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The 23rd Glossop Lecture: Mud to rock and back

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Abstract: As mudrocks underlie large areas of the UK, including major urban areas and infrastructure routes, they frequently form the bedrock at construction sites and slope and tunnel engineering works. They may also be used as fills or construction materials. They range widely in terms of strength and compressibility, depending on composition, degree of compaction and induration, weathering grade, fabric and structure. A review of the performance of mudrocks in engineering situations including slopes, tunnels and in embankment and foundation construction highlights the importance of durability and the role of chemical weathering processes, especially the oxidation of pyrite, in the engineering performance of these materials. It is necessary for the effects of changes in the environment of mudrocks, brought about both during and after completion of engineering works, to be anticipated early in projects so that design and construction measures that circumvent or avoid problems can be adopted. Advances in the understanding of factors controlling mudrock durability that can facilitate improved prediction of changes in properties are described.

It is argued that understanding controls on the properties of mudrocks underlies ways of avoiding the problems that can arise in civil engineering works involving these materials. It is apparent that there is much to be gained from the publication of case histories of past engineering projects, particularly those in which problems stemming from unexpected changes in the properties of mudrocks have occurred.

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This paper is based on the Glossop Lecture I was invited by the Engineering Group of the Geological Society to present on 23 November 2023. The topic I chose was ‘Mud to rock and back’. In this paper I review research that provides a basis for understanding the variation in the durability found in mudrocks of the UK and provides a means of assessing durability using index tests. The paper also includes the collation of the geotechnical properties of UK mudrocks from published and other sources, outlines research into the negative impacts of pyrite in mudrocks and outlines the chemical methods used to characterize the sulfur minerals many mudrocks contain.

David Shilston pointed out in his Glossop Lecture (Shilston 2022) that it has become a tradition that Glossop lecturers begin with a reference to the writings of Rudolph Glossop, in whose honour the Engineering Group of the Geological Society established the Glossop Medal. In the foreword for the 25th anniversary edition of the *Quarterly Journal of Engineering Geology*, Glossop (1992) explained that he had actively supported the formation of the Engineering Group in 1964, and the inauguration of QJEG in 1967. He was the first Chair of the journal’s editorial committee, having had an important role in establishing *Geotechnique*, the first issue of which was published in 1948. In the lecture Glossop (1969) gave on his retirement from chair of the Engineering Group of the Geological Society, he noted that at that time most engineering consultancies and contractors engaged on projects involving geological conditions employed geologists who ‘by working constantly with engineers had acquired a thorough understanding of the sort of problems that arise, and of the ways in which they could be overcome, and so they could truly describe themselves as “Engineering Geologists”’. The latter therefore would be capable of applying their knowledge of geological materials and processes to avoid engineering problems.

It is of note that besides the foreword by Glossop, the 25th anniversary volume also contained two important papers on

mudrocks: by Hawkins and Pinches (1992) on the engineering description of mudrocks and by Dick and Shakoor (1992) on lithological controls on mudrock durability. Of particular interest is that the first paper of the new *Quarterly Journal of Engineering Geology* was an assessment by Kennard *et al.* (1967) of the degradation properties of Carboniferous mudstones used for the construction of Balderhead Dam in northern England.

Williams and Norbury (2008) point out that Glossop recognized that the lack of application of geotechnics in the UK during the 1930s compared unfavourably with the situation in the rest of Europe and the USA where the application of scientific methods of soil mechanics in earth construction was more developed. Apparently, Glossop admired the emphasis that Terzaghi placed on geological conditions. It is likely that Glossop’s academic background and early career experiences in mining provided background and appreciation of the importance of geological materials and structures in civil engineering applications and in 1945 he observed that ‘a new and broad subject [was] emerging that included soil mechanics and other sciences which deal with geological materials and processes in relation to civil engineering’ (Glossop 1946). Williams and Norbury (2008) conclude their account Glossop’s role in the rise and development of geotechnology by quoting Skempton’s obituary following Glossop’s death in 1993 (Skempton 1993). He remarked that Glossop believed that soil mechanics applied without an understanding of geology could become seriously divorced from the realities of an engineering project. It is thus clear that Glossop believed that both geological conditions and geological processes need to be taken into account at all stages of civil engineering work. Although Glossop was most concerned with the behaviour and performance of engineering soils, it is clear that he combined knowledge of the composition and genesis of materials with laboratory and *in situ* test results to form an overall assessment of their properties in relation to engineering works.

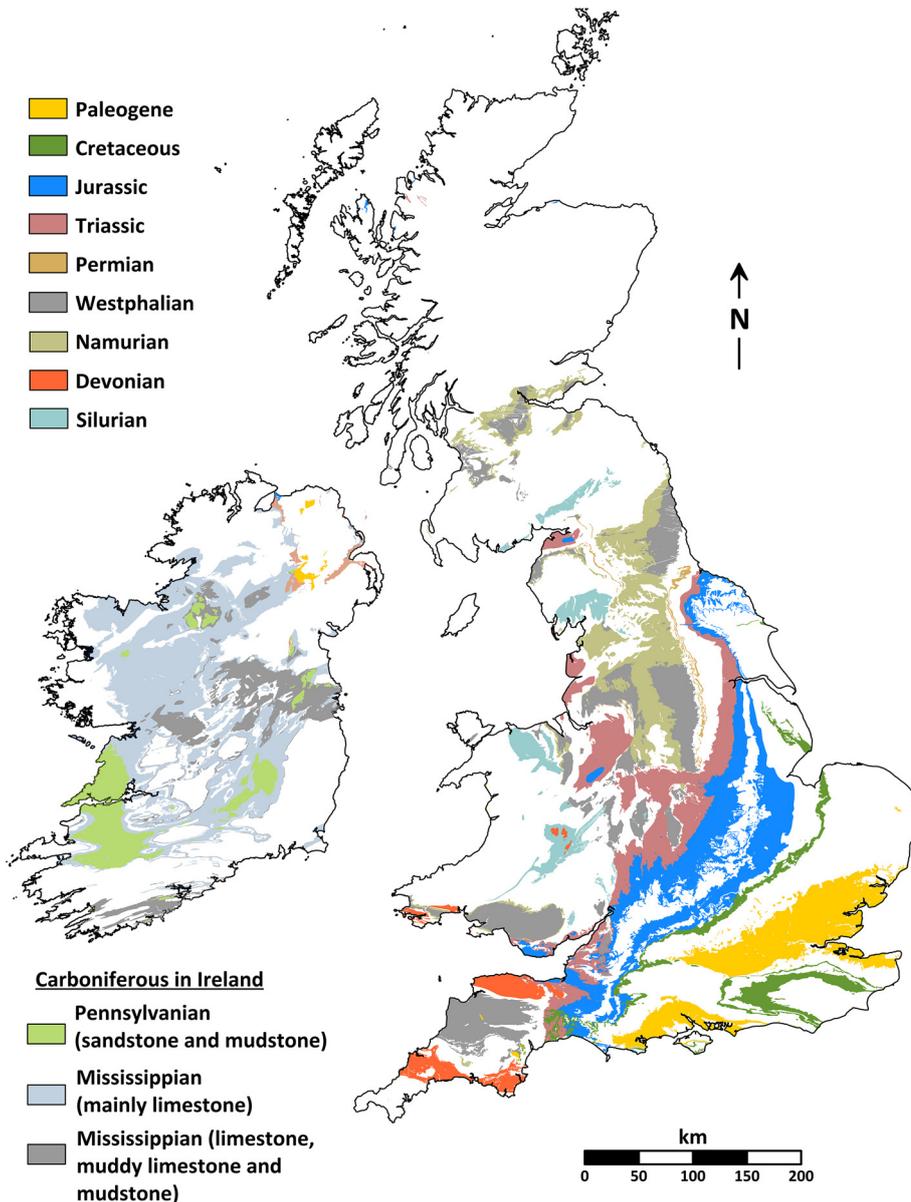


Fig. 1. Bedrock formations containing mudrocks in the UK and Ireland. It should be noted that Mississippian, Pennsylvanian, Namurian and Westphalian are divisions of the Carboniferous system. From BGS 2008 1:625 000 geology map of the UK: north and south, reproduced with the permission of the British Geological Survey ©NERC. All rights reserved. Also contains Irish Public Sector Data (Geological Survey Ireland) licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.

In this paper I review some of the problems that mudrocks can pose in engineering and explain how with information about their formation, composition and structure potentially problematic behaviour can be anticipated and avoided. Engineering works can bring about changes in the *in situ* stresses, water conditions and access to air that may affect mudrock properties. Owing to their composition and structure many mudrocks are sensitive to these changes that occur in the course, and after completion, of engineering projects. As Figure 1 shows there are several major mudrock formations of Paleogene, Cretaceous and Jurassic age in southern England, where many urban areas are situated, whereas older mudrock formations of Triassic and Carboniferous age underlie major urban areas of the midlands and north of England, south Wales and central Scotland. Infrastructure routes cross all these formations. Although these formations are predominantly mudrocks, in some locations they also contain other rock types, such as sandstones and limestones. Summary geological sequences quoted by Duff and Smith (1992) indicate that in England and Wales formations in Figure 1 between Namurian (Carboniferous) and Cretaceous ages contain between 30 and 100% mudrock, with about half of the sequences quoted having more than 50% mudrock. On the other hand, non-mudrock formations contain interbedded mudrocks that may have a significant impact on the behaviour of the

rock mass or the performance of the material. In Ireland, mudrocks occur in Triassic and Carboniferous sequences interbedded with limestones, sandstones and other rocks. There is a small area of mudrock of Jurassic age in the north, but Cretaceous and Paleogene mudrocks are absent.

Besides areas of surface outcrops shown in Figure 1, some mudrock formations lie buried beneath younger strata and may become involved in underground construction for tunnels, including those required for the safe deep burial of nuclear waste. As a consequence of the large amount of mudrock in UK geology, mudrocks are frequently encountered in engineering projects where they are present as the foundation materials, an excavation medium or as construction fills. Reviews of world and European clay deposits given in *Clay Materials in Construction* (Reeves *et al.* 2006) demonstrate that the UK is not unique in this regard. In spite of being widely distributed, mudrocks tend to generate little enthusiasm for investigation by either geologists or engineers. The fact that the materials rapidly degrade owing to weathering processes to form soils that become vegetated means that only in places of active erosion, such as river banks and coasts, or quarries and clay pits are mudrocks liable to occur in outcrops suitable for *in situ* studies. In addition, the thick sequences of mudrocks in which there is little apparent lithological change are not viewed with

excitement. On the other hand, mudrocks can be challenging materials in engineering applications, mainly owing to their relatively low strength and high compressibility, low resistance to weathering action and sensitivity to changes in water content and shrink–swell behaviour.

This paper begins by outlining the formation of mudrocks, and how mud becomes converted to rock. This provides background information on the ways in which the rock degrades to mud, and the controls on this process. Because rapid degradation and the presence of pyrite underlie many engineering problems involving mudrocks, most of the rest of this paper is devoted to rock to mud. Selected case histories in which the behaviour and performance of mudrocks had a significant impact in engineering projects of different types illustrate approaches to avoiding problems. Attention is given to the difficulties of determining the amount of pyrite and other sulfur minerals in rocks and soils, including the need for care with specifying the analysis methods used. Finally, the conclusions provide a commentary on the main points presented in the paper.

Mudrocks: definition and recognition

Although there may be agreement that mudrocks are fine-grained sedimentary rocks composed of quartz, clay and other minerals with an average grain size of less than 63 μm , current guidance on classification offered by British and European standards is divergent and vague. Figure 2 shows part of the rock classification schemes provided respectively by Eurocode 7 document BS EN ISO 14689:2018 and BS 5930:2015+A1:2020. Although, as pointed out by Norbury (2010), the logical name for rocks consisting of particles less than 2 μm in size is claystone, in the UK this term has been widely used to describe cemented nodules in clay deposits and the preferred term for materials of this category is mudstone. Norbury (2010) also notes that grouping claystones and siltstones into mudstone and shale, as in the Eurocode standard BS EN ISO 14689:2018, shown here in Figure 2a, fails to recognize the different behavioural characteristics of siltstones compared with mudstones or

claystones in which clay-sized material is in the majority. BS 5930:2015+A1:2020 specifies that all siliceous sedimentary rocks that contain less than 50% carbonate and with an average grain size of less than 63 μm are siltstones or mudstones, where siltstones are composed mainly of silt-sized material, but it is not then stated whether mudstones consist mainly of clay-sized material. Mention is made in BS 5930:2015+A1:2020 that combinations of rock names are possible including carbonaceous mudstone, which occurs widely in the UK, but no further definition is offered. It should be understood that the word clay has three different meanings: clay minerals, clay size and clay lithology. Clay minerals are a variety of crystalline solid with a defined atomic structure, clay size defines particles less than 2 μm in size and the clay lithology refers to a rock or soil formation that consists of clay minerals or clay-sized material.

In practice, it can be difficult to determine the precise average grain size of fine-grained rocks such as mudstone. Some soils and rocks contain particles that consist of aggregations of cemented grains (see Davis 1967) such that separation of the material into individual grains may not provide an accurate indication of how the material will behave in the engineering situation. Although clay particles tend to be smaller than 2 μm in size some may be larger than this and clay particles may be attracted to others to form aggregations or flocs in excess of 10–20 μm in size. On the other hand, quartz and other detrital mineral fragments may be of clay size so not all <2 μm material will always be clay minerals. Two commonly used methods for the determination of the amount of clay-sized material in a sample, sedimentation and laser light scattering, give different values. This is because in the sedimentation test, the size is determined from the settling velocity of an idealized sphere in distilled water, whereas clay minerals have a flat platy shape. On the other hand, in the laser particle size analyser, what is measured is the average size presented in a 2D view as laser light passes through a suspension of the sample. BS 5930:2015+A1:2020 explains that fine-grained soils should be distinguished on the basis of the plasticity they display and Norbury (2010) provides further advice on simple site or field-based methods for doing this, but for rocks in which disaggregation may result in breakage of grains, it may not be possible to obtain an exact determination. This issue is discussed by Czerewko and Cripps (2023), who point out that without recourse to complex and expensive analytical procedures such as electron microscopy or X-ray diffraction analysis, which would not usually be an option in routine ground investigations, it might be necessary to rely on visual identification, where silt particles are discernible by naked eye or low-power ($\times 10$) examination. Another source of possible confusion arises from different definitions of what constitutes clay size as, although 2 μm is used in British, European and US standards, in the old US Standard ASTM D422:2007, which has now been withdrawn, the limiting size was 5 μm .

Mudstones and siltstones are indurated, rock-like materials with a uniaxial compressive strength of over 600 kPa, or an undrained shear strength of 300 kPa or more, which is the division between very stiff soils and extremely weak rocks in European standards (BS EN ISO 14688-1:2018 and BS EN ISO 14688-2:2018 (for soils), BS EN ISO 14689:2018 (for rocks)), and British Standards (BS 5930:2015+A1:2020 (for soils and rocks)). Very stiff soils can be indented by thumbnail, but not by thumb pressure, whereas extremely weak rock can be scratched by thumbnail and a gravel-sized fragment can be crushed between the finger and thumb. In the UK this includes several Jurassic, Cretaceous and Paleogene mudrock formations (see Fig. 1) that have been compressed beneath the weight of overlying deposits that have been removed by erosion. Because of this process, the deposits are in an over-consolidated condition and they possess higher strength and stiffness than normally consolidated deposits in which the present overburden is the greatest amount imposed on the formation. Spink

(a) Extract from Table A.1 – Guide to naming rocks

Sedimentary rock types			
Grain size	Siliceous	Biogenic	
		Low porosity	Porous
2 μm to 63 μm	Siltstone	Limestone or dolomite	Calcsiltite Chalk
<2 μm	Claystone Mudstone		Calcilucite

(b)

Extract from Table 27 – Aid to identification of rocks for engineering purposes						
Grain size		Grain rocks (mostly sedimentary)				
mm	Grain size description	At least 50% of grains are of carbonate				
Grain size boundaries approximate	0.063-0.002	Argillaceous	SILTSTONE Mostly silt MUDSTONE	LIMESTONE AND DOLOMITE (Undifferentiated)	Calcsiltite	CHALK
	<0.002				Calcilucite	

SEDIMENTARY ROCKS

Calcareous rocks contain calcite (calcium carbonate) which effervesces with dilute hydrochloric acid

Fig. 2. Classification of mudrocks according to (a) BS EN ISO 14689:2018 and (b) BS 5930:2015+A1:2020. Source: diagram from Czerewko and Cripps (2023) courtesy of Emerald Publishing Ltd (2023).

and Norbury (1993) provide guidance on the identification and engineering geological description of weak rocks and over-consolidated clays, including weathered mudrocks. For the purposes of this paper mudrocks also include materials that are weaker than rocks, especially if they are in a weathered condition. BS 5930:2015+A1:2020 indicates that clay soils should be distinguished from coarse-grained soils on the basis of the plasticity displayed by the remoulded lump of the material. Thus, mudrocks may span the range of soil to rock strengths and forms of behaviour, including brittle or plastic styles of deformation. As noted above, the division between a soil and a rock is defined in terms of unconfined shear strength, but if subjected to high confining pressure or slowly applied stress, rock-like mudrocks may display plastic behaviour.

The word shale can lead to confusion because the characteristic fissility displayed by some clay-rich mudrocks develops as a result of weathering processes. Some inter-laminated mudstone–siltstones may also display such fissility, especially if organic matter or mica crystals are present on bedding surfaces. It means that a fresh mudrock may become a shale as a result of weathering action, so it is more logical to call mudrocks that split into thin (<6 mm thick) layers fissile mudrocks rather than shale.

Many mudrocks contain constituents other than quartz and clay minerals, including calcite, siderite, pyrite, feldspars and organic matter, either as detrital grains or intergranular cements. The variety of clay minerals in the material influences many aspects of the behaviour of mudrocks, although this may not be reflected in the classification, which is based on grain size.

Engineering problems involving mudrocks

Mudrocks occur in engineering because they are the *in situ* material in natural and cut slopes, foundations and tunnels. They may also be used as construction materials in embankments, fills and stabilized soils. They can be responsible for various forms of instability in slopes, ranging from flows to mass deep-seated failures such as rotational and translational slides and falls. Where interbedded with sandstones or limestones, mudrocks tend to undergo more rapid degradation owing to weathering processes, which in rock slopes can result in the more durable layers becoming unsupported, leading, as seen in Figure 3, to rock falls. Where strata are dipping towards a free face, instability in which the rock mass above the mudrock slides into the void may occur. In the case shown in Figure 3c the mudrock occurs in thin seams and instability may occur some years after the creation of the slope. Such layers can be difficult to detect in a sequence of stronger rock strata, especially in borehole cores. Large-scale rotational failures are likely to occur

where a slope is formed solely in a thick mudrock layer, as shown in Figure 4a, or where a thick mudrock layer is overlain by a stronger formation. Mudrocks may also be involved in flows, either of jointed gravel- or cobble-sized fragments of rock or, as Figure 4b shows, where the mudrock degrades and with high water content forms a slurry.

Rapid loss of strength and expansion are well-known forms of mudrock behaviour that can cause problems with the construction of foundations. Removal of overburden or lateral restraint for the installation of foundations may result in expansion of the mudrock and the opening of joints or fissures with the material. The material may also become degraded owing to exposure to weathering processes such that the material has reduced strength and greater compressibility than before construction began. In some cases an ill-timed rain shower can be responsible for such an effect. Sometimes problems occur in underground construction where the excavatability of the ground and the support of the excavation are important. Figure 4c shows a cutting in Ampt Hill Clay about 3 months after it was excavated, which was sufficient time for the surface to degrade to easily eroded mud, and because the clay also contains pyrite, calcium sulfate crystals known as selenite have also formed. This weakening of the clay and resulting high sulfate conditions are expected to have adverse impacts in the later stages of the project.

Some mudrocks contain layers of stronger materials that if not recognized can be difficult to excavate, so an unsuitable method of excavation is used, or owing to low strength the support for the ground is inadequate, leading to collapse of excavations. In other cases the excavated material can rapidly degrade during excavation and form a slurry such as that in Figure 5a, which was difficult to remove from the excavation, thus seriously impeding tunnelling operations. Besides being the *in situ* bedrock materials for many types of engineering structure, mudrocks are extensively used as a bulk fill materials for the construction of embankments, dams, landfill cells and infrastructure projects, and they serve as the *in situ* material for shallow and deep foundations and slopes.

Some types of mudrocks are prone to shrink–swell behaviour, such that they undergo large changes in volume with changes in moisture content, leading to cracking such as that in Figure 5b and disturbance to structures, as shown by the distortion of the road in Figure 5c.

As already mentioned, thin seams of mudstone can be challenging to detect in borehole cores, but other difficulties include a lack of recovery of core where nodules of ironstone or limestone in the rock cause the mudrock to become eroded and carried away in the flush fluid, or stress relief and changes in moisture content result in the fragmentation of the core, as shown

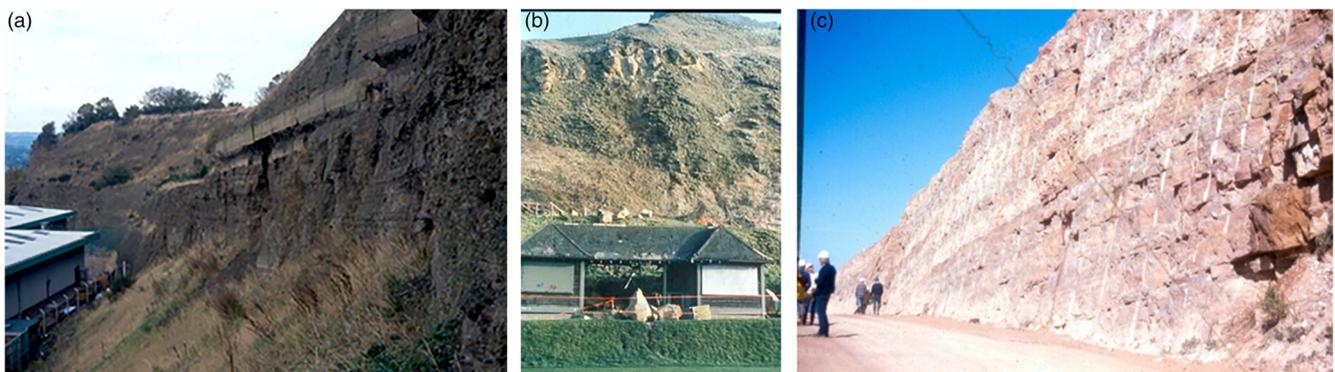


Fig. 3. Potential rockfall instability in interbedded sequences of mudstone with sandstone or limestone. (a) Rock face in former quarry in Carboniferous mudstone and sandstone in Sheffield, UK. (b) Damaged shelter owing to fall of limestone boulders in mixed Jurassic sediments in Scarborough, UK. (c) Rock slope in Llandulas, UK formed in Carboniferous Limestone in which degradation of thin interbedded mudstone seams may result in instability of the slope. The near vertical features in the rock face are drill holes.



Fig. 4. (a) Large-scale rotational failures in coastal cliffs in Cretaceous Speeton Clay, Speeton, UK. (b) Mudflow at the toe of the slopes in (a). (c) Surface degradation seen approximately 6 months after excavation of slope in Jurassic Amphill Clay in Buckinghamshire, UK.



Fig. 5. (a) Slurry formed in course of tunnelling excavation for Don Valley Intercepting Sewer, Sheffield, UK. (b) Shrink-swell action in Oxford Clay in Buckinghamshire, UK causing (b) surface cracking and (c) distortion to minor road.

respectively in Figure 6a and b. In the latter case not only is the intactness of the rock mass underestimated, but also the core is not suitable for strength and other tests.

The engineering problems caused by some mudrocks include rapid loss of strength and integrity when they are excavated and/or exposed to weathering action. Although the total extent of such changes might be determined by carrying out strength and compressibility determinations on samples of the original rock and material that has been subjected to artificial breakdown to its constituent particles, such an approach will not provide information

about the rate at which the changes are liable to occur in an engineering situation. Furthermore, the artificial breakdown process may not correctly simulate the natural weathering processes. Instead, the approach taken here is to explore the factors that influence the engineering problems created by mudrocks, including their composition and structural make-up. The changes in engineering properties, particularly the rapid loss of strength and softening of the material, that occur in response to changes in environmental and stress conditions brought about by engineering works are especially important. The approach taken in the research described below was to study the geological processes that change mud to rock, to facilitate an understanding of the material and from this derive information relevant to the degradation processes caused by environmental and stress changes that result from engineering works and operations.

Mud to rock

Formation of mud

The raw material out of which mudrocks are formed is derived by weathering processes on land that lead to the production of mud. The nature of these processes depends on climatic conditions: there are physical processes that result in the fragmentation of the rocks and soils exposed to weathering action, and chemical processes that change the mineral constituents through interactions with atmospheric gases and water. These chemical changes may result in the dissolution of minerals, which might then be carried away in solution, or minerals such as feldspar, augite, olivine that make up rocks becoming altered by weathering processes into clay minerals of different types, depending on the climatic conditions. Mud, therefore, consists of fragments of quartz, feldspar and other mineral grains that are usually accompanied by clay minerals, in which the overall average grain size is less than 60 μm .



Fig. 6. (a) Example of very poor core recovery of Carboniferous age Pennine Lower Coal Measures mudrock owing to erosive effect of ironstone nodules. (b) Fragmentation of Devonian age Mylar Slate Formation core owing to removal of overburden and changes in moisture content.

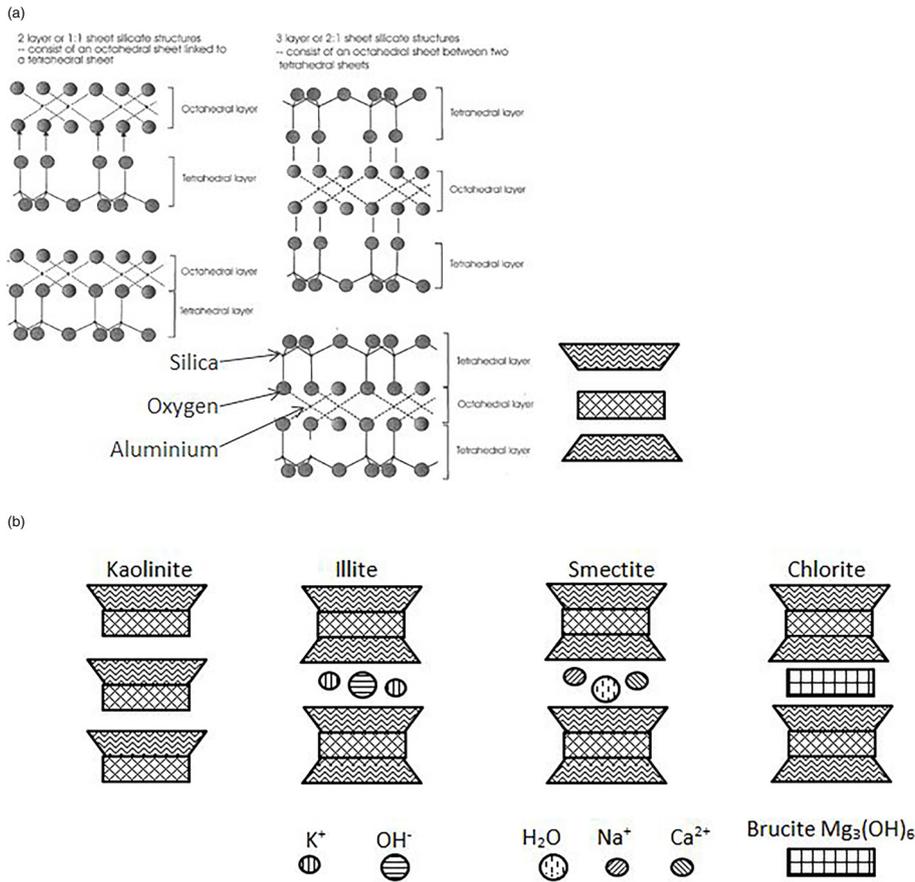


Fig. 7. Structure of clay minerals. (a) Two- and three-layer sheet silicate structures. (b) Arrangement of layers in different clay minerals. Source: after Reeves *et al.* (2006).

The four most important types of clay minerals are chlorite, kaolinite, illite and smectite. These all have a sheet-like micro-structure that imparts a flat, platy shape to clay mineral particles. The particles themselves are very small, usually less than 2 μm in size, although they may occur in aggregations of attached particles up to about 10 μm in size. The differences in behaviour of clay minerals and the mineralogical changes that occur to them owing to burial depend on their atomic structure. Clay minerals consist of silica layers in which one silicon atom is surrounded by four oxygen atoms in a tetrahedral arrangement (Reeves *et al.* 2006, chapter 2). The oxygen atoms are shared with adjacent tetrahedra such that a continuous sheet one tetrahedron thick is formed, as shown in Figure 7a. There are also octahedral layers in which aluminium and oxygen atoms form a sheet. Figure 7b illustrates how these tetrahedral and octahedral sheets are arranged in different configurations in the different clay minerals. In the case of illite two tetrahedral layers and one octahedral layer form a sheet that is bonded to the next similar sheet by potassium atoms and hydroxyl ions. In chlorite the sheets are linked together by an octahedral magnesium hydroxide (brucite) layer. Smectite is also formed of sheets of two tetrahedral layers and one octahedral layer but the sheets are bound to other sheets by various cations and water molecules, where the amount of water depends on the valence and concentration of the cations in solution. This is why in clays such as smectite, the clay particle itself shrinks and swells in response to changes of water content and water chemistry. In kaolinite the sheets are formed out of one tetrahedral layer and one octahedral layer and these units are bonded directly to identical units above and below. Some clay minerals have combinations of structures (e.g. mixed layer illite–smectite).

As a result of substitution of atoms in the atomic structure clay minerals exist in a hydrated state in which negatively charged surfaces attract water molecules and cations in solution to their surfaces. This sharing of water molecules between adjacent clay

particles imparts plasticity to clays. The amount of plasticity increases with thickness of the layer of water and cations between the particles and this depends on the chemistry of the water. As a polar liquid, water molecules adjacent to the clay particle orient themselves with their hydrogen atoms towards the clay particle and oxygen atoms further from the particle. Water molecules further from the clay particle also become oriented with the hydrogen atoms towards the particle, thus forming a double diffuse layer of water molecules. Thus, water between particles becomes polarized and attracted to the surfaces of adjacent clay particles. To balance the surface charges on clay particles, this diffuse double layer of water and cations will be of greater thickness if the solution is of low ionic strength and/or cations in solution have low valence, which will increase the volume and plasticity of the clay. In the case of smectite and other swelling clay minerals, the water within the crystal and between crystals depends on the cations in solution, where a low-valence cation such as sodium results in a larger amount of intra-layer water and high plasticity, whereas a higher valence cation, such as calcium, reduces the amount of intra-layer water necessary for electrostatic charge balance, giving lower plasticity.

The formation of clay minerals and other constituents of mud, together with the transportation and deposition of these materials, is described by Reeves *et al.* (2006). Clay minerals are mostly formed by chemical weathering of silicate minerals in rocks, whereas clastic constituents, which include quartz and feldspar, are derived by physical weathering processes. Smectite is usually formed under tropical and subtropical weathering conditions in which the rock mass is subjected to repeated wetting and drying episodes, but it may also be derived from volcanic ash-fall. Most illite is formed by weathering of micaceous rocks, and kaolinite may be formed by the hydrothermal alteration of feldspar or in weathered rock profiles in tropical regions. Once formed, the different constituents of mudrocks may then be transported by gravity, water or wind to places of deposition, such as lakes, flood plains, estuaries and the

sea, along with organic matter and ions in solution. The manner of deposition, the composition of the water and the activities of bacteria and other biological processes may modify the composition and influence the structure of the sediment. Calcium carbonate derived from algae or the shells and bones of organisms may also be deposited. This sediment may be buried beneath later deposits, which increases the pressure and temperature conditions, and results in conversion of mud to rock. Partly the changes are physical in that porosity is reduced as grains are forced into denser arrangements but, in addition, grains undergo mineralogical changes and cements are precipitated in inter-granular pores. These diagenetic changes occur at lower temperatures and pressures than occur when rocks are metamorphosed.

Tectonic forces within the Earth's crust may result in the formation of folds, faults and joints in the sediment, and with deeper burial of 5–10 km conversion into metamorphic rocks or melting to form igneous rock may occur. But in the case of the sedimentary rocks, such as mudrocks at or near the ground surface, tectonic processes have caused uplift to form land and any overlying sediments have been eroded away. The rocks that form the present land surface will be subject to weathering action and removed by gravity, water and wind action, or in some situations they form a residual layer of weathered material on the bedrock.

Burial and exhumation may be over very long periods of time of hundreds or thousands of million years, or over a shorter time, and may occur in repeated phases of burial and exhumation. The loading and unloading of ice sheets during past relatively recent glacial episodes of the Quaternary period and the effects of freeze–thaw action during periods of periglacial conditions also affect the properties of rocks and the structures they contain.

The original rock, the weathering environment and the depositional conditions are among a large number of factors that affect the composition and structure of mud, and there are also processes that cause changes to the structure and composition of the newly deposited sediment. For example, in anaerobic conditions, bacteria that metabolize sulfate from the connate (marine) porewater within the sediment proliferate, which leads to the formation of pyrite (iron sulfide) in the sediment, whereas a lack of oxygen, which occurs if the rate of deposition is rapid or water circulation is slow, results in the formation of calcium carbonate and in the preservation of organic matter. Hence, marine, organic-rich mudrocks usually contain pyrite, whereas in aerobic marine conditions the iron carbonate mineral siderite, together with calcite, will be formed. The activities of burrowing animals may also affect the sediment by physical mixing, changing the permeability and introducing organic matter.

As Reeves *et al.* (2006) explain, the environment of deposition significantly influences the nature of the sediment. In the presence of high concentrations of soluble ions such as in marine conditions, electrostatic charges on the surfaces of clay particles, which are platy in shape, cause them to congregate into flocs of various configurations. Flocculated clays in which the edges of clay particles are attracted to the surfaces of adjacent particles have high water content and form a low-density sediment with randomly arranged clay particles. Water depth and degree of agitation and oxidation are also important because if the water or upper layers of sediment become anaerobic, burrowing organisms, which would disrupt any sedimentary layering or particle alignment, will be absent. In silty clays the compression of clay particles into the voids between the larger silt particles will tend to randomize any orientation of clay particles in these deposits.

In conditions of low ionic strength waters, the surface charges on clay particles are not neutralized such that the particles will experience mutual repulsion and so do not form flocs. Instead, they tend to be deposited in flat-lying sub-horizontal arrangements that produce a lower water content, higher density and anisotropic

sediment than that of a flocculated clay. If bottom waters or the upper layers of sediment are anaerobic, then in the absence of bottom living or burrowing organisms this structure will be preserved, and as the clay is compressed it will result in a horizontal alignment of clay particles, typical of a fissile mudstone. If conditions change or the deposit contains silt-sized quartz or feldspar particles, this alignment can be weakened. Anaerobic conditions also favour the formation of pyrite and the preservation of organic matter in the deposit where the latter has the effect of forming sub-horizontal weak surfaces within the sediment.

In silty clay deposits the compression of the clays between the larger quartz and feldspar grains makes it likely that any clay particle preferred orientation will be destroyed, thus forming an isotropic sediment, whereas in clay-rich deposits, it is likely that it will be preserved or even enhanced, which, after induration, would produce a fissile mudstone.

As mentioned above, the newly deposited sediment may be preserved and converted to rock if it is buried beneath subsequent sediments. This depends on a geological situation in which a basin of deposition continues to subside and it receives a sustained supply of sediment. Studies conducted by Czerewko (1997) and others provide a framework to understand the mud to rock process. Czerewko's (1997) research was based on detailed studies of 49 UK mudrocks ranging from Cambrian to Carboniferous in age, in different states of induration, in which the composition, diagenetic rank, texture, geotechnical properties and slaking behaviour were investigated. Increases in temperature and pressure resulting from burial beneath later deposits cause structural and mineralogical changes to sediments. These diagenetic changes, which are less severe than those of metamorphism, increase the diagenetic rank of the sediment. One of the objectives of Czerewko's (1997) study was to determine whether the diagenetic rank and durability of mudrocks could be predicted using simple index tests, without recourse to the sophisticated and technically demanding mineralogical, chemical and textural studies and geotechnical testing performed in the research.

Diagenetic rank

An important aspect of Czerewko's (1997) research was the measurement of the diagenetic rank of the samples, which varies with the depth of burial and temperature attained during geological burial. There are four main ways of doing this:

- (1) Vitrinite reflectance, which is the reflectance of light from particles of organic matter in the sediment. Increasing temperature and pressure cause organic matter to release volatiles and in so doing it reflects more light.
- (2) Changes in the shape of the illite peak on the X-ray diffraction (XRD) trace occur with increasing diagenetic rank of a muddy sediment. A mixed illite–smectite clay mineral (mixed-layer clay or MLC) will produce a very broad 10 Å peak on the XRD trace (this is the distance between the layers in the atomic structure and is a diagnostic feature of the clay mineral) but as burial diagenesis progresses smectite becomes converted to illite, which results in a better ordered, larger crystal. Figure 8 shows a series of XRD scans in which the progressive conversion of smectite to well-ordered illite crystals increases the height-to-width ratio of the peak on the XRD trace. The extent of change is expressed by the width of the peak (2θ degrees) at half the height, defined as the Kubler Index (I_c).
- (3) Methylene blue value (Taylor 1985), which indicates the cation exchange capacity of the clay and implies its ability to swell. Thus, it identifies the presence of swelling clay minerals in the sample.

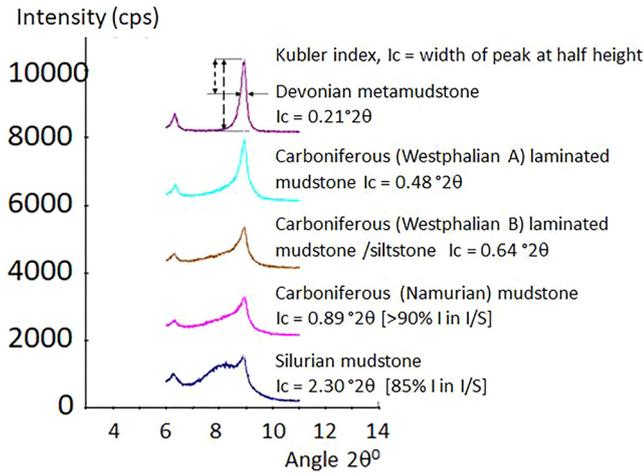


Fig. 8. Progressive change in illite crystallinity with diagenetic rank showing changes to shape of 10 Å peak on XRD trace (X-ray intensity, counts per second v. 2θ angle, where θ is the angle of incidence of the X-ray beam on the crystal surface). Source: after Czerewko (1997).

- (4) Spore colour (Marshall 1991) is also an indicator of the degree of maturation of sediments as spores become a darker shade with increased diagenetic rank

Changes to mud that occur as a result of burial beneath subsequent deposits to a depth of about 10–12 km, which been deduced from studies of clay sediments in basins of deposition, are illustrated in Figure 9.

Physical changes to the sediment, including increased density and reduction in water content, occur in parallel with mineralogical changes. Whereas quartz and feldspar are little affected by the temperature and pressure increases, clay minerals undergo successive diagenetic alteration. The complete conversion of smectite and mixed layer clay to illite is accomplished at a depth of burial of about 6 km, provided potassium is available in the system. Continued burial to a depth of about 10 km results in recrystallization of the rock to form a metamorphic slate or argillite depending on the stress conditions. Kaolinite also becomes unstable, forming dickite at intermediate depths and illite–chlorite at burial depths of 10–12 km.

Textural studies; diagenetic rank

The mineralogical and textural changes owing to burial diagenesis are illustrated in Figure 10, which shows SEM images of an Eocene

age mudrock and a Carboniferous age mudrock in which inter-particle mineral cement is present.

Czerewko (1997) demonstrated that the extent of these changes, and therefore the diagenetic rank of the rock, can be deduced by observing the density, degree of alignment of clay particles, extent of inter-particle contacts and presence of inter-granular cement in SEM images. In his study of a suite of 49 UK mudrocks of varying rank, each of these parameters was scored, as shown in Figure 11, and the sum of these scores proved to be a reliable prediction of diagenetic rank. Telmo Jeremias (2000) used the scheme shown in Figure 12 to assess the textural features and extent of diagenetic changes in a suite of Portuguese mudrocks he studied (see Cripps et al. 2023). These studies went on to evaluate the control exerted by diagenetic rank on the susceptibility of the mudrock to degradation owing to weathering processes, in other words the manner by which mudrock becomes converted to mud.

Compaction and cemented mudrocks

Compression of the sediment causes a reduction in water content from values as great as 70% when deposited to less than 5% in an indurated mudrock as the porosity is decreased and clay mineral inter-crystalline layer water is removed. In silty clay deposits any detrital calcite, quartz and feldspar grains will be forced into closer contact with each other such that pressure point solution results in the removal of ions at the points of contact and the neoformation of mineral phases in the pore space. This process has the effect of reducing pore space and increasing the size of grains and the grains become bonded at their points of contact. The vertical compression of the sediment will tend to rotate platy clay minerals into a sub-horizontal alignment and the size increase of grains will tend to occur horizontally, which enhances this horizontal particle alignment in the sediment, especially if it is clay rich. Pyrite and other diagenetic minerals will also increase in grain size and calcite and other cements will fill pore spaces. The conversion of clay minerals results in the release of ions into solution, which then augments the size of existing grains and results in the precipitation of minerals that then fill pore space and cement grains to their neighbours. Any organic matter in the sediment will lose volatiles, which makes it less susceptible to degradation in the presence of water. These changes occur progressively, so whereas they initially result in isolated groups of cemented and bonded grains, with continued diagenetic changes the size of these groups increases such that they coalesce and create networks of bonded and cemented grains. Ultimately, all the pore space will be filled so grains become pervasively cemented.

In a silty mudrock the greater amount of inter-particle contacts of clastic quartz grains will produce a stronger and less compressible

MUD	Qtz & f'spar	Illite & chl	Kaol	Smect & MLC	Diagen mins, Cement	Organics Vitrinite reflectnce	Water Porosity wc%	Material
Early diagenesis 3-4km 100C		Ic 1.0	Dickite	Smectite	Pyrite	Ro% 0.7	70	Stiff (over-consol) clays, Compaction clays
Late diagenesis 6-8 km 200C	Physical & minor alteration	Increasing crystallinity 0.42	Nacrite	Smectite -illite	Calcite	Decreasing volatiles & water	20 30	Very weak rock
Anchizone 10-12km 300C		Increasing crystallinity 0.25	Illite & chlorite	Increasing crystallinity Illite	Siderite		5	Weak rock
Epizone					Silica			Cemented mudrocks
ROCK						4.0	<1	Medium strong
								Strong meta-mudrock, slate

Fig. 9. Progressive diagenetic changes from top to bottom in mineralogy of mud in conversion to mudrock. Qtz, quartz; f'spar, feldspar; chl, chlorite; kaol, kaolinite; smect, smectite; MLC, mixed layer smectite–illite clay. Source: after Czerewko (1997); Merriman and Fray (1999); Merriman (2006); modified from Czerewko and Cripps (2009).

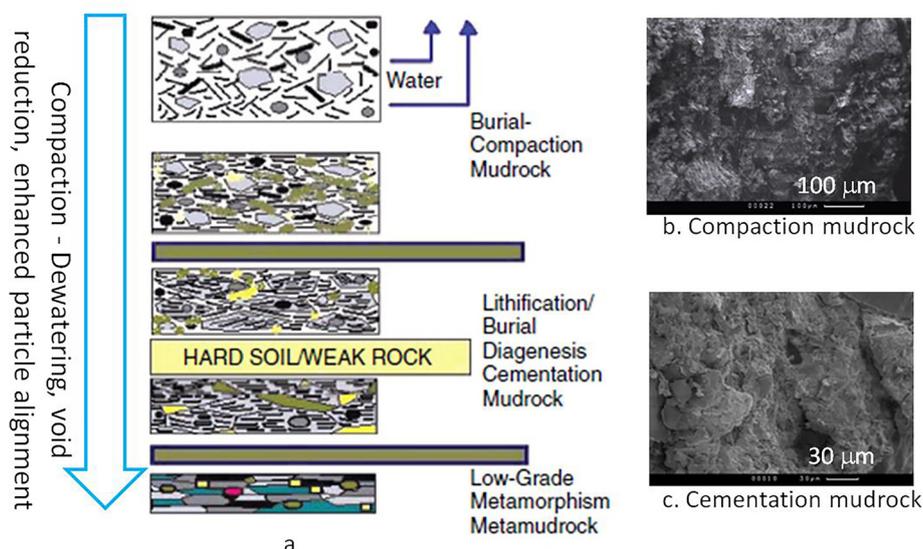


Fig. 10. Changes in texture caused by burial diagenesis of mudrock. Source: after Czerewko and Cripps (2023); courtesy of Emerald Publishing Ltd 2023.

mudrock than a clay-rich one. A quartz- or calcite-rich mudrock will result in a strong, low-compressibility and durable mudrock, whereas in clay-rich mudrocks clay prevents silt particles from coming into direct contact with each other, so the bonding will then be weaker and the clay particles are likely to become oriented perpendicularly to the major stress (vertical). Thus, the resulting mudrock is liable to be weaker, retain high compressibility and low durability, and also possess anisotropy.

The presence of inter-particle bonds and cemented groups of grains means that attempts to disaggregate an indurated mudrock to provide an original grading are liable to be unsuccessful. For example, physical crushing is liable to break aggregations of grains rather than separate the grains from each other and it may also result in breakage of grains themselves. The grading of the processed material will depend on the vigour of the crushing process rather than the original grading of the material.

Early in the scientific understanding of mudrock performance, Mead (1936) drew attention to the differences between what he called compaction and cementation shales. Figure 10 represents the distinctive differences between these types of mudrocks: the former owe their coherence purely to the reduction in porosity and development of frictional interlock between grains without significant inter-particle cementation whereas the latter are indurated owing to the additional presence of intergranular cements. This is an important distinction in terms of the performance of mudrocks in engineering situations, and one of the objectives of the research

described below was to investigate the effects of changes in diagenetic rank on the durability of mudrocks, as well as to devise practical methods for distinguishing between compaction and cementation mudrocks. Physical and mineralogical changes illustrated in Figure 8 that occur as a result of burial also result in the progressive loss from the sediment of depositional features such as bedding, changes in lithology and compaction shears that create structural flaws within the material. The conversion of smectite and mixed layer clays to illite and increases in grain size also ensue, and at the same time progressive reduction of pore space and cementation of grains occur, which makes the material stronger, less compressible and more durable. The conversion of swelling clays means that the material is less prone to changes in volume owing to changes of moisture content and the reduction in pore size restricts the movement of water through the rock. Both changes increase the durability of the material. Burial also results in the distortion of grains, so the material gains stored strain energy. On the removal of confinement from compaction mudrocks, in which only minor mineralogical and structural changes will have occurred, this strain energy will be rapidly lost as they take in water and expand. On the other hand, in cementation mudrocks in which a higher diagenetic rank will have been attained, swelling and water content increase will be delayed until the internal constraints provided by cementation and inter-particle bonds are weakened.

The process of burial and exhumation of mudrocks has resulted in UK stiff clay formations of Paleocene, Jurassic and Cretaceous age

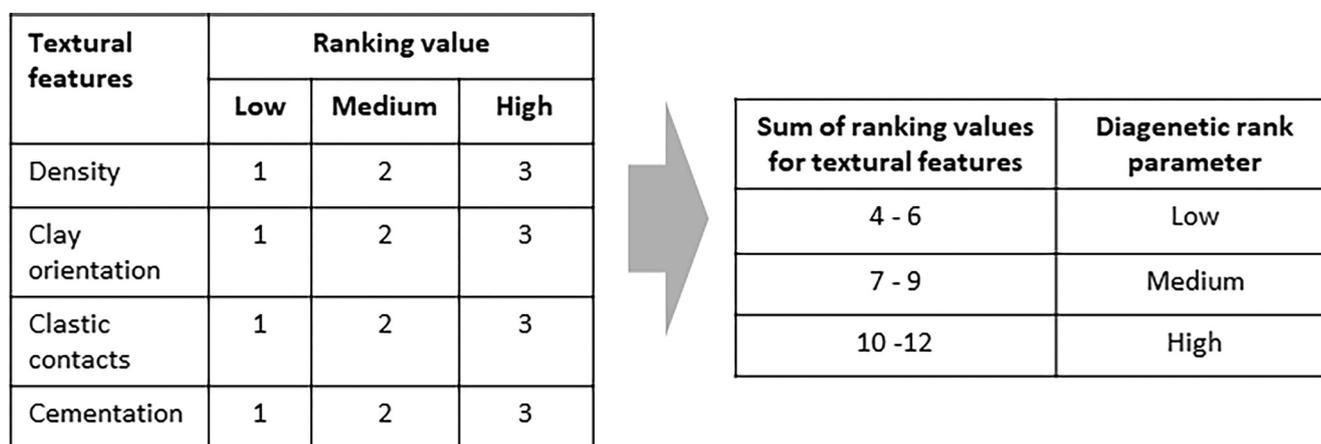


Fig. 11. Determination of diagenetic rank of mudrocks from textural features. Values for textural features are summed to determine diagenetic rank parameter. Source: after Czerewko (1997).

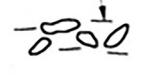
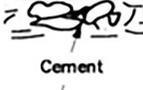
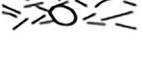
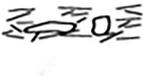
Feature	Description	Texture	Score
A. Particle Orientation	Platy minerals random.		1
	Platy minerals orientated.		2
	Laminations / micro-laminations.		3
B. Grain to grain relations	Grain to grain and/or cemented contacts		1
	Grain to grain and floating grains.		2
	Floating grains.		3
C. Clay fabric	Edge to edge or faces		1
	Mixed (1) and (3) modes		2
	Floating grains		3
D. Carbonate occurrence	1- 5 mm or sparry cement		1
	Mixed (1) and (3) modes		2
	Face to face		3

Fig. 12. Textural features used to assess the diagenetic rank of mudrocks. Scores for each textural feature are summed to indicate diagenetic rank parameter, as shown in Figure 11. Source: after Telmo Jeremias (2000) and Cripps and Czerewko (2017).

being in an over-consolidated condition. This means that they are in a denser and stiffer condition than clays that have been consolidated by the thickness of their present overburden. These features have important implications for the performance of the materials in engineering situations.

Uplift and unloading: rock to mud

Whether by natural erosion or excavation for engineering works, reducing the overburden on a mudrock is accompanied by elastic strain recovery as the material undergoes expansion. Exposure will also entail access to air and water so it will be accompanied by an increase in water content. The process is illustrated in Figure 13, where expansion is rapid in compaction mudrocks as strain energy is dissipated and moisture content increases and slower in cemented mudrocks in which expansion is prevented by inter-particle bonds, which must first be weakened. Owing to the tensile strength of strongly bonded and cemented rocks, expansion does not occur uniformly but will result in the creation of sub-horizontal fractures that will tend to develop along grain boundaries and any existing structural weaknesses such as bedding planes. These fractures tend to become more closely spaced towards the ground surface where overburden reduction is greatest. Because horizontal expansion is

more constrained than vertical expansion, high values of horizontal stress can be created in the rock, which can give rise to fissuring and deformation of stiff (over-consolidated) clays. Rock bursts, sometimes explosive in character, can occur where stronger mudrocks are rapidly destressed in excavations. The process accounts for the rise in k_0 values, the ratio of horizontal to vertical stress, measured in these clay formations beneath the weathered horizons. In the case of subsurface excavations in well-bonded cementation mudrocks, stress relief fractures are liable to be orientated sub-parallel to the face of the excavation. In stiff (over-consolidated) clays, systems of fissures are created by these stresses or they may result in deformation of the weaker layers accompanied by fracturing of any interbedded stronger beds in the formation. Obviously, the presence of fissures and fractures will reduce the strength of the material and increase its compressibility en masse, while also allowing air and water to penetrate more deeply into the material. The k_0 value rises towards the ground surface and the loss of inter-particle bonds allows expansion and increase of water content to occur.

Apart from the creation of fractures in the material that allow ingress of air and water, mudrock degradation also entails the removal of cements and the process of slaking, which occurs as a result of volume changes associated with changes in moisture content. Owing

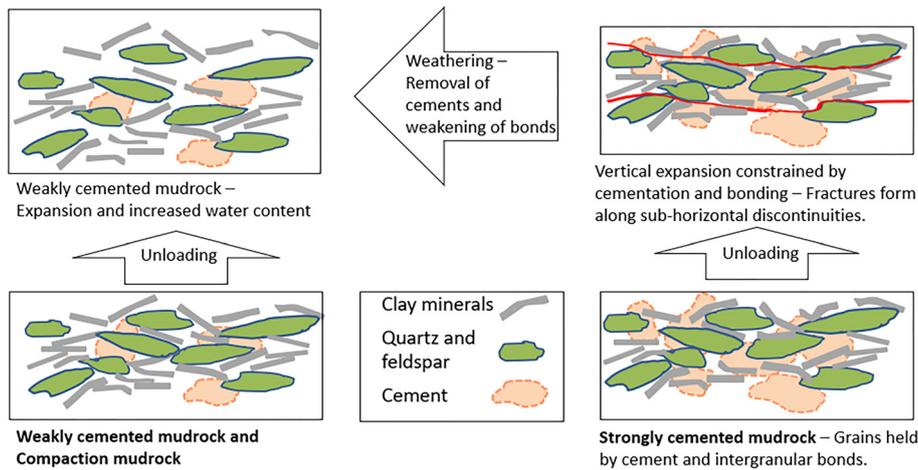


Fig. 13. Effects of removal of overburden in compaction and cemented mudrocks.

to the propensity for water molecules to be attracted to the surfaces of clay minerals and into the inter-layer sites of swelling clay minerals, clay minerals swell and shrink as their moisture content increases and decreases. These volume changes impose stress on inter-particle bonds, which may break, especially with repeated volume changes. The volume changes are liable to be greater in clay-rich mudrocks and mudrocks that contain swelling clay minerals such as smectite or mixed layer clay minerals. Mudrocks are also prone to air breakage (Taylor and Spears 1970; Taylor 1988), which occurs because during wetting air becomes trapped in narrow capillary pores in the material. As the rock is dried the interface between the air and water enters narrower pores, which owing to surface tension effects, increases the air pressure in voids sometimes to the extent that the tensile strength of the rock is exceeded, thus fracturing the rock, again especially if the process is repeated.

Some mudrocks have undergone phases of burial and exhumation, which will introduce other structural and mineralogical changes. Glacial loading and unloading and seasonal freeze-thaw effects during glacial and periglacial periods may also have affected the structural and mineralogical character of the materials and therefore influence their present durability properties.

The main changes during burial and exhumation are summarized in Table 1. Burial results in a reduction in porosity and moisture content associated with compaction as well as the loss of swelling clays, and the formation of inter-particle bonds and cements. Subsequent exhumation results in expansion, removal of cements, increased water content and fracture generation so, although mud is eventually formed, the assemblage of minerals will be dictated principally by the weathering environment, not by the original mud before burial.

Mudrock durability

Motivation for durability studies

Interest in mudrock durability was stimulated by problems of mudrock degradation in coal washery plants in the UK in the 1950s to 1960s. With post-World War II mechanization of the UK coal industry, freshly mined coal would often include rocks from above, below and within the seam that needed to be separated from the coal in washery plants. The creation of large volumes of clay slurry owing to the degradation of mudrocks was a problem in this process (Badger *et al.* 1957; Spears *et al.* 1970; NCB 1972). Taylor (1988) later reported that in the UK, lower durability mudrocks occurred in areas where lower rank coals were being mined. Lower rank coals are less transformed from original plant material than their high-ranking counterparts, where the latter possess higher carbon contents and lower water and volatile contents. More durable mudrocks were either kaolinite rich or were associated with coals of higher rank where burial to greater depth had reduced the swelling clay content, porosity and moisture content of the mudrocks.

Another stimulus to durability studies was the generation of a flow slide that engulfed part of the village of Aberfan in South Wales, UK in 1966, killing 144 people of whom 116 were children (Davies *et al.* 1967; Bishop 1973). Mine waste that was rock-like when tipped in a spoil heap on the valley side uphill of the village had degraded to the extent that a fast-moving and very dangerous flow slide was created when the spoil tip failed.

Degradation of mudrocks was a significant unexpected problem during the construction of sewer tunnels in the UK in both Sheffield and Leicester. Varley (1990) reported that whereas some of the rock

Table 1. Summary of effects of burial and exhumation in muddy sediments

Burial	Exhumation
Increased overburden stress, increased temperature	Degradation (unloading and weathering)
Compaction of sediment resulting in reduced porosity and water content	Expansion and increased water content
Loss of swelling or mixed layer clays	Fracture and fissure generation leading to greater access for water
Increase in illite grain size and crystallinity	Deformation of weaker horizons and fracturing of stronger members
Increase in vitrinite reflectance	Weathering of minerals and removal of cements by dissolution
Increased inter-particle contacts and pressure point solution creating bonds between grains	Breakage of mineral attachments owing to effects of shrink-swell and slaking behaviour
Liberation of ions from minerals undergoing mineralogical changes and pressure point solution	
Creation of aggregated groups of cemented grains and cemented skeletal framework	
Healing of structural flaws	

Table 2. Laboratory-determined yield stress values and estimated geological burial depth for selected Jurassic mudrocks (Campbell 1993)

Formation	Estimated geological burial depth at sample locations (m)	Laboratory-determined yield stress expressed as thickness of sediment (m)
Kimmeridge Clay	397–727	172–396
Oxford Clay	446–651	313–358
Lias Clay	554–878	178–284

fragments excavated by the road-header tunnelling machine used to excavate the tunnel through Carboniferous Coal Measures strata in Sheffield could be easily carried away using rubber belted conveyors, some mudrocks rapidly formed a slurry that had to be removed from the tunnelling shield by hand into skips, which greatly delayed progress. By identifying mudrocks liable to form slurry and changing the design of the conveyors and the method of working, the problems were avoided when later tunnels were excavated in Sheffield in similar geology (Deaves and Cripps 1994). Atkinson *et al.* (2003) reported that in a tunnel in Mercia Mudstone of Triassic age in Leicester, UK, the excavation process resulted in the release of swelling clay minerals, which created a highly plastic spoil that clogged the tunnelling machine.

Durability studies

Studies carried out by Campbell (1993) at the University of Sheffield sought to determine the effects of burial on the durability properties of 22 selected UK Jurassic compaction mudrocks sampled from surface exposures. The depth of burial estimated by summing the thicknesses of the younger formations that once overlay the sample locations varied between about 400 and 1900 m, but rather than this being the principal factor controlling durability, it was found that the most durable samples contained the highest amounts of organic matter. Although this correlation existed, other factors such as the presence of amorphous cements may have caused the effect and any diagenetic changes to clay minerals were too subtle to be detected by the durability tests used.

Campbell (1993) used a high-pressure oedometer, with a capability of almost 10 MPa, to determine yield stress values for two samples from each of the formations sampled. As Table 2 shows, the yield stress values were much less than the pressure apparently generated by the thicknesses of the geological formations formerly present at the sample locations, suggesting that despite precautions to avoid loss of moisture from the samples after sampling, stress relief effects had resulted in a loss of consolidation memory. It is also possible that disturbance to the samples, which had been obtained from quarries, occurred owing to periglacial freeze–thaw action. Unfortunately, vitrinite reflectance determinations on the samples did not provide a clear indication of diagenetic rank, probably because of the contaminating effect of Carboniferous organic material weathered from the then landscape.

Campbell (1993) also studied the degradation mechanisms in his samples, using various slaking tests, including wetting and drying and freeze–thaw, coupled with chemical treatments that would interact with clay minerals and remove cements, where the extent of breakdown was monitored by particle size analysis. Selected samples were also subjected to natural weathering action lasting 1 year. The product short-term slaking tests had a high percentage of fine material owing to the breakdown of particles mediated by prolonged contact with rainwater, similar to that created by tumbling in water or treatment with acid. The slaking tests initially produced a bimodal distribution of sand- and gravel-sized fragments. The breakdown of sand-sized fragments to produce dispersed mineral particles then occurred slowly by the shrink–swell action of clays or

**Fig. 14.** Slake durability testing apparatus. Source: ISRM (1979).

in dynamic slaking tests by mechanical grinding or impact of particles. Overall, degradation of the samples was dominated by the effects of physico-chemical actions involving clay minerals, rather than the mechanical processes measured in the slaking tests used. However, the slaking tests were useful for assessing the short-term slaking performance of UK Jurassic mudrocks, although differences in the mineralogy and diagenetic history of these mudrocks are too subtle to be revealed by such tests.

All the samples contained mixed layer smectite–illite and discrete smectite along with illite, kaolinite, calcite, quartz and pyrite. XRD determinations did not detect any obvious mineralogical alteration attributable to diagenesis during burial, but the as-deposited Jurassic sediment was not available for comparison. Changes in the clay mineralogy through the sequence studied probably related to climate changes during the Jurassic rather than any diagenetic effects. Whether calcite occurred as clastic grains or as an inter-granular cement had a significant impact on the performance of the material in the durability tests.

Czerewko (1997) also carried out slaking tests on his samples, using among other tests the standard dynamic slaking test devised by Franklin and Chandra (1972) and formalized by ISRM (1979), where the apparatus for the test is shown in Figure 14. Ten cuboid pieces of the samples weighing 40–60 g (total 450–550 g) are placed in 2 mm size mesh drums that are rotated partly submerged in water. The amount of material retained in the drum after 200 revolutions is expressed as a percentage of the original dry mass of material. The test continues by drying the material retained in the drum and subjecting it to further cycles of slaking. Czerewko (1997) subjected his 49 mudrock samples of different geological age and diagenetic rank to five cycles of slake durability testing, the results of which are shown in Figure 15. One of the findings of this research was that rather than two cycles in the test specification, it requires at least three cycles of testing to obtain a reliable result. Another finding was that because the mesh size is 2 mm, degradation into particles greater than this size is not measured. Furthermore, the test does not distinguish between low-durability mudrocks in which individual particles become separated from each other from low-durability mudrocks in which they remain in silt- and sand-sized aggregations that pass the 2 mm mesh sieve.

Assessment of durability using index tests

The objective of durability tests is to identify mudrocks that undergo degradation in particular engineering situations, such as in slopes and foundations, when used as engineered or non-engineered fills or in the course of excavation. The rate of degradation is important as the accompanying changes in geotechnical properties can occur rapidly, such as during the construction period, or at a slower rate such that the long-term serviceability of an engineering structure is compromised. Czerewko's (1997) study showed that the durability of mudrocks could be predicted by determining their diagenetic rank based on mineralogical and textural studies, as summarized in

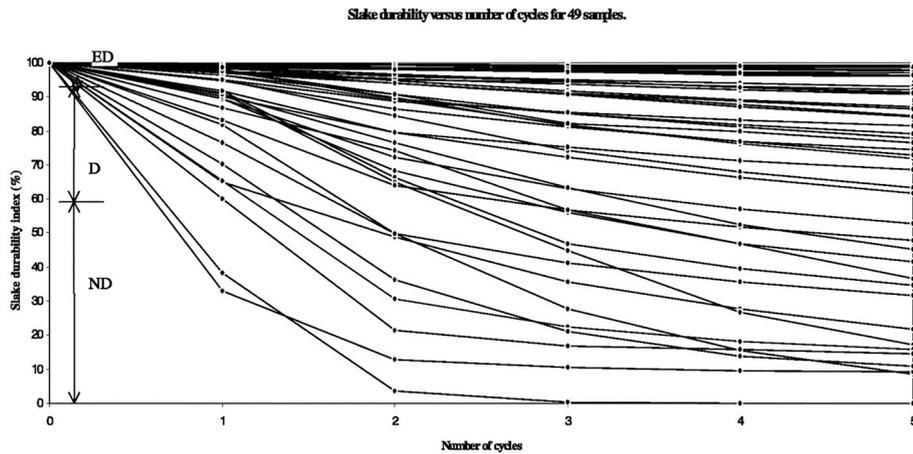


Fig. 15. Degradation of mudrocks in multi-cycle slake durability tests. Slake durability classification: ED (>95%), extremely durable; D (60–95%), durable, ND (<60%), non-durable. Source: Czerewko (1997); Czerewko and Cripps (2001).

Figure 10. However, such an evaluation, which requires sophisticated analytical equipment and expertise in interpreting the results of the tests, would not be suitable for routine evaluations of mudrock durability. In view of this, Czerewko (1997) evaluated the use of index tests, including static slaking, point load strength, porosity, water absorption, methylene blue value, fracture index and swelling for the assessment of durability. Standard slake durability and static slaking tests were also used and the results compared with assessments based on a full characterization of the material from the mineralogical and textural studies described earlier and with the results of natural weathering tests on selected samples. Static slaking consists of immersing dried pieces of rock weighing 200–500 g in water and observing the degradation that occurs over 24 h. Czerewko and Cripps (2001) explain that the procedure is similar to that described by Lutton (1977) but with larger rock specimens and a modified scheme for the assessment of the extent of degradation of samples, shown in Table 3. The original Lutton (1977) scheme for assessing the degree of breakage of samples assumed that complete degradation would occur rapidly, whereas in practice this is not always the case. Thus, in the modified scheme the

style and rate of degradation are recorded separately, where changes that occur in the first 4 h are regarded as fast, whereas those within the following 20 h test duration are slow. In the original version of Table 3 Czerewko and Cripps (2001) referred to sample deterioration instead of degradation as in this version and noted that the procedure is good for distinguishing between low-durability materials in which either individual mineral grains or sand-sized composite particles are created; also that it is suitable for assessing the potential for slaking where there is no mechanical disturbance to the material, such as exposure in a slope.

In the natural weathering tests cuboid samples weighing 40–50 g were placed in mesh bottomed containers that were sited in an exposed outdoor location for over 12 months. The extent of sample degradation was monitored periodically using the scheme presented in Table 3.

Figure 16 shows the scheme for assessing the durability of the 49 UK mudrocks used in Czerewko's (1997) investigation. The chosen index indicators were: static slake test (Czerewko and Cripps 2001), water absorption (ISRM 2007), which indicates diagenetic rank, and methylene blue value (Taylor 1985), which indicates swelling

Table 3. Modified static slake classification scheme (after Czerewko and Cripps 2001)

I_j value	Sample performance	Classification	Slake durability index, I_{d2}
1	No sign of sample degradation. Air bubbles may be emitted from sample	Extremely durable	>95%
2	No notable sample degradation, development of occasional hair-line fractures, usually bedding or parallel to bedding. Air bubbles emitted from these fractures		
3	Slight sample degradation, generally consisting of many closely spaced (10–20 mm), up to 1 mm open fractures parallel to bedding. Sample may exhibit up to 5% slaking, usually at the corners		
3i	As for 3, but with randomly oriented fractures		
4	Moderate sample degradation, generally consisting of many very closely spaced (5–10 mm), up to 2 mm open fractures parallel to bedding. Sample may exhibit up to 15% slaking, producing gravel-sized pieces and shards	Durable	60–95%
4i	As for 4, but fractures randomly oriented		
5	Moderate to high specimen degradation, consisting of extremely closely spaced (2–5 mm) fractures that are open up to 4 mm and generally parallel to bedding. Sample block/s have heavily desiccated appearance. Up to 25% slaking producing gravel-sized fragments and shards		
5i	As for 5, but fractures randomly oriented		
6	High degree of specimen degradation with only partial retention of block shape, either into multiple free-standing columns or as a column within a pile of slaked debris. Sample block/s have heavily desiccated and unstable appearance. Horizontal fractures are extremely closely spaced (2–4 mm) with many crossing fractures. Sample may exhibit up to 75% mass slaking	Non-durable	<60%
7	The sample block is largely completely degraded. The slaked debris (75–100% of the block) generally consists of a pile of angular gravel-sized shards or blocky fragments with occasional supported free-standing part of the block		
8	Total sample degradation consisting of a pile of soil-like debris, i.e. high proportional of sub-gravel-sized debris and some fine to medium gravel-sized fragments		

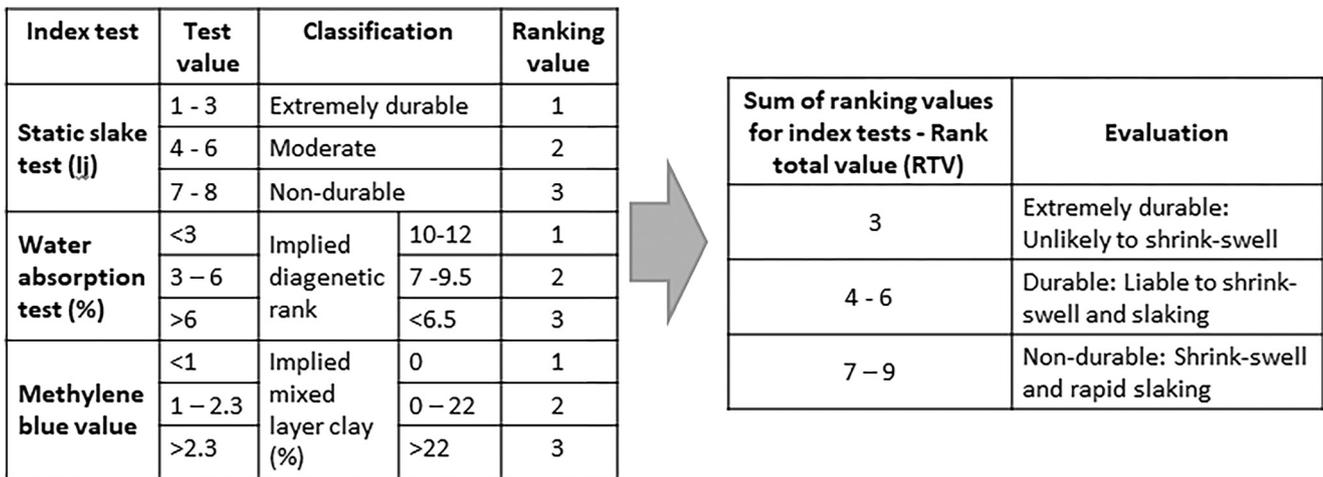


Fig. 16. Durability assessment method using index tests. Source: after Czerewko and Cripps (2002).

clays. The index indicators were simply scored as low (3), medium (2) and high (1) and the numerical total was obtained. Table 4 compares the outcome of this evaluation, the assessment based on mineralogical and textural studies (see Fig. 11), the results of the natural weathering tests and assessment based just on the standard slake durability test (ISRM 1979).

The results in Table 4 show full agreement between the assessments of durability using the mineralogical and textural studies, index testing and the natural weathering tests on seven of the samples. However, the standard ISRM slake durability test alone overestimated the number of durable mudrocks and underestimated the number of non-durable mudrocks. The research confirmed that the durability properties of mudrocks can be predicted with a good degree of accuracy from a score based on the results of water absorption tests, static slaking and the methylene blue value indicator of swelling clays.

Types of mudrocks

In order that the properties and performance of mudrocks are properly accounted for in engineering designs and construction operations the correct design approach needs to be used and the performance of the materials in the engineering situation must also be anticipated. In practice this requires that structural designs and decisions about construction operations are based on an accurate ground model, both in terms of the spatial distribution of the different rock and soil units present at a site and the performance of those materials under changing stress and environmental conditions. Guidance on the investigation of the ground conditions of sites for engineering construction is provided by BS 5930:2015 +A1:2020, Code of Practice for Site Investigation and BS EN:1997 2024, Part 2: Euro code 7: Ground properties.

These standards describe the process and methods of deriving the geotechnical design report model, which forms the basis for the engineering design and decisions about the construction method. This report must be based on a reliable geological interpretation for

the site and the data from appropriate tests to determine the geotechnical properties of all the materials to be affected by the proposed engineering works.

The selection of samples for testing and the manner of testing also depend on the reliable and unambiguous descriptions of the materials concerned. The possibility that the properties of the materials may significantly change before, during and after construction must be taken into account. The ground conditions and properties must also be recorded during construction and the performance of the built structure monitored so that the impact of any deviations from the predicted ground model and conditions, properties of materials or expected behaviour can be assessed and the need for changes in the design and construction method determined. It is also necessary to consider what post-construction monitoring and maintenance should be carried out.

Although a standard, specified scheme for the description of geological materials should be used, the schemes described in BS EN ISO 14688-1:2018, BS EN ISO 14689-1:2018 and BS 5930:2015+A1:2020 should be regarded as a minimum requirement, and it is important that the different types of mudrocks are distinguished in the descriptions. Table 5 is a scheme compiled by Czerewko and Cripps (2023) for the identification of mudrocks where the characteristics are determined using tests described by Norbury (2010). Besides accurately describing the material, it is important to record and, if possible classify, the impacts of weathering processes on the material. Guidance is given in BS 5930:2015+A1:2020, and further details are given by Anon. (1995). Czerewko and Cripps (2023) provide further discussion on the identification and description of mudrocks and go on to discuss mudrocks in engineering applications. They summarize the performance of mudrocks in the following three mudrock types:

- Compaction mudrocks (stiff over-consolidated clays): liable to undergo shrink-swell behaviour and rapid degradation owing to the presence of swelling clays. Pyrite is liable to be

Table 4. Comparison of different methods of durability assessment. (Czerewko 1997)

Assessment method	Durable	Intermediate	Non-durable*
Mineralogical and textural studies (49 samples)	12	20	17
Score based on static slaking, moisture absorption and methylene blue value (49 samples)	12	20	17
Natural weathering test (7 selected samples tested)	2	2	3
ISRM slake durability test only (49 samples)	16	20	13

*Durability classes defined in Figure 15.

Table 5. Identification and classification of mudrocks

Mudrock type; average grain size < 63 μm (<50% of grains less than 63 μm in size)	<2 μm (%)	Characteristics	Material type	
Non-indurated, compaction mudrocks Stiff over-consolidated clays $s_u < 300$ kPa, UCS < 0.6 MPa	66–100	Smooth, soapy feel with fingers Plastic*	Clay	
	33–65	Some particles visible with hand lens Slightly gritty feel with fingers Slightly plastic*	Silty clay Clayey silt	
	0–32	Particles visible with hand lens Gritty to touch with fingers Non-plastic*	Silt	
Indurated, UCS = 0.6–50 MPa	66–100	Some particles visible with naked eye Smooth non-gritty feel with blade or fingers Some particles visible with hand lens Surface softens with water and water becomes cloudy Slightly gritty feel with blade or fingers	Claystone†/mudstone	
	33–65	Particles visible with hand lens Surface softens with water and water becomes slightly cloudy Gritty to touch with blade or fingers	Mudstone	
	0–32	Some particles visible with naked eye	Siltstone	
Metamudrock, very low grade, UCS >25 MPa‡	66–100	Does not soften with water Sparkly appearance Partly to wholly recrystallized Grains visible with hand lens Some grains visible to naked eye	Massive Argillite	Foliated Slate
	33–65	Slate: some platy particles can be broken from edge with blade Partly to wholly recrystallized	Quartz argillite	Meta-siltstone quartzite
	0–32	Grains visible with hand lens		
	66–100	Grains visible to naked eye Recrystallized Some grains visible to naked eye	Argillite	Phyllite
Metamudrock, low grade, UCS >25 MPa‡	33–65	Phyllite: silky sheen and crenulated cleavage Recrystallized	Hornfels Hornfels quartzite	Metasiltstone–quartzite
	0–32	Grains visible to naked eye Quartzite: lustrous appearance		

Based on data from Potter *et al.* (1980) and Attewell (1997), after Czerewko and Cripps (2023). Courtesy of Emerald Publishing Ltd (2023). *Tests to assess plastic and non-plastic behaviour in terms of dilatancy, plasticity and dry strength are described by BS EN ISO 14688-1:2018. †Strength values for unweathered (fresh) material. UCS, uniaxial compressive strength. ‡In the UK this term is used for concretions in a bed of clay, rather than the bulk material. Such materials are referred to as mudstones.

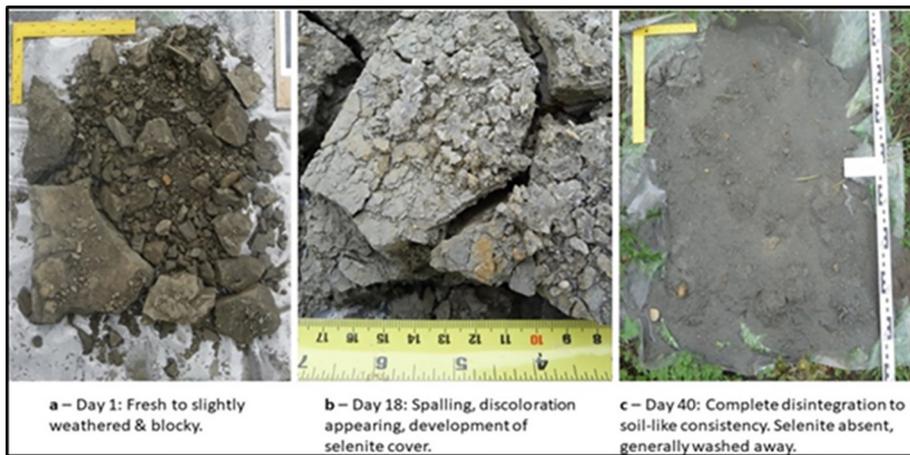


Fig. 17. Degradation of Lower Lias Clay owing to exposure to surface weathering conditions in the UK. Source: Cripps *et al.* (2023).

in the framboidal form such that on exposure to air and water it will rapidly lead to high-sulfate and acidic conditions. These changes are liable to occur within the construction period; for example, complete degradation occurred to the Jurassic mudstone shown in Figure 17 in just 6 weeks of exposure to UK weathering action.

- Weakly cemented mudrocks: liable to ravel into gravel-sized pieces on exposure. These mudrocks may contain swelling clays and framboidal pyrite. The changes may be rapid or slower: perhaps months to years, but much faster where there is mechanical disturbance to the material.
- Strongly cemented mudrocks: with a pervasive cement, low porosity, swelling clays absent and any pyrite converted to the less reactive crystalline form, degradation owing to weathering will be slow. Significant degradation over periods of tens of years with higher rates where bedding and joint structures in the rock mass control the process.

As Figure 16 shows, these categories can be assessed using index tests. Whereas static slaking causes non-indurated mudrocks quickly to degrade into individual particles, as illustrated in Figure 17, the cemented types will disintegrate more slowly into flakes, chips or chunks, depending on cementation, anisotropy and the presence of structural weaknesses. The effects of textural and structural features and mineralogical factors that control mudrock degradation are illustrated in Figure 18 and some of the underlying

differences in texture are illustrated in the accompanying SEM images.

Engineering properties of mudrocks: compilation

The compilation of the engineering properties of mudrocks came about because Roy Taylor, who sadly died in 1987, invited me to contribute a paper on the engineering properties of mudrocks for a Geological Society Engineering Group meeting in 1981. Relevant data were collected from published papers and reports on 26 UK mudrock formations ranging from Cambrian to Eocene in age. A result of this was table 6 of the resulting paper (Cripps and Taylor 1981), which here is reproduced as Table 6. It was not intended that the values should replace the need for specific investigations of materials at sites, but that they would assist the early stages and focus of investigations. A realistic range of values is reported for each parameter for (1) fresh and slightly weathered, and (2) moderately and highly weathered materials, and ignoring any very high or very low results. Also shown were the source references for each value. These references are not included in this paper, but they allowed the reader to refer back to original source of the value(s) and check any details that might be relevant to the particular situation. Any potentially significant features of the sampling and testing procedures used to obtain the data were noted, as indicated by a Greek letter. These notes are not reproduced in this paper. Each of the formations was allocated an identification number that was used to identify the data points in the accompanying graphs and tables.

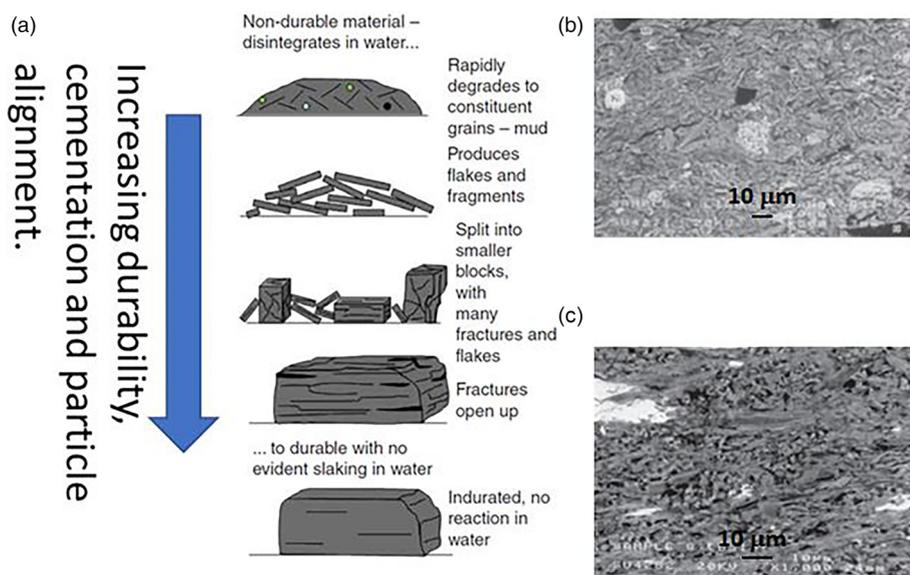


Fig. 18. (a) Effects of induration and structure on the degradation of mudrocks in water. (b) Scanning electron microscopy image of tightly compacted, well indurated massive Lower Coal Measures mudrock (NE England). (c) Scanning electron microscopy image of Upper Coal Measures fissile mudrock showing alignment of grains. Source: after Czerewko and Cripps (2023); Courtesy of Emerald Publishing Ltd 2023.

Table 6. Continued

Formation	Code on graphs	Water content (w %) (w %)		Liquid limit (w _l %) (w %)		Plasticity index, I _p (%)	Clay fraction, <2 μm (%)	Porosity, n (%)	Undrained shear strength, s _u (kPa) (range)		Undrained shear strength, s _u (kPa) (average)		Effective cohesion, c' (kPa)		Effective angle of friction, φ' (deg.)		Residual shear strength, φ' _o	Coefficient of volume compression, m _v (m ³ MN ⁻¹)		Equivalent modulus of elasticity, E = 1/m _v (MPa)		Modulus of elasticity, E _{sec} (MN m ⁻²)		Coefficient of consolidation, C _v (m ² a ⁻¹)			
		Weathered	Unweathered	Weathered	Unweathered				Weathered	Unweathered	Weathered	Unweathered	Weathered	Unweathered	Weathered	Unweathered		Weathered	Unweathered	Weathered	Unweathered	Weathered	Unweathered	Weathered	Unweathered	Weathered	Unweathered
<i>Carboniferous</i>																											
Etruria Marl	19	57	57	57	57	57	57	57	57	57	57						57										
		17-44	9-22	43-79	35-52	8-32	12-25	ø 21-35	40-240	120-620							8.5-17.5										
<i>Coal Measures</i>																											
● Mudstone	20	104	104	104	104	104	108,104	104	83	46	83	46	22	22,48	39		83	83						22,48			
		6-8	8	39-49	42	9-19	24-53	ψ 2-25	15-335	ν 9-103 MPa	100-180	ν 38-50 MPa	ν c _a 2-13 MPa	ν φ _a 28-39	12-14		0.1	10						ν 2-49 GPa			
													104	104										104			
													0-15	37-39										12-97			
● Shale	21	104	104	104	104	104	108	104	83	48	83	46	104, 117	40	1,04,108	40	117	83	83				104	48			
		9-14	9	42-45	44-51	12-19	37-87	ψ 3-30	15-335	ν 29 MPa	100-180		0-49	ν c _a 32	29	ν φ _a 12	16	0.08	12				9-49	ν 10 GPa			
																							104	25			
																								22,70			
● Scatearth	22	104		104	104	104	108	104		70			104	22	104	40	85							ν 2-21 GPa			
		11		33-34	30-35	13-41	33-77	ψ 3-28		ν 12-14 MPa			24-162	ν c _a 12 MPa	31-39	ν φ _a 16	13-26							104			
																								104			
																								32-138			
● Undivided	23	18,39	18	86,108		39	108,39		83				39	22,40	39	40,22	86,107							72			
		3-32	3	27-72		26-34	24-74		15-335				15	ν c _a 2-32 MPa	21	ν φ _a 12-39	9-36							σ 11-161			
Limestone series	24	45,82	82	45,82		82	82		82	82	82		45,3		45,3		45,3										
		15-88	36	40-106		28-45	20-74		ν 16-88	>200	ν 32-54		24-460		22-26		8-19										
Culm measures	25	88		88		88	41		41				88		88		88										
		2.5		39		16-17	21-32		ψ 10				11		31		23-32										
Remaining Lower Paleozoic rocks	26	50		50		50									10,11		10,11							50			
		3-28		25-35		11-21									τ 40-50.5		26.5-40							σ 107-2600			
Symbols on graphs		●	■	●	■	—	—		●	■	○	□	●	■	●	■											

α From medium hard lumps; γ state of weathering not known; δ high value of water content in mudflow; ε depth to approximately 30 m; ζ depth of 50-70 m; η higher value at 46 m depth; θ calculated by back-analysis; ι borehole sample; κ swell pressure plus 100 kPa; λ 100 mm diameter samples; μ Upper Gault Clay: 60-120%, Lower Gault Clay 9-110%; ν shear vane results; ξ Atherfield Clay; o undivided Lias Shales; π deep borehole sample; ρ may not be plastic; σ pressuremeter test; τ Silurian mudstone rock-fill; ψ higher value calculated from published values of bulk density, water content and specific gravity; υ tests on intact rock cores (s_u = 1/2σ_c); ω both values calculated from published values of bulk density, water content and specific gravity; c_a, φ_a apparent shear strength parameters. Values in italics identify references in Cripps and Taylor (1981).

Table 7. Laboratory-determined overburden pressures and burial depths reported in the literature for various UK mudrock formations (from Cripps and Taylor 1981)

Formation	Pre-consolidation pressure (kPa)	Reported estimated burial depth (m)
London Clay	1436–4137	152–396
Gault Clay	3430–8346	425–520
Lr Cretaceous Fuller's Earth	7104	610–760
Weald Clay	13229	1220–1370
Kimmeridge Clay	13229	1070–1220
Oxford Clay	9583–14504	330–1560
Jurassic Fuller's Earth	9583	760–885
Upper Lias Clay	14847	855–975

Variations in the properties in relation to their geological age, lithology, burial and exhumation, weathering grade and the sampling and testing methods were discussed in the accompanying text. It was apparent from laboratory-determined burial depths for the different formations shown in Table 7 that (stiff) over-consolidated clays had been buried to depths of up to 800 m, whereas for rocks the burial was over 1 km. However, in view of the mineralogical changes and the creation of cements and inter-particle

bonds, these burial depths, which were based on the yield stress determined by oedometer tests, may not truly represent the depth of burial (see Burland 1990).

Figure 19 is one of the graphs from the paper in which a trend of decreasing minimum water content for unweathered mudrocks and the maximum water content for weathered mudrocks with geological age can be discerned. Two more compilations of mudrock properties were published, which gave additional detail, by Cripps and Taylor (1986, 1987) for Tertiary and Mesozoic deposits respectively. A further, more comprehensive compilation, including data for some older Paleozoic formations, and younger Pleistocene glacial deposits and Recent alluvial clays, was published by Reeves *et al.* (2006). Further discussion of the engineering properties of mudrocks is provided in Chapter 36 of the *ICE Manual of Geotechnical Engineering* (Czerewko and Cripps 2023). Lee *et al.* (2015) describe the various datasets, including geotechnical properties, available from the British Geological Survey, for soils and rocks near the ground surface.

Pyrite

Presence of pyrite in UK mudrocks

Pyrite is a minor but important constituent of many rocks and certain unconsolidated glacial and alluvial deposits. It is usually present in dark coloured mudrocks. Table 8, which is an updated version of a table presented in Taylor and Cripps (1984), shows the approximate amounts of pyrite and carbonate in various mudrock formations. Pyrite can occur in the different forms illustrated in Figure 20, of which the gold coloured cubic form known as fool's gold is the most familiar, but in mudrocks it is usually present in the framboidal or fine-grained forms. The grains of the framboidal or fine-grained forms of pyrite are microscopic in size and dark coloured, and are not visible to the naked eye or hand lens, so their presence needs to be confirmed by microscopy or inferred by chemical analysis. It should be noted that in Figure 20a the scale bar is 10 mm, whereas on the SEM images in Figure 20b and c, it is 10 μm .

Pyrite in mudrocks: case histories

The implications of pyrite in ground engineering work are described by Cripps *et al.* (2019), which followed a presentation at the Engineering Group of the Geological Society's 2018 conference, 'Keeping lessons alive in Engineering Geology'. The paper presents seven case studies in which pyrite had a significant impact on engineering works of different types, as briefly explained below.

The landslide at Mam Tor, near Castleton, Derbyshire, UK

The A625 Sheffield to Manchester road, which had been constructed in the early part of the nineteenth century, twice crossed this unstable ground, which, as Skempton *et al.* (1989) explain, caused the closure of the road to through traffic following a major movement in approximately 1977. Prior to this, major works were frequently required to maintain the road in an adequate condition. As Figure 21 shows, the instability is an impressive landslide about 900 m long by about 300 m wide with a steep backscarp formed in Mam Tor Beds, which is an alternating sequence of silty mudstone and sandstone beds of Namurian (Carboniferous) age. The main part of the landslide is a rotational slump underlain by Bowland Shale, which is a black or dark grey laminated mudstone that contains pyrite with beds of siltstone, also of Namurian age. To the south the ground is formed of Carboniferous limestone, which is older and lies unconformably beneath the Bowland Shale.

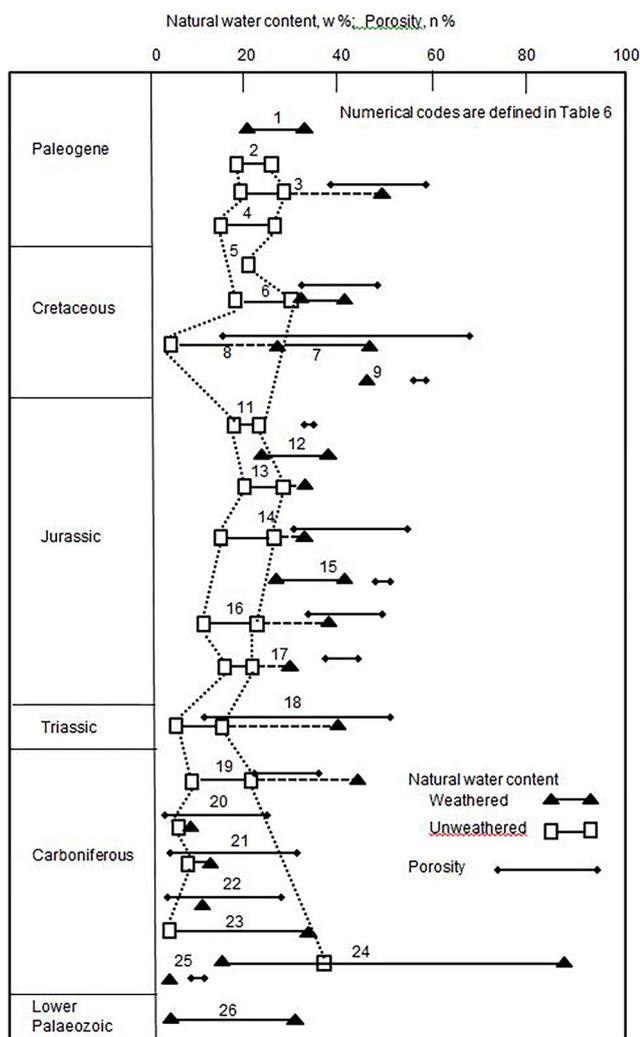


Fig. 19. Variation of natural *in situ* water content and porosity for mudrocks of different ages. (Porosity values for unweathered samples, where some values calculated from bulk density.) Source: Cripps and Taylor (1981).

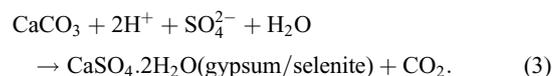
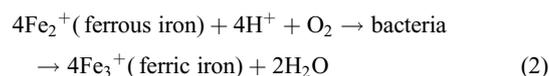
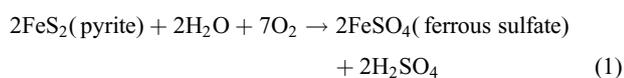
Table 8. Pyrite and carbonate minerals contents recorded in UK mudrocks (from Czerewko et al. 2016)

Stratigraphic unit		Pyrite content (%)	Carbonate mineral content (%)	Carbonate minerals
Paleogene	London Clay, blue-grey fissured silty clay	0.6–4	0.4–5.2	Calcite, dolomite
	Basal London Clay, sandy clay	2.5–41	na	Calcite
	Lambeth Group, laminated and shelly clays	0.4–19.2	0–18	Calcite
	Lambeth Group, mottled clays	<0.2	0	
Cretaceous	Weald Clay	0.6	1–6	Calcite
	Gault Clay	0.7–1	0.7–33	Calcite
Jurassic	Ancholme Clay	0.2–4	2.7–4.3	Calcite
	Kimmeridge Clay	0.4–4	8–36	Calcite
	Oxford Clay	3–15	4.5–15	Calcite
	Whitby Mudstone	3–17	1–16	Siderite
	Lias Clay	1–8	2–49	Calcite
Carboniferous	Coal Measures, claystone	0.1–6.9	2.2–3.2	Siderite, calcite
	Coal Measures, mudstone	1.2–8.2	0–9	Calcite
	Coal Measures, siltstone	0–2.3	0–37	
	Limestone	0.2–10		
Devonian	Namurian mudstone	0–6	0–0.5	
	SW England, mudrock to argillite	0–4.3		Calcite, dolomite, siderite
Silurian	Wales and Southern Uplands, Scotland, metamudrock to argillite	0.1–4.2	0–2.2	Calcite, siderite
Ordovician	Wales, mudrock to slate	0.4–7.1	0–2.7	Calcite, siderite
Cambrian	North Wales, slate	0.5–5.4	0–0.8	Dolomite

na, not analysed.

In fact, as the superficial geological map in Figure 22a shows, there are a number of similar landslides on the hillsides in nearby valleys and elsewhere in the Dark Peak area. Most of them cut through sequences of interbedded mudstone and sandstone underlain by mudstones. The lower part of the landslip at Mam Tor is an earth flow spreading out across the valley floor, as seen in the LiDAR image (Fig. 22b). The landslide is still moving and this will probably continue well into the future.

Vear and Curtis (1981) reported that streams and water seepages that occur on the landslide were acidic in condition and contained high levels of sulfate and metal ions such as aluminium, magnesium, calcium and potassium. This and characteristic brown deposits of iron oxyhydroxide in the water courses pointed to them containing solutions formed by the oxidation of pyrite. The reactions for this process are shown below in a simplified form:



Equation (1) shows the chemical conversion of pyrite to ferrous sulfate in the presence of oxygen and water. In equation (2) the ferrous iron in solution is oxidized to ferric iron by bacterial action. As this is a strong oxidizing agent for pyrite, the presence of appropriate bacteria greatly accelerates the rate of pyrite oxidation and the oxidation process is also much faster for framboidal or fine-grained or impure pyrite. The reactions result in the formation of hydrogen ions, making the conditions acidic, which results in reactions (equation 3) with carbonate minerals such as calcite and dolomite, which are present in the rock. The result of this is the generation of calcium sulfate in the form of selenite, the crystalline form of gypsum. As shown in Figure 23a, the expansive formation of selenite in fractures and bedding surfaces of Bowland Shale

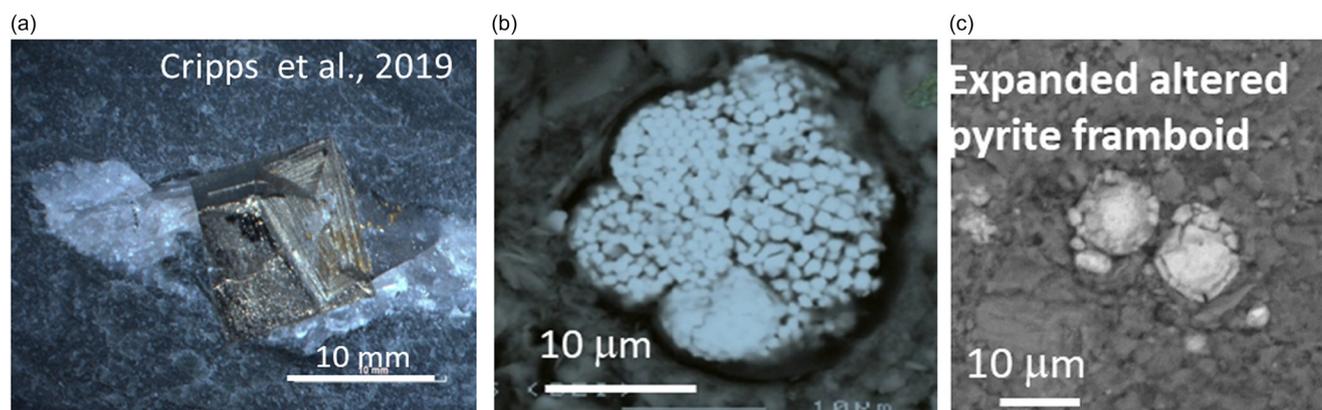


Fig. 20. Different forms of pyrite. (a) Cubic crystals in slate of Cambrian age from Bethesda, UK. (b) Framboidal pyrite in Lower Lias Clay, Gloucestershire, UK. (c) Altered pyrite in Carboniferous mudstone from Dublin, Republic of Ireland. Source: Cripps et al. (2019).

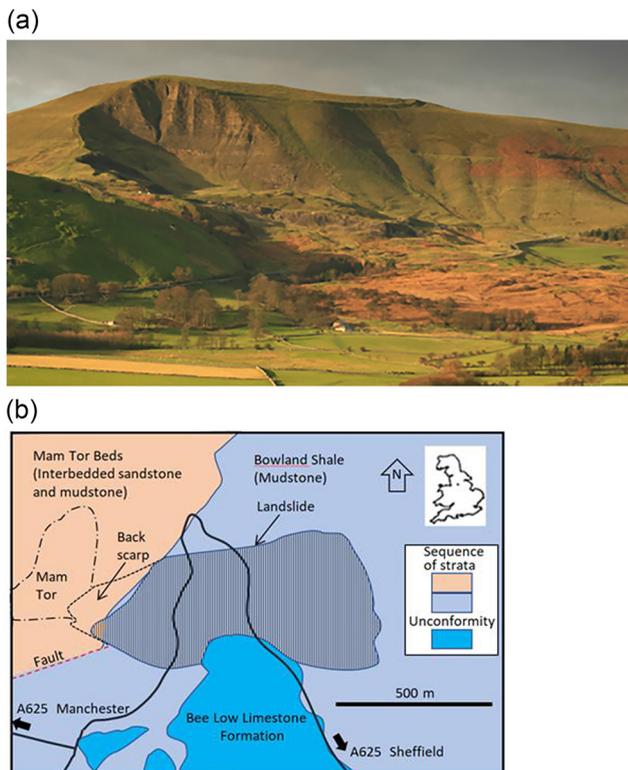


Fig. 21. (a) Landslide at Mam Tor with steep back scarp and earth flow forming the pale brown raised area of the toe (copyright Bill Bevans www.billbevanphotography.co.uk). (b) Bedrock geological map of Mam Tor landslide. The A625 road crossed the unstable ground in two places. Source: BGS 1975, reproduced with the permission of the British Geological Survey © UKRI 2023. All Rights Reserved.

outcrops is responsible for the fragmentation of the rockmass. The dissolution of carbonates in equation (3) removes cements from the rock, while also producing carbon dioxide gas, which although not poisonous, can be dangerous.

The reactions also result in the production of iron oxyhydroxide or ochre, large amounts of which are formed at water seepages in, among other places, the toe (earthflow) area of the landslide. These orange, yellow and brown deposits occur where atmospheric oxygen results in hydrolysis reactions with ions in solution. Stream sediments and vegetation become coated in these deposits, as seen in Figure 23b, which is a characteristic feature of these pyrite oxidation processes.

Figure 24 is Vear and Curtis’s (1981) model for the chemical processes occurring at Mam Tor, based on the measured composition of a seepage of groundwater discharging from a Bowland Shale outcrop. The presence of potassium and aluminium in solution implies that reactions between acid and clay minerals are

occurring, which might have an effect on rock strength and stability. As pyrite is the only source of sulfate ions in solution, the model implies that 1.5 g of pyrite per litre of discharge would need to be oxidized to produce the measured quantity of sulfate in solution (2.4 g l^{-1}) and given the flow rate of the spring this would suggest that about 20 tonnes of pyrite per year were being removed from the rock mass in the source area of the spring discharge. Vear and Curtis (1981) point out that the seepage in question probably originates from groundwater flow through a geological fault zone, which would expose a large volume of broken rock to groundwater. Reactions between the acidified, sulfate-rich groundwater and the rock would remove carbonate cements and result in the production of iron oxyhydroxide (limonite) and selenite at or near the ground surface, which, as Figure 23a shows, has a destructive impact on the rock mass.

Measurements of the residual shear strength of Bowland Shale were carried out by Steward (1984) using a Bromhead Ring Shear apparatus that was modified so that the composition of the porewater could be changed without interrupting the test. As Table 9 shows, introducing Na and K changed the residual shear strength by one or two degrees compared with distilled water and the effect was greater for higher concentrations. Although the stability of the landslide is probably controlled mainly by groundwater levels, the results implied that the exchange of clay mineral cations could also affect the stability.

Al-Dabbagh (1985) evaluated various means of disaggregating the mudstone to form a sample for ring and reversing shear box tests, including end-over-end tumbling in water for 5–7 days, crushing using a tungsten carbide disc mill, ultrasonic disaggregation, crushing using a steel pestle and mortar, and alternating oven drying and soaking in water. Various combinations of these treatments and different size fractions obtained by dry sieving were tested. He also back-analysed the Mam Tor landslide and 10 other landslides in the area to determine the residual shear strength mobilized on the slip surfaces, which was an average of $\phi_r' = 11^\circ$, $c_r' = 0$. As the results in Table 10 show, tumbling in water, which produced a similar grading and particle shape to naturally weathered mudstone, gave the lowest strength, with successively higher ϕ_r' values for ring shear tests on crushed samples, reversing shear box on tumbled samples and reversing shear box on crushed samples, whereas the tumbled sample tested in a reversing shear box test gave the closest value to the back-analysed value.

The Dam at Carsington Reservoir, near Matlock, Derbyshire, UK

The second example concerns the reconstruction of the embankment dam that impounds Carsington Reservoir, which is situated near Matlock in Derbyshire. It is part of a pumped storage scheme in which water is extracted from the River Derwent via connecting

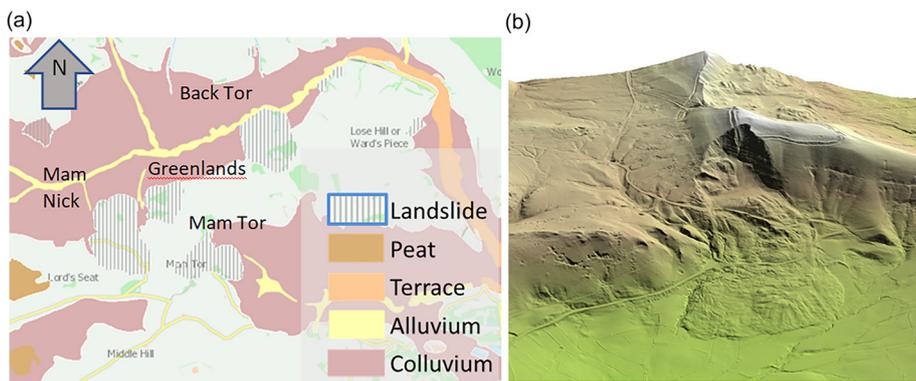


Fig. 22. (a) Superficial geology map of Mam Tor area. Source: BGS 1975, reproduced with the permission of the British Geological Survey © UKRI 2023. All Rights Reserved.) (b) LiDAR image of Mam Tor, view from east. (Courtesy of J. Hunter. Made available under the Open Government licence v3.0 © Crown Copyright 2022.)

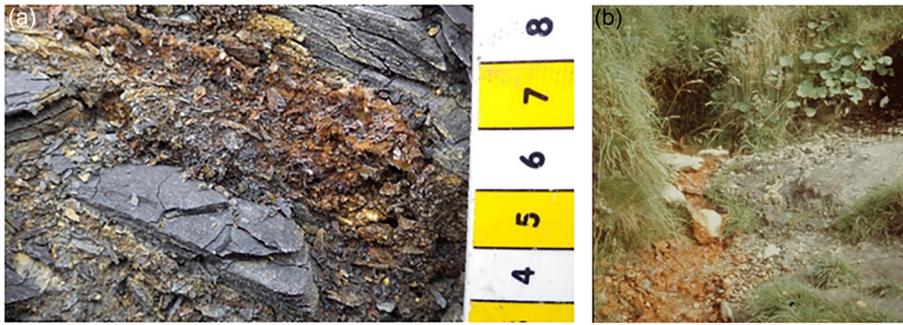


Fig. 23. (a) Expansive formation of selenite with iron hydroxide in joints and bedding surfaces of Bowland Shale, causing expansion and break-up of the rock. (b) Orange-brown iron oxyhydroxide deposits coat rock fragments in stream discharge at Mam Tor.

tunnels and returned there when required to augment the river flow. The original dam, which was about 1200 m long by up to 30 m high in the centre of the valley, was constructed out of compacted Bowland Shale with crushed limestone drainage blankets, as indicated diagrammatically in Figure 25a. Unfortunately, in June 1984, before filling of the reservoir with water commenced, a 500 m section of the dam’s upstream shoulder failed, as shown in Figure 26a. The nature, causes of and investigations into the failure are discussed by [Rocke \(1993\)](#) and [Skempton and Vaughan \(1993\)](#). Early investigations revealed both that oxidation of pyrite in the mudstone was occurring and that the mudstone had been degraded in the processes of excavation, transportation and compaction in the dam. Besides iron hydroxide, gypsum was present in the drainage layers (Fig. 26b), which may have impeded the functioning of the drains and resulted in ground strains. [Reid and Cripps \(2019\)](#) concluded that no allowance was apparently made in the design for the effects of pyrite oxidation in the mudstone or these degradation processes. The drainage waters (Fig. 26c) from the site were acidic, sulfate rich and contained metals, such that they needed to be treated to control the pollution of the local stream to which they were discharged.

Shear strength values for the reconstruction were based on drained triaxial shear strength tests, and it was necessary to ensure that any reductions in strength of the mudstone that might occur as a consequence of chemical weathering and physical degradation were anticipated. A series of tests undertaken by [Anderson and Cripps \(1993\)](#) provided data on the effects of acid leaching on the shear strength of samples of the mudstone, comprising (1) mudstone to be used for construction, (2) mudstone that had been leached in acid and then remoulded into samples, (3) remoulded samples that were leached by through-flow of acid and (4) mudstone from the original dam, which by then was about 5 years after construction. The leaching was intended to mimic the action of sulfuric acid generated by the oxidation of pyrite and from a brief literature search it would appear that the preparation of the (2) samples is the only time that this type of *in situ* leaching of remoulded samples has been reported.

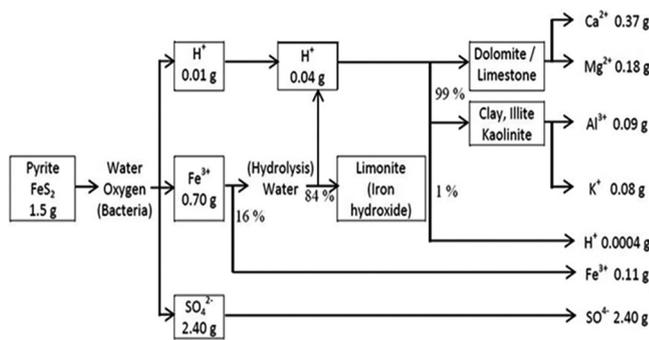


Fig. 24. Chemical processes that explain the composition (per litre) of water being discharged from one spring at Mam Tor. Source: [Cripps et al. \(2019\)](#).

The test results in Figure 27 and in Table 11 fitted to a fixed $c' = 25$ kPa showed that the embankment samples were a little stronger than the material intended for the reconstruction, suggesting that there has been little loss of strength in 5 years. The strengths of the different leached samples (2) and (3) were similar to each other, with a reduction of about 4° in the effective angle of friction, to around 22° .

Cross-sections shown in Figure 25a and b respectively show the designs of the original and the reconstructed dam. Significant changes were introduced in design of the reconstructed dam, notably in the shoulder upstream of the core: the most weathered mudstone, which would have the lowest permeability, was used to construct the core of the dam (C); more weathered mudstone (T), which would have an intermediate permeability, was used against the core and at the base of the dam’s shoulder; and the least weathered, most permeable mudstone (S) was used for the rest of the dam’s shoulder. The shoulder materials (S) had an effective shear strength of 24° , measured in drained triaxial tests on 100 mm diameter remoulded samples, but in view of the possibility of loss of strength with time, the design was based on 22° . The up- and downstream slopes were shallower than in the original dam, there were no drainage blankets in the mudstone and a carbonate-free quartz gravel was used for the basal drainage layer.

Regular sampling and chemical and mineralogical analyses of the samples used in the reconstruction were performed to confirm that the selection of material accorded with the design. The results of chemical tests carried out at Sheffield University for individual samples were very scattered but averages for the S, T and C mudstones shown in Figure 28 demonstrate logical progressive changes in the chemistry of the mudstones as they become more weathered, as follows:

- loss of pyrite, calcite and dolomite, although much pyrite remains in partly weathered T material;

Table 9. Effect of changes to chemistry of porewater on residual shear strength of Bowland Shale (from [Steward and Cripps 1983](#))

Test	Chemistry of porewater	Average residual shear strength (degrees)*
NaNO ₃ to KNO ₃	NaNO ₃ (0.1 M)	21
	Distilled water flush, then NaNO ₃ (0.1 M)	24
KNO ₃ to NaNO ₃	Distilled water	22
	KNO ₃ (0.1 M)	23
	Distilled water flush, then NaNO ₃ (1.0 M)	20
Acid and groundwater	H ₂ SO ₄ (14%)	25, 27
	Groundwater	18

*Normal pressure = 294 kPa, $c'_t = 0$.

Table 10. Residual shear strength values of Bowland Shale prepared by (A) end-over-end tumbling in water or (B) crushing using a tungsten carbide disc mill (from Al-Dabbagh et al. 1998)

Sample	Method	Size fraction (µm)	Ring shear		Shear box	
			c_r' (kPa)	ϕ_r' (°)	c_r' (kPa)	ϕ_r' (°)
1	A	<425	2.5	7.5	8.2	11.5
	B	<425	6.1	10.5		
	B	<75	5.0	10.5	12.4	8.5
	B	212–75	3.6	13.0		
2	B	212–425	15.4	13.5		
	A	<425	2.4	10.5		
3	B	<425	21.3	12.0		
	A	<425	3.8	12.5		
	B	<425	14.5	19.0		

- increase in alumina with respect to silica, which is a reflection of a relative gain in clay minerals as pyrite, dolomite and calcite are removed in solution;
- water-soluble sulfate values rise as weathering progresses from S to T mudstones and then falls as the material is leached, as in the more weathered C mudstone in which it is low.

Reid and Cripps (2019) point out how experience at Carsington demonstrates the vital importance of geochemical factors in engineering. Unfortunately, besides contributing to the rapid degradation of the fill material, the consequences of pyrite oxidation

processes, which, as equation (3) shows, involve the production of CO₂ gas, which is heavier than air, were fatal for four workmen who in 1983 were killed because of the presence of this gas in a manhole drainage chamber. In addition, Reid and Cripps (2019) explain they discovered serious discrepancies in the values of sulfate and sulfide in the tests from different laboratories. All the testing was performed according to the then current British Standards, but some of the preparation and testing procedures were not suitable for use with mudstone. Further details of this are given in the section ‘Determination of sulfur in geological materials’ of this paper with regard to the determination of pyrite in construction materials. Care needs to be taken when using standards to ensure they are appropriate to the particular application.

It is regrettable that information about the dam and reservoir at the Carsington Reservoir visitor centre makes no mention of the failure and the reconstruction of the dam, or of the problems with constructing the tunnels that connect the reservoir to the River Derwent. It would be a great story that might inspire people to study geology and geotechnical engineering. However, the success of this and other projects does demonstrate that, given due regard for the construction materials and geological processes, a successful dam can be built using pyritic mudstone.

Thaumasite in motorway bridge foundations and fills for highway structures

At the end of the twentieth century it was found that a number of 30-year-old M5 motorway bridge foundations in Gloucestershire, UK were seriously weakened because the cement binder in the

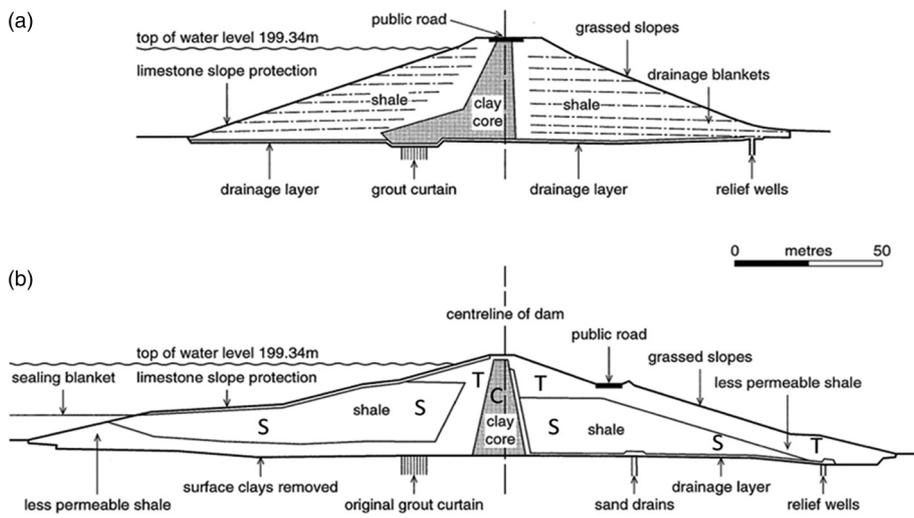


Fig. 25. Cross-sections showing (a) structure of the original and (b) the reconstructed dams at Carsington. S, T and C respectively denote mudstone types selected for the shoulder, transition and core sections of the reconstructed dam. Source: after Banyard et al. (1992).



Fig. 26. (a) Aerial view of dam at Carsington shortly after failure in 1984; upstream face of dam is seen finished in pale coloured limestone rip-rap for erosion protection. (b) Limestone drainage blanket layer within mudstone fill, where brown colour is due to iron hydroxide coatings to the rock fragments and the layer has been displaced at the failure surface. (c) Discharge from drainage system, which contained high levels of metals, sulfate and acidity. Source: (a) Cripps et al. (2019).

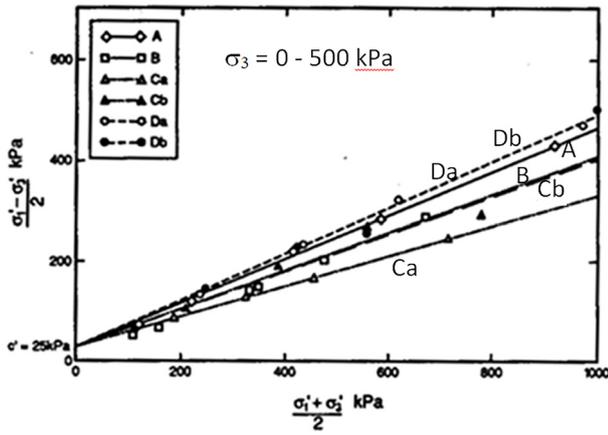


Fig. 27. Drained triaxial test results for remoulded mudstone from Carsington. Source: Anderson and Cripps (1993).

Table 11. Shear strength values of remoulded samples of Bowland Shale from the Carsington Dam

Sample	Sample treatment	$c' = 25$ kPa ϕ' (degrees)
A	Original (treated)	26.3
B	Bucket leached (10% H ₂ SO ₄)	22.2
Ca	Sample leached (20% H ₂ SO ₄)	18.1
Cb		22.5
Da	Original embankment	27.9
Db		27.8

Pre-test treatment: fragments >120 mm removed and sample soaked in water, 75 μm -20 mm fraction oven dried and remoulded into 38 mm diameter samples.

concrete had been converted to thaumasite, a very weak hydrated calcium silicate sulfate mineral (see Floyd *et al.* 2003). As Figure 29a shows, the foundations were formed in excavations that were back-filled with locally derived Lower Lias Clay, which contained pyrite. At the time of the ground investigation and construction only water-soluble sulfate levels in the unweathered

clay would have been determined and these were very low, whereas tests for sulfide minerals such as pyrite were not performed. The exposure of the clay to oxygen and water during and after construction resulted in the oxidation of pyrite, which produced porewaters containing high levels of sulfate, which led to the degradation illustrated in Figure 29a and b. This lack of attention to pyrite in soils and rocks in contact with concrete was addressed by the publication of Building Research Establishment Special Digest 1 (BRE Special Digest 1:2005), which set out procedures for classifying aggressive ground and the design of concrete that will resist such conditions. One of the results of various investigations into thaumasite formation and the effects of clay weathering on concrete carried out at Sheffield University (Hill *et al.* 2003) was the finding that sulfate-resisting cement was not immune to thaumasite formation and that the presence of chloride (either from connate porewaters or from road salt) changes the vulnerability of the concrete to damage.

At about the same time, galvanized steel culvert linings on the A50 road near Derby were found to be seriously corroded, as illustrated in Figure 29c, such that they needed to be replaced soon after construction. Investigations revealed that the locally derived Trent Valley gravel used as fill contained pyrite, so although at the time of construction it possessed low sulfate values, pyrite oxidation had resulted in the generation of acid and sulfate that had damaged the steel culvert linings. The pre-construction ground investigations included some tests for total sulfur that could have indicated the possibility that pyrite was present, but these results were not considered in the assessment of the material, which was probably based on pH values and possibly the results of water-soluble and a few acid-soluble sulfur tests. Alluvial gravels would not be expected to contain pyrite, but it may have been formed under anaerobic conditions in organic-rich muddy sediments interbedded with the gravel. The outcome of investigation of the problem was the publication of TRL Report 447 (TRL 2001), which set out test procedures and terminology for the investigation of materials containing pyrite and assessing the effect of pyrite oxidation in fills being considered for use in the vicinity of concrete or steel in highway projects.

TRL Report 447 (TRL 2001) and BRE Special Digest 1:2001 provided guidance on the investigation of pyrite-bearing materials,

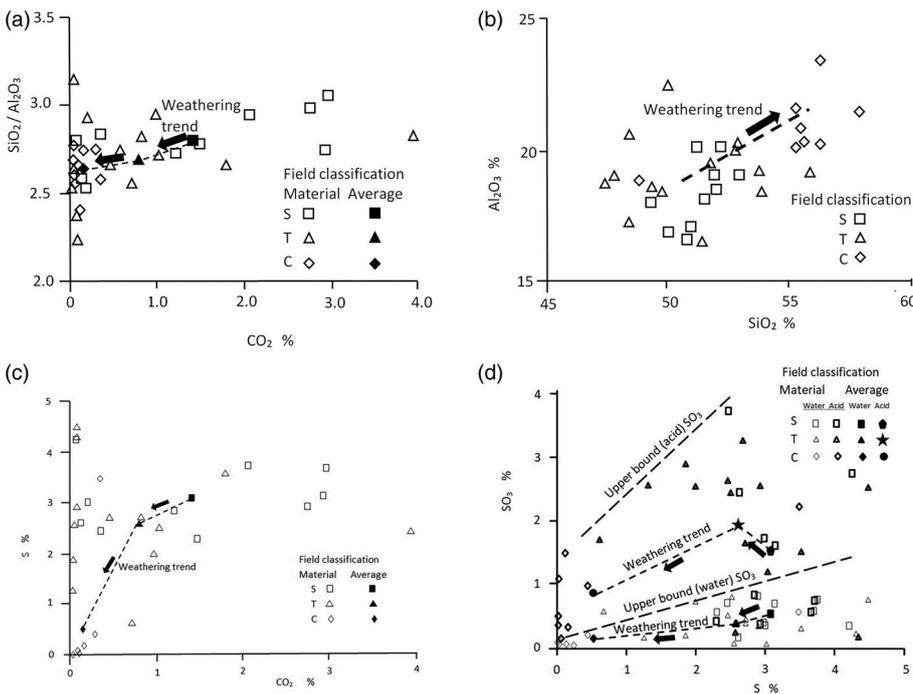


Fig. 28. Weathering trends indicated by chemical tests carried out at Sheffield University on mudstones used in the reconstruction of the Carsington Reservoir dam. Mudstones classified in the field as: S, slightly to moderately weathered mudstone; T, highly to completely weathered mudstone; C, soft to stiff thinly laminated or unbedded (residual) clay. (a) Silica:alumina ratio v. carbonate content. (b) Alumina v. silica content. (c) Sulfide sulfur (pyrite) v. carbonate content. (d) Water- and acid-soluble sulfate v. sulfide content.

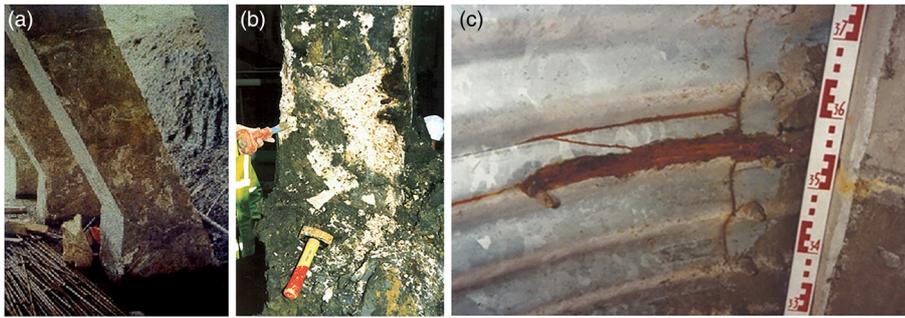


Fig. 29. Degradation of concrete foundations and steel culvert linings. (a, b) Degraded concrete bridge foundations revealed after removal of mudrock fill in which it was buried. (c) Damage to galvanised steel lining on A50 near Derby. Source (a, b) contains public sector information licensed under the Open Government Licence v3.0, from Thaumassite Expert Group (1999); (c) TRL (2005).

Table 12. Measured and derived parameters for sulfur in soils and rocks (TRL 2005)

Parameter		Test or formula	Symbol	Units
Measured parameters	Water-soluble sulfur	TRL 447 Test 1	WSS	mg l ⁻¹ S
	Acid-soluble sulfur	TRL 447 Test 2	ASS	% S
	Total reduced sulfur	TRL 447 Test 3	TRS	% S
	Total sulfur	TRL 447 Test 4	TS	% S
	Monosulfide sulfur	TRL 447 Test 5	MS	% S
Derived parameters	Water-soluble sulfate	15000 × WSS	WS	mg l ⁻¹ SO ₄
	Acid-soluble sulfate	3 × ASS	AS	% SO ₄
	Total potential sulfate	3 × TS	TPS	% SO ₄
	Oxidizable sulfides	TPS – AS	OS	% SO ₄

including sampling and testing procedures, and set limits on the allowable amounts of sulfur compounds in different situations. Both documents were subsequently revised and reissued with small changes as TRL Report 447 (TRL 2005) and BRE Special Digest 1:2001 respectively, and the maximum amounts of sulfur compounds allowable for highway fills shown in Table 12 were later incorporated into Highways Agency Specifications (Highways England 2016a, b).

The seven case histories in the paper by Cripps *et al.* (2019) also considered problems with stabilized soils, earthworks and foundation fills, all of which can be seriously affected by the presence of pyrite. Recently it has become apparent from current construction projects that lessons about the impact of pyrite and rapid degradation of clays have yet to be learned in certain quarters. Figure 30 shows the effects of acid sulfate-rich waters on the steel reinforcement of a temporary reinforced soil wall. Cripps *et al.* (2019) describe a number of projects in which lime or cement



Fig. 30. Damage to steel reinforcement of reinforced soil wall in Lower Lias Clay in Somerset, UK.

stabilization of pyritic clays has resulted in subsequent heave and damage to highways. Figures 31a and 4c respectively show damage to a temporary site concrete slab roadway on lime-stabilized pyritic Kimmeridge Clay and the softening, erosion and selenite crystal formation that occurred shortly after the excavation of a cutting in pyrite-bearing Ancholme Group (Amphill) Clay, also of Jurassic age. The selenite crystals shown in Figure 31b formed in less than 3 months after the excavation of the cutting shown in Figure 4c, and continued formation of selenite is likely. Apart from the removal of pyrite and calcite cements from the clay, the material has also experienced expansion, softening and degradation, so, as illustrated in this figure, the exposed slopes are subject to erosion and gullyng. The production of selenite will have resulted in high levels of sulfate and chemical aggressivity of the clay and these features may hinder or necessitate unexpected changes in subsequent engineering design and construction phases of the project, and remedial works may be required. Czerewko *et al.* (2011) describe how the pre-construction assessment of pyritic Lower Lias Clay provided reassurance regarding the long-term performance of highway earthworks near Nottingham, UK.

Expansion of fill beneath cast *in situ* floor slabs

The seventh case history in the paper by Cripps *et al.* (2019) described problems caused by the use of mudstone and muddy limestone containing pyrite to support the floor slabs of buildings in Ireland. According to Tuohy *et al.* (2012) up to 23 500 dwellings and other buildings in 74 developments in Ireland might be affected by this problem and it might cost between €25 000 and €80 000 to put each of them right. Czerewko and Cripps (2022) recently published a case study of the investigation in 2008 of one particular development of 350 houses situated near Dublin. At the time of the investigation the houses, which comprised two- and three-storey buildings, were only 4–5 years old. Another investigation into the damage sustained by a building in Dublin owing to the expansion of pyrite-bearing mudstone is described by Matheson and Quigley (2016). In fact, cases of expansion of fill or bedrock containing pyrite had been documented in the 1970s and 1980s in the UK, with



Fig. 31. (a) Heave damage to concrete slab on lime-stabilized Kimmeridge Clay. (b) Selenite crystals formed *in situ* in slopes shown in Figure 4c. (c) Selected selenite crystals seen in (b). Examples from Buckinghamshire, UK.



Fig. 32. (a) Mode of construction of dwellings affected by expansion of fill beneath floor slabs in Ireland. (b) Floor slab of house near Dublin, showing evidence of hogging. (c) Cracks formed in dry lining plasterwork in a damaged dwelling, near Dublin. Source: after Czerewko and Cripps (2022).

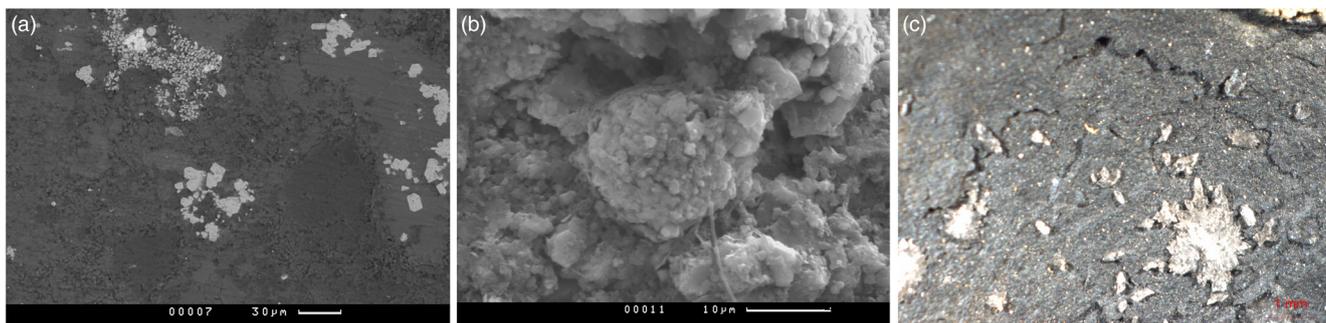


Fig. 33. (a) SEM image of cubic and framboidal pyrite in a calcareous mudstone particle. (b) SEM image of reacted pyrite framboid with development of a ferric sulfate reaction rim and discrete platy selenite crystals. (c) Selenite crystals on surface of a crack in a mudstone particle.

Table 13. TRL (2005) and Highways England (2016a, b) specifications for structural backfills on highways

Parameter	Units	Maximum value within 500 mm of concrete or cement bound materials	Maximum value within 500 mm of metals	
			Galvanised steel	Stainless steel
Water-soluble sulfur, WS	mg l ⁻¹ SO ₄	1500	300	600
Oxidizable sulfur, OS	% SO ₄	0.3	0.06	0.12
Total potential sulfide, TPS	% SO ₄	0.6	Not applicable	Not applicable

cases in NE England, SW England and Wales, as well as in the USA and Canada reported in the literature (Quigley and Vogan 1970; Penner *et al.* 1972, 1973; Nixon 1978; Taylor and Cripps 1984; Hawkins and Pinches 1987; Hawkins 2014), so the problems could have been anticipated. Whether the houses were owner occupied or owned by landlords, it was a serious problem, as mortgage companies will not lend on properties affected by serious structural defects.

Figure 32a shows the nature of the construction, with fill supporting a concrete cast *in situ* floor slab, and the load-bearing

outer walls supported on footings in stiff clay (glacial till) over bedrock. In some cases internal walls were constructed on the floor slab, whereas in others foundations carried the load to the natural ground below. As Figure 32b and c illustrates, the harm to buildings included serious cracking to walls, heave, cracking and distortion of the floor slab resulting in sticking doors and other forms of damage. Various possible causes for the damage were investigated, including shrinkage of timber, foundation settlement and faulty design and construction. The fill from beneath the floor slabs of four houses in

Table 14. Comparison of different methods for the determination of sulfur compounds (from Cripps et al. 2019)

Parameter	TRL (2005) and BS 1377-3:2018+A1:2021	BS 1377-3:1990	BS EN 1744-1:2009 + A1:2012	Comments
Water-soluble sulfate (WS) (in 2:1 water/solids extract)	TRL 447 Test 1; BS 1377 Clauses 7.3–7.7; results in mg l ⁻¹ SO ₄	Clause 5.3 and 5.5; results in g l ⁻¹ SO ₃	Clause 10.1; results in % SO ₃ of dry sample mass	Provided units are converted to mg l ⁻¹ SO ₄ , there should be no substantial difference between the methods for rocks and aggregates. There may be differences for weak rock because of differences in sample preparation. BS EN 1744-1 Clause 10.1 is not suitable for testing of soils as preparation of the whole sample may give lower results and the higher drying temperature of 110 ± 5°C will affect sulfate solubility in the 2:1 water/soil extract. The preparation of the solution for analysis using hot water is unsuitable for natural aggregates, soils and rocks
pH	TRL 447 Test 1; BS 1377 Clause 12.5	Clause 9	No test	If BS EN 1744-1 is used, pH should be determined as part of the Clause 10.1 test
Acid-soluble sulfate (AS)	TRL 447 Test 2; BS 1377 Clause 7.9; results in % SO ₄	Clause 5.2 and 5.5; result in % SO ₃	Clause 12; result in % SO ₃	Provided units are correctly converted, there should be no difference between the methods for fine-grained soils. There may be differences for coarse-grained soils and weak rock because of differences in sample preparation
Total sulfur (TS)	TRL 447 Test 4A and 4B; BS 1377 Clause 7.10; results in % S	No test	Clause 11.2; result in % S	The high-temperature combustion methods used in TRL 447 Test No 4B, BS 1377 Clause 7.10 and BS EN 1744-1 Clause 11.2 are closely similar and these are the preferred methods. The BS EN 1744-1 Clause 11.1 test should not be used as dissolution with H ₂ O ₂ /HCl employed in the latter is not suitable for complex mixtures of sulfur and silicate minerals
Total reduced sulfur (TRS)	TRL 447 Test 3; BS 1377 Clause 7.11; results in % S	No test	No test	The TRL 447/BS 1377-3:2021 Test is the only one that will extract all forms of reduced sulfur, including the most common form, pyrite, as well as monosulfides. TRS may generally be determined by difference using TRS = TS – AS/3; however, TRS will be overestimated if sulfates resistant to acid are present; e.g. baryte (BaSO ₄)
Monosulfide sulfur (MS)/acid-soluble sulfides	TRL 447 Test 5; BS 1377 Clause 7.12; results in % S	No test	Clause 13; results in % S	Results should be similar for both methods. However, both tests extract only monosulfide minerals. These are usually highly reactive but form only a small part of the total reduced sulfur content. The tests will not determine disulfide minerals, such as pyrite

which damage was apparent was subjected to detailed investigation, including mineralogical and chemical testing, and SEM examination of representative samples of the material.

The fill was found to be dark grey mudstone and muddy limestone, and it contained pyrite as fine-grained crystals and framboids, some of it altered and showing evidence of having expanded (Fig. 33). Occasionally there were visible pyrite crystals. Figure 33c shows clusters of selenite crystals formed within cracks and on bedding planes in the mudstone particles, which would have caused them to expand. Such crystals were also present on the surfaces of aggregate particles, which would push them apart. As selenite is a relatively soft mineral it is unlikely that these crystals would have present when the fill was placed and compacted, which strongly implies that they formed after the fill was placed and in so doing, caused it to expand. Cracks in mudstone particles would provide pathways for water and air to access the pyrite and for reaction products to be taken out. The pressure created by the formation of the selenite was sufficient to lift the floor slab. Expert witnesses in a case described by Matheson and Jones (2015), at the High Court in Dublin, argued that the growth of selenite could have filled the pore space in the fill passively without causing expansion. However, Matheson and Jones (2015) explain that that features of the gypsum crystals was consistent with them having grown forcefully in cracks, thus causing fill particles to expand. In fact, the growth of existing crystals in cracks requires lower surface energy than creating new ones in a void, even if for growth to occur, the sides of a crack must be pushed further apart. The expansion is greater if the particles are weak and laminated.

Chemical testing of the fill indicated that it contained sufficient remaining pyrite and calcite for expansion to continue for a considerable length of time, so the only viable solution to the problem was to replace the fill with pyrite-free rock. This entailed stripping of fixtures and fittings from the houses, removal of the floor slabs and replacement of the fill with pyrite-free stone. Then after casting new floor slabs the houses were refitted. This is obviously an expensive and disruptive procedure that required the occupier to move out for about 3 months. Czerewko and Cripps (2022) explain that the concrete blocks used for construction were also examined and found to contain pyrite-bearing mudstone. Various other research studies into the mudstone fill expansion problem were carried out in Ireland and Sheffield, UK. Studies by Taylor (2015) at Sheffield University demonstrated that once the reaction had started, preventing access to water slowed the expansion, but did not stop it.

Unfortunately, the Home Bond Warranty scheme, which in the event of faulty construction should have covered the cost of remediation, ceased in 2011 to provide cover for damage cause by pyritic expansion of fill, which left many homeowners without any prospect of their property being remediated. The Home Bond scheme and some insurance companies and construction companies did, however, cover the cost of replacing the fill. The Pyrite Remediation Scheme (<https://www.pyriteboard.ie/What-is-Pyrite-Resolution-Board.aspx>) was established in 2013 by the Government of Ireland to provide funding for the remediation of houses damaged by pyritic heave, subject to conditions and where there were no alternative practicable means of financing the necessary works.

Determination of sulfur in geological materials

Anticipating and reacting to the presence of pyrite in geological materials can be achieved only if the presence of sulfur compounds in materials is accurately measured. Until TRL Report 447 (TRL 2001, 2005) and BRE Special Digests 1:2001 and 2005, no guidance was given on this in UK technical literature. Although procedures for determining water- and acid-soluble sulfate and carbonate were specified in BS 1377:1990 and various other British Standards provided methods for determining pyrite in slags, coke

and coal, none of these was designed to analyse soils and rock. TRL Report 447 (TRL 2001, 2005) updated the chemical analysis procedures using instrument-based analytical techniques rather than gravimetric determination of sulfate in solution using barium chloride, as the latter is sensitive to variations between chemists and laboratories. Instead, high-temperature analyser or microwave digestion in aqua regia with inductively coupled plasma mass spectrometry (ICP-MS) analysis to determine total sulfur, were specified. The methods also included a direct determination of pyrite and another troublesome but rarer sulfide mineral called pyrrhotite, but as this method is a fairly complex chemical procedure, it is not ideal for routine testing, so the normal way of determining the amount of pyrite is to calculate it from the difference between the total sulfur and the acid-soluble sulfur. Pyrite is not dissolved by the acid used in the latter test so in most situations in which pyrite and selenite/gypsum are the only sulfur-bearing minerals, the amount of pyrite is indicated by this difference. The small amount of pyrite in organic material, which is present in most dark coloured mudstones and would not be released by the acid treatment, introduces a minor inaccuracy using this procedure. As baryte (BaSO_4) is also resistant to dissolution in acid used to take gypsum into solution but will contribute to the total sulfur present, its presence will lead to pyrite being overestimated.

TRL Report 447 (TRL 2005) established reliable methods for comprehensive determination of sulfur compounds in soils and rocks. The results of the measured parameters in Table 12 were used to determine the derived parameters indicated in the table that were used in TRL447 to specify the limits shown in Table 13 for sulfur compounds in fill for highway projects. BRE Special Digest 1:2005 applied these values to determine the chemical aggressivity of the ground for buried concrete structures, IS 398-1:2013, 2017 applied them for assessing the expansion of fill in Ireland and BRE Digest 522:2011 for fill in the UK. However, in 2016 it was apparent that these were not always being understood or used correctly, with the possibility of inappropriate materials being used in construction.

Table 14, which is from Cripps *et al.* (2019), compares differences in the methods and units to express the results in BS 1377-3:1990; BS1377+A1:2021, TRL Report 447 (TRL 2005) and BS EN 1744:2009+A1:2012, with significant differences highlighted. The need to clarify the use of the parameters in Table 12 resulted in the publication of papers in *QJEGH* and *Ground Engineering* (Czerewko *et al.* 2016; Reid *et al.* 2017). These also drew attention to the potential for inaccurate assessment of pyrite using standard BS EN1744:2009+A1:2012, which in 2016 became the standard for chemical tests for aggregate materials in the UK under the Construction Products Directive of 2004.

Unfortunately, the older gravimetric method of analysis involving the use of barium chloride to precipitate the sulfur in solution is specified in BS EN1744:2009+A1:2012. If properly carried out this should give accurate results, but many testing laboratories prefer to use modern instrument-based methods for these determinations, and therefore substitute their own methods such that the tests are not true to the standard and the results may vary depending on the procedures used. The different drying temperatures are liable to affect the solubility of gypsum so inaccuracies in acid- and water-soluble sulfate values are likely to occur. Another more serious problem arises with the determination of total sulfur, as the acid digestion in the BS EN 1744:2009+A1:2012 clause 11.1 test will not take pyrite into solution, with the result that the amount of pyrite present will be seriously underestimated. Using this test will not determine pyrite, which is a serious deficiency of this standard.

To overcome this deficiency in the default test for aggregates, revisions to BS 1377:1990 were made in 2018, so that it now aligns with the TRL–BRE procedures. Therefore BS1377-3:2018+A1:2021 should be specified for characterizing the chemical character of soils and rocks for construction, including aggregates. This does

depend on practitioners being aware of the potential problems with 1744:2012, as this is the default standard used by the aggregates supply industry (see BS EN 13242:2002+A1:2007). Further information is given in Chapter 37 of the *ICE Manual of Geotechnical Engineering* (Reid *et al.* 2023), which covers sulfates and sulfides in construction materials in some detail.

Conclusions

In spite of all the information about mudrocks and pyrite that is provided in the technical literature, text-books and the guidance on carrying out ground investigations provided in BS 5930:2015+A1:2020 and other standards, the case histories considered in the paper confirm that the behaviour and performance of mudrocks in engineering situations is not always correctly anticipated. In most cases, problems are due to rapid degradation of material properties or the presence of pyrite, which are avoidable if the possibility of them occurring is anticipated and appropriate investigations are carried out. Problems created by rapid degradation and pyrite oxidation can be avoided if appropriate measures are adopted in the engineering design and during the construction. Making changes to the engineering design or construction method during construction is liable to delay projects and increase costs, and post-construction remedial measures, which are liable to be expensive to carry out, may be required where mudrocks fail to perform in the manner anticipated.

As explained in the paper, oxidation of pyrite and the formation of selenite can create serious problems during or after construction such that changes in the design of structures or the construction method, or remedial works are required. This situation may arise when construction begins before the whole design has been finalized or because aspects of the design are decided in ignorance of, or before, the properties and performance of the materials concerned are fully investigated. Although application of the observational approach of Peck (1969) implies that structural design might follow evaluation of the ground conditions that are revealed during construction, it is important that there are contingency plans for the various likely scenarios. Incorrectly anticipating the performance of materials or the implications to construction and engineering design of ground conditions at the outset of a project will usually result in limiting the constructional and design options available to the design team. Making late-stage changes to construction procedures and engineering designs is likely to delay completion, increase the cost of a project and/or result in costly and disruptive post-construction remedial works being required.

Unfortunately, the nature of the problems that may arise with mudrocks means that standard methods of determination of the geotechnical properties for design may not provide adequate means of anticipating their performance in engineering applications. However, various forms of sample pre-treatment, specialist testing and field trials are available to deliver the necessary information. The possibility of rapid degradation and sulfate generation are features of mudrocks that need to be considered at the early stages of projects so that appropriate methods of construction and parameters for design can be used. Relatively simple ways of doing this, including the static slake test, are described in the paper. The possibility of sulfide oxidation or the presence of sulfates can be determined by carrying out relatively inexpensive determinations of total sulfur. Trial embankments and examination of exposed materials are of great benefit in investigations and assessments. Specialist testing may be required to give suitable parameters for design. Such assessments need to be carried out by experienced staff who are aware of the likely performance of the material concerned and the impact of the construction processes, engineering works and climatic change processes on the environmental conditions.

Changes to the access to air and water, groundwater conditions and *in situ* stress conditions throughout the construction period and

design life of the structure are especially important. Degradation of mudrock materials can occur on very short timescales, for example in the period between a ground investigation being carried out and construction commencing or during the construction period, and even one rainfall event could have a significant impact on material properties and behaviour. Relevant site observation, inspection and understanding of potential problems are important for managing and mitigating avoidable problems or issues. Pyrite should be considered a possibility in all dark coloured mudrocks.

The successful construction of roads, railways, dams, slopes, embankments, tunnels, foundations and other structures on, in and out of mudrocks is proof that problems can be avoided by taking the properties and performance of these materials into account in engineering design and construction operations and correctly anticipating the effects of the engineering on the materials. However, the engineering geologist needs to be involved in the early stages of projects as most problems are predictable given the correct data and experience. The publication of case histories is especially helpful for avoiding problems with the construction process, engineering design or geological situation. Although for legal, financial and reputational reasons there can be reluctance to publish case histories for projects, especially where there were problems, it is these latter cases that provide the greatest amount of learning from mistakes. The lack of attention to the behaviour of mudrocks results in avoidable increased cost as designs and construction methods are changed at a late stage or remedial works become necessary. As explained in this paper, a lack of attention to pyrite oxidation processes or the deterioration of geotechnical performance can have serious financial or even have fatal, consequences. Geological processes occur over a wide range of timescales, from millions of years in the slow movement of tectonic plates to days or weeks for weathering processes, such as those described in this paper. The fact that the behaviour and performance of mudrocks can change over relatively short time periods and in response to changes in their environment needs to be taken into account at all stages of engineering design and construction processes.

Vote of thanks

Honoured guests, ladies, gentlemen, good evening.

I first encountered John and his work when tackling a clay mineralogy problem alongside Professor Peter Fookes, the First Glossop Lecturer, and more recently when trying to understand the unusual weathering of a tropical soil. But even before then, I had read and regularly consulted John's important 1981 paper, co-authored with Roy Taylor, and published in the *Quarterly Journal of Engineering Geology*. I feel sure that the paper's short title, 'The engineering properties of mudrocks', contributed to its success. The paper met a demand for an overview of British mudrocks and I recall that a copy was to be found in the personal libraries of many engineering geologists and geotechnical engineers.

I looked at the paper the other day and discovered that it has 119 references, which is a measure of the breadth and depth of its coverage of mudrocks. The paper's text and figures are helpful and incisive, but it is the large, tabulated summary of engineering properties that is truly memorable. The table encompasses 26 mudrocks ranging from the youngest, the Barton Clay of Paleogene age, back through geological time to a group called, rather enigmatically, the 'remaining Lower Paleozoic rocks'.

In their various forms, mudrocks (or mudstones) are the most abundant sedimentary rock on Earth. It is relevant therefore that John's Glossop Lecture this evening has reminded us of a point made in his 1981 paper: the importance of understanding *why* mudrocks behave in the way that they do.

As John has demonstrated, the answers to questions about mudrock behaviour emerge from the key factors that distinguish mudrocks from other naturally occurring materials: their mineralogy and the ability of clay minerals to take on and release water, to change their chemistry, and to rearrange their mineral fabric in response to changes in stress.

But, of course, John did not stop there. Engineering geology is an applied science. His case histories of the practical application of an understanding of mudrock properties to real world problems have brought them alive. And I feel sure that his examples will have made some personal connections with your everyday project work.

Thus, as well as being an academic researcher, John is a teacher and communicator. I well recall, many years ago, being with him on a very rainy day at the Mam Tor landslide. He was helping with a weekend field trip in the Peak District, organised for Atkins' early-career ground engineering professionals. It's a tough task to enthuse people on a wet, slippery hillside in the rain – but he did it!

And he has done it again this evening, here in the more comfortable surroundings of the Royal Institution.

So, please now join me in thanking Dr John Cripps for delivering his Glossop Lecture, and in looking forward to reading the lecture in print.

David Shilston

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