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# The influence of weathering on index properties and undrained shear strength for the Charmouth Mudstone Formation of the Lias Group at a site near Banbury, Oxfordshire, UK

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**Abstract:** The Lias outcrop extends continuously from Dorset to Yorkshire in England, with outlying areas in Somerset and Wales. It underlies the transport routes between a number of major UK cities. Understanding the material properties of the Lias Group is therefore important for infrastructure construction and maintenance across England and Wales.

This study examines the influence of weathering on the engineering properties of the Charmouth Mudstone Formation (Lias Group) in light of recent developments in ground-investigation practice including: (i) the use of modern visual weathering classifications for soils and rocks; and (ii) the availability of large ground-investigation datasets from the construction of the High Speed Two (HS2) railway.

The variability in the undrained shear strength data was consistent with the moisture content, liquidity index and plasticity index of the samples, but they were poorer indicators than shown in previous studies. The visually-assessed weathering class and the depth below ground level were found to be more useful indicators of the undrained shear strength of the clay and mudstone samples of the Charmouth Mudstone Formation.

**Supplementary material:** Dataset for the Undrained Shear Strength and Index Properties of Charmouth Mudstone Formation Samples Excavated Near Banbury, Oxfordshire, UK, is available from the University of Bath Research Data Archive at https://researchdata.bath.ac.uk/id/eprint/1012

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The Whitby Mudstone and Charmouth Mudstone of the Lias Group (formed 174–183 and 183–199 myr ago, respectively: Cox *et al.* 1999) were formerly known as the Upper Lias Clay and Lower Lias Clay. They were deposited within the shallow seas of the Wessex Basin, the Worcester Basin, the East Midlands Shelf and the Cleveland Basin, leading to remarkably uniform sediment sequences up to 200 m thick (Hobbs *et al.* 2012). Glacial and periglacial conditions in the last 200 kyr resulted in overconsolidation (glacial) and weathering (periglacial). The Lias outcrop now extends continuously from Dorset to Yorkshire in England, with outlying areas in Somerset and Wales (Hobbs *et al.* 2012). It is therefore of engineering significance to a number of major transport routes including the A303, and the M4, M40, M1 and A1 motorways, and the northeastern and northwestern rail routes; as well as the construction of the High Speed Two (HS2) railway and the Yorkshire polyhalite mines. Understanding the effect of both past and contemporary weathering processes on the material properties of the Lias Group is therefore important for infrastructure construction and maintenance across England and Wales.

Chandler (1972) presented data on the weathering of the Whitby Mudstone Formation and developed a descriptive weathering classification scheme (zones I–IV) from borehole records obtained from up to 15 m below ground level (mbgl) at five sloping sites. These results showed that greater weathering correlated with increased oxidation, increased moisture content and reduced undrained shear strength. Different weathering zones showed distinct relationships between undrained strength and moisture content, with the relationship between undrained shear strength and depth also being potentially weathering dependent.

Six zones of weathering (zones I–VI) were subsequently identified in shallow (up to 4.5 mbgl) excavations in the Charmouth Mudstone Formation at Blockley, Gloucestershire (Coulthard and Bell 1993). Relationships between weathering and the reduced undrained shear strength of excavated samples were developed using indicators such as the iron content, fissure spacing, moisture content, liquid limit and plasticity index.

An assessment of the Lias Group using data from across England and Wales, including a geological description of the Charmouth Mudstone Formation, was given by Hobbs *et al.* (2012). Information from the British Geological Survey (BGS) Geotechnical Properties Database (Hobbs *et al.* 2012) showed that the undrained shear strength of the Lias Group increased with depth, but with significant variability in strata at less than 15 mbgl. Similar weathering effects were observed in other overconsolidated clays and mudstones in England, including, for example, the London Clay and the Mercia Mudstone (Cripps and Taylor 1981).

The HS2 railway between London and Birmingham (Munro 2021) crosses the Lias Group outcrop near Banbury, Oxfordshire, England. This paper explores the impact of weathering on the clay and mudstone strata of the Lias Group, based on measurements from the HS2 ground investigation. This study re-examines the influence of weathering on the engineering properties of the Charmouth Mudstone Formation in light of recent developments in ground-investigation practice. These include: (i) the use of modern visual weathering classifications for soils and rocks (Spink and Norbury 1993; British Standards Institution 2020; Norbury 2020); (ii) the digitalization and transfer of ground-investigation data through the AGS Data Format (Chandler *et al.* 2006); and (iii) the availability of high-quality deep, localized ground-investigation datasets.

The aim of the study was to understand the influence of weathering on the *in situ* physical, mineralogical and chemical properties of clays and mudstones from deep (up to 45 mbgl) exploratory holes in the Charmouth Mudstone Formation (Lias Group). The Spink and Norbury (1993) weathering classification, descriptive statistics and inferential statistics were used to explore data from a large, localized ground investigation covering the full extent of the Charmouth Mudstone Formation outcrop near Banbury, Oxfordshire, UK.

## Method

### *Data and processing*

Samples of Charmouth Mudstone were taken from a total of 373 individual exploratory holes along an 18.2 km length north of Banbury (Fig. 1). Hobbs *et al.* (2012) described the Charmouth Mudstone Formation in the region of the site (the East Midlands Shelf) as 100–150 m thick, with a remarkably uniform internal stratigraphy. The weathering profile was described as gradational, resulting from glacial, periglacial and contemporary weathering in this region (Quaternary Province 4: Foster *et al.* 1999). The lithology of the formation is principally mudstone, weathering to clay at shallower depths. However, some thin limestone bands, sandstone bands and superficial deposits are also present. These were excluded from the analyses presented in this paper.

The exploratory holes included trial pits and boreholes drilled using rotary, cable percussive and windowless sampling rigs, as part of the commercial ground investigation for the construction of the HS2 railway. The details of the ground investigation and subsequent laboratory testing were recorded in factual reports and in the .ags text format, known as the AGS Data Format (AGS 2011). The data were filtered to include only clay and mudstone samples from the Charmouth Mudstone Formation. Samples from superficial deposits or from bands of limestone and sandstone within the Charmouth Mudstone Formation were not included in the analyses.

The ground-investigation and testing data reported by commercial laboratories and considered in this study are summarized in Table 1. Soil classification data, including moisture content ($w$, in %), liquid limit ($w_{LL}$, in %) and plastic limit ($w_{PL}$, in %) were obtained from 1256 samples. Unconsolidated, undrained (UU) triaxial shear strength (in kPa) data were obtained from 223 tests on 202 samples (14 tests were multi-stage). The rotary cored UU triaxial samples were *c.* 100 mm in diameter and *c.* 200 mm long, and were tested at a cell pressure equal to the estimated *in situ* total vertical stress ($\sigma_v$) (202 tests), $2\sigma_v$ (14 tests) or $3\sigma_v$ (seven tests). Undrained shear strength measurements in stiff clays are influenced

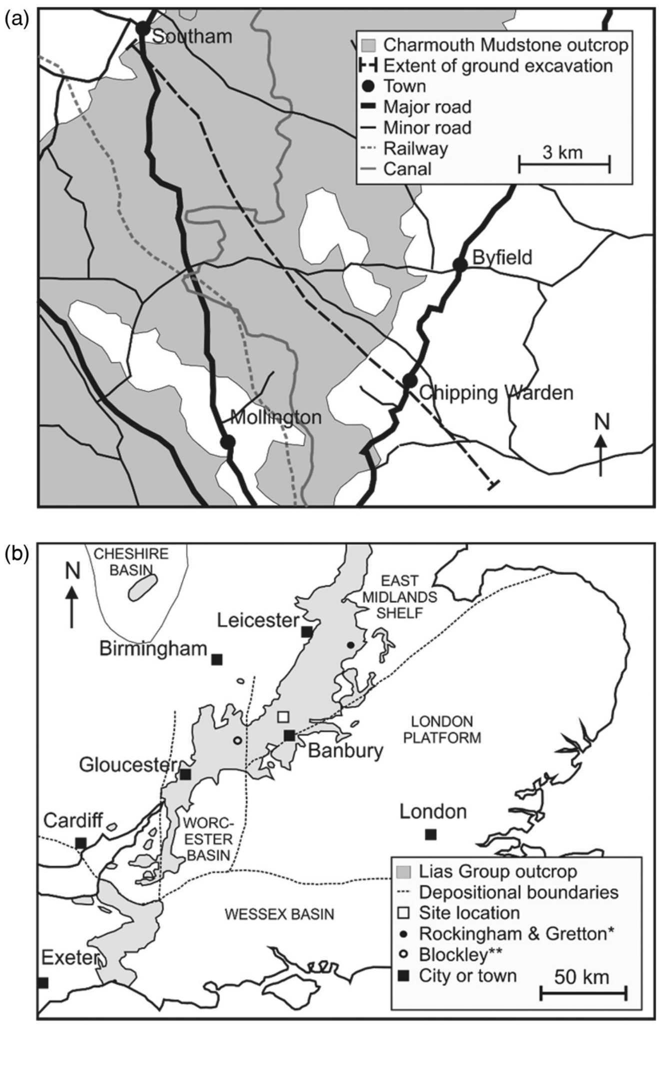


**Fig. 1.** The site location plan showing: (**a**) the extent of a 18.2 km-long ground investigation in the Charmouth Mudstone Formation (the formation outcrop is shown as grey), between Southam and Banbury, UK; and (**b**) the site, nearby towns and cities in relation to the Lias Group outcrop and main sedimentary basins (adapted from Cox *et al.* 1999). The locations of *Rockingham and Gretton (Chandler 1972), and **Blockley (Coulthard and Bell 1993) are shown.

**Table 1.** *A summary of soil laboratory testing data reported by commercial laboratories for samples from the Charmouth Mudstone Formation, excavated near Banbury, Oxfordshire, UK*

| Weathering class* | No. of classification samples† | No. of chemical tests‡ | No. of UU triaxial tests§ |
|---|---|---|---|
| E | 249 | 6 | 19 |
| D | 276 | 10 | 23 |
| C | 177 | 25 | 27 |
| Bb | 86 | 1 | 26 |
| Ba | 155 | 35 | 49 |
| A | 270 | 19 | 62 |
| Other (incomplete data) | 43 | 24 | 17 |
| Total | 1256 | 120 | 223 |

*After Spink and Norbury (1993).
†Tested to BS 1377-2:1990 (British Standards Institution 2010*a*) and BS EN ISO 17892-1:2014 (British Standards Institution 2014).
‡Tested to TRL446 (Reid *et al.* 2005).
§Unconsolidated undrained triaxial tests, BS 1377-7:1990 (British Standards Institution 2010*b*).

by sample disturbance due to boring, sampling and testing (Vaughan *et al.* 1992; Phoon and Kulhawy 1999). Ding and Loehr (2019) showed that the variability due to sample disturbance was least for isotropically consolidated undrained triaxial compression (CIUC) tests, slightly greater for unconsolidated undrained triaxial compression tests (UU) and greatest for unconfined compressions (UC) tests. The UU triaxial shear strength data were selected for these analyses because they are routinely undertaken in practice; and hence a large dataset was available from the HS2 ground investigation. The variability of the soil classification and undrained shear strength data is summarized in Appendix A.

Chemical testing data, determined by commercial laboratories according to TRL Report 447, Test 1 (Reid *et al.* 2005), were obtained from 120 of the 1256 soil classification samples. These included measurements of pH, water-soluble sulfate (mg $l^{-1}$), acid-soluble sulfate (% $SO_4$) and oxidizable sulfides (% $SO_4$). Whole-rock and clay mineral X-ray powder diffraction (XRD) data were obtained from 14 samples at four borehole locations using a PANalytical X'Pert3 Diffractometer employing copper Kα radiation ($\lambda_i$ = 0.15406 nm). Microscopic examination was undertaken to estimate modal mineral content (Dickinson 1970) for a thin, epoxy-resin-impregnated sample prepared from a sawn slice of Class A mudstone retrieved from 17.60 mbgl.

Borehole logs, including a strata description and a visual weathering classification, were available for all 373 exploratory holes. Standpipe piezometer data, comprising approximately nine monthly readings in 2017, were obtained from 29 borehole locations.

The weathering profile was recorded in the commercial ground investigation according to BS 5930:2015+A1:2020 'Approach 4', for weak rocks (classes A–E) (British Standards Institution 2020). For the purpose of this paper, this was converted to the Spink and Norbury (1993) classification for Lias Clay (Table 2) by separating the strata recorded as Class B weathering into CLAY (Class Bb) and MUDSTONE/CLAY (Class Ba) according to the information in the strata description. This separation of the partially weathered Class B material was found to be significant in the subsequent data analyses.

The Spink and Norbury (1993) weathering classes range from unweathered mudstone (Class A) through partially weathered (classes Ba and Bb), distinctly weathered (Class C), destructured (Class D) to reworked (Class E) clay. The weathering classification considers indicators such as fissures (e.g. spacing and orientation), soil fabric (e.g. lithorelicts and bedding features), visible chemical changes (e.g. colour) and evidence of chemical processes (e.g. oxidation, leaching or mineral deposition). Details are summarized in Norbury (2020).

The data were used to explore the influence of weathering, as defined by the weathering class, on the soil classification properties, chemical properties and undrained shear strength of the samples.

The soil descriptions included 14 different colours, with up to three being used for any one stratum. These descriptions were reclassified into three groups, to identify the presence of oxidation, as follows.

(1) Grey: descriptions including all shades of grey (dark grey, grey, bluish grey, light grey and greenish grey), but with no brown staining described.

(2) Brown: descriptions that included brown or grey with brown staining (brown, dark brown, brownish grey and greyish brown).

(3) Brown chroma: descriptions that included brown chroma (yellowish brown, orangish brown and reddish brown).

**Table 2.** *Formation-specific weathering classification for Lias Clay in accordance with BS 5930:2015 + A1:2020 Approach 4 (British Standards Institution 2020) and using the Spink and Norbury (1993) descriptions. Adapted from Norbury (2020)*

| Weathering class for weak rocks* | Weathering class for Lias Clay† | Example description‡ | Zone§ |
|---|---|---|---|
| Reworked (E) | Reworked (E) | Stiff light grey and light brown mottled, becoming grey with depth, CLAY. In upper parts, frequent coarse-sand-sized haematite and rotated lithorelicts up to 1 mm. In lower parts, lithorelicts are rotated and up to coarse gravel size (30 mm). Frequent short polished shear surfaces throughout | Landslip/ solifluction |
| Destructured (D) | Destructured (D) | Not observed | IV |
| Distinctly weathered (C) | Distinctly weathered (C) | Very stiff to stiff fissured light brown CLAY. Fissures extremely to very closely spaced (10–30 mm) with remoulded light grey gleyed clay up to 20 mm thick and containing occasional polished surfaces. Lithorelicts horizontally aligned. Frequent gypsum crystals | III |
| Partially weathered (B) | Partially weathered (Bb) | Very stiff fissured and sheared bluish grey CLAY. Fissures generally very closely spaced stained brown with discoloration penetrating. Shears show 1–2 mm displacement. Infrequent gypsum crystals | IIb |
| Partially weathered (B) | Partially weathered (Ba) | Extremely weak to very stiff fissured bluish grey MUDSTONE/CLAY. Fissures generally very closely spaced stained brown. Rare gypsum crystals | IIa |
| Unweathered (A) | Unweathered (A) | Extremely weak to very weak fissured bluish grey MUDSTONE. Fissures generally closely spaced. Bedding horizontal | I |

*According to BS 5930:2015 + A1:2020, Approach 4: general classification for weak rocks (British Standards Institution 2020).
†After Spink and Norbury (1993).
‡Descriptions provided by Norbury (2020) in accordance with the general classification for weak rocks.
§From Chandler (1972).

Information describing the fabric of the strata was extracted from the borehole strata descriptions and assigned to the triaxial data, where possible. This included the discontinuity (fissure or bedding) spacing and bedding thickness of each stratum. The discontinuity spacing (in mm) in each stratum was classified as extremely closely spaced (<20 mm), very closely spaced (20–60 mm), closely spaced (60–200 mm), medium spaced (200–600 mm), widely spaced (600–2000 mm) or very widely spaced (>2000 mm), in accordance with Norbury (2020). A minimum discontinuity spacing was assigned to 81 of the 223 triaxial samples.

### *Statistical analysis*

In addition to the conventional, visual assessment of the data, statistical techniques were applied to compare possible explanatory variables for the outcome variable of undrained shear strength. In this context, an explanatory variable was any parameter that could be used to predict another parameter (the outcome variable). The term explanatory variable was used rather than independent variable because many geotechnical parameters are not independent (e.g. the variables of depth and total stress or moisture content and liquidity index).

Key explanatory variables for the undrained shear strength were identified during preliminary data visualization (e.g. Spiegelhalter 2019). The sample elevation was considered as an explanatory variable during preliminary data visualization. It was subsequently excluded from the analyses because it showed a weaker correlation with the outcome variable than the sample depth.

When considering the triaxial test data, the correlation variables included the weathering class (A–E), which was considered as an ordinal categorical variable, and the continuous variables of log-transformation of undrained shear strength (in kPa), log-transformation of sample depth (in m), moisture content ($w$, in %), liquidity index ($I_L$) and plasticity index ($I_P$, in %). Spearman's rank correlation coefficient was used to test the strength of association between the variables. The log-transformation of the undrained shear strength and the depth did not affect the Spearman rank correlation values. Spearman's test ranks the data (Spearman 1910), before applying Pearson's equation (Dodge 2008), to obtain the correlation coefficient ($\rho$). This allows the correlation between the weathering class (an ordinal categorical variable) and the other (continuous) variables to be compared.

Regression was used to compare directly the ability of the explanatory variables to predict the dependent variable of undrained shear strength. Linear regression was used to compare the ability of each explanatory variable (Table 3) to predict an assumed linear relation with the natural log-transformation of the undrained shear strength (outcome variable). This was undertaken for (i) all samples (classes A–E) and (ii) the weathered samples (classes Ba–E). Multiple regression (using multiple explanatory variables) was not undertaken to avoid collinearity or interdependence between the different explanatory variables (e.g. the moisture content and the liquidity index).

The results of the linear regression were interpreted using the coefficient of determination ($R^2$) to measure the amount of variability in one variable that was shared by another (the greater the value of $R^2$, the better the model fit). The $R^2$ value corresponds to the proportion of variation in the dependent variable that is explained by the model.

In regression analyses, the $P$ value indicates the probability of the explanatory variables being linearly related to the dependent variable by chance, if the null hypothesis (no effect) is correct. Evidence that the null hypothesis is not correct can be described as moderately significant, significant and highly significant for $P$ values of 5% ($P$ = 0.05), 1% ($P$ = 0.01) and 0.1% ($P$ = 0.001), respectively. A $P$ value of 0.01 was chosen as the threshold for these analyses.

## Results

Figure 2 shows the Ordnance Survey (2015) northing and elevation of the 1256 Charmouth Mudstone Formation samples projected onto a north–south cross-section of the site. This shows that the ground level varied by *c.* 65 m along the 18.2 km length of the ground investigation. Clay samples from weathering classes Bb–E are located close to the ground surface, with less weathered mudstone material (classes A and Ba) at greater depth. A zone of deep weathering is indicated by the Class Ba mudstone at the centre and towards the north of the cross-section. Limestone bands (not shown) indicated an apparent dip towards the south of less than 1° in the north–south cross-section. Standpipe piezometer data (not shown) indicated a water level of 0.5–1 mbgl across the site in April 2017, with limited variation (up to 0.5 m) over a 9 month period.

The results of whole-rock XRD analysis show a uniform distribution of quartz, illite and smectite minerals with depth. There were high levels of calcite close to calcite-rich rocks in one borehole at 3 and 38.50 m depth (Table 4). Microscopic examination of a Class A sample (17.60 mbgl) showed the modal occurrence of quartz (25%), micas (17%) and chlorite (5%), with smaller volumes of pyrite, siderite, calcite and feldspars, and a matrix of clay minerals (37%). Most of the XRD samples were from Class A and Class Ba strata, so it was not possible to compare the

**Table 3.** *Linear regression of the log-undrained shear strength of the 223 triaxial samples of Charmouth Mudstone for five different explanatory variables. Results are shown for (a) all samples (weathering classes A–E) and (b) weathered samples (weathering classes Ba–E)*

| Explanatory variable | Intercept | Trend | $P$ value of trend | $R^2$ |
|---|---|---|---|---|
| (a) Outcome variable = log-undrained shear strength | | | | |
| Weathering class | 5.08 | −1.25* | <0.001 | 0.51 |
| Log-depth | 3.79 | 0.69 | <0.001 | 0.54 |
| Moisture content | 7.49 | −0.12 | <0.001 | 0.43 |
| Liquidity index | 4.77 | −3.36 | <0.001 | 0.43 |
| Plasticity index | 7.14 | −0.07 | <0.001 | 0.24 |
| (b) Outcome variable = log-undrained shear strength | | | | |
| Weathering class | 4.88 | −0.67† | <0.001 | 0.30 |
| Log-depth | 4.11 | 0.46 | <0.001 | 0.37 |
| Moisture content | 6.42 | −0.07 | <0.001 | 0.38 |
| Liquidity index | 4.77 | −3.36 | <0.001 | 0.37 |
| Plasticity index | 7.14 | −0.07 | <0.001 | 0.21 |

*A linear trend was fitted through the weathering class categories.
†A linear trend was fitted through the weathering class categories.

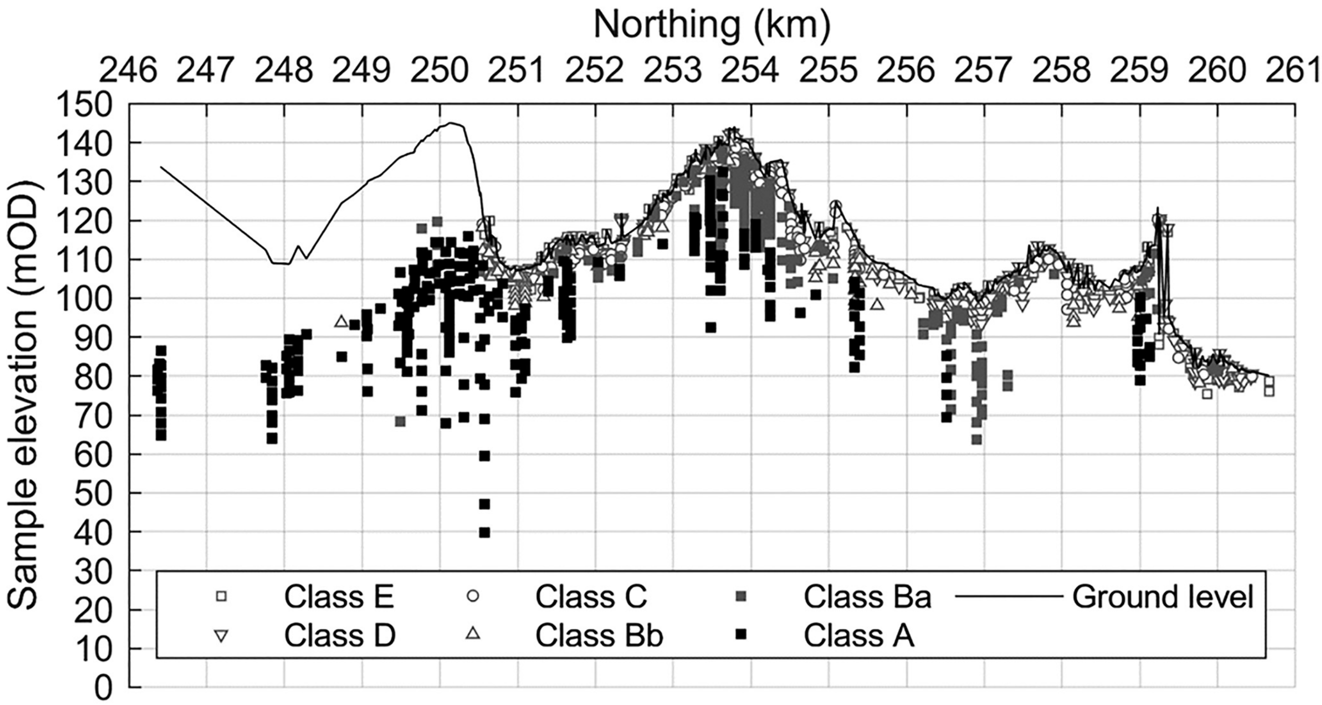


**Fig. 2.** The location of 1256 soil classification samples projected onto a north–south cross-section and categorized by weathering class (A–E). Note that samples from the overlying Dyrham Formation and Whitby Mudstone Formation are not shown.

influence of weathering (e.g. classes C–E) on mineralogy. Particle size information from the clay and mudstone samples showed that the mean average fines content (<0.063 mm) was 88% and relatively uniform throughout the ground profile; with some samples of low fines content (<40%) at shallow depth (<3.5 mbgl).

### *General classification*

Figure 3 shows a boxplot of the depths of the 1256 soil classification samples, categorized by weathering class. This shows that the least weathered material (Class A) was at the greatest depth, while the most weathered material (classes C–E) was located close to the ground surface (<5 mbgl). The medians of the sample depths are different for each weathering class, but there is a strong overlap between the depth ranges. This indicates a gradational weathering profile; in agreement with regional-scale observations of glacial, periglacial and contemporary weathering (Hobbs *et al.* 2012).

The soil classification data showed the greatest variation in material properties near the ground surface (up to 5 mbgl), with reduced variations at greater depth (Appendix A). Below 5 mbgl, both the moisture content and liquidity index of the samples decreased with increasing depth below ground level. The plastic limit, liquid limit and plasticity index decreased slightly with depth, but to a lesser extent and with significant variability. These results are in agreement with trends shown for data from the East Midlands Shelf, the Worcester Basin and the Wessex Basin (Hobbs *et al.* 2012). The plasticity results are shown in Figure 4, categorized by weathering class. The median values show that the mudstone (classes A and Ba) was of intermediate plasticity and the more weathered clay material was of high plasticity. Boxplots of the soil classification data (Fig. 5) showed that the moisture content and liquidity index of the samples increased with increased weathering, in agreement with Chandler (1972). The plasticity index of the samples increased with increased weathering, but with significant overlap between the weathering classes.

**Table 4.** *Whole-rock XRD results for Charmouth Mudstone samples from four borehole locations*

| | Whole rock (wt% by mineral phase) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample depth (and weathering class) | Quartz | Calcite | Pyrite | Illite + mica | K-Feldspar | Kaolinite | Chlorite | Illite–smectite | Plagioclase | Siderite | Total |
| 3.00 m (C) | 16 | 62 | 2 | 11 | 0 | 6 | TR | 3 | 0 | 0 | 100 |
| 5.07 m (C) | 23 | 5 | 3 | 36 | 3 | 15 | 6 | 7 | 3 | 1 | 100 |
| 10.85 m (Ba) | 25 | 7 | 2 | 30 | 3 | 13 | 5 | 5 | 2 | 9 | 100 |
| 13.00 m (Ba) | 22 | 4 | 2 | 40 | 3 | 14 | 5 | 8 | 2 | 1 | 100 |
| 17.60 m (A) | 22 | 5 | 3 | 35 | 2 | 16 | 6 | 7 | 2 | 2 | 100 |
| 19.18 m (Ba) | 23 | 5 | 3 | 38 | 2 | 13 | 5 | 8 | 2 | 2 | 100 |
| 19.65 m (A) | 20 | 4 | 3 | 39 | 3 | 16 | 6 | 7 | 2 | 0 | 100 |
| 19.75 m (Ba) | 22 | 5 | 3 | 39 | 2 | 14 | 5 | 7 | 2 | 2 | 100 |
| 23.20 m (A) | 18 | 8 | 9 | 34 | 2 | 13 | 6 | 8 | 2 | 0 | 100 |
| 25.64 m (A) | 21 | 6 | 9 | 33 | 2 | 12 | 6 | 8 | 3 | 0 | 100 |
| 30.15 m (A) | 19 | 5 | 4 | 40 | 2 | 14 | 5 | 8 | 2 | 0 | 100 |
| 31.55 m (A) | 16 | 7 | 3 | 35 | 2 | 19 | 5 | 9 | 2 | 1 | 99 |
| 38.50 m (A) | 10 | 46 | 10 | 17 | 0 | 8 | 3 | 5 | 0 | 0 | 99 |
| 40.60 m (A) | 20 | 8 | 5 | 35 | 2 | 15 | 4 | 8 | 2 | 1 | 100 |

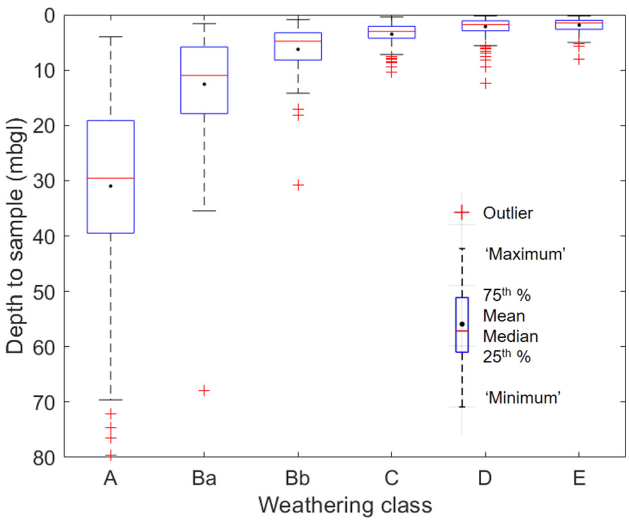


**Fig. 3.** A boxplot showing the sample depth (mbgl) of the 1256 soil classification samples categorized by weathering class (A–E). Note that the maximum and minimum whisker lengths are the 75th and 25th percentiles ±1.5 times the interquartile range, respectively.

Figure 6 shows the sample depth and strata discontinuity spacing (in mm) of 81 triaxial samples from strata with extremely close (12 samples), very close (two samples), close (21 samples), medium (10 samples), wide (23 samples) and very wide (13 samples) discontinuity spacing. The minimum discontinuity spacing was extremely close (<20 mm) in the weathered strata, which corresponded to triaxial samples from less than 12 mbgl (classes Bb–E). All triaxial samples from Class Ba were located in strata with close (60–200 mm) and medium (200–600 mm) spaced discontinuities, while most triaxial samples from Class A were located in strata with close (60–200 mm) to very widely spaced discontinuities (>2000 mm). The bedding thickness of the strata associated with the triaxial samples (not shown) was described as thinly laminated (<6 mm) to very thinly bedded (20–60 mm), but did not show a relationship with sample depth or weathering class.

Chemical testing showed that oxidizable sulfides ($SO_4$), such as pyrite, were absent at 0–2 mbgl and rare at 2–4 mbgl, in agreement with measurements in other Jurassic mudstones (St John 2020). These zones extended below the measured groundwater level (0.5–1 mbgl), indicating that the weathering profile was created during a past period during which the groundwater level was lower than it is now. Comparison of the oxidizable sulfide ($SO_4$) data with the soil colour descriptions (Fig. 7) showed close agreement. Oxidized brown chroma soil extended to 2.25 mbgl, with a mean and 75th percentile $SO_4$ of 0.34% and 0.6%, respectively. Oxidized brown soils extended to 4 mbgl with an equally low mean and 75th percentile $SO_4$ of 0.12% and 0.5%, respectively. In contrast, the clay

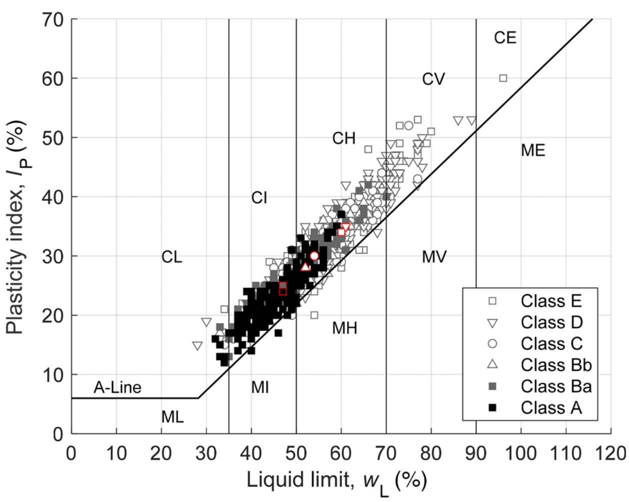


**Fig. 4.** A Casagrande plot showing the plasticity results for all soil samples (1256 samples) categorized by weathering class (A–E). Median values for each weathering class (A–E) are outlined in red.

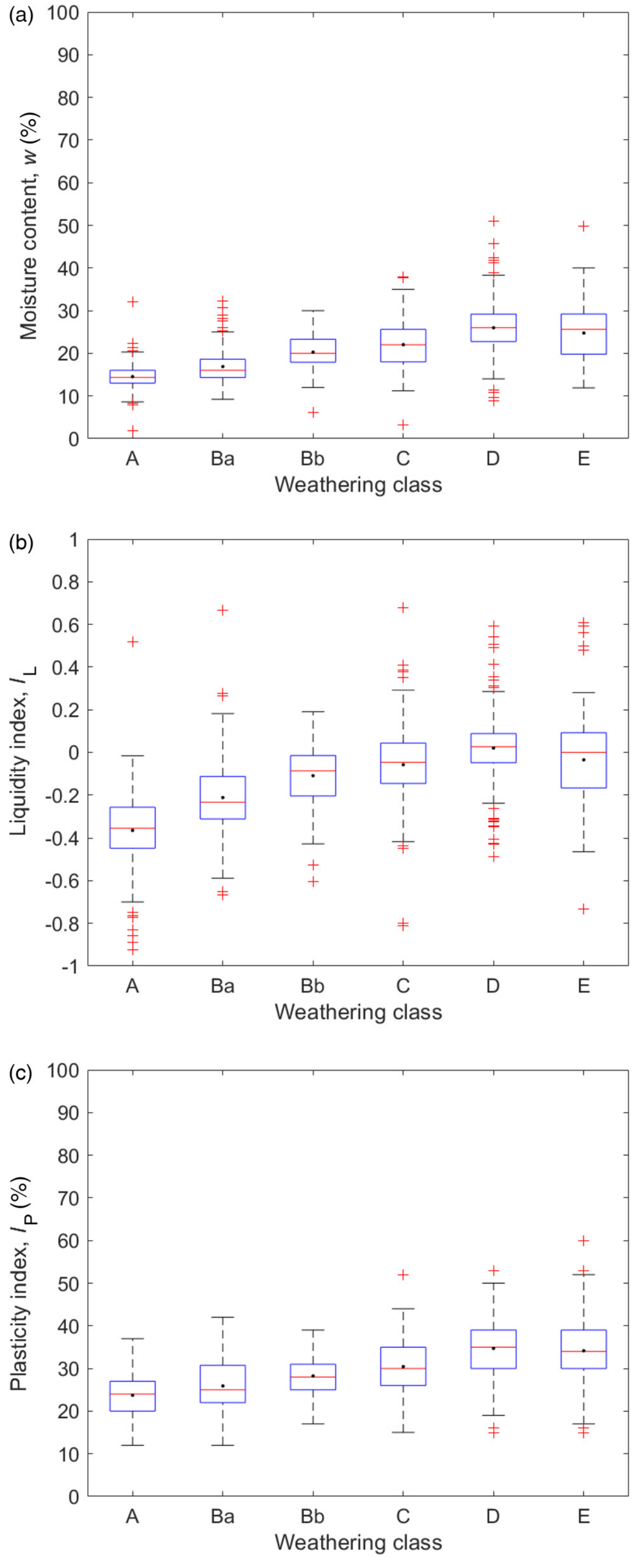


**Fig. 5.** Boxplots of soil classification data (1256 samples) categorized by weathering class (A–E). Values for (**a**) moisture content (%), (**b**) liquidity index and (**c**) plasticity index (%) are shown.

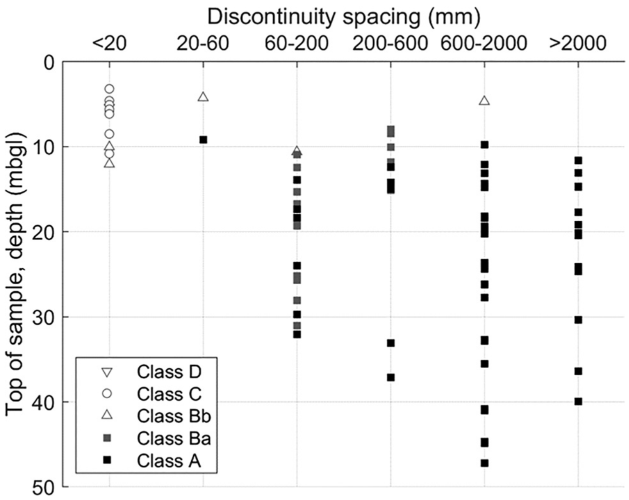


**Fig. 6.** The minimum discontinuity spacing described in the soil strata description corresponding to the locations of 81 of the 223 triaxial samples (classes A–D) compared to the sample depth (mbgl). The discontinuity spacings were classified as: (i) extremely close (<20 mm); (ii) very close (20–60 mm); (iii) close (60–200 mm); (iv) medium (200–600 mm); (iv) wide (600–2000 mm); and (v) very widely spaced (>2000 mm).

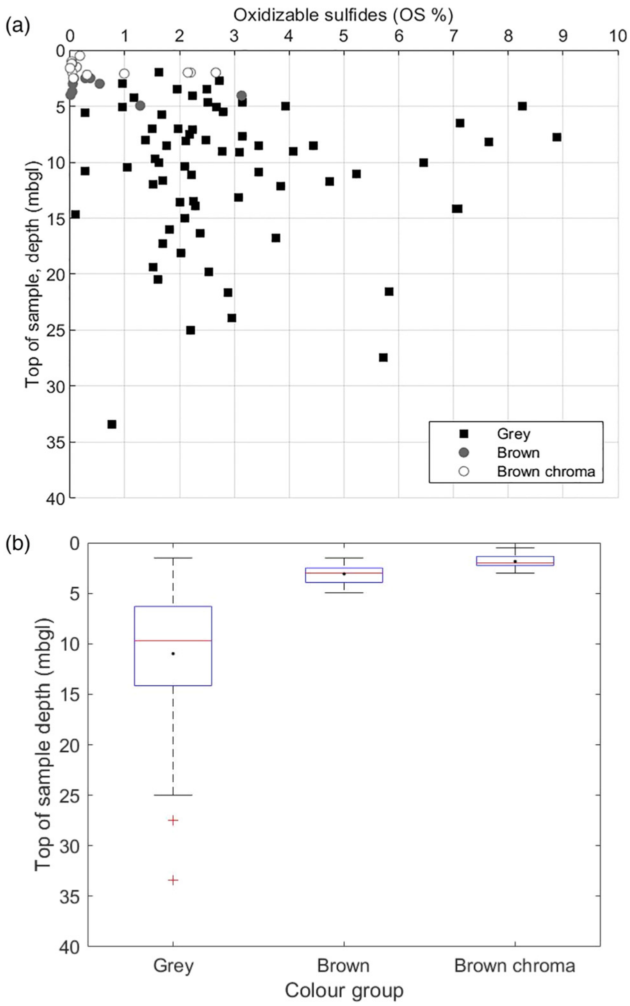


**Fig. 7.** A comparison of oxidizable sulfides ($SO_4$) with (**a**) depth of sample (mbgl) and (**b**) colour of sample. The data include 69 grey samples, 11 brown samples and 16 brown chroma samples.

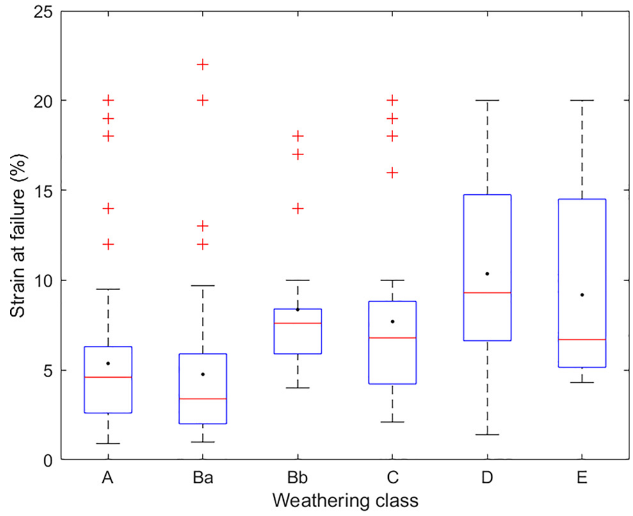


**Fig. 8.** The axial strain at failure of Charmouth Mudstone Formation samples (223 triaxial tests) categorized by weathering class (A–E).

and mudstone at greater depth was characterized as grey in colour with a higher mean (2.9%) value of $SO_4$. The pH of the soil increased linearly with depth, from *c*. 7.5 at the ground surface to *c*. 9.5 at 20 mbgl (not shown).

The axial strain at failure (Fig. 8) was much greater in the more weathered clay samples (classes D and E) than in the less weathered,

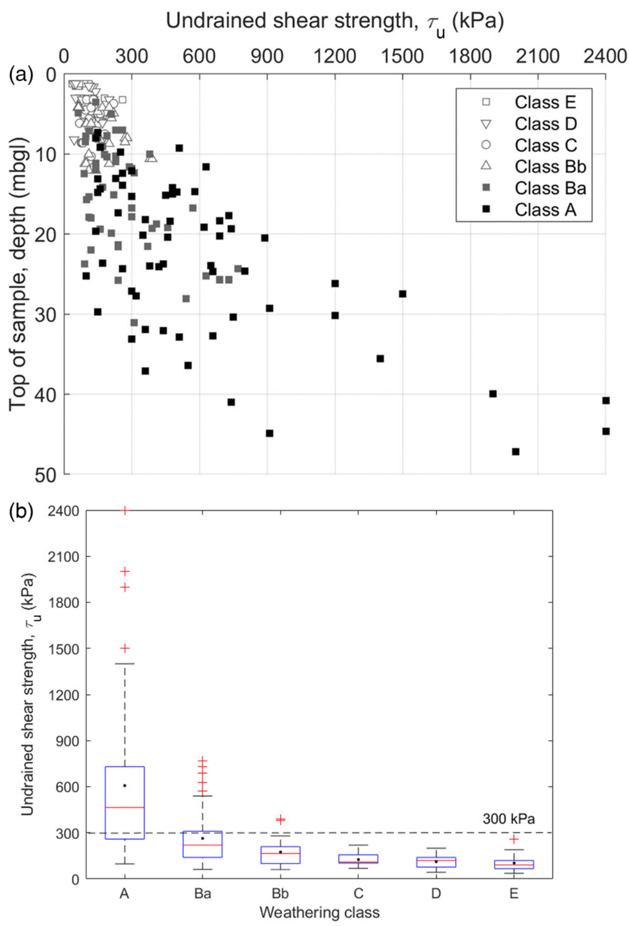


**Fig. 9.** The undrained shear strength (kPa) of Charmouth Mudstone Formation samples (223 tests) compared to (**a**) sample depth below ground level (m) and (**b**) weathering class (A–E).

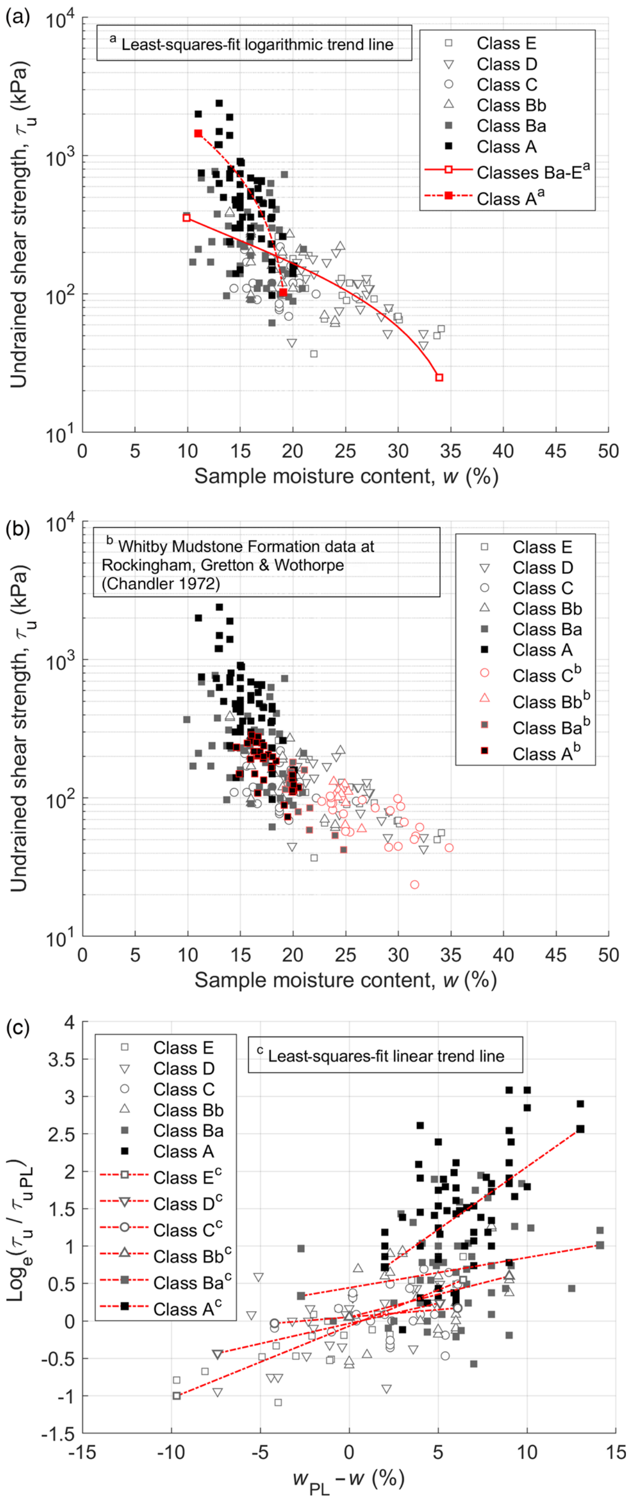


**Fig. 10.** The moisture content (%) of the Charmouth Mudstone Formation samples (classes A–E) (**a**) compared to the undrained shear strength (kPa), (**b**) compared to the undrained shear strength (kPa) and comparative data from the Whitby Mudstone Formation (Chandler 1972) and (**c**) normalized by the plastic limit ($w_{PL}$) and compared with the natural logarithm of the undrained shear strength divided by the undrained shear strength at the plastic limit ($\tau_{uPL}$).

mudstone samples (classes A and Ba), in agreement with Chandler (1972). Most of the unconsolidated, undrained (UU) triaxial samples from weathering classes A, Ba, Bb and C exhibited brittle failure. Figure 9 shows that the undrained shear strength data may be categorized in three groups:

- Class Bb, C, D and E material, characterized by an undrained shear strength of less than 210 kPa (75th percentile) and located at depths of less than 11 mbgl (75th percentile).
- Class Ba material, characterized by an undrained shear strength of between 140 and 310 kPa (interquartile range), located at depths of between 10 and 20 mbgl (interquartile range).
- Unweathered, Class A material characterized by a higher undrained shear strength of more than 260 kPa (25th percentile), increasing with depth (median value 465 kPa) and located at depths greater than 15 mbgl (25th percentile).

Figure 10a shows the undrained shear strength as a function of the moisture content of each sample, categorized by weathering class (classes A–E). It includes least-squares-fit logarithmic trend lines for the weathered (classes Ba–E) and unweathered material (Class A). The weathered materials (classes Ba–E) were grouped together because there was limited difference between the trend lines fitted to individual weathering classes (not shown). Figure 10a shows increased undrained shear strength with decreasing moisture content. The undrained shear strength of the unweathered material (Class A) varied considerably over a small range of moisture content values. It varied over a larger range of moisture content values in the weathered material (classes Ba–E). This is consistent with the idealized relationship between moisture content and undrained shear strength proposed by Chandler (1972), and with results for the Lias Group (Chandler 1972; Hobbs *et al.* 2012) and London Clay (Chandler and Apted 1988).

Figure 10b compares the data from Figure 10a with that from the Whitby Mudstone Formation at Rockingham, Gretton and Wothorpe, 55–75 km distant (Chandler 1972). The results are in broad agreement, showing decreased undrained shear strength and increased weathering with increased moisture content. However, the Chandler (1972) data from 38 mm-diameter samples show a higher moisture content and a more limited range of undrained shear strength values than those from the 100 mm-diameter samples from the Charmouth Mudstone Formation.

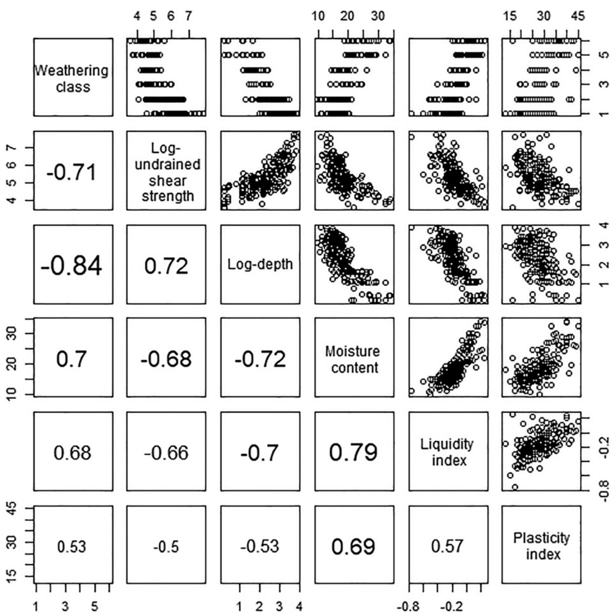


**Fig. 11.** The relationship between the explanatory material property variables for 223 triaxial tests of Charmouth Mudstone (classes A–E). The upper triangular matrix of the figure shows the cross-plots of the variables. The lower triangular matrix of the figure shows the Spearman's rank correlation between the variables.

Figure 10c shows the undrained shear strength data, normalized by the undrained shear strength at the plastic limit (assuming $\tau_{uPL}$ = 110 kPa: Skempton and Northey 1952) plotted against the difference between the actual moisture content and the plastic limit (measured $w_{PL}$). A linear trend in Figure 10c allows an estimation to be made of the slope of the isotropic normal compression line ($\lambda$) from index test data in plastic soils (Wood 1990; Powrie 2018). More importantly, it should eliminate variations due to differences in the index properties between the different weathering classes (which is small in this case). While the scatter in the data is considerable, Figure 10c does show that the weathered (classes Ba–E) samples had moisture contents closest to the plastic limit and showed some plasticity, while the stronger Class A samples ($\log_e(\tau_u/\tau_{uPL}) > 1$ and, hence, $\tau_u > 300$ kPa) did not. In this regard, it is interesting to note that the weak linear trend shown by the weathered samples in Figure 10c stops at $\log_e(\tau_u/\tau_{uPL})$ > 1; this corresponds to $\tau_u > 300$ kPa, which is the soil–rock boundary defined in BS EN ISO 14688-2 (British Standards Institution 2018*a*) and BS EN ISO 14689 (British Standards Institution 2018*b*).

### *Statistical relationships*

Figure 11 shows the relationship between the variables of log-transformation of the undrained shear strength (in kPa), weathering class (classes A–E), log-transformation of sample depth (in m), moisture content ($w$, in %), liquidity index ($I_L$) and plasticity index ($I_P$, in %) in the triaxial test data. The log-transformations were applied to the undrained shear strength and the depth to obtain linear relationships with the remaining explanatory variables for the regression analyses. This did not affect the rank correlation values shown in Figure 11. The upper triangular matrix of Figure 11 shows cross-plots of the variables. The lower triangular matrix shows the Spearman's rank correlation between the variables. In Figure 11 the log-transformation of undrained shear strength shows the strongest correlation with the log-depth and weathering class, a slightly weaker correlation with the moisture content and liquidity index and the weakest correlation with the plasticity index.

Table 3 summarizes the statistics for regressing the natural-log-undrained shear strength in the triaxial test data using different explanatory variables. A least-squares regression was fitted for each explanatory variable; the intercept, trend value (including its significance) and coefficient of determination ($R^2$) are shown. Table 3 shows that the regression of the natural-log-undrained shear strength on the log-depth for all samples (classes A–E) showed a highly significant trend ($P < 0.001$), with $R^2 = 0.54$: that is, 54% of the variability in the log-undrained shear strength can be explained by the log-depth. Regression of the log-undrained shear strength on the weathering class also showed a highly-significant positive trend ($P < 0.001$), with $R^2 = 0.51$: that is, 51% of the variation in the log-undrained shear strength can be explained by the weathering class. Regression of the log-undrained shear strength on the moisture content, liquidity index and plasticity index showed highly significant negative trends ($P < 0.001$), with $R^2$ = 0.43, 0.43 and 0.24, respectively. Table 3 also shows that when the unweathered samples (Class A) were excluded from the regression, the weathered samples (classes Ba–E) showed the highest $R^2$ values for moisture content, depth and liquidity index ($R^2$ = 0.38, 0.37 and 0.37, respectively), while the weathering class was a weaker explanatory variable ($R^2$ = 0.30). This shows that the weathering class is an explanatory variable for undrained shear strength in the Charmouth Mudstone Formation samples (classes A–E), but is less explanatory if only weathered samples (classes Ba–E) are considered.

## Discussion

The clays and mudstones of the Charmouth Mudstone Formation were clearly influenced by the process of weathering. Their undrained shear strength ($\tau_u$) varied from values associated with rocks ($\tau_u > 300$ kPa) in the unweathered state, through to those associated with clays ($\tau_u < 300$ kPa) in the weathered state. The undrained shear strength was therefore influenced by factors affecting the strength of rocks (e.g. joints, fractures and fissures) and of clays (e.g. effective stress and specific volume/water content). Analyses of the data showed a progression from rock-like to soil-like characteristics with increased weathering, including changes in strength, discontinuity spacing, colour, moisture content and Atterberg limits.

Previous examinations of the Lias Group considered samples from shallow depth (<15 mbgl), which included many weathered, clay-like samples (Chandler 1972; Coulthard and Bell 1993). These undrained shear strength measurements were obtained using *in situ* shear vane tests (Coulthard and Bell 1993), and unconsolidated, undrained tests on 38 mm-diameter samples (Chandler 1972). The results conformed to soil mechanics principles relating the undrained shear strength of the samples to their moisture content and plasticity index.

The samples included in these analyses showed a weaker relationship between the undrained shear strength and plasticity index than previous examinations (Chandler 1972; Coulthard and Bell 1993). The undrained shear strength data were obtained from unconsolidated, undrained tests on 100 mm-diameter, rotary-cored samples. They were excavated from greater depths (up to 47 mbgl) than previous investigations and included a greater proportion of unweathered (Class A) and partially weathered (Class Ba) mudstone samples.

The sample depth and weathering class were stronger explanatory variables of undrained shear strength than the moisture content or plasticity index of the samples (classes A–E). However, the weathering class was less explanatory for the weathered samples (Classes Ba–E). This was because the weathering class includes consideration of discontinuities in the clay and mudstone fabric, which are known to reduce the undrained shear strength measured in triaxial and *in situ* tests (Ward *et al.* 1965; Marsland 1971; Cripps and Taylor 1987). The discontinuity spacing was wider in the strata descriptions corresponding to the location of the unweathered Class A samples (close to very widely spaced: 60 to >2000 mm) than the more weathered Class C samples (extremely close: <20 mm). If fissure and shear discontinuities were influencing the brittle failure of the 100 mm-diameter triaxial samples, this would explain the greater variability in the Class A mudstone data than that from the more weathered clay samples or in previous investigations, because there was greater variation in the occurrence of discontinuities within a single Class A sample. Fabric discontinuities in clays and mudstones, such as relict shears and fissure spacing, can be assessed via visual inspection and classification (i.e. the weathering class), but not from laboratory classification tests.

The Class Ba mudstone was the most difficult to interpret and classify given the data available from the ground investigation. At this site, Class Ba described strata visually similar to an unweathered mudstone (Class A), but with a (lower) shear strength closer to that of a weathered clay (classes Bb and C). The measured or observed features, including the colour and moisture content of the Class Ba mudstone samples, corresponded with those of the Class A mudstone. However, the triaxial test results for the Class Ba material showed an average undrained shear strength of less than 300 kPa, similar to the Class Bb and Class C samples. Most of the Class Ba samples came from strata with more closely spaced discontinuities than the Class A samples. Therefore, the reduced shear strength of the Class Ba samples, relative to the Class A samples, may be due to discontinuities that could not be seen by eye (e.g. in the Zone IIb material described by Chandler 1972), but can be inferred from the closer discontinuity spacing described in the associated borehole log. The depth of the Class Ba samples (up to

31 mbgl) suggests that this alteration to material structure and strength was due to periglacial unloading and weathering-induced material alteration at shallower depth.

## Conclusions

The following conclusions can be drawn from the examination of clay and mudstone samples from the Charmouth Mudstone Formation (Lias Group) at a site near Banbury, Oxfordshire, to inform the classification of Lias Group materials and other weathered mudstones:

(1) Both the visual inspection and chemical testing data show that there is a gradational weathering profile in the Charmouth Mudstone Formation, progressing from the ground surface and characterized by overlapping weathering classes. This progresses

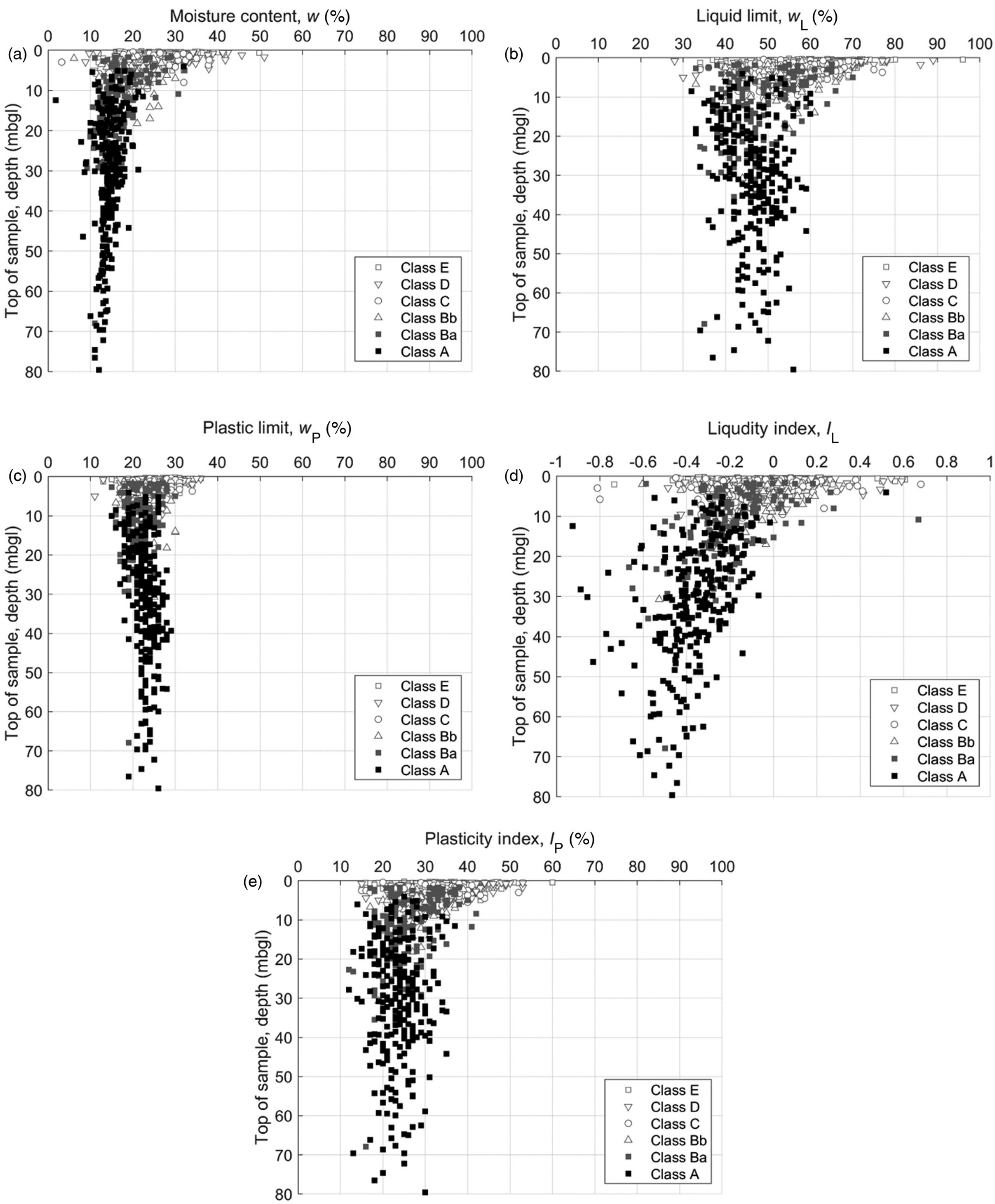


**Fig. A1.** The soil classification data (1256 samples) categorized by weathering class (A–E), and compared to sample depth for (**a**) moisture content (%), (**b**) liquid limit (%), (**c**) plastic limit (%), (**d**) liquidity index and (**e**) plasticity index (%).

**Table A1.** *A summary of median values for the soil laboratory testing data (all weathering classes) from samples excavated near Banbury compared to those from the Charmouth Mudstone Formation across the East Midlands Shelf, Worcester Basin and Wessex Basin (Hobbs et al. 2012)*

| Material property | Median | Median (Hobbs *et al.* 2012) |
|---|---|---|
| Moisture content (%) | 20 (*N* = 1256) | 21 (*N* = 5528) |
| Liquid limit (%) | 54 (*N* = 1256) | 52 (*N* = 3182) |
| Plastic limit (%) | 24 (*N* = 1256) | 24 (*N* = 3181) |
| Liquidity index | −0.10 (*N* = 1256) | −0.06 (*N* = 2923) |
| Plasticity index (%) | 30 (*N* = 1256) | 28 (*N* = 3181) |
| Undrained shear strength (kPa) | 180 (*N* = 223) | 125 (*N* = 1627) |

**Table A2.** *A summary of the mean ($\bar{x}$) and the coefficient of variation (COV (%)) values for the soil laboratory testing data from the Charmouth Mudstone Formation, excavated near Banbury, Oxfordshire, UK*

| | Weathering class | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | All | | Class A | | Class Ba | | Class Bb | | Class C | | Class D | | Class E | |
| Material property | $\bar{x}$ | COV (%) | $\bar{x}$ | COV (%) | $\bar{x}$ | COV (%) | $\bar{x}$ | COV (%) | $\bar{x}$ | COV (%) | $\bar{x}$ | COV (%) | $\bar{x}$ | COV (%) |
| | (*N* = 1256) | | (*N* = 270) | | (*N* = 155) | | (*N* = 86) | | (*N* = 177) | | (*N* = 276) | | (*N* = 249) | |
| Moisture content (%) | 21 | 32 | 15 | 18 | 17 | 24 | 20 | 20 | 22 | 24 | 26 | 23 | 25 | 26 |
| Liquid limit (%) | 54 | 21 | 47 | 12 | 48 | 16 | 54 | 47 | 54 | 15 | 60 | 15 | 60 | 15 |
| Plastic limit (%) | 24 | 14 | 23 | 11 | 22 | 13 | 23 | 12 | 24 | 14 | 25 | 14 | 26 | 13 |
| | (*N* = 223) | | (*N* = 62) | | (*N* = 49) | | (*N* = 26) | | (*N* = 27) | | (*N* = 23) | | (*N* = 19) | |
| Undrained shear strength (kPa) | 302 | 116 | 607 | 85 | 264 | 67 | 175 | 51 | 126 | 31 | 112 | 40 | 104 | 53 |

from reworked clay (Class E) to unweathered (Class A) mudstone. The influence of a contemporary weathering profile (classes C–E) extends to *c.* 2–4 mbgl, and is characterized by brown-coloured soil with a low oxidizable sulfides ($SO_4$) content and extremely to very closely spaced discontinuities. The grey, unweathered Mudstone (Class A) is stronger, has more widely spaced discontinuities and is located at depths greater than 12 mbgl. The unweathered mudstone (Class A) and weathered clay soils (classes Bb–E) are separated by a poorly defined zone of weathered Class Ba material that is visually and chemically similar to the Class A mudstone, but has more closely spaced discontinuities and an undrained shear strength closer to that of a clay ($\tau_u < 300$ kPa).

(2) These analyses show that the most influential variables affecting the undrained shear strength of the Charmouth Mudstone samples (classes A–E) are the visually assessed weathering class and the sample depth. The moisture content and liquidity index are also indicative of the variation in undrained shear strength, particularly in the weathered material (classes Ba–E). Correlations between moisture content and undrained shear strength have been shown to be useful at other locations (Chandler 1972; Coulthard and Bell 1993) for the shallow (up to 15 mbgl), weathered clays ($\tau_u <$ 300 kPa) in the Lias Group. However, the results show that when characterizing the undrained shear strength of the deeper (up to 47 mbgl), less weathered clays and mudstones (e.g. $\tau_u > 300$ kPa), knowledge of the visually inspected weathering profile is equally, if not more, useful than the sample moisture content.

(3) High-quality borehole logging and the systematic description of soils and rocks provides a valuable resource for the interpretation of undrained shear strength in weathered mudstone. It can be used to distinguish between weathered and unweathered mudstone samples, and complement quantitative measures such as index testing.

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**Author contributions** **KMB**: conceptualization (lead), formal analysis (lead), methodology (equal), writing – original draft (lead); **LB**: data curation (lead), investigation (lead), software (lead); **AS**: formal analysis (equal), visualization (lead), writing – review & editing (supporting); **FAL**: writing – review & editing (supporting); **SG**: conceptualization (supporting), supervision (equal); **WP**: supervision (equal), writing – review & editing (supporting); **SB**: writing – review & editing (supporting); **NS**: supervision (equal), writing – review & editing (supporting)

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**Competing interests** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data availability** The datasets generated during and/or analysed during the current study are available in the University of Bath repository: researchdata.bath.ac.uk.

## Appendix A

Figure A1 shows the soil classification data (1256 samples) compared to sample depth and categorized by weathering class for the moisture content ($w$, in %), liquid limit ($w_{LL}$, in %), plastic limit ($w_{PL}$, in %), liquidity index ($I_L$) and plasticity index ($I_P$, in %). The data show greatest variation in the weathered material near the ground surface (up to 5 mbgl), with reduced variation at greater depth. Table A1 shows that the median values of the soil classification data (Fig. A1) and the undrained shear strength data (Fig. 9a) are comparable with median values published by Hobbs *et al.* (2012) for the Charmouth Mudstone outcrop across the East Midlands Shelf, the Worcester Basin and the Wessex Basin.

The variability in the soil laboratory testing data was quantified using the coefficient of variation (COV), where the COV of a dataset is defined as the standard deviation divided by the mean. Table A2 shows the COV values for the moisture content, liquid limit, plastic limit and undrained shear strength data. The COV reduced when the data were categorized by weathering class but the values remained high; showing the highly variable nature of the weathered Charmouth Mudstone Formation. For example, the COV for the undrained shear strength data was 116% but this COV reduced to

85, 67, 51, 31, 40 and 53% when they were categorized as Class A, Ba, Bb, C, D and E, respectively. This is greater than reported COV values of 38% in high-quality unconsolidated, undrained (UU) tests on soft alluvial clays (Ding and Loehr 2019), and a COV of 43% for uniaxial compressive strength (UCS) tests on Eagle Ford Shale, a weak to extremely weak rock (Hsu and Nelson 2002). A systematic summary of site-specific statistics for clay soils across 91 sites (ISSMGE TC304 2021) showed a mean undrained shear strength COV of 28.2%, with a range of 6–56%.

*Scientific editing by Stuart Millis; Stephen Coates*

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