The implications of diagenetic history and weathering on the engineering behaviour of mudrocks

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Abstract: The variability of mudrocks has important consequences on their behaviour during geotechnical work. The characteristic composition and weathering processes that led to formation and deposition of the constituent mineral grains followed by the diagenetic processes that influence the mineralogy and morphology of the resultant mudrocks result in considerable variability in terms of engineering behaviour. During uplift and exposure, the effects of stress relief and weathering further influence intrinsic characteristics including mineralogy, porosity, particle cohesion and the degree of fracturing. Thus near-surface mass properties differ considerably from the intact properties of the rock material.

Structural features resulting from exposure affect the properties of rock masses and properties of the intact rock material in different ways. Since mudrocks are commonly encountered in engineering works including slopes, foundations and earthworks it is imperative to characterise the properties of the rock mass during construction and in the post construction period. Constructional processes and longer-term weathering processes may result in material with significantly changed properties.

Studies have shown the importance of mineralogy, structure and cementation in controlling physical breakdown in response to the removal of overburden and weathering action. Whilst these features can be used along with engineering tests to identify potentially problematic materials, conventional laboratory assessments may prove to be too time consuming and expensive to perform under normal circumstances. These problems have been investigated with respect to the mineralogy, texture and structure of a range of mudrocks of varying durability. Various index and chemical tests have been appraised in terms of their value as predictive tools for identifying mudrocks that are liable to be susceptible to rapid breakdown and these have been investigated in terms of the controlling mineralogical and diagenetic factors responsible for the behaviour.

Résumé: La variabilite des mudrocks a des consequences improtantes sur leur comportement pendant le travail geotechnique. Les processus caracterestiques de composition et de desegregation a que cela a menes a la formation et le depot des grains mineraux constitutifs survis des processus diagnetic suivants, qui influencent la mineralogie et la morphologie des mudrocks resultants ont comme consequence la variabilite considerable en termes de comportement de technologie. Pendant le soulevement et l'exposition, les effets de la détente ed de survivre a des caracteristiques intrinseques d'influence comprenent la mineralogy, la porosite, la cohesion de particules ed degre de rupture. Ainsi les proprietes de masse proches de la surface different condederablement des proprietes intactes du materiel de roche. Les dispositifs structuraux resultant de l'exposition affectent les proprietes des masses de roche et des proprietes du materiel intact de roche dans differentes manieres. Puisque des mudrocks sont generalement produits dans la technologie travaille inluant les pentes, la base et les terrassements qu'il est imperative de caracteriser les proprietes de la masse de roche pendant la construction et dans la periode de construction de Poteau. Les processus de construction et les processus survivants a plus long terme peuvent avoir comme consequence le materiel avac les proprietes sensiblement changees. Les etudes ont montre l'importance de la mineralogy, de structure et de la cementation en commandant la panne physique en reponse au deplacement des terrains de recouvrement et en survivant a l'action de desegregation. Tandis que ces dispositifs peuvent etre emploues avec la technologie examines pour identifier les materiaux potentiellement problematiques, ces evaluation conventionelles de laboratoire peuvent s'averer trop longues et cheres d'executer dans les circonstances normales. Ces problemes ont ete etudies en ce qui concerne la mineralogy, la texture et la structure d'une gamme des mudrock de la longevite variable. Le divers index et les essays chimiques ont ete evalues entermes de leur valeur en tant qu'outils predictifs pour l'identification des mudrocks que sont susceptibles de la panne rapide et ceux – ci ont ete etudies ent termes de controle des facteurs mineralogiques et diagenetic responsables du comportement.

Keywords: Mudstone, weak rock, durability, index tests, properties, weathering.

INTRODUCTION:

Formation and diagenesis of mudrocks

Mudrocks are often considered as challenging in engineering situations and problematic in classification and laboratory testing. They are composed of a wide range of minerals, more so than other sedimentary rock types. The range of minerals is a direct result of detrital input and chemical precipitation at the time of deposition and the intrinsic post-depositional diagenetic changes that may create new mineral assemblages by the formation of new minerals or the alteration of existing ones. Burial processes involve compaction and cementation that result in lithification, which transforms sediment into rock. This is an ongoing process into the early stages of metamorphism involving continual reduction of void space and conversion of the mineral suite by recrystallisation and authigenic mineral growth resulting from the elevated temperature and confining stress conditions. During early diagenesis weak bonds are established between clay minerals and primary cementation occurs between points of contact of the constituent grains as a result of reprecipitation of iron hydroxides and carbonates from solution. These burial induced changes result in reductions in void ratio and the conversion, crystal-growth and recrystallisation of clay minerals also results in secondary cementation. As a result of the physical and chemical processes associated with diagenesis and non-intrinsic external stress processes (Jeans, 1989) mudrocks inherently contain a range of discontinuities at scales ranging upwards from intra-granular, to inter-granular and microfractures to macrofractures (Clayton & Serratrice, 1993), which affect their engineering behaviour. At low stress levels these materials tend to undergo brittle styles of failure, whereas this changes to ductile failure at high stress levels, making the behaviour difficult to classify.

As the changes from sediment to rock are progressive it can be difficult to determine whether to define argillaceous deposits as engineering soils or rocks. Terzaghi and Peck (1967) describe a soil as "natural aggregates of mineral grains that can be separated by such gentle mechanical means as agitation in water" and rocks as "a natural aggregate of minerals connected by strong and permanent cohesive forces". BS5930 (1999) defines hard soil, very weak rock as a uniaxial compressive strength range of 0.6 to 1.25 MPa or an undrained shear strength range of over 300 kPa. Although bonds and structures are created in sediments as soon as deposition takes place, the nature of mudrocks quite often places them on the boundary between hard soils and weak rocks, which makes them difficult to test and classify. Soil classification tests such as particle size analysis and Atterberg limits, which require destructuring of the material do not provide an accurate indication of behaviour of the material even on a small scale, but rock classification based on particle size and mineralogical composition may not be appropriate either given the difficulty of separating the individual grains from each other. Weaver (1989) states that confusion arises by applying unindurated sediment terminology to rocks. For example clay is used to refer to a specific grain size (<2μm) and also clay minerals (which are finely crystalline hydrous aluminium (Mg, Fe) layer silicates or hydrous phyllosilicates), which in unindurated sediments are generally within this size group. In consolidated and indurated sediments, which have been diagenetically altered the clay minerals are more commonly silt grade sized (2-60μm). Therefore to save confusion mudrocks can be defined as consolidated rocks with an appreciable content (<50%) of hydrous phyllosilicates of clay and silt size. In terms of their physical durability, Mead (1936) distinguished between compaction mudrocks and cementation mudrocks, whereby cementation mudrocks tend to be more durable although this changes drastically with removal of cement by dissolution.

As a result of composition, lithification and diagenetic history, mudrocks may vary greatly in their engineering behaviour, which is largely dependant on their degree of compaction and cementation. In addition the porosity and void ratio are controlled by the degree of packing, and density depends on mineralogy, which are affected by burial history and diagenesis. This is particularly exemplified by Coal Measures and other Carboniferous mudrocks of the UK, which shall be discussed in this paper. British Coal Measures mudrocks are dominantly non-marine, mature sediments with a high average clay mineral content of over 75%. They range from durable mudrocks to non-durable and over-consolidated clays.

Breakdown mechanisms

On exposure at the surface, the degradation processes of mudrocks tend to be dominated by slaking, whereas chemical breakdown is liable to be important in some carbonate rich mudrocks or if iron sulfide mineral species are present.

When mudrocks are exposed due to uplift, weathering process or by the actions of man, stress is relieved resulting in the development of discontinuities or fracturing. Low strength contributes to the formation of these structures and results in them being closely spaced through the body of the material. Volume changes resulting from alternating changes in moisture content cause the material to slake by breaking up along the existing discontinuities. Therefore the determination of microfractures is a vital part of assessing the vulnerability of a material to this form of breakdown. Taylor (1988) attributes the process of slaking to the development of high pore air pressures in the material. When samples are being dried air is drawn into discontinuities including outer voids. When the sample is re-saturated this air is pressurised by the water being drawn into narrow pores by surface tension forces or capilliarity. This process stresses the sample and when the stress exceeds the tensile strength of the sample slaking occurs. On a micro-scale, desiccation of the sample during natural exposure creates negative pore water pressures and depending on the strength of weak intercrystalline bonds may produce tensile failure in the sample.

Although air breakage by successive cycles of wetting and drying is considered to be the most important breakdown mechanism in mudrocks, chemical processes may also contribute to the degradation of the material. The presence of diagenetically immature minerals, which result from pre-depositional or contemporaneous weathering, give an enhanced susceptibility to slaking. Clay minerals such as smectite, and mixed layer illite-smectite are subject to high volume change in response to changes in moisture content or changes in pore water chemistry. In addition if pyrite is present, then oxidation may generate acidic solutions and due to reaction with mineral species such as clay minerals and carbonate cements, sulfate mineral species such as gypsum and jarosite may be precipitated, causing expansion. These volume changes generate stresses in the fabric of mudrocks resulting in expansion and slaking.

Slake durability tests measure the resistance to breakdown of a mudrock resulting from exposure to successive cycles of wetting and drying. It is found that compaction mudrocks disintegrate rapidly in these tests whereas cemented mudrocks are more resistant. However if, in the latter case, cements are removed by chemical reactions a point is reached at which the material will slake. Although quartz intercrystalline overgrowths which develop during diagenesis, tend to be more resistant, producing a more durable mudrock, the presence of diagenetic mineral cements such as carbonates and sulfides, which are less resistant to weathering, may permit an apparently durable mudrock to undergo rapid disintegration. Such behaviour would not be predicted by standard slake durability tests.

Mudrock breakdown during normal weathering, results from the combined processes of disintegration and decomposition. The processes are both physical such as stress relief, and chemical such as dissolution or oxidation of mineral components. They result in the disintegration of a formerly indurated rock mass to form an engineering soil together with a series of intermediate materials. Therefore determination of a mudrock's durability should involve evaluation of short term durability determined by physical testing and prediction of the long-term durability. The latter must be based on a detailed understanding of the mineralogy and microstructure of the material.

It is notoriously difficult to obtain good quality undisturbed samples of mudrocks. Inevitably stresses are imposed on the material, which may break weak mineral bonds or permit the opening up of pre-existing discontinuities. The brittle nature of mudrocks and sensitivity to changes in the effective stress conditions of samples and changes in moisture content presents limitations in terms of rock testing protocols, which require a high standard of specimen preparation not achievable with most mudrocks. Therefore only the most resistant and durable sections of sequences in what is a non-homogenous mudrock deposit may be testable. In other cases only the highly weathered residual soil component may be sampled and tested, thus giving a false impression of engineering parameters. Therefore many standard rock tests are unsuitable and soil tests give misleading results for a high proportion of mudrocks. It has been found that index tests and physical determinations of properties such as porosity, degree of saturation and fracture condition provide a more appropriate approach in the successful assessment of intact mudrocks. Anticipation of the effects of weathering and of the new engineering environment, which allows selection of appropriate geotechnical soil design parameters, is vitally important.

COMPOSITION AND LITHOLOGICAL PROPERTIES OF MUDROCKS

Mudrocks are defined by Stow (1981) as comprising >50% siliclastic constituents with >50% being less than 63 μm in grain size and include claystone, mudstone and siltstone which are in turn distinguished by the proportion of clay and silt size constituents. The siliclastic component of mudrocks largely consists of clay minerals with their unique characteristic of plasticity within a certain range of moisture contents and the propensity to shrink and swell. Shaw and Weaver (1965) produced a modal mineral composition of over 400 analysed consolidation and cementation mudrocks which consisted of 60% clay minerals, 30% quartz, 5% feldspar, 4% carbonates, 1% organic material and <1% iron oxides and traces of mineral phases including sulfide and sulfate minerals such as respectively pyrite and gypsum.

The mineralogy of mudrocks is controlled by many factors including the source and type of clastic input, environment of deposition and diagenetic processes involving low temperature alterations. The clastic input consists of minerals such as quartz, feldspars, organic material, carbonate shell fragments together with phyllosilicate minerals including muscovite mica, chlorite and clay minerals such as illite. In addition, dissolved ions and colloidal phases pass into the depositional environment, which include metalloids such as sodium, calcium and magnesium, iron oxides, sequioxides and hydroxides, and dissolved sulfates and carbonates. Based on the depositional redox conditions and chemical composition of the environment, the components may form into various mineral phases that occupy the intergranular pore space. Carbonates including calcite (calcium carbonate) form under marine conditions whereas siderite (iron carbonate) forms under partly reducing and brackish water conditions more typical of a non-marine environment. Under reducing marine and non-marine conditions within the shallow sediment surface or under anoxic bottom water conditions pyrite may form where the input of detrital iron, iron oxide, iron hydroxide and sulfur from dissolved sulfates or organic sources are present in sufficient quantities.

Burial produces diagenetic transformations of certain clay mineral constituents of mudrocks. These occur in response to an increase in the overburden pressure related to the thickness of the overlying sediment and temperature increases. Such diagenetic modifications bring about changes in mineralogy and structure of the sediment. A number of progressive mineralogical changes such as illitization of smectite, and modification of kaolinite with eventual conversion to metakaolinite chlorite or dickite occur. At depths greater than ~500m the removal of expandable layers from clay structures and decomposition of kaolinite to chlorite occurs. Reactions involving the conversion of these less stable minerals into more stable clay minerals are accompanied by the release of Si^{4+} and Ca^{2+}, which results in the precipitation of quartz and carbonate cements. Burial pressures also cause clay minerals to develop strong diagenetic bonds that bind them together into agglomerations referred to as crystallites. This process converts soil like deposits comprising a mass of unbound individual constituents into a rock comprising physically and chemically bonded mineral constituents forming a coherent engineering continuum. The effects of diagenesis on mudrocks mineralogy and physical state are summarised in Figure 1 (Czerewko & Cripps, 2006).

The conversion of minerals is accompanied by growth of the new minerals. This process is commonly referred to as Ostwald ripening (Eberl et al, 1990) and it contributes to the loss of porosity and increase in cementation. It is difficult to follow the extent of conversion of clay mineral suites in mudrocks during deep burial as starting mineralogies are generally not known. Illite 'crystallinity' has been found to be a useful indicator of relative diagenetic rank and therefore the maturity of clay mineral suites, since illite is the most widely occurring clay mineral in mudrocks. In diagenetic studies it is only prograde sequences of events that are considered, whereas in engineering geology, the process of weathering must also be considered to arrive at a complete understanding of rock behaviour. Coulthard and Bell (1993) noted a change in mineralogy within a weathered sequence of Lower Lias Clay, which is accompanied by degradation in engineering properties. Further reference to the illite crystallinity parameter is made in this paper only as a means of defining diagenetic rank of a material. More details are given by Weaver (1989) and Czerewko & Cripps (2006).

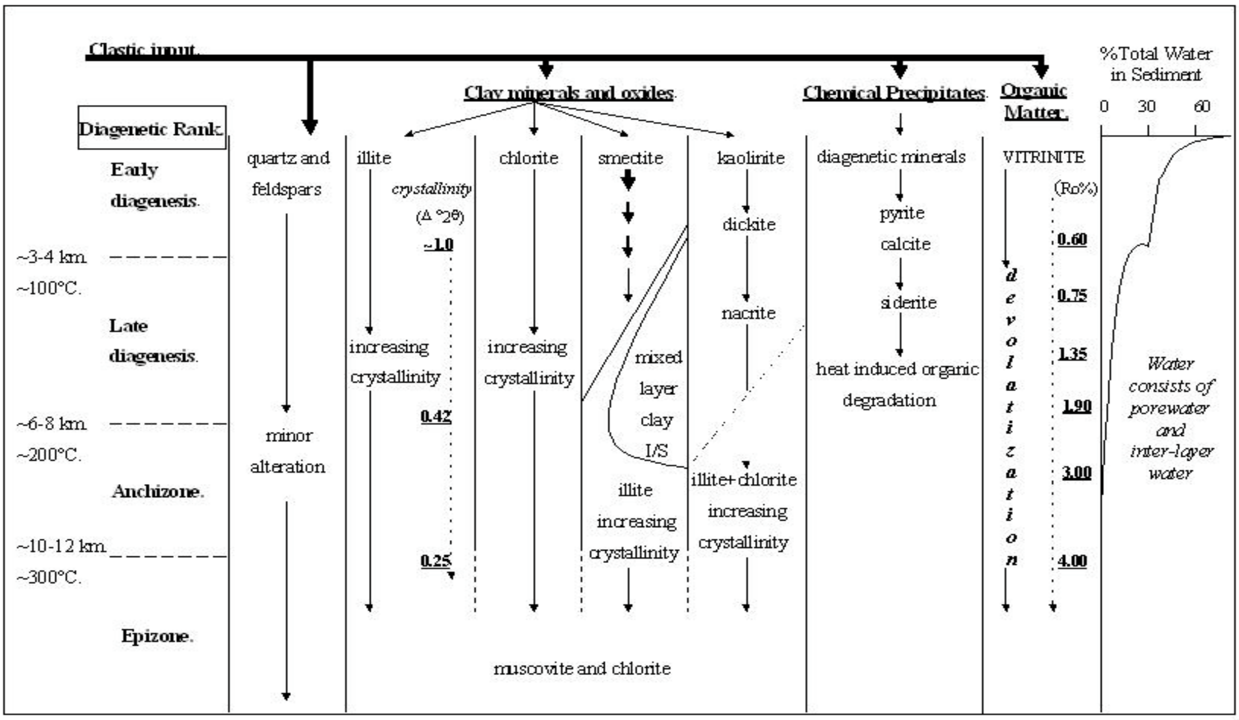


Figure 1. Changes affecting mudrocks as a result of input and burial.

DIAGENETIC INFLUENCE ON THE ENGINEERING AND WEATHERING PROPERTIES OF MUDROCKS

Compaction is the main physical post-depositional process affecting mudrocks, where progressive burial and exhumation generate a state of continual change in the fabric of clays and mudrocks (Rieke and Chilingarian, 1974). Depending upon the electrolytic condition of the depositional environment and cationic valency of the constituents, clays are generally deposited as aggregates or 'flocs' having an open cardhouse or honeycomb type structure or as individual 'dispersed' grains. (Van Olphen, 1963; Moon and Hurst, 1984; Czerewko, 1997)). In the cardhouse or honeycomb forms, the platy clay particles occupy an edge-to-edge or face-to-face arrangement producing a deposit with relatively high porosity, in the region of 70 to 90%, and high water content. Burial compaction eventually destroys such structures producing a tighter packing of the constituent clay and clastic mineral constituents (see Figure 1).

The porosity of a clay deposit decreases rapidly for the first 300-500m of burial (Baldwin, 1971). This change is governed by a number of factors which include composition, rate of deposition, pore structure and permeability, availability of permeable zones to allow the removal of pore water, decomposition of organic matter, chemical diagenetic processes and the state of the interstitial fluids (Chilingarian, 1983). This lithification process changes the physical properties of the material. Constituent grains are brought into closer contact as water is expelled from pore spaces. If the non-clay clastic constituents are brought into contact, a framework of pores is provided and clay minerals tend to be squeezed and re-orientated to fill these voids. Where no clastic framework develops the reduction in porosity is associated with reorientation of clay particles so that the crystallographic Z-axis tends towards a vertical orientation.

During formation and early diagenesis the presence of swelling clay mineral species such as smectite and mixed layer illite-smectite and absence of a network of cemented grains, engender poorly indurated materials that have a high tendency to disaggregate upon immersion in water. Such materials, which show very low resistance to slaking are referred to as compaction mudrocks by Mead (1936). The induration processes, including conversion of less stable reactive clay mineral species to chlorite or illite and precipitation of carbonate and silica cements, are accompanied by physical changes including micro-discontinuity closure, mineral realignment, reduction in void space and porosity and an increase in density. These latter changes, which characterise cementation mudrocks (Mead, 1936), enhance the durability by restricting access of air and water to any remaining reactive phases. They therefore improve the engineering performance of mudrocks by making them stronger, less compressible and less susceptible to the effects of weathering.

The textural changes play an important role in changes to the weathering performance and engineering behaviour of the resulting mudrocks. The strong clay bonds formed during burial have the ability to release strain energy on a time-dependent basis once the rocks undergo retrogressive processes such as uplift and weathering (Taylor, 1988; Dick and Shakoor, 1992; Dick, 1992).

Engineering behaviour

Mudrocks are found in various stages of induration, where the principal variables are consolidation, re-crystallisation and cementation. The latter are a reflection of burial and diagenetic history of the material. They may be characterized in terms of mineralogy, chemistry and physical properties. Although a mineralogical or chemical investigation provides knowledge of the mineral suite present, this cannot be used in itself to predict the engineering behaviour of the rock.

The effects of reduction in void space and increases in dry density that accompany burial compaction are demonstrated in Figure 2 which shows an example of a well consolidated, cemented Coal Measures mudrock. These changes are associated with mineralogical changes producing re-crystallisation and cementation of grains. These textural properties influence the engineering properties of the mudrocks especially strength and durability.

In many engineering applications durability is the most important engineering property of mudrocks. It will be clear from the discussion above that the lithological factors that control the durability of mudrocks include their degree of induration and their mineralogical composition. The two principal controls on mudrock degradation namely physical and physio-chemical, are controlled by the distribution and inter-relationship between voids including pores and micro-fractures (see Figure 3) along with volume changes in mixed-layer clay minerals.

The changes caused by burial that have a direct influence on the physical properties of the resulting material, may be visually indiscernible except on a micro scale. The variable effects of diagenetic changes are demonstrated in Table 1, which presents properties determined by Czerewko (1997) for a range of mudrocks ranging in age from Cambrian to Carboniferous. Mudrocks of one particular diagenetic rank display a wide range of properties, especially durability, as features such as the degradation of non-cementing mineral species such as clays exerts a control in samples.

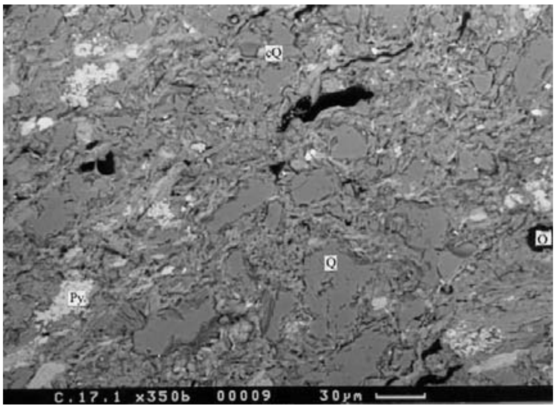


Figure 2. SEM Backscatter image of a dense, well compacted Coal Measures mudrock, (O = organic debris; Q = quartz grain; cQ = contact quartz grains)

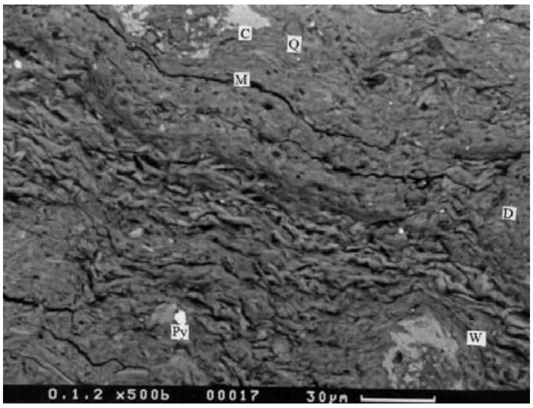


Figure 3. SEM Backscatter image of a partly weathered mudrock showing open distribution of micro-discontinuities and voids (Py = Pyrite;

Table 1. Typical range of properties of mudrocks of different diagenetic maturity (n=41).

Diagenetic Class (Ic)	Textural Rank	MC Abs %	Total Porosity %	Ij'	Id_3 %	Ev %	UCS MPa
Early Diagenetic Ic = >1.0º2θ	6-7.5	2.45-12.31	3.0-10.8	5-7	10-75	0.87-3.12	0.3-5.7
Mid Diagenetic Ic = >1.0º2θ	6-9.5	1.04-5.86	3.2-9.8	4-6	28-86	0.35-6.3	0.6-9.2
Late Diagenetic Ic = >1.0º2θ	8-10	2.32-4.15	3.7-8.4	2-5	81-98	0.02-0.24	4.1-11
Epizone Ic = >1.0º2θ	9.5-12	0.15-1.58	1.7-6.5	1-3	97-100	0.005-0.46	10-16

Ic = Illite crystalinity; MC Abs = Moisture absorption; Ij'= Modified jar slake index (Czerewko & Cripps, 2001); Id_3 = Slake durability test, 3rd cycle classification (Taylor, 1988); Ev = Volumetric swelling; UCS = Unconfined compressive strength.

As the range of mudrock lithotypes is large, so are their physical properties. For example slates and argillites will generally tend to be strong, durable materials, whilst low durability mudrocks may have initial high strength, but tend to deteriorate relatively quickly. Weathering produces materials that, in terms of engineering behaviour, are part way between rock-like continua and fully destructured residual soil comprising discrete mineral constituent grains. A characteristic weathering response of mudrocks is the reversal of lithification to diagenetic grain size artefacts comprising crystallites ranging from gravel to silt size grains. In non-indurated mudrocks weathering returns the material to an assemblage of constituent minerals, whereas in indurated mudrocks the breakdown of silt and gravel sized grain aggregations is required to reach this stage. The removal of induration may involve the intervention of chemical processes such as dissolution and removal of cement phases and effects of electrolytic modifications by leaching and cation exchange, which alters the structural characteristics of individual clay mineral particles. The silt and gravel sized grains may behave in the short-term as coarse-grained (frictional or non-cohesive) soils. Weathering processes will result in the development of a metastable material with crushable particles. Such crushable soils (Nakata et al., 1999) may undergo large volume changes in response to changes in stress conditions. They do not conform to soil mechanics behaviour predicted for soils consisting of non-crushable particles.

Further weathering results in a fine-grained (cohesive) soil material that may contain metastable particles or 'crystallites'. This sensitivity to stress level and weathering effects means that laboratory determined engineering properties may not represent the properties of the material as it occurs in the engineering situation. This is further considered below with examples presented of consistency and shear strength parameters obtained from mudrocks in various states of weathering from Carboniferous Coal Measures sequence. The properties often straddle the weak rock-hard soil boundary and they contain transitional metastable components. These effects of material properties are typically exemplified in the UK by problems in slope stability of Coal Measures strata and are often encountered in natural landforms or engineered slopes affected by weathering.

Durability of mudrocks

The typical troublesome responses exhibited by mudrocks when exhumed during engineering projects are their unique tendencies to swell and slake when unloaded and exposed to water. Slaking, which results from alternation in water content, takes two forms, physical and physiochemical (Taylor, 1988). In less indurated or uncemented mudrocks, it has been found that a few cycles of wetting and drying of unweathered material cause rapid breakdown. This was attributed by Taylor (1988) to air breakage within voids and along discontinuities together with negative pore water pressure formation on drying which leads to tensile failure of weak inter-crystalline bonds (Kennard et al., 1967). Russell (1982) in his study of Ordovician mudrocks, found that the development of micro-fracturing directly affects the rate of breakdown of mudrocks, as during wetting and drying, breakdown is initiated along the fractures by air breakage due to capillary suction of water (Badger et al., 1956). Certain species of clay minerals such as smectites have been implicated as the cause of swelling and slaking tendencies in certain mudrocks, although Taylor & Smith (1986) point out that many British mudrocks of Carboniferous and older age do not contain discrete smectite phases and yet these properties still persist. They attribute the factor controlling expansion to be the cation types present in clay minerals. However, it is clear that voids including pores and micro-fractures also govern swelling, as they provide the access routes for water to gain access to clay minerals (Dick and Shakoor, 1992). Morgenstern & Eigenbrod (1974) found that there is a direct correlation between strength loss during weathering of mudrocks and changes to the initial void ratio, bulk density and initial moisture content. It therefore can be seen that the engineering properties of swelling, slaking and strength in mudrocks are controlled to a large extent by physical factors such as porosity, void ratio, dry density and moisture content as well as the bulk mineralogy.

Previous studies have highlighted the importance of clay mineralogy, structure and cementation in controlling physical breakdown and, while it is possible to use these features to determine the durability and identify potentially unstable materials, conventional laboratory assessment is time consuming and expensive to carry out. Furthermore, the laboratory assessment of the durability of indurated mudrocks by conventional rock testing is commonly hindered due to difficulties with sample preparation and tendency to slake when exposed to water. An alternative approach is to carry out slake durability determinations using the method pioneered by Franklin and Chandra (1972), but experience with this test indicates insensitivity when rating low durability rocks. This problem has been investigated by Czerewko and Cripps (1998) with respect to the evaluation of the mineralogy, texture and structure of a suite of mudrocks of varying durability. Various index tests were appraised in terms of their value for providing predictive tools for identifying mudrocks liable to be susceptible to rapid breakdown due to slaking processes. It was found that a suite of practical and inexpensive index tests consisting of the modified jar slake test which determines structural features; moisture absorption which determines textural features including voids and porosity; and the methylene blue adsorption test which evaluates mineralogy susceptible to swelling derived the same durability classification for mudrocks as more detailed and expensive mineralogical, textural and physical testing. The suite of index tests provides a means of routine testing and characterisation of material for large projects. A detailed presentation of the procedure has been given by Czerewko and Cripps (2002) and is summarised below.

Certain simple index tests were found to correlate strongly with fundamental aspects of mudrock diagenesis, particularly mineralogy and texture, which control their engineering behaviour. Analysis showed that specific textural and mineralogical characteristics were controlling factors in the durability of specific mudrock lithotypes as seen in Table 2 and the index tests were capable of determining these characteristics.

A predictive matrix approach based upon these simple index tests has been successfully applied to the characterisation of mudrocks by means of a ranking system shown in Table 3. The results from each test are weighted according to the categories presented in Table 3. The data from the selected index tests are summed to produce a rank durability value for each sample. This procedure is useful for assessing mudrock samples that due to exhumation and weathering are unsuitable for characterisation using standard rock test procedures, but also do not fall into the category of soils. Where soil tests are adopted for characterisation, the samples typically require preparation by particle size reduction and sample size reduction producing a sample with characteristics not typical of the material under investigation.

Table 2. Control features in mudrock types and relevant index tests.

Mudrock type	Durability controlling features	Index test
Argillite	Strength and durability structurally controlled	**Moisture absorption**, **jar slake index**, **methylene blue index,** microfracture index
Claystone	Mineralogy especially swelling clays and organic carbon and discontinuities	Loss on ignition, moisture adsorption, **moisture absorption**, **methylene blue index**.
Mudstone	Textural features such as micro-fractures	**Jar slake index**, **moisture absorption**.
Mudstone-(Fissile and laminated)	Textural features and mineralogy	**Jar slake index**, **moisture absorption**, moisture adsorption, microfracture index, **methylene blue index**.
Siltstone	Textural features especially porosity and micro-fractures and clay mineralogy	**Jar slake index**, **moisture absorption**, **methylene blue index,** microfracture index.

Table 3. Categories and ranking values for the index characterisation matrix.

Jar slake test

Ij	Classification	Rank [A]
1 - 3	Extremely durable	1
3 - 6	Moderately durable	2
6 - 8	Non durable	3

Moisture absorption determination

Moisture absorption %	Diagenetic rank parameter	Rank [B]
<3	10 - 12	1
3 - 6	7 - 9.5	2
> 6	<6.5	3

Methylene blue adsorption

MBA	%MLC	Rank [C]
<1	0	1
1 - 2.3	0 - 22	2
>2.3	>22	3

Rank Total Value Designation

RTV	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 effect from rock testing procedures
> 7	Non-durable material - prone to rapid swell or slake	Category of rock and soil – requires non routine testing approach

In the paper by Czerewko and Cripps (1998), rank durability values for 41 samples tested were calculated and compared against a durability classification based on values determined by the more sophisticated Slake durability and Volumetric swelling tests, the results showed good agreement between the two procedures in identifying problematic mudrocks. It was found that slight discrepancies occurred in the durability classification between the two procedures particularly in cases where the durability values borderline between classification groups. It was concluded that where the slake durability test classifies samples as durable and the index characterisation matrix procedure classifies them as non durable it is due to the discrepancy inherent due to the drum mesh size in the slake durability test apparatus. In the case of these samples Czerewko & Cripps (2001) show that there has been slaking of the sample in the slake durability test drum but mainly to 2-5mm sized fragments as seen in Figure 4. Therefore using the slake durability test procedure alone would leave the investigator unaware of the potential non-durable behaviour of the sample as determined by using the matrix procedure or the jar slake test alone.

Further practical validation of the durability assessment procedures was undertaken by Czerewko (1997) to evaluate the applicability of the slake durability and jar slake tests in predicting behavioural response of 7 selected Coal measures mudrock samples to natural weathering. The samples were prepared as for the slake durability test procedure and maintained in a purpose built, outdoor test rig in Sheffield for 12 months. On completion of testing, the samples were characterised using the descriptive jar slake procedure and by grading to determine the equivalent slake durability characterisation, based on the percentage of >2mm sample material, the results are presented in Table 4. The results indicate that the static modified jar slake tests characterisation accurately predicted the response to natural weathering of all samples to natural weathering, whereas the dynamic slake durability test overestimated the durability of sample C141, and underestimated the durability of samples C21, C83 and C133. This highlights the need to evaluate mudrocks by the appropriate means to the engineering application envisaged, for example, the slake durability test is appropriate for dynamic exposure such as in highways and tunnelling, whereas the modified jar slake test is more appropriate in static environments such as foundations and natural or engineered slopes.

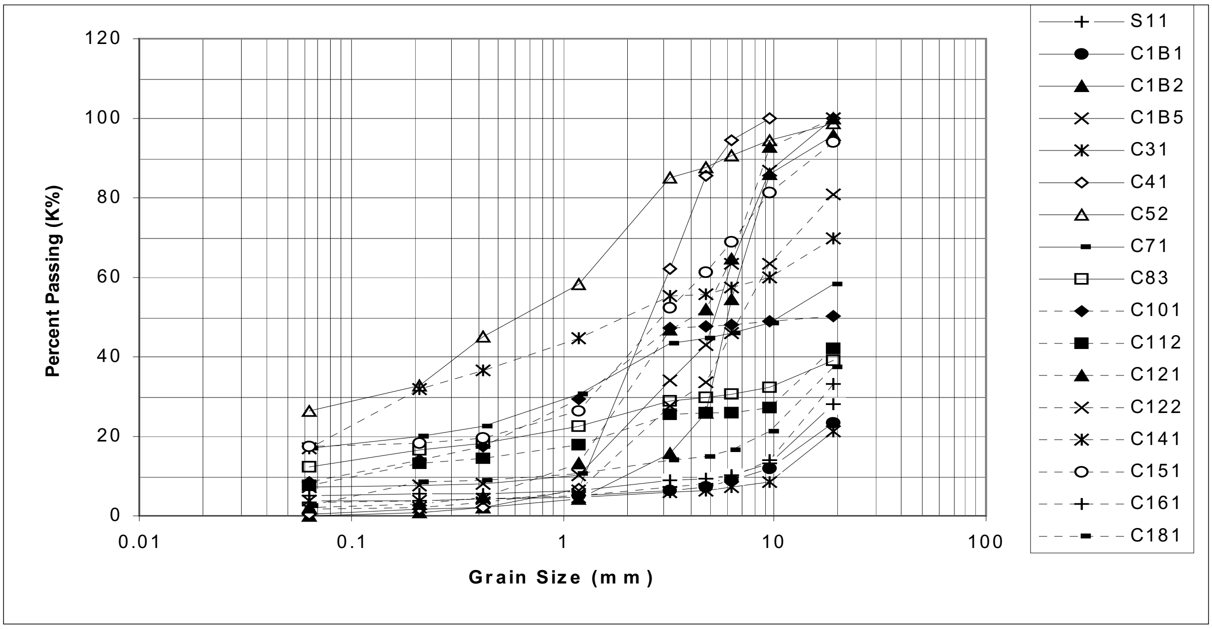


Figure 4. Particle size reduction of material in the Slake Durability Test.

Table 4. Comparative durability characterisation of naturally weathered mudrocks.

		Initial characterisation		**After 12 month weathering**	
Sample	**Description**	**ID_3**	**Ij'**	**ID_3**	**Ij'**
C1B1	Carb Claystone	97.5	6	99	5
C21	Mudstone	46.8	7	95	7
C31	Mudrock	97.5	3-4	97	3-4
C83	Mudstone	81.7	2	98	2
C92	Carb Claystone	98	2	98	2
C133	Mudstone	10.4	5-6	66	6
C141	Mudstone	63.3	7	31	7

Carb = carbonaceous.

Weathering and shear strength reduction.

There are few published results, which indicate the effects of physical and chemical weathering on the shear strength of in situ rock-like mudrocks. Investigation by Spears and Taylor (1972) of a large quantity of Middle Coal Measures mudrocks specimens from a site near the village of Wales [SK 476821], south-west of Sheffield in the East Pennine coalfield, produced the following observations. For intact material ranging from claystone, mudstone and siltstone, shear strength results varied depending on the nature of the material, but for fully weathered material, shear strength parameters dropped to c' = 0.6 kPa, ϕ' = 26° and residual parameters of c' = 3.7 kPa, ϕ' = 14.5° were measured. Cripps and Taylor (1981) undertook a review of mudrocks properties from extensive literature search, a summary of shear strength parameters for UK Coal measures material are presented in Table 5.

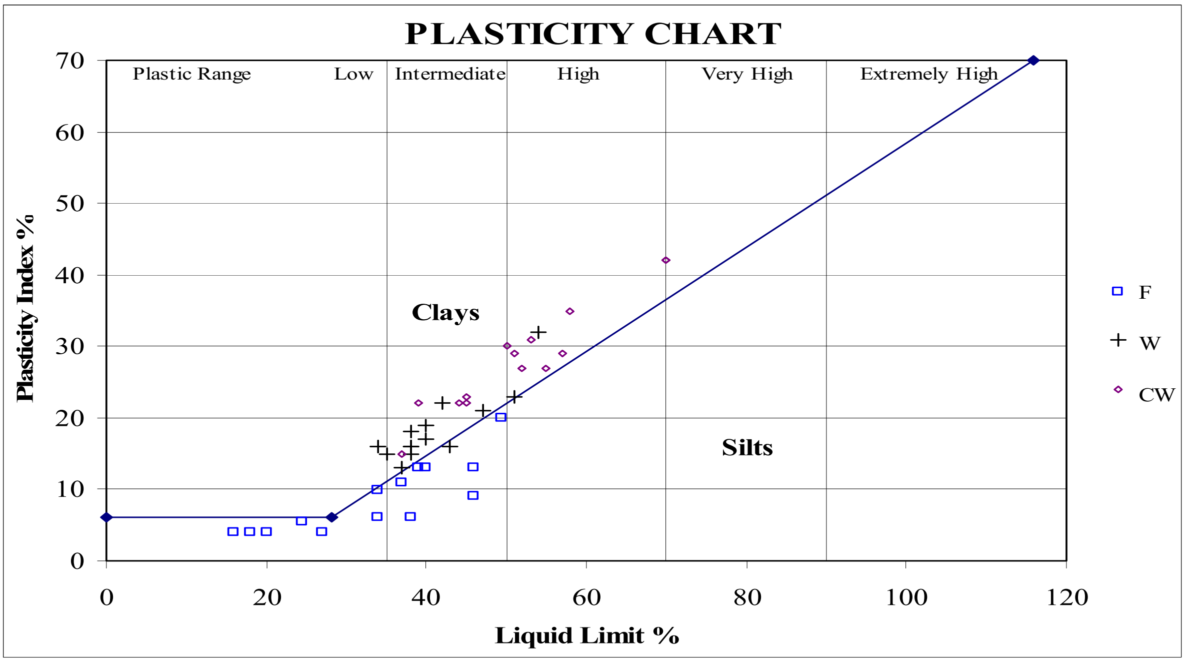
The results show an evident reduction in shear strength from fresh to weathered material for the mudstone and carbonaceous mudstone, whereas there is little difference for the seatearth, which often comprise a leached deposit containing relatively inactive clay mineralogy. Otherwise for mudstone it appears that materials have passed through a degradation and softening process caused by natural weathering reducing the crystallite constituent to discrete particles. The consistency results presented in Table 5 show no apparent trend.

Table 5. Classification and shear strength parameters for UK mudrocks from Cripps & Taylor, 1981.

Material	**W_L%**	**W_P%**	**I_P%**	**Class**	**c' kPa**	**ϕ' °**	**ϕ'_r °**	**c_a MPa**	**ϕ_a °**
Mudstone									
F–S weathered	42	29	13	MI	20-131	30-45.5	-	2-13i	28-39
M-H weathered	39-49	30	9-19	MI	15-30	21-30	12-14	-	-
Carbonaceous Mudstone									
F–S weathered	44-51	26	15-23	MI	-	30-45.5	-	32i	12i
M-H weathered	42-45	27-32	16	MI/CL	15	29-39	16	-	-
Seatearth									
F–S weathered	34	18-21	16	CL	20-131	32-37	-	2-32i	12-39i
M-H weathered	30-34	20-23	12-15	CL	16-38	31-39	13-26	-	-

F = fresh; S = slightly; M = moderately; H = highly; W_L% = liquid limit; W_P% = plastic limit; I_P% = plastic index; MI = silt of intermediate plasticity; CL = clay of low plasticity; c'/ϕ' = effective cohesion/effective friction angle; ϕ_r' = residual friction angle; c_a/ϕ_a = apparent cohesion/angle of friction; i = intact sample.

Recent data for investigative and commercial work undertaken by the authors (Czerewko, 1997) involving Coal Measures material from within the Pennine basin for a number of sites have been reviewed and apparent trends resulting from weathering are apparent from soil consistency data and shear strength data. Consistency data for a number of fresh unweathered mudrock, weathered mudrock and material comprising completely weathered mudrock as residual soil are presented in Figure 5. The data shows an apparent trend for fresh material classified as silt of low to intermediate plasticity; weathered material classified as clay of low to intermediate plasticity; and completely weathered material classified as clay of intermediate to high plasticity. It is not unreasonable to conclude from these data that these materials have again passed through a degradation and softening process as a result of natural weathering in the last circa 10,000 years of post glacial weathering. The transformation of annealed mineral crystallites that are ionically unreactive with respect to clay exchange sites and therefore exhibit silt like behaviour as comprising indurated mudrocks to individual and accessible exchangeable clay sites is believed to have occurred.



F = fresh; W = weathered; CW = completely weathered.

Figure 5. Comparison of classification data for various mudrock weathering states. The plastic index given is determined as per the Building Research Establishment, 1993 modified procedure.

Although Spears & Taylor (1972) found little correlation in consistency limits from their study, the data presented in Figure 5 indicates that the data for mudrock and carbonaceous mudstone material collected from various sites within the Sheffield area of South Yorkshire shows a trend in consistency limits for fresh, weathered and completely weathered mudrock classes. Fresh material that is typically disaggregated to provide material appropriate for testing typically returns values characteristic of low to intermediate plasticity silt class, weathered material from the same site profiles shows intermediate to high plasticity and clay characteristics and completely weathered residual soil material behaves as intermediate to very high plasticity clay. This would suggest that the fresh material comprising annealed mineral crystallites with little exchange characteristics resulting from diagenetic processes behave as unreactive silt material. With effects of stress relief and progressive weathering, removal of cement and disordering of clay minerals shows degenerative capabilities with respect to engineering behaviour which progressively worsens with prolonged weathering resulting in a completely weathered residual soil counterpart.

This progressive material modification as a result of weathering would also affect the engineering properties, particularly shear strength, which would alter as material behaviour changes from that of an intact rock through gravel to a clay-silt material on weathering, this is demonstrated by test results obtained by drained shear box tests presented in Table 6. The data presented is for a selected range of samples classed as carbonaceous mudstone and mudrock. The data trend shows high shear strength parameters for intact material as seen from sample 1a, but the results for residual shear strength are much reduced. Values for weathered and completely weathered material show a drop in shear strength parameters as would be expected based on the material breakdown during weathering with results controlled by interaction of the individual mineral grains rather than the cemented crystallite controlled rock mass. The data show a narrower range for residual values, which vary from ϕ_r' ° = 24.5 for intact Carbonaceous mudrock (sample 1a) to ϕ_r' ° values of 26 to 10.2 for completely weathered material. The results are dependent on the constituent mineralogy and resultant grain size distribution of material being tested, this is reflected in the consistency data presented in Table 6, which shows the same trend as seen in Figure 5 with change in material behaviour from silt like to clay like tendencies upon weathering. It can be seen that based on these limited data, a more pragmatic approach is required for the selection of shear strength parameters for design purposes as peak values will often not reflect the long-term properties of exposed mudrock due to weathering alteration.

Table 6. Mudrock shear strength parameters from samples from the Pennine basin ranging from fresh to completely weathered material.

Sample	State	Location	Age	Classification				Shear strength			
				W_L%	W_P%	I_P%	Class	c_p' kPa	ϕ_p' °	c_r' kPa	ϕ_r' °
1a	I-F	SD963173	Carboniferous LCM	20	16	4	ML	260	40	0	24.5
1b	R-F	SD963173	Carboniferous LCM	27	23	4	ML	2	16	0	9.5
1c	R-W	SD963173	Carboniferous LCM	24	18	6	ML	25	22.5	20	20
2a	I-CW	SE063268	Carboniferous UMG	51	29	22	MH/CL	48	18	0	10.9
2b	I-CW	SE063268	Carboniferous UMG	50	34	16	MI	70	18.5	0	10.2
2c	R-CW	SE063268	Carboniferous UMG	52	31	21	MH	-	-	0	10.9
3a	R-CW	SK351828	Carboniferous LCM	47	25	22	CI	25	22.5	0	16
3b	R-CW	SK351828	Carboniferous LCM	51	24	27	CH	0	49	0	26
3c	I-CW	SK351828	Carboniferous LCM	50	29	21	MH	30.5	29	0	26
4a	R-W	SK172822	Carboniferous N	32	19	13	CL	-	-	8.2	11.5
4b	R	SK172822	Carboniferous N	19	28	9	CL	-	-	21.3	12
4c	R	SK172822	Carboniferous N	25	19	6	ML	-	-	14.5	19
5a	R-W	SK399857	Carboniferous MCM	40	27	13	MI/CI	26	23.5	20	16
5b	R-CW	SK399857	Carboniferous MCM	42	20	22	CI	21	19.5	17	11
5c	R-CW	SK399857	Carboniferous MCM	45	22	23	CI	24	21	0	14

I = intact specimen; R = remoulded specimen; F = fresh; W = weathered mudrock; CW = completely weathered.

CONCLUSIONS

The term 'mudrock' encompasses a broad spectrum of materials that display properties ranging from soils to strong rocks. These properties arise from a combination of compositional and structural features, including the presence of discontinuities and cracks. In turn the characteristics of mudrocks are a function of a series of changes that occur during deposition, burial, exhumation and weathering. Factors of importance include the amount of clay and non-clay minerals, the mixed layer clay components, carbonate and other cements, and minerals such as pyrite. Burial tends to reduce the mixed layer clay content, increase the amount of pore filling cementing minerals and a framework of cemented grains may also be produced. These changes are accompanied by destruction of flocs, particle realignments and reductions in moisture content and porosity. Stress relief and changes in moisture content result in the opening of discontinuities and development of new ones, which give rise to a discontinuous system. The rate at which degradation occurs depends on the state of induration of the mudrock, but in most cases significant changes occur in engineering properties in constructional or engineering design time-scales, of hours to tens of years. Due to the interaction between controls on the geotechnical properties no single compositional factor or structural factor can be used to predict their engineering performance.

It has been shown that degradation of shear strength parameters resulting from weathering is reflected by consistency values. Variation from silt to clay of low to high swell occurs, indicating breakdown of crystallites formed during prograde diagenesis and retrogressively broken down due to exhumation stress relief and exposure to weathering.

Coal Measures mudrocks range from material of high strength and durability with high resistance towards weathering induced breakdown to material of variable strength and moderate to poor durability. In the former, rock-like characteristics are displayed on exposure with high strength and moderate durability in the medium term. The weaker material has variable strength with a propensity for shrink-swell behaviour and the formation of crushable soils in which the strengths are highly dependant on small increases in weathering grade of cemented particles.

Procedures are available to determine the long-term durability of materials from which the selection of appropriate engineering parameters may be made such as peak or residual shear strength parameters for the design of foundations and slopes or other structures. Caution is required with this prediction of the response of the material to weathering processes or to environmental changes brought about by the particular engineering works, as the properties depend on the present weathering state and rate at which the properties change in response to changes within the environment. Selection of appropriate slaking test procedures will assist the assessments. Where a mudrock is to be exposed to a dynamic environment such as tunnelling, the dynamic slake durability test is an appropriate means of evaluation, whereas if a mudrock is to be exposed to a static environment such as an engineered slope, then the static modified jar slake test forms a more appropriate means of assessment. It should be remembered that a high slake durability index value may arise because, although material has broken down during the test, it is not recorded as having done so if it does not pass through the 2mm mesh test drum.

Assessment of durability is greatly assisted by carrying out a series of index tests aimed at evaluating porosity, breakdown in water and the presence of swelling clay minerals. The use of appropriate index tests procedures such as the Rank Total Value procedure allow the nature of the material to be appropriately elucidated. The procedure allows further decision to be made on the material behaviour and therefore what type of testing is most appropriate for characterisation including non-standard approaches comprising mineralogical and geochemical characterisation. Recovery of in situ competent material for testing may either bias the results towards the more competent members of the formation or else the rapid deterioration of material experienced during sampling and preparation for testing results in data that are misleading in terms of the behaviour of the in situ material. However, an appraisal that includes consideration of the likely changes in behaviour using the procedures based on simple yet pertinent index test procedures, as described in this paper, will be very valuable.

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REFERENCES

BADGER, C.W., CUMMINGS, A.D. & WHITMORE P.L. 1956. The Dissintegration of Shales in Water. *Journal of the Institute of Fuel*. **29**, 417-423.

BALDWIN, B. 1971.Ways of deciphering compacted sediments. *Journal of Sedimentary Petrology*, **41**, 293-301.

BRITISH RESEARCH ESTABLISHMENT. 1993. Low-rise buildings on shrinkable clay soils. Part 1. BRE Digest 240.

CHILINGARIAN, G.V. 1983. Compactional diagenesis. *In: Sediment Diagenesis* (Eds. A. Parker and B.W. Sellwood). Reidel Pub. Co., Dordrecht, 57-168.

CLAYTON, C.R.I. & SERRATRICE, J.F. 1993. The mechanical properties and behaviour of hard soils and soft rocks. *General Report on Session 2 of the International Symposium on Hard Soils-Soft Rocks*, Athens, 1993.

COULTHARD, J.M. & BELL, F.G. 1993. The influence of weathering on the engineering behaviour of Lower Lias Clay. *The Engineering Geology of Weak Rocks*, Cripps et al. (eds.) Balkema, Rotterdam. 183-192.

CRIPPS, J.C. & TAYLOR, R.K. 1981. The engineering properties of mudrocks. *Quarterly Journal of Engineering Geology,* London, **14**, 325-346.

CZEREWKO, M.A. 1997. Diagenesis of mudrocks, illite crystallinity and the effects on engineering properties. Unpublished PhD Thesis, University of Sheffield, UK.

CZEREWKO, M.A. & CRIPPS, J.C. 1998. Simple index tests for assessing the durability properties of mudrocks. *The Geotechnics of Hard Soils-Soft Rocks*. (Ed. A. Evangelista & L. Picarelli). A.A. Balkema, Rotterdam, 127-135.

CZEREWKO, M.A. & CRIPPS, J.C. 2001. Assessing the durability of mudrocks using the modified jar slake index test. *Quarterly Journal of Engineering Geology and Hydrogeology*. **34**, 153-163.

CZEREWKO, M.A. & CRIPPS, J.C. 2002. The classification of mudrock durability based on index properties. *Engineering Geology for Developing Countries*. (Ed. J.L. van Rooy & C.A. Jermy). A.A. Balkema, Rotterdam, 182-189.

CZEREWKO, M.A. & CRIPPS, J.C. 2006. (in preparation). The influence of diagenesis on the engineering properties of mudrocks*. Quarterly Journal of Engineering Geology and Hydrogeology*.

DICK, J.C. 1992. Relationships between durability and lithological characteristics of mudrocks. Unpublished PhD thesis, Kent State University.

DICK, J.C. & SHAKOOR, A. 1992. Lithological controls of mudrock durability. *Quarterly Journal of Engineering Geology,* London, **25**, 31-46.

EBERL, D.D., SRODON, J., LEE, M., NADEAU, P. H. & NORTHROP, H. R. 1990. Sericite from the Silverton Caldera, Colorado: correlation among structure, composition, origin and particle thickness. *American Mineralogy*, **72**, 914 - 934.

FRANKLIN, J.A. & CHANDRA, A. 1972. The slake durability test. *International Journal of Rock Mechanics and Mineral Science*, **9**, 325-341.

JEANS C.V. 1989. Clay diagenesis in sandstones and shales: an introduction. *Clay Minerals*, **24**, 127-136.

KENNARD, M.F., KNILL J.L. & VAUGHAN P.R. 1967. The geotechnical properties and behaviour of Carboniferous shale at the Balderhead Dam. *Quarterly Journal of Engineering Geology*. London, **1**,3-24.

MEAD, W.J. 1936. Engineering geology of dam sites. *Transactions of the 2nd International Congress on Large Dams*, Washington, DC, **4**, 183-198.

MOON, C.F & HURST, C.W. 1984. Fabric of muds and shales: an overview. *In: Fine-grained sediments: deep-water processes and facies.* (Eds. D.A.V. Stow and D.J.W. Piper). Blackwell Scientific Publications, Oxford, 579-593.

MORGENSTERN, N.R. & EIGENBROD, K.D. 1974. Classification of argillaceous Soils and Rocks. *Proceedings of the American Society of Civil Engineers Journal of the Geotechnical Division*, **100**, 1137-1156.

NAKATA, Y., HYDE, A.F.L., HYODO, M. AND MURATA, H. 1999 A probabilistic approach to sand crushing in the triaxial test, *Geotechnique* **49**, No. 5, 567 - 583

RIEKE, H.H. & CHILINGARIAN, G.V. 1974. Compaction of Argillaceous Sediments. *Developments in Sedimentology*, **16**, Elsevier.

RUSSELL, D.J. 1982. Controls on shale durability: the response of two Ordovician shales in the slake durability test. *Canadian Geotechnical Journal*, **19**, 1-13.

SHAW, D.B. & WEAVER, C.E. 1965. The mineralogical composition of shales. *Journal of Sedimentary Petrology*, **35**, 213-222.

SPEARS, D.A. & TAYLOR, R.K. 1972. Influence of weathering on the composition and engineering properties of in situ Coal Measures rocks. International Journal of Rock Mechanics and Mining Science, **9**, 729 - 756.

STOW, D.A.V. 1981. Fine-grained sediments:Terminology. *Quarterly Journal of Engineering Geology*. London, **14**, 243-244.

TAYLOR, R.K. 1988. Coal Measures mudrocks: composition, classification and weathering processes. *Quarterly Journal of Engineering Geology*, London, **21**, 85-99.

TAYLOR, R.K, & SMITH. T.J. 1986. The Engineering Geology of Clay Minerals: Swelling, Shrinking and Mudrock Breakdown. Clay Minerals, **21,** 235-260.

TERZAGHI, K., & PECK R.B. 1967. *Soil mechanics in engineering practice*. 2nd edition, John Wiley and Sons, New York.

VAN OLPHEN, H. 1963. *An Introduction to Clay Colloid Chemistry*. Interscience, New York, N.Y.

WEAVER, C.E. 1989. Clays, Muds, and Shales. *Developments in Sedimentology*, **44**, Elsevier.