordance with ISO 14689:2017's classification [49], marlstone contains at least 50% of carbonate grains. Nevertheless, it is presumed that rocks containing less than 50% carbonate, as either grains or cement, will be classified as marlstone. ISO standards [50,51] help to identify, describe and classify soil-like mudrocks.

Table 9. Classification of mudrocks according to ISO 14689:2017 [49].

Genetic group		Sedimentary				
		Clastic sedimentary				
Usual structures		Bedded				
Composition		Grains of rock, quartz, feldspars, and clay minerals				At least 50% of grains are of carbonate
Predominant grain size (mm)	0.063	Argillaceous or Lutaceous	Mudstone Shale: fissile mudstone	Siltstone: 50% fine-grained particles	Marlstone	
	0.002			Claystone: 50% very fine particles		

3.2. Engineering Geological Classifications

Attempts at engineering definitions of mudrock have been proposed by several authors [55,57–63], and a main concern in the classification of such materials is the division between soil and rock. The distinction between 'compaction shales', which are consolidated muddy sediments without intergranular cement, and 'cemented shales', which contain intergranular cement, was proposed by Mead [58] and followed by Underwood's classification [59].

The latter was the first to distinguish the control of soil-like and rock-like properties on mudrock breakdown behaviour. Additionally, as pointed out by Cripps and Taylor [7], induration, stress history, and weathering are factors that strongly influence engineering properties. Another approach to defining a soil/rock boundary is based on the strength characteristics of the materials [55,57,60–62]. Commonly field strength criteria and laboratory testing, mainly uniaxial compressive strength (UCS) results, are used for this purpose (Table 10).

Table 10. Strength criteria for mudrocks [33].

Term	Strength	Description
Strong mudrock	σ_c 50–100 MPa	Can only be scratched by knife or pick end of a geological hammer and can only be broken with more than one firm hammer blow.
Medium strong mudrock	σ_c 25–50 MPa	Can be deeply scored by a knife or pick end of a geological hammer, and a thin slab can be broken by heavy hand pressure. Specimen is readily fractured with a single firm blow of geological hammer or split with a knife blade. Cannot be peeled with a pocket knife.
Weak mudrock	σ_c 5–25 MPa	Small gravel-sized fragments can be deformed with heavy finger pressure, shallow indentations readily made by firm blow with point of geological hammer. Can be peeled by a pocket knife with difficulty.
Very weak mudrock	σ_c 1–5 MPa	Crumbles under firm blow with point geological hammer, can be peeled by a pocket knife.
Extremely weak mudrock	σ_c 0.6–1 MPa	Can be indented by thumbnail.
Extremely high strength clay	s_u 0.3–0.6 MPa	Field description will generally be as a 'very stiff clay'. Crumbles, does not remould, and can be indented by thumbnail.
Very high strength clay	s_u 0.15–0.3 MPa	Determine by testing—field description as a 'very stiff clay'.
High-strength clay	s_u 0.075–0.15 MPa	
Medium-strength clay	s_u 0.075–0.04 MPa	Field description will generally be as a 'stiff clay'. Crumbles, breaks, remoulds to lump.
Low strength clay	s_u 0.04–0.02 MPa	Field description will generally be as a 'firm clay'. Cannot be remoulded, rolls to thread.
Very low strength clay	s_u 0.02–0.01 MPa	Field description will generally be as a 'soft clay'. Moulds by light finger pressure.
Extremely low strength clay	s_u < 0.01 MPa	Field description will generally be as a 'very soft clay'. Extrudes between fingers.

σ_c = Unconfined compressive strength s_u = Undrained shear strength NB $\sigma_c = 2s_u$.

However, it is recognized that there is no specific strength limit that is widely accepted as a soil/rock boundary, and there is a lack of standardization of the definition of weak rock, as different institutions and researchers suggested different UCS values [33,55,57,61,62], and whether loading results in brittle or plastic deformation depends on the confining conditions and the rate of loading. In the range of mudrocks with low UCS values, the same material may be classified by different classifications as rock or as soil, with severe geotechnical and contractual consequences where such materials are involved in engineering works.

The increase of civil engineering works dealing with mudrocks as natural ground on construction and ground engineering sites and as made ground, fill, and construction material promoted the development of several classification schemes based on mechanical and engineering properties. Such classifications aim to provide criteria to deal with mudrocks in design studies and in the organization and management of the construction process.

Table 11 lists the soil/rock features and index tests selected for some of the most widely used classifications. Slake durability is adopted by several classifications to anticipate the breakdown behaviour of mudrocks. Plasticity is commonly adopted in schemes for less indurated materials, and strength (particularly uniaxial compressive strength and/or point load strength) are used to distinguish between soil-like and rock-like mudrocks as well as to subdivide the stronger types.

Gamble's [64] durability-plasticity classification of mudrocks, based on the plasticity index and two-cycle slake durability index, differentiates six durability classes and is suitable for less indurated mudrocks. Figure 12 displays this classification for Portuguese, UK, North American, and Iranian mudrocks.

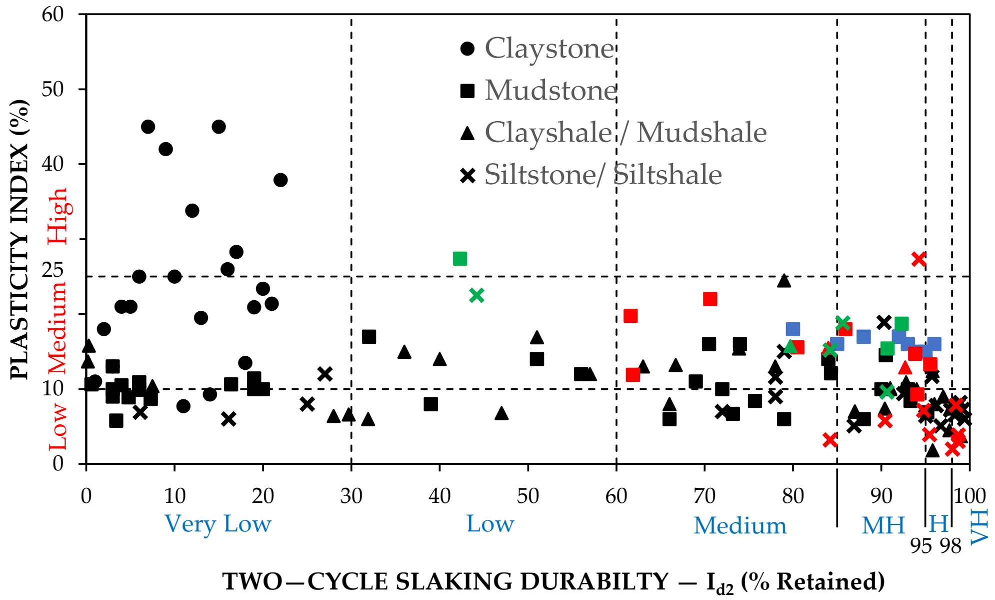


Figure 12. Durability–plasticity chart of Gamble for Portuguese mudrocks (green) [11], UK mudrocks (blue) [32], USA mudrocks (black) [14,15,34,42], and Iranian mudrocks (red) [22].

Morgenstern and Eigenbrod's [60] classification is based on a strength softening test, slaking test, rate of slaking, and liquid limit. Clays and mudstones are differentiated according to the results from the initial shear strength (c_{uo}) and strength loss (Δc_u) resulting from the immersion of the materials in water. Materials with c_{uo} values less than 1.8 MPa and Δc_u greater than 60% are classified as clays, while materials with c_{uo} values higher than 1.8 MPa and Δc_u less than 40% are classified as mudstone. However, the scheme proposed is time-consuming to apply, and only the part based on the rate of slaking and liquid limit is usually performed to estimate the potential for slaking [65].

Table 11. Soil and rock features and index tests adopted in some of most widely used mudrock engineering geological classifications [11].

Soil and Rock Characteristics and Index Tests	**Classifications**										
	Gamble [64]	**Morg. and Eigen. [60]**	**Olivier [66,67]**	**Franklin [68]**	**Grainger [55]**	**Taylor [57]**	**Dick et al. [21]**	**Jeremias [11]**	**Czerewko and Cripps [43]**	**Erguler and Shakoor [40]**	**Ulusay and Erguler [69]**
Mineralogy (from XRD analysis)					√	√					
Anisotropy (Flakiness ratio)					√						
Microfracture frequency index							√				√
Dry density								√			
Grain size					√						
Absorption water							√				
Moisture absorption									√		
Atterberg limits	√	√		√	√						
Methylene blue adsorption value								√	√		
Uniaxial compressive strength			√		√	√					
Undrained Shear strength		√			√						
Point load strength			√	√	√	√					
Cone indenter number					√						
Free swelling strain			√								
Slake durability (evaluated by Jar Slake)		√							√		
Slake durability (evaluated from slake durability test)	√			√	√	√	√	√		√	
Rate of slaking		√									
Disintegration ratio										√	

Olivier's [66,67] geodurability classification is based on uniaxial compressive strength or point load strength and 'Duncan' free swelling coefficient (Figure 13). This classification was developed for mudrocks of Karoo Supergroup, South Africa and six durability classes from very poor to excellent were recognized. According to Olivier [67], the main drawback of this classification is that it is necessary to test a large number of samples to obtain representative values of the index parameters, which is challenging for less indurated mudrock types.

Franklin's [68] mudrock rating system is based on slake durability and plasticity index and point load strength, and it is suitable to classify both soil-like and rock-like mudrocks, which are distinguished from each other on the basis of a slake-durability index (I_{d2}) of 80%. For I_{d2} values less than 80%, the mudrock is soil-like, and it is classified based on the results achieved by the slake durability test plus plasticity index (PI) and plotted in the left part of the chart in Figure 14. If I_{d2} values are greater than 80%, the mudrock is rock-like, and it is classified using slake durability and point load strength (I_{S50}), with the result plotted in the right part of the chart in Figure 14.

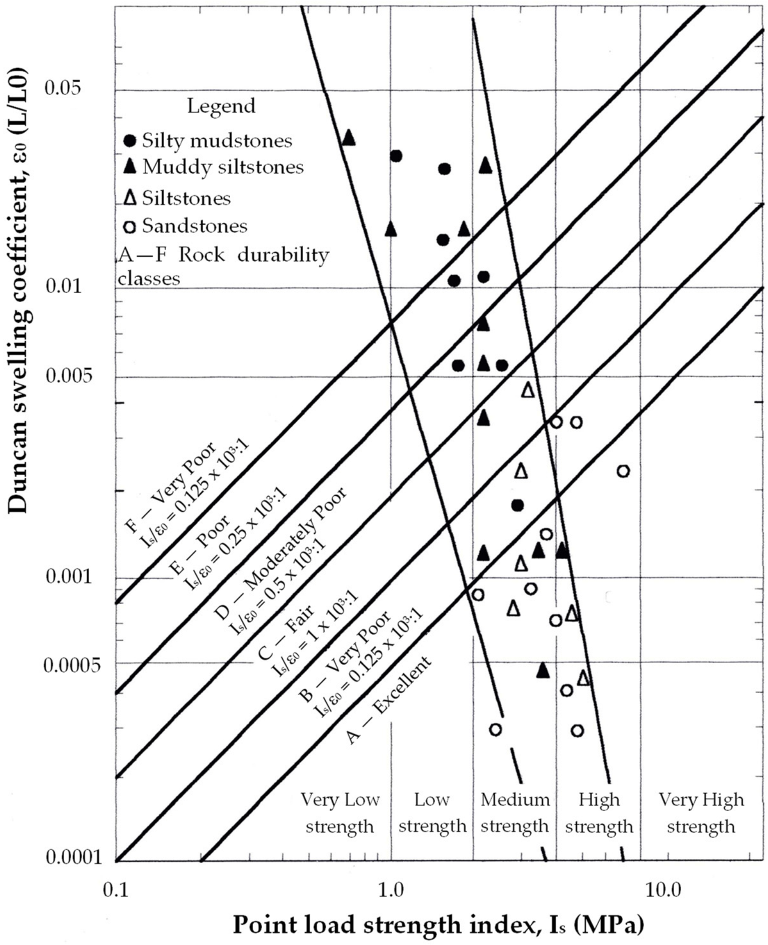


Figure 13. Olivier's geodurability classification [67].

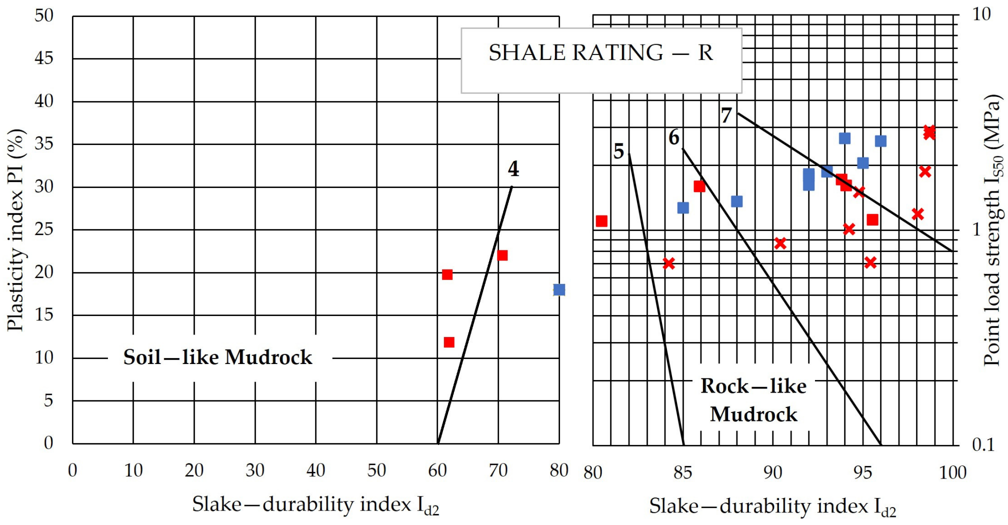


Figure 14. Franklin's mudrock rating chart for UK mudrocks (blue) [32] and Iranian mudrocks (red) [22].

Some correlations based on limited data between the mudrock rating-system values and aspects of the engineering performance of mudrocks observed in civil engineering works are provided by Franklin [68]. Figure 14 shows Franklin's mudrock rating system with some data for UK and Iranian mudrocks.

Grainger's [55] mudrock classification for engineering purposes in Figure 15 is based on composition, uniaxial compressive strength, slake durability, and an anisotropy criterion. This classification uses some previous concepts, such as the quartz content to identify indurated mudrock lithotypes and Morgenstern and Eigenbrod's [60] strength criterion plus a slake durability index (I_{d2}) greater than 90% to differentiate durable and non-durable mudrocks. An assessment of anisotropic fabric is proposed to differentiate shale from non-shale lithotypes based on a flakiness ratio less than 2/3 for non-durable mudrocks and on a ratio between orthogonal strengths determined through point load or cone indenter testing greater than 2 for durable mudrocks.

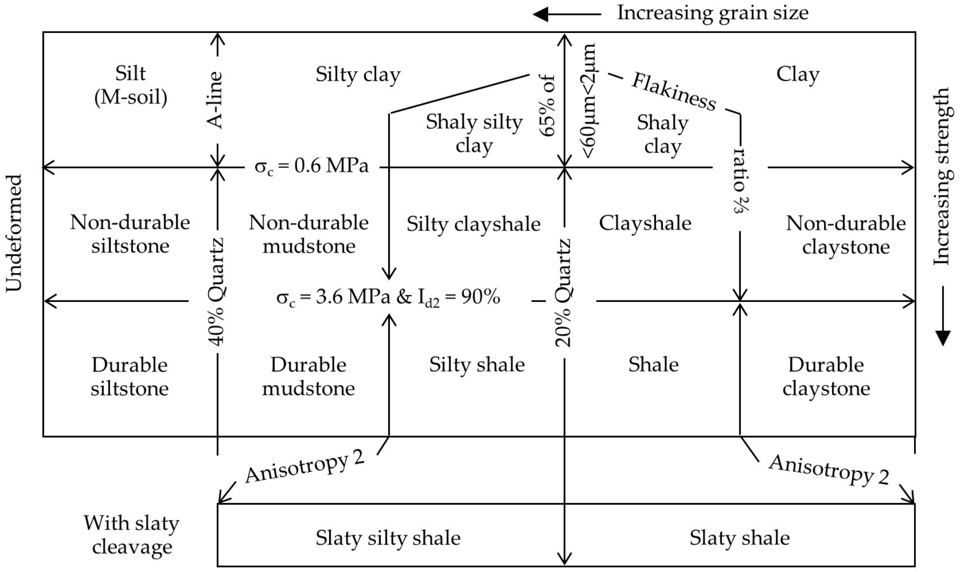


Figure 15. Grainger's mudrock classification for engineering purposes [55].

Taylor's [57] mudrock classification is based on composition, uniaxial compressive strength, and slake durability. This classification also uses the quartz content method to distinguish between mudrock lithotypes, and this defines a mudrock as durable if UCS > 3.6 MPa and the 3-cycle slake durability index is greater than 60%.

Dick et al.'s [21] mudrock durability classification is based on the lithological characteristics of the mudrocks. Accordingly, durability assessment should be achieved separately for claystones, mudstones, siltstones, shales, and argillites. They suggested that durability assessment of the different mudrock lithotypes may be determined from correlations between slake durability index (I_{d2}) and the amount of expandable clay minerals for claystones, the frequency of microfractures for mudstones, and water absorption value for both siltstones and shales.

Jeremias's [11] mudrock classification in Table 12 is based on dry density, methylene blue adsorption value, and slake durability index.

Table 12. Jeremias's durability index (DI) [11].

Slake Durability		**Dry Density**		**Methylene Blue Adsorption Value**		**Durability Index**	
I_{d2} (%)	**Rank Value**	**γ_d (Mg.m^{-3})**	**Rank Value**	**MBA (g/100 g Fines)**	**Rank Value**	**DI**	**Total Rank**
<50	1	<2.19	1	4.1	1	Low	<6
50–85	2	2.19–2.38	2	2.8–4.1	2	Medium	6–7
>85	3	>2.38	3	<2.8	3	High	>7

The amount of void space and the nature and amount of clay minerals are two major parameters for mudrock durability assessment, evaluated by dry density and methylene blue index tests. Accordingly, data from Portuguese mudrocks were used to define a durability index (DI) determined from the scoring of the three index tests, each one on a scale 1 to 3, and thus, an overall rating between 3 and 9 may be obtained. Therefore, more durable mudrocks have rank values greater than 7, while non-durable materials have rank values less than 6 and an overall rating of between 3 and 9.

Czerewko and Cripps's [43] mudrock durability classification is based on the static slake test, moisture absorption, and the methylene blue value. This classification was developed using data from UK mudrocks, and each test was scored on a scale of 3 to 9 (Rank Total value). Table 13 shows this classification which includes a description of sample evaluation and comments on durability behaviour expected in engineering situations are also provided [70].

Table 13. Czerewko and Cripps's classification of mudrocks [70].

Rank Total Value	Sample Evaluation	Comment
3	Extremely durable material—not prone to swell or slake	Suitable for engineering appraisal using rock test procedures
4–6	Durable material—may gradually swell and slake	May suffer deleterious effects from rock testing procedures
7–9	Non-durable material—prone to rapid swell and slake	Category of rock and soil—requires non-routine testing approaches

Erguler and Shakoor [40] proposed a mudrock durability classification based on the disintegration ratio (D_R) and second-cycle slake durability index (I_{d2}) following the six classes defined in Gamble's classification. Accordingly, the six categories of the Erguler and Shakoor's classification are as follows: very low (I_{d2} 0–30%—D_R 0.00–0.19), low (I_{d2} 30–60%—D_R 0.20–0.49), medium (I_{d2} 60–85%—D_R 0.50–0.78), medium-high (I_{d2} 85–95% —D_R 0.79–0.91), high (I_{d2} 95–98%—D_R 0.92–0.95) and very high (I_{d2} 98–100%—D_R 0.96–1.00).

Erguler and Ulusay [69] proposed a mudrock durability classification based on fracture frequency observed in the field and a newly defined index slake durability rating-SDR. A rating value of zero is assigned to the weakest rock material that disintegrates totally when subject to atmospheric process, and a rating of 100 is assigned to a material that does not show disintegration in the field. SDR is defined as SDR = 100–100λ where λ means fracture frequency, defined as the number of fractures per meter. For the Turkish rocks studied by these researchers, values ranging between 0 and 1 mm^{-1} and up to 1 mm^{-1} were obtained for the least durable material. A six-class classification based only on SDR value was proposed, and general information related to physical and mechanical properties as well as visual and verbal descriptions for each class, was provided.

4. Final Considerations

Because of their small grain size, composition, and structural features and the possibility of mudrocks causing problems in engineering applications, a number of special techniques for investigation and assessment must be deployed. Guidance for both research studies and for routine investigation works for engineering concerning key features of mudrocks is given in standards and in the literature. Unfortunately, detailed characterization of mudrocks involving mineralogical, textural, and geotechnical determinations often entails the use of specialist investigations that are costly and time-consuming to perform. An alternative, more practical approach is to employ a selection of suitable index tests to distinguish problematic from non-problematic materials and to derive suitable values for key geotechnical design parameters. This methodology is particularly appropriate for the reconnaissance phase of projects, and suitable schemes for this are proposed by Jeremias [11], Czerewko and Cripps [43], Erguler and Shakoor [40] and Erguler and Ulusay [69]. However, these classification schemes were developed using data derived from rocks collected on particular geological formations (Portugal, the UK, the US, and Turkey). Therefore, for their general application, further testing involving other geological formations is needed. Furthermore, the particular problems liable to occur with a mudrock in the proposed engineering situation must be recognized and allowed to direct the investigation to avoid or mitigate any potential problems.

Siltstones, mudstones, and claystones are differentiated based on texture (grain size), and whether the material is massive or laminated depends on the spacing of the individual beds or laminae. For fieldwork and studies which do not comprise laboratory testing, the mudrock geological classifications proposed by Lundegrad and Samuels [6] and ISO 14689:2017 [49] are suitable. In studies requiring a more detailed classification of the mudrocks present, the quartz or quartz plus feldspar content method is a useful approach to distinguish between the different lithotypes of mudrocks following the criteria proposed by Spears [56] and Taylor [57].

Mudrock engineering geological classifications are based mainly on the results of index tests, and by adopting some of the concepts of previous classifications, Grainger's scheme [55] provides valuable guidance for the assessment of the engineering performance of these rocks. However, this and many classifications require the preparation of standard sized rock specimens for UCS tests which is often a problematic task in mudrocks. It is argued that the Czerewko and Cripps [43], Jeremias [11], and Erguler and Shakoor [40] schemes overcome this drawback as they use index tests that do not need special sample preparation providing an approach for mudrock durability assessment, which may be applied easily in practice. The Erguler and Ulusay [69] classification based on field observations would also appear to be a useful addition to the available schemes.

One of the purposes of this paper is to alert engineers contemplating the design and construction of works entailing mudrocks, either as in situ materials or as construction materials, to the possibility of unanticipated forms of behaviour. The engineering performance of mudrocks can be subject to rapid deterioration, and the rate at which this occurs may be accelerated by environmental changes, including a reduction in confining pressure and exposure to weathering processes caused by the engineering works themselves. Besides the possibility of design parameters being over-estimated, the changes may also affect the values obtained in geotechnical tests, resulting in designs that are too conservative. The broad range of factors that control the engineering properties of mudrocks and the wide variety of factors in an engineering application with the potential for creating a mismatch between anticipated and actual performance present a challenge to the geo-engineer. However, having recognised that mudrocks may result in ground engineering problems, the testing and classification schemes described in this paper should provide ways of anticipating and mitigating or avoiding problematic forms of behaviour.

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