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Engineering geology of British rocks and soils

Mudstones of the Mercia Mudstone Group

British Geological Survey
Urban Geoscience and Geological Hazards Programme
Research Report RR/01/02

BRITISH GEOLOGICAL SURVEY

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Urban Geoscience and Geological Hazards Programme (UGGH)

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Cover illustration

Earthwork operations in Mercia Mudstone for the Derby Southern By-pass.
Alan Forster, BGS © *NERC*

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‘As soon as we pass from steel and concrete to earth, the omnipotence of theory ceases to exist’

Karl Terzaghi, 1936

Proceedings of the first International Conference on Soil mechanics and Foundation Engineering — The relationship between soil mechanics and foundation engineering.

‘In civil engineering projects the largest element of technical and financial risk usually lies in the ground’

‘The ground is a vital element of all structures which rest on it or in it, and there is no other element about which less is known’

‘Insufficient attention is given to desk studies to provide valuable information at low cost’

(from: Report of the Site Investigation Steering Group of the Institution of Civil Engineers on *Site Investigation in Construction, Volume 1, Without Site Investigation Ground is a Hazard*. Thomas Telford, London 1994.

Summary

This report is the second of an on-going series that is examining the distribution, engineering properties and regional variation of geological formations that are significant to civil engineering, construction and land-use in Britain. In this volume the mudstone of the Mercia Mudstone Group is described in terms of its outcrop, mineral composition, geotechnical properties and engineering behaviour.

Chapter 2 describes the global setting in which the Triassic sediments were laid down and how the Mercia Mudstone Group, which comprises the major part of these sediments in Britain, was formed under hot desert conditions in a series of interconnected, inland basins with periodic connection to the sea. The variation in sedimentary environment gave rise to a range of different lithological associations that can be divided into five units that are traceable, in broad terms, across Britain. In some areas more detailed stratigraphic subdivisions have been identified.

Chapter 3 examines the composition of the Mercia Mudstone Group in terms of its mineral components, how it varies as a consequence of the different sedimentary environments in which it was deposited and the physical and chemical changes after its deposition. It indicates how an understanding of the mineral composition of the mudrock, especially of the clay fraction, can help to indicate its engineering behaviour particularly in terms of plasticity and strength. The latter part of the chapter describes in detail the regional variation in lithology and mineral composition of the mudstone of the Mercia Mudstone Group.

The published literature of the past 30 years concerning the engineering behaviour of the Mercia Mudstone is reviewed in Chapter 4, with regard to mineralogy, index properties, consolidation, strength, deformability, swelling, compaction, permeability, rock mass properties and geophysical properties. Particular attention is paid to the development of schemes for describing weathered material.

Chapter 5 looks briefly at the problems encountered in coring and sampling Mercia Mudstone due to its mechanical nature, which has characteristics common to both soil and rock, resulting in behaviour which is predominately influenced by weathering and jointing rather than by sedimentary discontinuities. Some recommendations are made as to the minimum procedures necessary to ensure adequate recovery of the material for engineering purposes.

The structure, compilation and method of statistical analysis of the project's geotechnical database are described in Chapter 6. Emphasis was placed on the collection of only good quality, reliable data with a good geographical spread rather than including poor quality data that would add little useful information and might obscure the interpretation. The analysis of the database forms the basis for Chapter 7 which describes the geotechnical properties of the Mercia Mudstone, how they vary stratigraphically, regionally and with weathering grade. Extended box, scatter line and bubble plots are used to illustrate the variation of index test results including particle size, chemistry, consolidation, compaction, swell/shrink and strength. Statistical summaries of the geotechnical data are presented as tables and extended box plots in the Appendix. The determination of particle size, its relation to clay mineral content and the problems encountered caused by the incomplete disaggregation of clay particles are discussed in detail.

The use of in situ testing of Mercia Mudstone is described in Chapter 8. These tests have been developed in response to the considerable difficulties that are experienced in the determination of the mass strength and mass stiffness of weak rocks such as the Mercia Mudstone due to the fissured nature of the unweathered rock. Pressure meter tests, plate bearing tests and penetration tests (static, dynamic and standard) are described.

Chapter 9 summarises the main conclusions and is followed by a list of references.

Preface

The British Geological Survey (BGS) has a responsibility for providing information on the physical properties of rocks and sediments to enhance a wide range of activities both on land and offshore. The BGS maintains laboratory facilities and undertakes a wide range of geotechnical and geophysical tests on core samples from boreholes, block samples from trenches, and samples from rock exposures in survey areas. As the national repository for geoscience data in the UK, the Survey also holds an extensive archive of geotechnical data in the form of site investigation reports acquired from the public domain. The geotechnical data acquired from these surveys are currently being brought together in one common database format, via specific studies related to various geological map sheets or general studies such as the *Engineering geology of British rocks and soils project,* the latest report of which is described below.

Early work concentrated on the production of engineering geological maps and over the years a wide range of different types of maps have been produced both for BGS projects and specialised commissioned studies for the Department of Environment, Transport and the Regions (DETR). These maps were developed with an associated database and often a table, in which the engineering properties of all the formations on the map were assessed from the point of view of civil engineering construction. This approach produced a generalised geotechnical and geophysical appraisal of the geological formations encountered on the maps, but did not examine the variability of these properties for specific formations outside the area of interest. Hence, the present approach of studying a single formation in more detail over its total extent both vertically and laterally was instigated. The Mercia Mudstone study described below is the second in this series of geotechnical studies.

Although it is not the intention to look at every geological formation in the UK, the overall project is intended to study those formations which present serious engineering problems or upon which significant areas of the built environment are founded. It is anticipated that the project will take a number of years to characterise the necessary formations.

The study of the second formation has also refined the methodology established by the first study, of the Gault Clay, mainly with regard to improving the selection and databasing of geotechnical data from site investigation reports.

The *Engineering geology of British rocks and soils* project thanks the many people who have helped in the course of this study. Special thanks are due to the project's advisory panel of Mr David Patterson (Highways Agency), Dr John Perry (Mott MacDonald) and Prof Mike Rosenbaum (Nottingham Trent University) whose constructive criticism and advice are invaluable in ensuring the project aims and outputs remain focussed on the needs of the user community, and in guiding future progress. Thanks are also due to the many staff of the British Geological Survey, not named in the report as co-authors, who have contributed to the success of the project.

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Programme Director
(Environment & Hazards)
British Geological Survey Keyworth
Nottingham
March 2002

Engineering Geology of British Rocks and Soils

Previous project reports:
Gault Clay. 1994. British Geological Survey Technical Report WN/94/31

Future project reports for studies currently underway:
Lambeth Group (draft report in preparation)
Lias
Brickearth

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1 Introduction

1.1 BACKGROUND TO THE REPORT

The Mercia Mudstone Group is a sequence of predominantly mudrock strata which underlies much of central and southern England and on which many urban areas and their attendant infrastructure are built. It is the mudstone that is most commonly encountered in construction and it is the mudstone with which this report is primarily concerned. In order to assist readability this report uses the widely used, though stratigraphically inaccurate, term ‘Mercia Mudstone’ rather than the strictly correct but repetitious term ‘mudstone of the Mercia Mudstone Group’ or ‘Mercia Mudstone Group mudstone’.

Although the Mercia Mudstone appears to cause few serious geotechnical problems compared with other, higher plasticity, clays (Jones, 2000) it is significant to the construction industry because it is frequently encountered in civil engineering activities involving foundations, excavations and earthworks. Its nature is such that its properties may vary between a soil and a rock depending on its detailed lithology and its state of weathering. As a result of this, in some cases, weaker material may be found below stronger rather than the more normal weathering progression where the weakest material occurs at the surface and becomes fresher and stronger with depth. Consequently sampling and testing is difficult because the material may not be suited to either soil or rock techniques. There is a significant problem with regard to measuring particle size grading and plasticity due to the difficulties with disaggregating the component particles. Some parts of the Mercia Mudstone sequence may be subject to shrinking and swelling with changes in moisture content to a sufficient degree that structural damage to buildings or disruption in some types of construction work is caused.

The Mercia Mudstone Group contains sandstone beds and evaporite minerals, mainly halite (sodium chloride) and gypsum (calcium sulphate, $2H_2O$). These lithologies can cause significant problems to construction but they have not been addressed by this study on the basis that it is the mudstones that represent by far the greater part of the sequence. Other reports may address these materials in the future. Halite is very soluble in water and is never encountered at the natural ground surface in this country having been removed by groundwater at some depth. Similarly gypsum, though less soluble, is frequently absent in the near surface zone. Sandstone represents a small proportion of the sequence in most areas and is rarely a problem to construction.

This report on the mudstone of the Mercia Mudstone Group is the second of a series on the rocks and soils of Britain which aims to satisfy a need of geologists and engineers for reference works describing the engineering behaviour of important geological formations.

1.2 METHODOLOGY

The properties and behaviour of geological materials are controlled by their texture, structure and mineral composition. These factors are a reflection of their depositional environment, diagenesis and subsequent tectonic history that also have a major influence on the current engineering behaviour of the strata as a whole. Also, the near-surface zone has been influenced by Earth surface processes acting in the more recent past. In many instances the behaviour of the material cannot be predicted unless the recent geological history of the site is understood.

The Mercia Mudstone study comprised several interdependent parts. An extensive literature search was carried out at the start of the study to collect and review previous work thus guiding the activities of the study. At the same time an extensive geotechnical database was assembled from high quality site investigation reports which was then analysed to establish the typical range and values of the most commonly determined geotechnical parameters and to look for regional variation in geotechnical properties. When the scope of the database was clear, a sampling and testing programme was carried out to investigate in more detail some of the geotechnical properties and behaviour not satisfactorily covered in the database.

2 Geological background

2.1 GLOBAL SETTING

The crustal plates of the Earth's surface moved together during the late Carboniferous Period resulting in the fusion of all the continental masses to form the single, super continent of Pangea (Figure 2.1). However, at the start of the Permian tensional stresses within the super continent resulted in the formation of a large infra-continental basin at a latitude of 15° to 20° north of the equator. This is a similar geographical location on the Earth's surface to that of the current position of the Sahara Desert in northern Africa. This rifting was to lead ultimately to the opening of the Atlantic Ocean farther to the west. To the south, the Variscan mountain range of the Hercynian fold belt separated the developing basin from the Tethys Ocean and the continental mass that was to become Africa. To the north lay the landmass created when Laurentia had fused with Greenland and Fenno-Scandia to form Laurasia (Figure 2.2).

The climate of the basin was interpreted by Warrington and Ivimey-Cook (1992) as being of a monsoonal nature with prevailing winds from the north-east or east. When the wind met the Variscan mountains it resulted in high rainfall events which led to periodic floods draining northward into the basin. The deposits of the Triassic Period in what is now called northern Europe were laid down within this framework. The Triassic Period extended from about 250 Ma to 205 Ma before the present time (Forster and Warrington, 1985) and derives its name 'Triassic' from the threefold lithostratigraphic division, recognised in Germany, of Buntsandstein (sandstone), Muschelkalk (carbonate) and Keuper (mudstone). However, in Britain, which is on the western margin of the basin, this three-fold division does not represent the local sequence. The Muschelkalk facies is missing and Triassic rocks are represented by the Sherwood Sandstone Group (formerly Bunter Sandstone), Mercia Mudstone Group (formerly Keuper Marl) and the Penarth Group (formerly the Rhaetic). These have been described by Warrington and Ivimey-Cook (1992) who identified five lithological associations within the Triassic (Figure 2.3).

The lowest division, below the Hardegsen Disconformity, comprises an unfossiliferous sequence of sandstone, pebbly sandstone and conglomeratic sandstone laid down as channel deposits in a braided stream fluvial environment of a major, northward-flowing river system. This environment lasted for approximately seven million years at the start of the Triassic Period (Scythian) and the deposits are now preserved as the lower part of the Sherwood Sandstone Group. Above this is a complex basinal sequence, between the Hardegsen unconformity and the Arden Sandstone and its equivalents, which spans about 20 million years from Scythian to Carnian times. During the early part of this period the regional climate became progressively more arid and inland sabkhas, saline mudflats and temporary lakes slowly advanced southwards

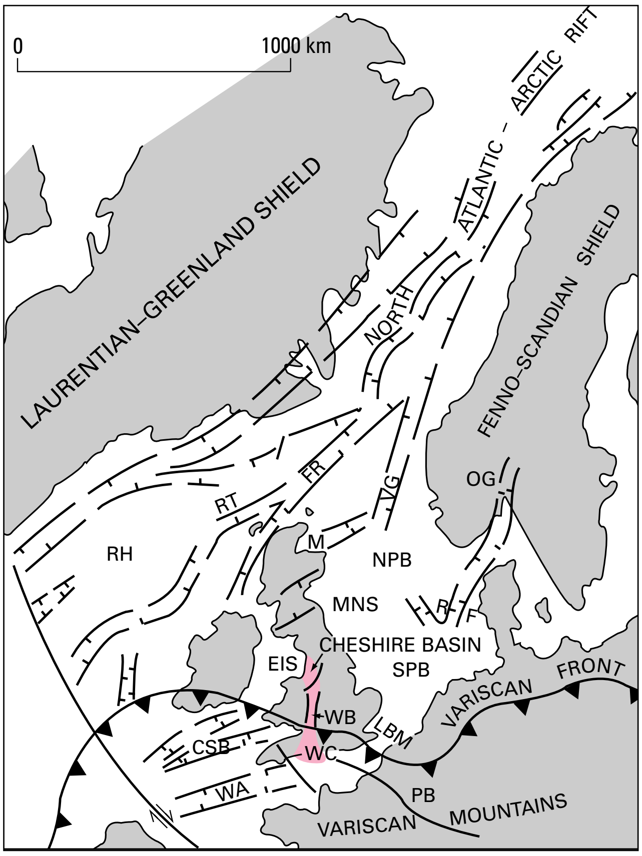


Figure 2.2 Permo-Triassic regional tectonic framework of the North Atlantic region. CB = Cheshire Basin, WB = Worcester Basin, WC = Wessex Basin, NPB = North Permian Basin, SPB = South Permian Basin, LBM = London Brabant Massif (after Chadwick and Evans, 1995).

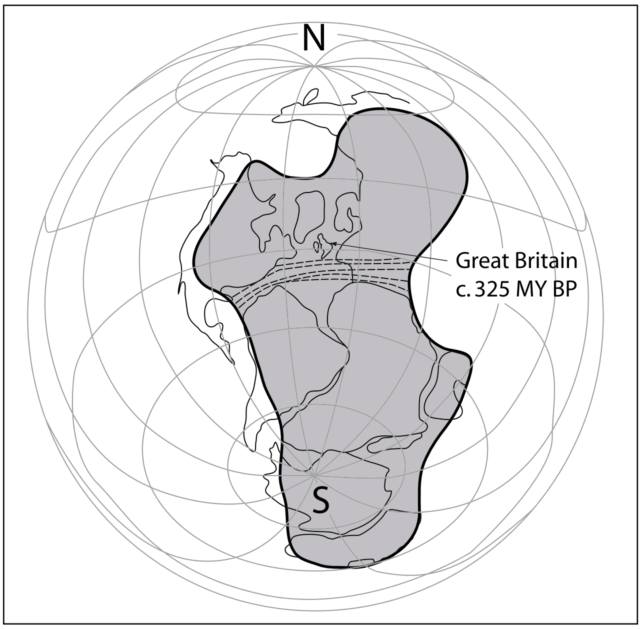


Figure 2.1 Supercontinent of Pangea in the late Carboniferous Period 325 million years ago formed by the collision of the continental masses of Laurasia and Gondwana (after Keary and Vine, 1990).

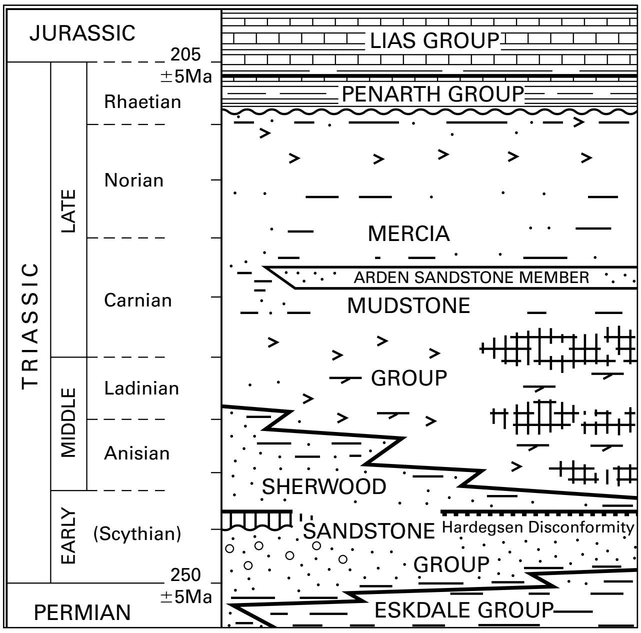


Figure 2.3 Triassic lithofacies in England and the Southern North Sea (after Warrington and Ivimey-Cook, 1992).

to replace the fluvial environments of the Sherwood Sandstone Group. In the south and west of Britain, fluvial sandstones (Sherwood Sandstone) pass laterally into interbedded sandstones, siltstones and mudstones, which were deposited in a fresh to brackish water estuarine or intertidal environment and themselves pass into evaporite (including halite) bearing mudstone (Mercia Mudstone and Haisborough Groups) which are found to the north-west. The base of the Mercia Mudstone Group is thus diachronous with the lowest beds of the group becoming progressively younger southwards. Thick Mercia Mudstone sequences continued to accumulate within fault-bounded basins, but deposition gradually transgressed onto adjacent basin margins, so that the group generally overlies and confines the major, early Triassic Sherwood Sandstone Group, but locally overlaps the group to overlie rocks of Carboniferous or older age of adjacent high ground.

The Arden Sandstone, and equivalent sandstone bodies in other areas, indicates a brief episode of deltaic or estuarine deposition in which grey-green siltstone, mudstone and thick sandstone beds were deposited over a period of a few million years. Following the Arden Sandstone, during a period of 12 million years from the end of the Carnian into Rhaetian times, typical Mercia Mudstone Group deposits were laid down, similar to the basinal argillaceous evaporite bearing deposits below the Arden Sandstone. They included both subaqueous and subaerial deposits but only sulphates are present in the evaporite sequences because they are the result of deposition from interstitial brines or shallow water, hypersaline sabkha environments. The sequence ends in late Triassic (Rhaetian) times with an unconformity that marks the start of a widespread marine transgression. Rising sea level flooded the mudflats and, initially, laid down the widespread, dark grey to black marine mudstone of the Westbury Formation of the Lower Penarth Group that was followed by the mudstone and thin limestone beds of the Upper Penarth and Lias Groups. The Mercia Mudstone Group that comprises the deposits between the Sherwood Sandstone and the Penarth Group is described in more detail regarding lithological variations across its outcrop in the UK in the following section.

2.2 MERCIA MUDSTONE DEPOSITION IN BRITAIN

The stresses that formed the main basin to the east of Britain also led to the formation of a series of small, fault-bounded, subsiding basins in southern, central and north-west England that were controlled by the reactivation of fractures in the basement. Thus, in the south-west the controlling faults have an east–west (Variscoid) trend, in the Midlands a north–south (Malvernoid) trend and in the north a north-east–south-west (Caledonoid) trend (Chadwick and Evans, 1995).

The Mercia Mudstone Group was deposited in a mudflat environment in three main ways: settling-out of mud and silt in temporary lakes; rapid deposition of sheets of silt and fine sand by flash floods; and the accumulation of wind-blown dust on the wet mudflat surface. It is composed mainly of red and, less commonly, green and grey mudstones and siltstones. Substantial deposits of halite occur in the thicker, basinal successions of Somerset, Worcestershire, Staffordshire and Cheshire. Sulphate deposits (gypsum and anhydrite) and sandstone beds are common at some stratigraphical levels and are minor constituents throughout the remainder of the group. The outcrop of the Mercia Mudstone Group extends northwards from Lyme Bay, through Somerset and on to both sides of the Severn Estuary (Figure 2.4). It continues northwards through Hereford and Worcester before broadening out to underlie much of the central Midlands. The outcrop bifur-

Figure 2.4 Outcrop of the Mercia Mudstone Group in Britain. The numbered regions correspond to those shown in Table 2.1, as follows: 1. Wessex Basin; 2. Somerset/Avon/ South Wales; 3. Worcester/Knowle Basins; 4. Stafford/Needwood Basins; 5. Cheshire Basin; 6. West Lancashire; 7. Carlisle Basin; 8. East Midlands/NE England.

cates around the Pennine Anticline, with the eastern limb running through Nottinghamshire into the Vale of York, before eventually reaching the North Sea coast at Teesside. The western limb underlies northern Shropshire, Cheshire and Merseyside and much of the Formby and Fylde peninsulas, passing offshore below the Irish Sea before extending onshore again on the northern side of the Lake District near Carlisle. In Cheshire, Warwickshire, the Vale of York and the Carlisle area, large parts of the outcrop are masked by thick Quaternary deposits (mainly glacial till), with more patchy cover of superficial deposits elsewhere. Thick sequences of the group dip below younger Mesozoic rocks in Dorset, Hampshire, north-east England and the southern North Sea. In the south-east of England, the group pinches out in the subsurface around the margins of the London Brabant Massif, an ancient cratonic area composed of Lower Palaeozoic rocks. The group is absent in the subsurface below London and the Home Counties.

2.3 LITHOSTRATIGRAPHICAL CLASSIFICATION

The mainly arid, continental depositional environment has resulted in few fossils being preserved and this, coupled with similar material being deposited over long periods of time within, but not necessarily uniformly, over the area has resulted in extreme difficulty in correlating deposits from one area to another. The current lithostratigraphical classification of Triassic rocks in England and Wales is based on an extensive review carried out by the Geological Society of London (Warrington et al., 1980). The review correlates stratigraphical sequences from 28 areas of Britain. The terms Bunter and Keuper, based on supposed time correlation with the German Triassic sequence, were discontinued in favour of a more rigorous lithostratigraphical approach using the gross lithological characteristics of the various rock units. The former Bunter and Lower Keuper Sandstone units are now combined into the Sherwood Sandstone Group, with the Mercia Mudstone Group corresponding closely to the former Keuper Marl division.

Many local names have been applied to formations within the Mercia Mudstone Group as shown in the correlation charts of Warrington et al. (1980). The profusion of names reflects either the original depositional restriction of a unit to an individual basin or the subsequent geographical isolation of a formation at outcrop due to post-Triassic erosion. Thus, many of the lithostratigraphical subdivisions that have been recognised in the Mercia Mudstone are unique to individual basins. However, despite this localised nomenclature, five broad subdivisions, labelled A to E in Table 2.1, are recognisable within the group in most basins and are used in the following description (Howard et al., 1998). The relationship of current stratigraphical divisions to former terminology has been addressed by Powell (1998) and includes terms relating to the Mercia Mudstone Group.

2.4 LITHOLOGICAL CHARACTERISTICS

The lithological characteristics of the subdivisions A to E of Howard et al. (1998) are as follows:

Unit A

This is a transitional lithological unit between the Sherwood Sandstone and Mercia Mudstone groups, and is characterised by interbedding of brown mudstones and siltstones with paler grey-brown sandstones in approximately equal proportions. Bedding is generally planar or sub-planar, and most sandstone beds are less than 0.5 m thick with intervening mudstone and siltstone partings of similar thickness. The sandstone is typically very fine to fine-grained, less commonly medium-grained, highly micaceous, and moderately cemented by ferroan calcite or dolomite. Beds of fine to medium-grained sandstone up to 5 m thick are present locally. These have a lenticular geometry with internal cross-stratification and probably represent sand-filled fluvial, distributary channels. Sulphates (gypsum and anhydrite) are present as small veins and nodules but are not as abundant as in higher units. The unit is typically a few tens of metres thick, but reaches a maximum of 270 m in the Cheshire Basin.

This unit was formerly known in many areas as the 'Waterstones' due to the supposed resemblance of the highly micaceous bedding planes to ‘watered silk’. This is the most difficult unit of the Mercia Mudstone Group to define because in most basins, both the base and top are gradational, and lateral facies transition into the upper beds of the Sherwood Sandstone and the lower beds of Unit B of the Mercia Mudstone can be demonstrated. In many areas it has not been distinguished and Unit B lies directly on the Sherwood Sandstone. Thus, south of Birmingham, Unit A tends not to be mappable as a formation and, where recognised, is usually included in the top of the Sherwood Sandstone Group. Elsewhere, the unit forms the basal formation of the Mercia Mudstone Group and has been assigned a different formational name (e.g. Tarporley Siltstone, Sneinton Formation) in each basin. The base of the unit is both conformable and gradational but also diachronous, becoming generally younger southwards from the East Irish Sea area to Worcestershire. The Eastern England Shelf is a notable exception; there the base of the unit is unconformable and is marked by a patchily distributed basal conglomerate up to 1 m thick with a strong, calcareous cement. Geophysical log correlation indicates that the lower part of Unit A in the Nottingham area is stratigraphically isolated from strata of the same age in the Needwood Basin to the west, but the upper part is in spatial continuity in the subsurface between these zones.

Unit B

This unit consists mainly of red and, less commonly, green and grey dolomitic mudstones and siltstones. These show a variety of fabrics ranging from finely laminated to almost totally structureless. In many cases the primary depositional fabric has been deformed by frequent wetting and drying of the substrate following deposition and the consequent growth and solution of salts. Thin beds of coarse siltstone and very fine sandstone occur at intervals throughout the unit. Individual sandstone beds are typically 20 – 60 mm thick, greenish grey in colour, planar and or current-ripple laminated and have strong, intergranular dolomite cements. Less commonly, gypsum cements occur; these may be dissolved by meteoric waters in the near-surface zone to leave a weakly-cemented or uncemented sand at outcrop. Sandstone beds are usually grouped into composite units of three or more beds, with greenish grey mudstone interbeds of equal thickness. These composite units vary from 0.15 to 1 m thick and many are sufficiently resistant to form low, cuesta-like landforms. These resistant beds are locally termed ‘skerries’, the more persistent of which have been named in some basins.

Substantial deposits of halite, some of considerable economic importance, occur within this unit in the thicker,

Wessex Basin	Somerset/Avon /South Wales	Worcester/ Knowle basins	Stafford/ Needwood basins	Cheshire Basin	West Lancashire	Carlisle Basin	East Midlands	MERCIA MUDSTONE GROUP UNIT
PENARTH GROUP						PENARTH GROUP		PENARTH GROUP
Blue Anchor Formation *24m*	Blue Anchor Formation *30 40m*	Blue Anchor Formation *7 11m*	Blue Anchor Formation *7 18m*	Blue Anchor Formation *15m*	absent	Stanwix Shales *up to 300m*	Blue Anchor Formation *4 10m*	E
mudstone *up to125m*	mudstone *up to 130m*	Twyning Mudstone Formation *60 125m*	mudstone *up to 135m*	Brooks Mill Mudstone Formation *160m*			Cropwell Bishop Formation *30 80m*	D
Weston Mouth Sandstone *11m*	Butcombe/North Curry Sandstone *up to 7m*	Arden Sandstone *3 12m*					Dane Hills/ Hollygate Sandst *up to 10m*	C
mudstone *up to 175m*	Somerset Halite *up to 150m* mudstone *thickness unknown*	Droitwich Halite *up to 45m* Eldersfield Mudstone Formation *up to 350m*	Stafford Halite *up to 65m* mudstone *up to 180m*	Wilkesley Halite *up to 400m* Wych and Byley Mudstone formations *up to 580m* Northwich Halite *up to 290m* Bollin Mudstone Formation *up to 460m*	Breckells and Kirkham Mudstone formations *up to 450m* Preesall Halite *up to 200m* Singleton and Hambleton Mudstone formations *up to 180m*		Edwalton, Gunthorpe and Radcliffe formations *up to 160m*	B
SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	Sugarbrook Member *10 45m*	Maer/Denstone Formation *up to 160m*	Tarporley Siltstone Formation *up to 270m*			Sneinton Formation *up to 90m*	A
		SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP

Table 2.1 Lithostratigraphical summary of the Mercia Mudstone Group in England and Wales. Some formations and halite beds of local extent are omitted. Mercia Mudstone Group Units A to E correspond to those defined in the text (after Howard et al., 1998).

basinal successions of Dorset, Somerset, Worcestershire, Staffordshire, Cheshire, west Lancashire and the East Midlands (Table 2.1). The halite beds do not crop out at surface, but their projected surface position is often marked by subsidence hollows and collapse breccias formed in overlying strata. These features are formed not only by natural dissolution but also by the effects of salt extraction by brine pumping. Sulphates (gypsum and anhydrite) are abundant throughout the unit as veins but are not of economic importance.

The unit is typically 150 to 300 m thick, though with substantial variation between basins. Up to 1200 m occurs in the Cheshire Basin, which includes two thick halite units with a combined thickness of over 600 m.

In the Worcester Basin, the unit is assigned to a single formation, the Eldersfield Mudstone. In the Cheshire Basin and west Lancashire, major halite units have been used to subdivide the succession, with some further division of the mudstone based on lithological character. In the East Midlands, the formations are based partly on fairly subtle lithological characteristics and partly by using skerries as mappable marker beds. The unit is not named in other basins, though some of its components are (e.g. Somerset Halite, Droitwich Halite).

Taking the unit as a whole, original depositional continuity is likely, at least in part, between all the basins. However, correlation of individual formations between the basins is highly uncertain and most should be considered as being restricted to individual basins or even parts of basins.

Unit C

This is a thin but widespread unit that has been mapped at surface, albeit discontinuously, from the Dorset coast into Nottinghamshire. The unit has not been formally identified in the Needwood or other basins to the west and north-west, although it may be represented by a series of un-named sandstone beds lying just above the Wilkesley Halite in the Cheshire Basin (Wilson, 1993). In Worcestershire and Warwickshire, the unit is represented by the Arden Sandstone. Equivalents in south-west England are the Butcombe, North Curry and Weston Mouth sandstones. The Dane Hills Sandstone of Leicestershire and the Hollygate Sandstone of the Nottingham district represent this unit in the East Midlands.

In central and south-west England the unit typically consists of up to 12 m of thickly bedded, medium to coarse-grained, cross-stratified sandstone. The sandstone is moderately to strongly calcareous or dolomitic and in some places cemented by quartz. The most resistant beds have been quarried locally for building stone. However, these beds of sandstone are discontinuous and lenticular in geometry and probably represent the fills of fluvial distributary channels. Where thick sandstone beds are absent the unit is represented by dark greenish grey siltstone and mudstone with a few thin beds of dolomitic, very fine to fine-grained sandstone. In the East Midlands, the Hollygate Sandstone consists of up to 8 m of fine to medium-grained pale grey sandstone interbedded with predominantly red-brown mudstone; the sandstone beds are cemented mainly by gypsum; stronger cementation by intergranular dolomite or quartz overgrowths occurs only in small patches and thin beds. The sandstone weathers to a very poorly cemented or uncemented sand in the near-surface zone but is more competent below a few metres depth from the surface.

The unit forms a distinct marker in geophysical logs that can be traced in boreholes from Dorset to North Yorkshire; it is probably continuous in the subsurface between these areas. Generally, BGS maps surveyed since 1980 show the unit as a continuous, though locally very thin formation except in areas thickly covered by superficial deposits. Older maps, including those covering Somerset and Dorset, show the unit as a series of isolated outcrops. Therefore, the apparent discontinuity of surface outcrop may be partly due to differences of approach between 'old' and 'new' mapping.

Unit D

This unit resembles Unit B, but resistant dolomitic sandstone units ('skerries') are less common and structureless red-brown, dolomitic mudstone dominates. Halite is absent (although pseudomorphs after halite occur sporadically) but beds, nodules and veins of gypsum are abundant either as thick beds and veins or as nodular masses. Locally, gypsum forms deposits of economic importance, for example near Burton-on-Trent, Nottingham and Newark. Gypsum is absent in the near-surface zone due to dissolution by meteoric water, weakening the fabric of the rock and locally resulting in a general lowering of the land surface by up to 3 m.

The unit is represented by the Twyning Mudstone in the Worcester Basin, the Brooks Mill Mudstone in the Cheshire Basin and the Cropwell Bishop Formation in the East Midlands. The unit is unnamed elsewhere. As with Unit B, (though not as markedly) the unit thickens substantially into the more rapidly subsiding depositional basins, with the thickest sequence (140 m) developed in the Cheshire Basin and the thinnest (30 m) in the East Midlands.

As a whole, the original depositional continuity can be inferred between all the basins in Table 2.1. Spatial continuity is preserved in the subsurface between Dorset and Yorkshire, but the successions in the Needwood, Stafford, Cheshire, west Lancashire and Carlisle basins are spatially isolated.

Unit E

This thin but widespread unit is the uppermost within the Mercia Mudstone Group and is represented in all basins except the west Lancashire area. A single name, the Blue Anchor Formation, has been applied to this unit throughout England and Wales since 1980 (Warrington et al., 1980). In south-west England and South Wales, the unit consists of interbedded greenish-grey, dark grey and green dolomitic mudstones and dolostones with common gypsum. Elsewhere, the unit is more homogeneous in lithology and consists of apparently structureless, pale greenish grey dolomitic mudstones and siltstones known formerly as the Tea Green Marl.

The unit is up to 40 m thick in south-west England but is generally less than 15 m thick elsewhere. It was probably deposited in a coastal sabkha environment with periodic marine influence, presaging the widespread marine transgression that deposited the dark grey to black mudstones of the lower part of the overlying Penarth Group (Westbury Formation). The base of the Penarth Group is a non-sequence, typically resting on a shrinkage-cracked and bored top surface of the Blue Anchor Formation.

2.5 MARGINAL CONGLOMERATES

Towards the margins of depositional basins and on the flanks of contemporaneous landmasses such as the

Mendips and Charnwood Forest, the Mercia Mudstone Group contains abundant though laterally impersistent beds of conglomerate and breccia, commonly strongly cemented by dolomite. These conglomerates were deposited as alluvial fan-gravels and contain abundant, large, often angular, pebbles of local derivation. They are especially common towards the base of the group where it onlaps onto Carboniferous or older rocks. Sandstone beds also occur locally towards basin margins in some areas; the Redcliffe Sandstone of the Bristol area, which is up to 50 m thick, is a notable example.

2.6 FOLDING AND FAULTING

In most parts of England and Wales the Mercia Mudstone Group has been subjected to only mild tectonic deformation (Figure 2.5). Dips are generally less than five degrees except in the vicinity of faults, though steeper radial dips occur locally around the flanks of contemporaneous landmasses such as the Mendips. Larger faults affecting the Mercia Mudstone Group, for example in the Cheshire Basin, represent the reactivation of earlier, Carboniferous or older structures. Recent geological mapping in the Nottingham and Worcester districts indicates that the Mercia Mudstone Group is disturbed by numerous small faults (Figure 2.6); these may be present elsewhere but are not mappable below even a thin cover of superficial deposits. Though most of these faults have throws of 5 m or less, this is often sufficient to isolate blocks of minor aquifers formed by the thin beds of dolomitic siltstone and sandstone within the Mercia Mudstone Group succession.

Figure 2.5 Gentle folding and minor faulting in Mercia Mudstone at Haven Cliff, east of Seaton, Devon.

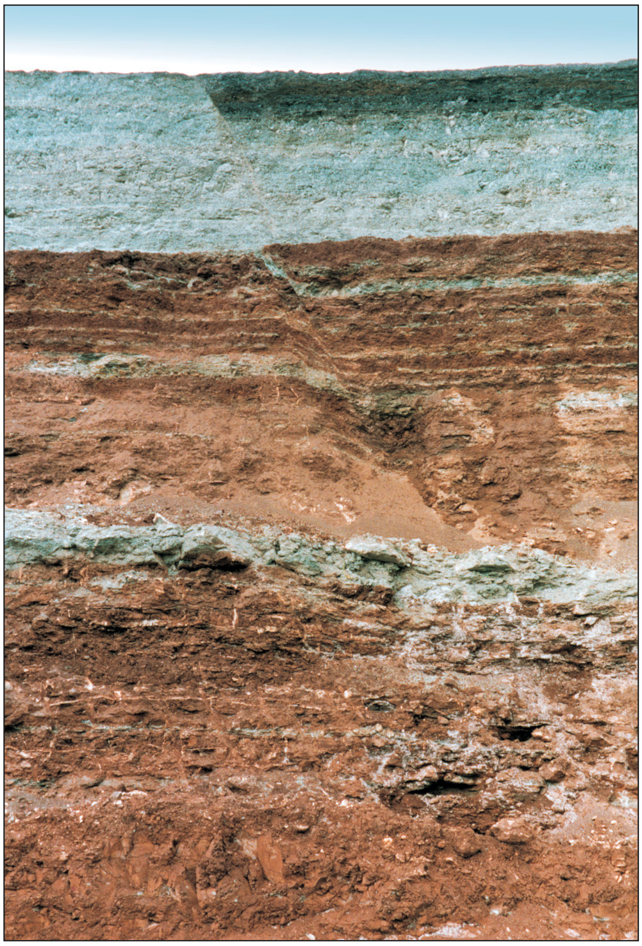


Figure 2.6 Minor fault in the Cropwell Bishop and Blue Anchor formations of the Mercia Mudstone with Westbury Formation exposed at the top right of the section at Cropwell Bishop, Nottinghamshire.

3 Mineralogical considerations

3.1 INTRODUCTION

An appreciation of the mineral composition, diagenesis and small-scale structure of the Mercia Mudstone Group can aid an understanding of its engineering behaviour. The plasticity of clays and mudstones is strongly influenced by the amount and type of clay minerals present, particularly those of the less than 0.002 mm grain-size. The nature and distribution of intergranular cement in a mudstone will also affect its plasticity as well as its strength, deformation, susceptibility to weathering and the nature of the weathered material.

The mineral assemblage usually includes quartz, carbonates, sulphates, mica, clay minerals and iron oxides and significant thicknesses of halite deposits are present, at depth, in some basins.

In the 1960s mineralogical studies of 'Keuper Marl', mainly from the West Midlands, found that the clay mineral content of the mudstones ranged from 60% to more than 90% (Dumbleton and West, 1966a, b; Davis, 1967). These values were determined mainly by X-ray diffraction analysis (XRD). However, when the clay content was determined by particle size analysis it was usually found to be between 10 and 40% (Sherwood & Hollis, 1966; Davis, 1967). The analysis of whole-rock mineral composition using X-ray diffraction methods may not be reliable because phyllosilicates of greater than 0.002 mm, such as silt-size mica and chlorite, interfere with the measurement of clay-size illite and chlorite. Therefore, it is unlikely that the Mercia Mudstone Group contains material with such a high percentage of clay-size clay minerals.

The changes in the clay mineral assemblage present in a sequence of rocks have been used as stratigraphical markers in the absence of fossils (Taylor, 1982; Leslie, 1989). The clay mineral assemblage and the mineral composition of evaporite deposits are also indicative of the depositional environment. Most of the available mineralogical analyses of the Mercia Mudstone Group relate to material from the south-west of England, South Wales and the Midlands (Jeans, 1978). Bloodworth and Prior (1993) carried out a detailed study of the clay mineralogy, carbonate and sulphate content of the Mercia Mudstone Group in the Nottingham area. In other areas information was found principally in geological descriptions from British Geological Survey memoirs and other literature.

The Mercia Mudstone Group has been a source of several industrial minerals. Gypsum is currently worked in the East Midlands in the Cropwell Bishop Formation (Figure 3.1). Halite is extracted, by controlled pumping in the Northwich and Middlewich areas and from a mine at Winsford.

The Mercia Mudstone is an important material for brick manufacture and is worked in the East Midlands, the West Midlands and the south-west. In the past anhydrite, celestite, sandstone and agricultural marl have been worked and 'Draycott Marble' from the 'Dolomitic Conglomerate' was quarried in south-west England. A number of minor mineral deposits associated with 'Dolomitic Conglomerate' were also extracted in the Bristol area including pyrolusite and smithsonite as well as a number of pigments.

Figure 3.1 Gypsum working in the Cropwell Bishop Formation of the Mercia Mudstone Group in the quarry at Cropwell Bishop.

This report is concerned primarily with the mudstone facies of the Mercia Mudstone Group and more information about the mineralogy of other lithologies is described elsewhere (Entwisle, 1997).

3.2 DIAGENESIS

The physical and chemical changes that occurred within the Mercia Mudstone after deposition (diagenesis) have altered its original mineralogy and structure. A detailed account of the diagenesis of the Mercia Mudstone Group in the Cheshire Basin was given by Milodowski et al. (1994) who described early, middle and late diagenetic processes. A detailed description of the diagenesis of the clay minerals was given by Bloodworth and Prior (1993).

3.2.1 General diagenesis

Early diagenetic changes included the precipitation of nodular anhydrite and gypsum as 'desert rose' cements in mud in the near-surface zone. This disrupted the sedimentary fabric, which may have beeen further disrupted by the hydration of anhydrite, which was deposited from hot high salinity brines (<42°C), to form gypsum.

The oxidation state of iron was controlled during this period which determined the colour of the rock. The red iron oxide was characteristic of wind-blown detrital material in hot, arid environments but bacterial decomposition of organic matter after deposition may have reduced the ferric iron to ferrous iron. If sufficient organic matter was present to reduce all the ferric oxide the resulting rock became green/grey. Petrographic observations by scanning electron microscope of the red/brown mudstones (Milodowski et al., 1994) showed that they contained minor amounts of disseminated, fine-grained red iron oxide and that the green/grey mudstones contained small amounts of framboidal and other fine grained pyrite.

Authigenic clays such as corrensite and smectite developed in lacustrine environments with a high degree of evaporation, which maintained high salinity conditions, and may line pores between grains in coarser material.

Dolomitic and anhydritic mudstones often undergo some degree of recrystallisation during burial. Silty laminae within the dolomitic-anhydritic mudstones often contain euhedral quartz, K-feldspar and albite overgrowths. Locally, these may fuse to form tightly interlocking cements. Silt laminae and interbeds may be preserved with relatively uncompressed fabrics due to this cementing. Anhydrite cement may also fill cavities left by the dissolution of halite that may be redeposited elsewhere as veins or as a cement. In the later stages of diagenesis ferroan dolomite and ankerite (calcium/magnesium/iron carbonate) occur as rhombic overgrowths on corroded earlier dolomite. In arenaceous facies of the Tarporley Siltstone Formation fibrous illite lines intergranular pore spaces.

3.2.2 Diagenesis of clay minerals

Clay minerals are classified as 'detrital' if they remained unaltered after their deposition or 'authigenic' if they formed after deposition by the reaction of detrital minerals with the pore fluid. The diagenesis of the clay mineral components of the Mercia Mudstone Group was studied by Jeans (1978), Taylor (1982), Leslie et al. (1993), Bloodworth and Prior (1993), Milodowski et al. (1994), and Pearce et al. (1996). The clay mineral assemblage comprises a 'detrital' phase (illite and chlorite) and an authigenic phase of mixed layer clays (generally chlorite-smectite, but also illite-smectite in south Devon), smectite, palygorskite and sepiolite. The 'detrital' clay assemblages were preserved when the climate was relatively wet and the influx of fresh water deposited terrigenous material and created conditions of low salinity. When conditions became more arid the authigenic clays, in particular the mixed layer clays, formed in magnesium-rich alkaline groundwaters during conditions of extreme salinity, (Jeans, 1978; Bloodworth and Prior, 1993) and became components of the clay mineral assemblage. Smectite and sepiolite, often associated with gypsum and anhydrite, are also associated with an increase in salinity and alkalinity.

Studies using X-ray diffraction and scanning electron microscope techniques suggested that both illite and chlorite have undergone regrading during diagenesis by the absorption of K^+ by illite and Mg^{2+} by chlorite (Taylor, 1982 and Leslie et al., 1993). The sharper X-ray diffraction peaks observed for silt-sized fractions, as compared to those for the whole rock and the clay-sized fraction, suggested that the silt-sized mica and chlorite were probably well crystallised, and the clay fraction contained authigenic illite and chlorite possibly when associated with other authigenic clays (Pearce et al., 1996). Scanning electron microscope studies of mudrocks from the Cheshire Basin have shown authigenic illite to be present in intergranular pore spaces (Milodowski et al., 1994).

It is likely that the authigenic clays were formed early in diagenesis by reactions between the detrital clays and alkaline groundwater rich in Mg^{2+}. The composition of the groundwater was influenced by factors such as climate and topography that controlled the rainfall, evaporation and the circulation of water into and between the basins of deposition. The presence and concentration of authigenic gypsum and dolomite may also have influenced the development of the clay assemblage.

A model for the production of magnesium rich authigenic clays was put forward by Bloodworth and Prior (1993) who suggested that reactions between detrital, degraded illite and saline water rich in magnesium, calcium, hydrogen, carbonate and sulphate ions resulted in an authigenic 'precursor smectite'. Smectite that formed at an early stage of diagenesis was accompanied by the formation of dolomite and gypsum. Smectite that formed in conditions of higher salinity and alkalinity may have been restrained from further diagenetic changes by the cementation of the rock fabric by calcium sulphate. This reduced permeability and hence the passage of pore fluids which reduced the availability of alumina and the potential for chemical changes to occur. Sepiolite and palygorskite formed in conditions of high salinity with low levels of dissolved CO_2 and relatively high levels of dissolved silica. A relatively low content of aluminium ions in the groundwater favoured the formation of sepiolite rather than palygorskite. Chlorite may have formed from the magnesium rich precursor smectite during burial if sufficient aluminium ions were present and temperatures exceed 100°C. Corrensite was formed in conditions of low alkalinity and salinity.

3.3 MINERAL COMPOSITION

3.3.1 Non-clay minerals

The main non-clay minerals present in Mercia Mudstone are quartz, calcium and magnesium carbonates, calcium sulphates, micas, iron oxides, and halite. Feldspar may also be present and several heavy minerals occur in very small quantities. The distribution of carbonate and evaporite minerals in the Mercia Mudstone Group is summarised in Figure 3.2.

Quartz (SiO_2) is present throughout the Mercia Mudstone Group and it is usually the main sand- and silt-sized detrital mineral and may be well-sorted to poorly-sorted. In the Cheshire Basin the quartz is usually angular (Milodowski et al., 1994) but elsewhere the grain shape varies between angular and sub-rounded even within the same sample. Quartzitic sandstones are sometimes cemented by syntaxial overgrowths and welded grain contacts of redeposited quartz may support an open structure. This occurs in parts of the Arden Sandstone Member and skerries in both the West and East Midlands (Strong, 1976, 1979, 1983). However, the recrystallisation of quartz as overgrowths may not result in a coherent cementing of the grains (Smith et al., 1973).

Dolomite ($MgCO_3.CaCO_3$) and calcite ($CaCO_3$) are important constituents of the Mercia Mudstone Group and are often the main cementing agents. Dolomite is usually the dominant carbonate and may comprise up to 50% of the carbonate-rich beds. Calcite may comprise up to 30% of the rock in some mudstones and over 30% in the limestone lithologies of South Wales. Calcite and dolomite both occur as finely disseminated particles but dolomite may also develop as euhedral rhombs more than 10 µm across and calcite may be found as discrete patches (Pearce et al., 1996). The carbonates may have formed as a cement at an early stage of burial, or at a later stage of diagenesis when the dolomite becomes iron-bearing, and may form ankerite. Authigenic carbonates fill intergranular pores spaces which reduces porosity and permeability. Dolomite cement showed little or no degradation in weathered, near-surface samples according to Pearce et al. (1996).

Calcium sulphate is commonly present in the Mercia Mudstone Group as both the hydrous form gypsum ($CaSO_4.2H_2O$) and the anhydrous form anhydrite ($CaSO_4$). Anhydrite is stable at depth or at the surface at temperatures above 42°C but transforms to gypsum, in the presence of water, in the near-surface zone if the overlying beds are removed by erosion. The conversion to gypsum is accompanied by an increase in volume of 63% (Shearman et al., 1972) which can produce brecciation and distortion of the surrounding rock. In general, the transformation is complete within 50 to 100 m below the surface. Gypsum may be found as finely disseminated crystals in pores, as a cement, as nodules or veins and as massive deposits up to 2 m thick that may also contain anhydrite. Gypsum is usually found in the upper part of the Mercia Mudstone Group particularly in the Cropwell Bishop Formation and its stratigraphic equivalents in other basins. Gypsum is often removed by groundwater in the near-surface zone.

Strontium sulphate (celestite) is present in small quantities as disseminated crystals or small nodules in the more gypsiferous parts of the Mercia Mudstone Group. In the Bristol area the nodular beds are sufficiently rich in celestite for their extraction to be commercially viable and they were the world's main source of this mineral until the late 1970's. The celestite-rich beds are probably the same age as the gypsum rich beds of the East Midlands (Thomas, 1973).

Halite is present in the major basins or at basin margins of the East Irish Sea Basin, the Cheshire Basin, the Staffordshire Basin, the Worcestershire Basin, the Somerset Basin and East Yorkshire. It is present either as high purity beds with interbedded mudstone or, mixed with mudstones and siltstones in 'Haselgebirge facies'. Halite is highly soluble and is not usually found within 40 to 60 m of the surface in Britain since it is removed by groundwater. Its solution results in the collapse of overlying strata which forms a breccia.

Mica is often present as silt-sized to fine sand-sized plates usually of muscovite with some biotite. Haematite or pyrite is present at or below the detection limits of X-ray diffraction analysis. Where iron is present as Fe^{3+}, usually as haematite, the rock is red and where it is in its reduced Fe^{2+} form, usually as pyrite, the rock is green or grey (Leslie, 1989).

Other non-clay minerals which may be present as minor constituents of the Mercia Mudstone Group are feldspar and heavy minerals such as titanium-iron oxides, apatite, zircon, monazite, tourmaline, rutile, magnetite, anatase, barytes, barycelestite, ilmenite, xenotime and chromite. Several copper minerals and native copper are present in the mineralised zone at the base of the Weatheroak Sandstone near Redditch (Old et al., 1991). Pyrite is commonly overgrown and replaced by later diagenetic sulphides of copper, zinc, lead, arsenic, cobalt, nickel, silver and mercury. Anhydrite may be replaced by chalcopyrite, chalcocite and pyrite in the Cheshire Basin. Malachite specks are present in a celestite-rich breccia at Henbury near Bristol (Kellaway and Welch, 1993).

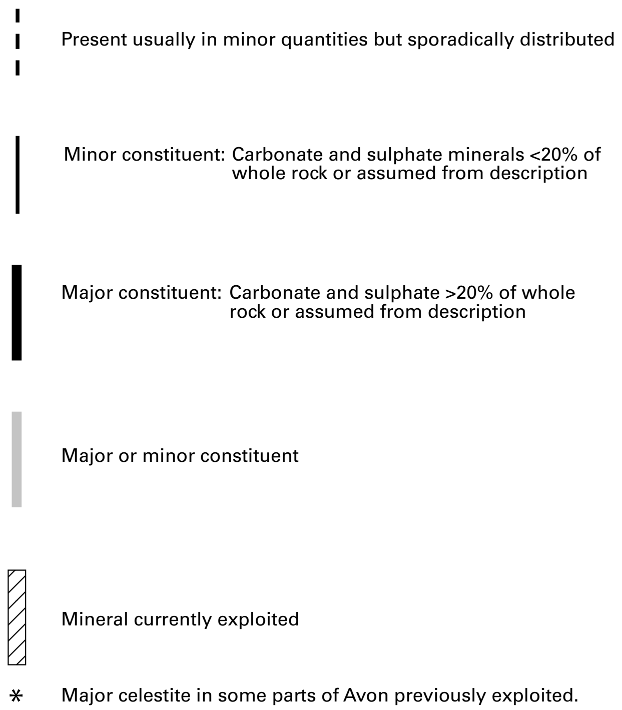
3.3.2 Clay minerals

The major clay minerals of the Mercia Mudstone Group are illite, chlorite, mixed layer clays (illite-smectite, chlorite-smectite) and, in some horizons, smectite. The distribution of clay minerals in the Mercia Mudstone Group is summarised in Figure 3.3.

The detrital clays illite and chlorite are present throughout the Mercia Mudstone Group, illite is the major component of the clay mineral assemblage and has been reported as clay-size mica in some reports (Perrin, 1971). Chlorite is a minor component and is present as detrital, well-crystallised, silt-sized particles up to 0.05 mm long and as poorly- to well- crystallised clay-sized particles. In the lower and the upper parts of the red Mercia Mudstone and the Blue Anchor Formation they are often the only clay minerals which have been identified.

The authigenic clay minerals; smectite, palygorskite, sepiolite and mixed layer clays (chlorite-smectite) are usually present as clay-sized particles in the middle part of the Mercia Mudstone Group but are often absent from the lower and upper strata. Smectite may be present as a minor part of the clay mineral assemblage at some horizons in the middle and upper part of the red Mercia Mudstone but it is rare in the lower part and absent in the Blue Anchor Formation. Magnesium-rich palygorskite and sepiolite are present in minor or trace quantities. Sepiolite is often associated with the Arden Sandstone Member and equivalent strata (Jeans, 1978; Bloodworth and Prior, 1993) and in some skerries and gypsum bands above and below this member (Taylor, 1982). Palygorskite is sometimes present in the upper red beds associated with gypsum. These minerals have not been identified in the Cheshire Basin. Palygorskite and sepiolite may be present in concentrations below the detection limit of X-ray diffraction techniques and are not recorded unless a more sensitive technique is used such as a scanning electron microscope with a back scatter facility.

The mixed layer clays can be highly variable in the proportions of their component clays. The mixed layer clay chlorite-smectite may be dominated by chlorite or smectite or may form the regularly interlayered mineral corrensite. A study of chlorite-smectite in the Nottingham area by Bloodworth and Prior (1993) found that the proportion of smectite interlayers increased as the proportion of mixed layer clays in the clay mineral assemblage increased.



Key to Figure 3.2 *(opposite)* The distribution of carbonate and evaporite minerals in the Mercia Mudstone Group.

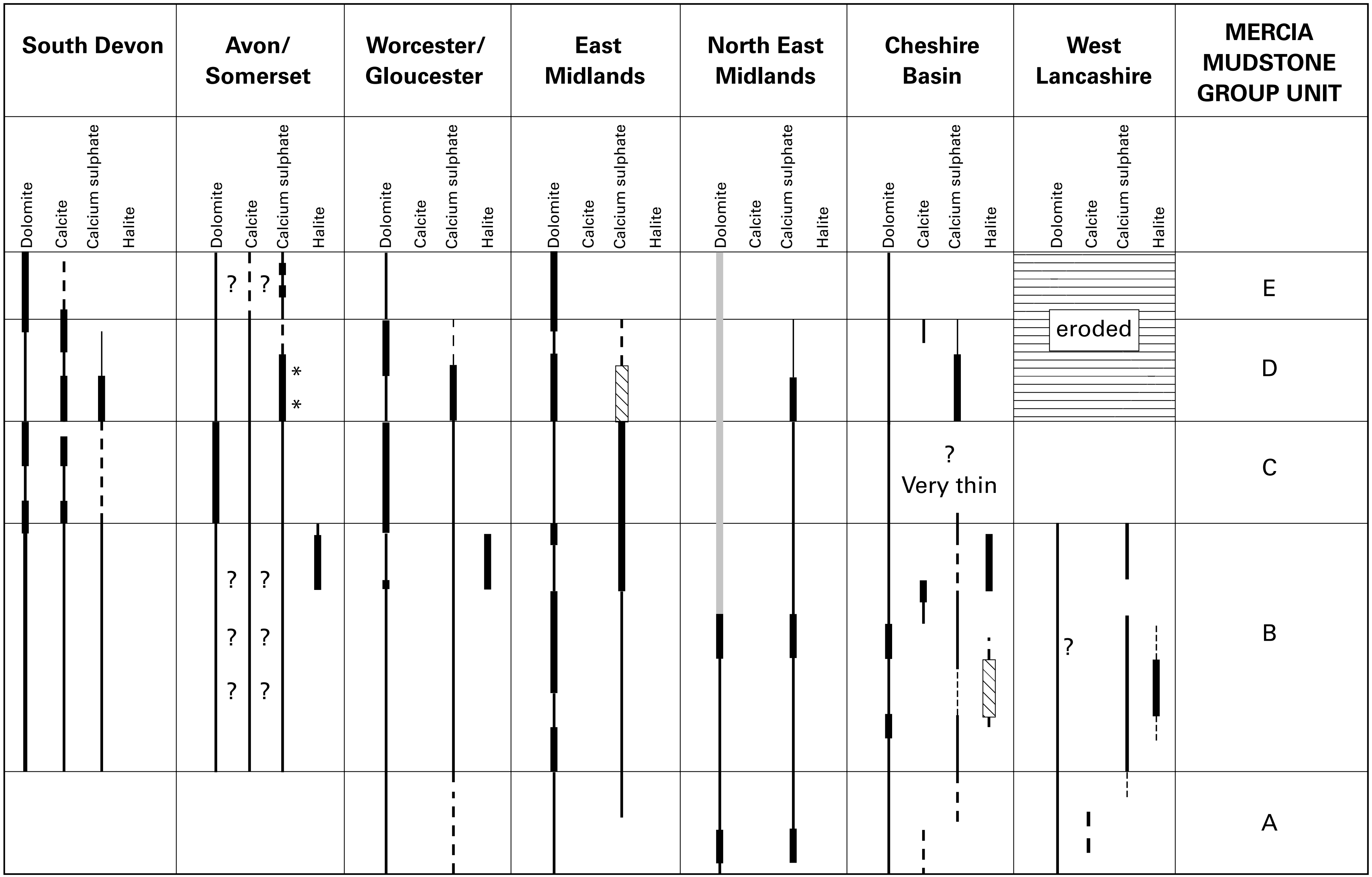


Figure 3.2 The distribution of carbonate and evaporite minerals in the Mercia Mudstone Group.

3.4 REGIONAL MINERALOGICAL VARIATION

This section is limited to those areas for which mineralogically information was available and does not include the East Irish Sea Basin and north Cumbria.

3.4.1 South-west England and South Wales

MARGINAL DEPOSITS

The marginal deposits of the sedimentary basin in the south-west comprise breccias, conglomerates and sandstones with intercalations of finer material. They were largely derived from local sources as scree and flash flood deposits and were formerly named ‘dolomitic conglomerate’. The most highly dolomitised breccias and conglomerates are buff, yellow or orange-brown in colour, whereas the less dolomitised are red and green or grey green. In areas where they lie on Carboniferous Limestone the basal deposits may fill palaeo-caves in the limestone.

The marginal deposits in the Cardiff area of South Wales comprise up to 35 m of coarse clasts with finer interbeds and have been subdivided into continental and lacustrine shore subfacies (Waters and Lawrence, 1988). The continental subfacies comprises conglomerate, much of which is derived from the Carboniferous Limestone, and sandstone with local fine intercalations. These deposits interdigitate with red mudstone and grade into the typical red mudstone of the Mercia Mudstone Group. The distribution of the deposits was controlled by the basement topography at the time of their deposition.

The lacustrine shore deposits, to the west and south of Cardiff, are of clastic or carbonate types. The clastic sediments are reworked deposits of the lake shore and the carbonate deposits are of limestone and associated evaporitic beds. They can be seen at Sully Island and at Dinas Powys. At the base of the Sully Island succession is a thin, clastic shore zone deposit above which is a residual ferricrete or perilittoral dolomite. Above this there is an evaporitic dolomite comprising an array of zoned rhombic crystals, up to 300 mm in length, and partially dolomitised calcite spar. The rhombic dolomite may be ferroan and haematite cement is common. Some parts of the bed have suffered dissolution and fracturing and the cavities are filled by ferroan calcite spar. The rhombic dolomite may be replaced by haematite stringers or irregular laminae with a residue of quartz grains.

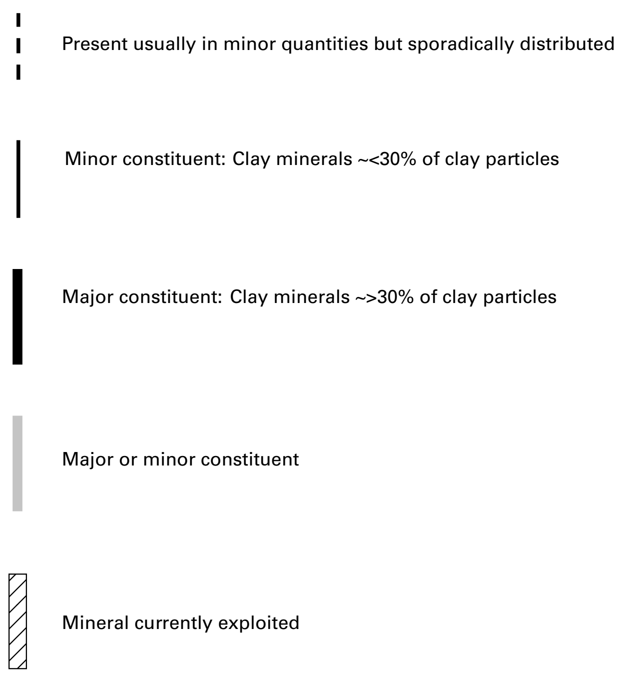
The Evaporitic Dolomite Unit (Leslie, 1989) consists of 6 – 9.2 m of red dolomite, detrital clays (mainly illite) and quartz with a haematite-rich cement. This unit comprises four sections. Lower and upper sections are of laminated and rippled dolomite. The dolomite contains between 52 and 53% calcium carbonate. Most of the sedimentary structures have been lost due to recrystallisation. Above the lower section there are about 3 m of dolomite containing replaced evaporite nodules. Some nodules, originally composed of calcite spar with abundant anhydrite inclusions, have been partly dolomitised. Other nodules contain either carbonate or quartz-replacement sulphate nodules. Underlying the upper unit is about 2 m of carbonate that precipitated at or just below the water table.

BASIN DEPOSITS

In the main part of the basin in south-west Britain red or green, dolomitic or calcareous, mudstones, siltstones and sandstones, typical of the Mercia Mudstone Group, were deposited. Evaporite deposits of gypsum and anhydrite occur as nodules, beds or net-like deposits and, in the centre of the basins, thick halite deposits such as the Somerset Halite Formation were formed. Sandstones are siliceous and/or dolomitic. In Gloucestershire and Somerset the evaporites contain strontium sulphate (celestite) and barium sulphate (barite). Very small amounts of galena and zinc blende are present disseminated in the evaporites or in small cavities.

Jeans (1978) described three mudstone facies separated by two cycles of carbonate-sandstone-carbonate, the ‘Dunscombe Cycle’ and the ‘Weston Cycle’ between Sidmouth and Branscombe and between Seaton and Charton, in south Devon. However, these two cycles are the same and probably equivalent to the Arden Sandstone Member (Warrington et al., 1980). In the lowest mudstone, the dolomite content ranged from 1% to 20% and was dominant over calcite that was in the range 0% to 5%. Above this mudstone is a cycle of carbonate-sandstone-carbonate. Within the carbonate facies the relative importance of the two carbonates varied, sometimes dominated by calcite but most of the ‘cycle’ was dolomite-rich (up to 50% dolomite). The sandstone group also contained more dolomite than calcite. The upper mudstone, usually, contained more calcite than dolomite particularly near the top. Dolomite was the dominant carbonate of the Blue Anchor Formation, of which it formed up to 50% in some beds.

Illite and chlorite dominated the clay mineralogy of the lower mudstone. Higher up the succession there was a change to a greater proportion of the mixed layer illite-smectite in south Devon and to chlorite-smectite in other areas. Higher up and into the carbonate-sandstone-carbonate cycle the clay mineral assemblage consisted of illite, chlorite, mixed layer illite-smectite, smectite and sepiolite. The more complex assemblage was also present in the lower part of upper mudstone. However, higher up and into the Blue Anchor Formation the clay assemblage



Key to Figure 3.3 *(opposite)* The distribution of clay minerals in the Mercia Mudstone Group.

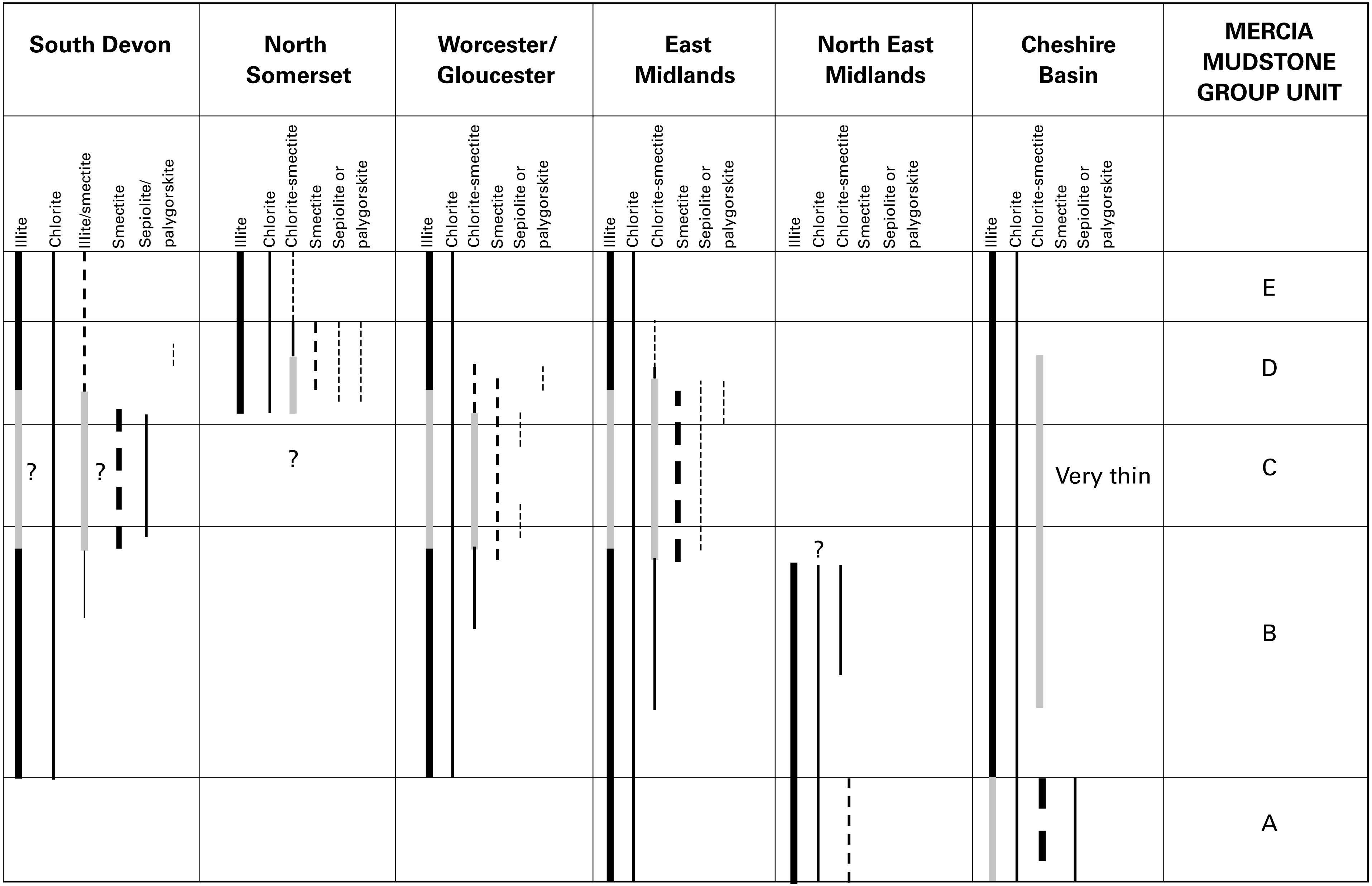


Figure 3.3 The distribution of clay minerals in the Mercia Mudstone Group.

changed to a 'detrital' assemblage of illite and chlorite with a minor component of illite-smectite and trace quantities of palygorskite at some levels (Mayall, 1981; Leslie, 1989). At Branscombe the transition from less than 85% to greater than 85% illite and chlorite took place between 45 and 65 m below the base of the Blue Anchor Formation. Nodular gypsum was abundant in laterally impersistent beds in the lower part of the Blue Anchor Formation and the upper 300 mm of red mudstone.

A similar transition in clay mineral content, was identified between 50 and 70 m below the Blue Anchor Formation at St. Audrie's Bay in Somerset. The authigenic clay minerals were mainly mixed layer chlorite-smectite with smectite and in some beds minor sepiolite or palygorskite (Leslie et al., 1993). Above the transitional zone and in the Blue Anchor Formation more than 90% of the clay mineral assemblage comprised illite and chlorite with minor chlorite-smectite, intermittent smectite, and palygorskite. The Blue Anchor Formation may contain between 60% and 80% carbonate in beds of 0.2 to 0.9 m thick.

In the Upper Mercia Mudstone Group at the Penarth Cliffs in South Wales, the clay mineral assemblage was illite, chlorite and minor mixed-layer chlorite-smectite clay. Smectite, palygorskite and sepiolite have not been identified.

3.4.2 West Midlands

The Eldersfield Mudstone Formation forms the lower part of the Mercia Mudstone and contains between 2% and 33% dolomite. The lower parts of this formation usually contain less than 10% calcite and it may be absent, for example in the Stowell Borehole in Gloucestershire. The dolomite content of the Arden Sandstone Formation is usually between 10% and 30%. The dolomite content of the upper red mudstone, the Twyning Mudstone Formation, is normally between 10 and 20% and its calcite content is usually similar to the rest of the succession. The Blue Anchor Formation contains between 10 and 30% dolomite (Jeans, 1978).

Illite and chlorite are present at the base of the Mercia Mudstone Group. The clay mineral assemblage in most of the middle and upper Eldersfield Mudstone Formation, Arden Sandstone Formation and the lower part of the Twyning Mudstone Formation comprises a mixture of illite, chlorite, and mixed layer chlorite-smectite clay (often present as corrensite). Smectite is present, sometimes with sepiolite in, and adjacent to, the Arden Sandstone Formation. The dominant clay minerals in the upper part of the Twyning Mudstone Formation and the Blue Anchor Formation are illite with subordinate or minor chlorite.

Skerries in the Warwickshire and Worcestershire area are usually dolomitic sandstones or siltstones with angular to sub angular quartz grains which are often cemented with dolomite. Quartz, gypsum and barycelestite cements are rare (Old et al., 1987). The Weatheroak Sandstone, near Redditch (Old et al., 1991) is a pale, flaggy sandstone, typically cavernous, calcareous or felspathic with green mudstone interbeds. Copper mineralisation is present at its base. Secondary malachite predominates, mostly as grain coatings. In particularly heavily mineralised specimens cuprite and native copper inclusions, tenorite overgrowths, chalcocite and hydrous copper silicate are also present. A vuggy, fine-grained, felspathic sandstone above the Weatheroak Sandstone is composed of angular to sub-rounded quartz with some feldspar and is grain supported with a well developed secondary silica cement. In this area the Arden Sandstone Formation is usually a dolomitic, sometimes calcareous, quartz sandstone or siltstone. It may be close-packed and contain some grain to grain pressure welding and minor secondary quartz growth. Phosphate bioclasts may also be present (Strong, 1983).

Skerries in the Blue Anchor Formation may be composed of angular or sub-angular quartz in a micrite matrix; or composed of silt-size, and less commonly, sand-size quartz grains scattered in a uniform microspar matrix. Some skerries are composed of bioclastic fragments up to several mm in diameter in a micrite or microspar matrix (Strong, 1979; 1983).

3.4.3 Cheshire Basin

The eight formations recognised within the Mercia Mudstone Group in the Cheshire Basin (Evans et al., 1993; Wilson, 1993) are the Tarporley Siltstone Formation, Bollin Formation, Northwich Halite Formation, Byley Mudstone Formation, Wych Mudstone Formation, Wilkesley Halite Formation, Brooks Mill Mudstone Formation and the Blue Anchor Formation. They were described by Wilson (1993) and the mineralogy, petrology and diagenesis were studied by Milodowski et al., (1994).

TARPORLEY SILTSTONE FORMATION

Tarporley Siltstone Formation (formerly known as the Keuper Waterstones) is the basal formation of the Mercia Mudstone Group. The Helsby Sandstone Formation, the highest formation of the Sherwood Sandstone passes gradationally into, and in part is laterally equivalent to, the Tarporley Siltstone. This represents a transition from the dominantly aeolian and fluvial quartz sandstones of the Sherwood Sandstone to inter-tidal deposits at the base of the Mercia Mudstone Group. Typically the Tarporley Siltstone Formation comprises interbedded siltstone, reddish brown and greenish grey mudstone and thin, fine- to medium-grained sandstone. In some areas the coarser sandstone and siltstone facies are more typical of the Helsby Sandstone Formation. In the Malpas area a major part of the Tarporley Siltstone passes into a dominantly sandstone facies, the Malpas Sandstone. The rocks comprise largely detrital, angular, quartz silt and clay minerals with minor amounts of detrital K-feldspar, albite, mica (muscovite and biotite), chert fragments, and titanium-iron oxides. Minor amounts of sub-micron-sized iron oxide are present in the red-brown facies but are largely absent in the grey or green facies. Detrital heavy minerals are present mainly at the base of siltstone laminae and interbeds, and include ilmenite, zircon, rutile, magnetite, tourmaline, apatite, monazite, xenotime and chromite. The clay minerals are dominated by illite with variable proportions of smectite and chlorite. However, corrensite was dominant with minor illite in a sample from the Bridge Quarry, Grinshill (NGR SJ 523 238) (Milodowski et al., 1994). The petrography of the Tarporley Siltstone Formation shows that many of these sediments comprise well defined, small, complex, fining upwards cycles rather than discrete siltstone and mudstone laminae.

The Malpas Sandstone contains well-rounded low grade, metamorphic silty mudstone grains composed of illite, quartz and chlorite. This assemblage is typical of the Lower Palaeozoic basement rocks from the Midlands or Wales.

Bollin Mudstone Formation

The lower half of the Bollin Formation (Wilson, 1993) is reddish brown, massive mudstone with interlaminated reddish brown or greenish grey mudstone and siltstone with some thin beds of sandstone. The upper half is mainly reddish brown, interlaminated mudstone and dolomitic siltstone. In some areas, near the top of this formation, halite beds up to 2 m thick are present and crystals of halite occur elsewhere.

Many of the siltstones are silty, micro-crystalline dolomites and anhydritic micro-crystalline dolomites in rhythmical cycles of 0.2 to 0.4 mm thick. The laminae may be silty but can also be gypsiferous or anhydritic mudstone or gypsum or anhydrite. The gypsum or anhydrite may locally disrupt the sedimentary fabrics. Siltier facies contain mainly fine angular detrital quartz grains with minor amounts of albite and K-feldspar in a clay matrix. Trace amounts of apatite, anatase, rutile, titanium-iron oxides, zircon, monazite and xenotime are also present. Micaceous laminae are present which contain silt and fine sand size muscovite and biotite. The red-brown rocks contain disseminated iron oxide but this is absent from the green facies. Dolomite is an important component and occurs as rhombs or irregular specks with an average dimension between 0.005 mm to 0.02 mm. In more silty specimens or in silty bands quartz occurs as angular grains averaging from about 0.03 mm to about 0.05 mm in diameter. Bands of fibrous gypsum are often present. Other minerals present are muscovite and tourmaline.

The typical clay assemblage in this formation is dominated by illite with minor chlorite and occasionally corrensite. In earlier studies (Taylor et al., 1963) the only clay mineral identified, from thin section, was illite.

Northwich Halite Formation

The Northwich Halite Formation (formerly the Lower Saliferous Beds) is up to 283 m thick and comprises 25% mudstone and 75% halite. Mudstones and siltstones are interbedded with the halite and contain laminated gypsum or anhydrite and microcrystalline dolomite similar to the underlying Bollin Formation and the overlying Byley Mudstone Formation. The purest parts of the sequence consist of 95% sodium chloride but may contain inclusions and thin laminae of gypsum, anhydrite or micro-crystalline dolomite. The halite has undergone extensive and probably repeated recrystallisation. Euhedral halite crystals have grown within the mudstone and siltstones producing ‘Haselgebirge facies’.

Illite and chlorite are present throughout the mudstone and siltstone facies. A gradual increase in the corrensite content of the clay mineral assemblage occurs upwards from zero at the base of the formation to an important component at the top.

Byley Mudstone Formation

The Byley Mudstone Formation forms the lower part of the ‘Middle Keuper Marl’. This formation has a laminated facies, and a blocky structureless facies. The laminated facies contain red and green interlaminated siltstones and mudstones commonly 0.2 mm to 5 mm thick (Wilson, 1993 and Milodowski et al., 1994). The mudstones are commonly rich in dolomite and gypsum or anhydrite. Arthurton (1980) noted that detrital quartz was generally dominant in the siltstones but dolomite was usually present and may be dominant. Interlaminated siltstones and mudstones are typically convoluted into folds. Gypsum nodules are present in the laminated facies; veins are common and mostly sub-parallel to the laminations. The laminations are of siltstone and dolomitic siltstone that pass into microcrystalline dolomite or anhydrite or a mixture of both. Fissures that developed under hypersaline conditions are filled by fine-grained anhydrite or anhydrite-dolomite. The mineralogy of the Byley Mudstone Formation is similar to that of the Bollin Mudstone Formation.

Samples of brecciated Byley Mudstone Formation from near Knutsford were well-packed, cemented, contained gypsum and/or anhydrite to varying degrees and were stronger than expected (Strong, 1992). The breccias may be primary depositional breccias or conglomerates rather than the result of collapse following halite dissolution. Some samples were cemented by gypsum and anhydrite that may be the result of a complex sequence of partial dissolution followed by deposition in the voids. Calcite and microcrystalline calcite were also present. The main detrital components were angular, silt-sized quartz and clay minerals with minor K-feldspar, albite, muscovite and traces of green, chloritised biotite, fine-grained titanium oxides, zircon, monazite and ilmenite. Fine-grained, disseminated iron oxide was present in the red-brown facies but was absent in the green facies. The formation comprises a uniform clay mineral assemblage of illite, corrensite and minor chlorite.

Wych Mudstone Formation

The Wych Mudstone Formation is typically a structureless reddish-brown siltstone, silty mudstone and mudstone with occasional thin, very fine quartz sandstone beds. The formation often contains abundant disseminated dolomite and anhydrite or gypsum. Nodules of gypsum and anhydrite are also present. The hydration of anhydrite has, in places, disrupted the strata to form a breccia. The dominant minerals are mainly quartz as angular, silt- or sand-sized detrital particles within a matrix of fine clay, with minor amounts of K-feldspar and coarse muscovite, also of detrital origin. The clay content is similar to that of the Byley Mudstone Formation and consists of a uniform assemblage of illite, corrensite and minor chlorite.

Wilkesley Halite Formation

The mineralogy of the Wilkesley Halite Formation is similar to that of the Northwich Halite Formation. However, the clay mineral assemblage is a fairly constant assemblage of illite, corrensite and minor amounts of chlorite.

Brooks Mill Mudstone Formation

The Brooks Mill Mudstone Formation consists of two generally structureless reddish brown mudstones with subordinate sandstones and anhydrite or gypsum beds. A 6.4 m thick anhydrite or gypsum bed with interspersed mudstone partings occurs about one third distance above the base of the formation (Wilson, 1993). The formation also contains typically about 10% dolomite and some calcite (Jeans, 1978).

The mudstones show an intercalation of reddish-brown, silty, pelloidal mudstones with thin laminae of ferruginous clay-pellet sandstone, structureless to weakly laminated dolomitic mudstones and reddish-brown or green, silty micro-dolomite and silty dolomitic mudstones and siltstones.

The red-brown mudstone comprises highly compacted pelloidal mudstone often interbedded with fine-grained sand laminae. The clay minerals present are illite, corrensite and chlorite at the base and illite with chlorite at the top.

BLUE ANCHOR FORMATION

The Blue Anchor Formation consists of poorly laminated greenish-grey mudstones with some local brown mottling. The detrital minerals are dominated by angular, silt- or sand-sized quartz in a clay matrix with minor to trace quantities of K-feldspar, muscovite, biotite and chlorite with trace quantities of apatite, altered titanium-iron oxides, zircon, xenotime and monazite.

The clay mineral assemblage is illite and minor chlorite that is similar to the upper part of the Brooks Mill Mudstone.

3.4.4 East Midlands

The Mercia Mudstone Group in the East Midlands consists largely of red-brown and some grey-green, laminated or structureless, dolomitic, commonly gypsiferous, mudstone and argillaceous siltstone. Thin beds of greenish-grey or grey dolomitic siltstone or sandstone skerries are also present.

LEICESTERSHIRE

The Mercia Mudstone Group in Leicestershire consists of red-brown, silty mudstones with greenish-grey bands and patches. Thin, pale, greenish-grey, quartz siltstones occur throughout and sandstones (skerries) are present in the upper part of the Group. Gypsum occurs throughout as nodules, up to 100 mm across, and as secondary veins of satin spar (Worssam and Old, 1988).

Marginal facies of coarse breccias and sandstones are present at the interface with Precambrian inliers in Charnwood Forest where breccias fill depressions in the former Triassic land surface. The sandstones are interbedded with red-brown mudstones and often contain clasts of the local basement rock. The marginal facies usually pass laterally into typical Mercia Mudstone within a distance of a few metres.

An account of the petrography of the skerries in the Coalville area was given by Worssam and Old (1988). The skerries are moderately well sorted siltstones with thin, alternating quartzitic and carbonate (mainly dolomite) layers. Grains are angular to sub-rounded and are usually coarser in the quartzitic layers than the carbonate ones. The quartzitic layers also contain dolomite grains up to 0.02 mm across. Mica usually makes up to 10% of a skerry and is mostly muscovite with some biotite that may be partially or completely altered to chlorite. Plagioclase, apatite, zircon and microcline are present in small amounts.

The clay minerals of the Gunthorpe Formation near Ibstock are dominantly illite with chlorite and little or no mixed-clay chlorite-smectite. However, at Loughborough chlorite-smectite or corrensite is an important component in the upper part of the formation. In the Cropwell Bishop Formation at Croft, illite, chlorite-smectite or corrensite and chlorite are present. However, at the top of the Cropwell Bishop Formation and the Blue Anchor Formation in Leicester the clay assemblage comprises illite and chlorite (Jeans, 1978).

NOTTINGHAM AREA

The stratigraphy and the clay mineralogy of the Mercia Mudstone Group in the Nottingham area were described by Bloodworth and Prior (1993) and Jeans (1978).

Sneinton Formation

The Sneinton Formation is approximately equivalent to the 'Keuper Waterstones' and includes the Woodthorpe and Colwick formations (Warrington et al., 1980) and their equivalents (Elliott, 1961). It is marked by an upward change from dominantly sandstone to interbedded sandstones and mudstones. It consists of interbedded fine- to medium-grained sandstones, siltstones and mudstones; pebbly sandstones are rare and occur mainly at the base. These beds are mainly red-brown with micaceous laminae and gypsum nodules. The sandstone beds are generally about 0.3 m thick but may range up to 1.90 m. The argillaceous beds are mostly less than 0.7 m thick but can be up to 4.1 m.

The whole rock dolomite content varies from about 2% to more than 20% in the middle of the formation and is generally more than 6% with the lowest values usually near the base (Bloodworth and Prior, 1993; Jeans, 1978). Gypsum is not present at the base of the Sneinton Formation in the Cropwell Bridge Borehole but occurs higher up starting at about 15 m above the unconformity with the Nottingham Castle Formation (Sherwood Sandstone Group). Above this the rock contains between 1 and 20%. The peak value is about 8 m below the top of the formation. The clay mineral assemblage is dominated by illite with subordinate chlorite and smectite is uncommon.

Radcliffe Formation

The Radcliffe Formation (Elliott, 1961; Warrington et al., 1980; Charsley et al., 1990 and Howard et al., in preparation) comprises finely laminated and colour banded, red-brown, brown, pink, mauve and grey-green, locally micaceous mudstones. A few thicker beds of fine-grained sandstone occur. The mineral composition is similar to the Sneinton Formation but is generally more dolomitic, containing between 20 and 40% dolomite, which decreases towards the top of the formation (Bloodworth and Prior, 1993; Jeans 1978). The clay mineral assemblage is dominated by illite with minor chlorite.

Gunthorpe Formation

The Gunthorpe Formation (Charsley et al., 1990) is equivalent to the Carlton and Harlequin formations of Elliott (1961) and Warrington et al. (1980). It consists of interbedded, red-brown, orangey red-brown and subordinate grey-green mudstones, siltstones and very fine-grained sandstones. The mudstones and siltstones are blocky and the sandstones occur in thinly-bedded and laminated facies. The skerries consist of dolomitic siltstones and fine-grained sandstones and are present at many levels and individual skerries may be persistent or impersistent. Gypsum occurs as nodules (Ambrose, 1989) and in veins (Rathbone, 1989).

The dolomite content within the Gunthorpe Formation varies between 7% and 30%, and the gypsum content between 0% and 24%. The dolomite content may be cyclical within the sequence. The main difference between this formation and those below is the appearance of mixed layer chlorite-smectite clays. The clay mineral assemblage contains illite, mixed layer chlorite-smectite and chlorite.

The chlorite content decreases slightly from the bottom to the top of the formation but the illite content decreases rapidly in the lower part of the Gunthorpe Formation as the corrensite content increases. Near to the top of the Gunthorpe Formation the mixed layer clays may be absent.

Edwalton Formation

The Edwalton Formation was defined by two persistent skerries, the Cotgrave Sandstone Member at its base and the Hollygate Sandstone Member at its top (Elliott, 1961; Warrington et al., 1980; Charsley et al., 1990; Howard et al., in preparation). The Cotgrave Sandstone Member is a persistent, red-brown or yellow, fine- to medium-grained sandstone with localised mudstone and siltstone interbeds. The sandstone is poorly cemented and contains voids due to the dissolution of gypsum. Most of the Edwalton Formation consists of thick, blocky, silty mudstone and siltstone and thinner grey-green units, some of which are poorly laminated. Some dolomitic siltstone and fine- to medium-grained sandstone skerries occur within this formation. The Hollygate Sandstone Member comprises up to six beds of grey-green to yellow or brown, fine- to coarse-grained, commonly poorly cemented sandstones. Typically the sandstone makes up 60% to 75% of the member. The remainder is red-brown with some grey-green, mostly silty, mudstones with sand grains.

Gypsum is usually an important constituent of the rock and may make up to 50% of the whole. The dolomite content, usually, varies between 2% and 20% but can be as high as 50% (Bloodworth and Prior, 1993). Jeans (1978) found calcite below the Hollygate Sandstone Member. The clay mineral assemblage of the Edwalton Formation comprises illite, mixed layer chlorite-smectite and chlorite. The proportion of the mixed layer clays increases towards the top of the formation and replaces illite. The chlorite content is fairly constant throughout. Corrensite is present throughout and smectite is present at the top of the formation. Sepiolite occurs in the Hollygate Sandstone Member (Bloodworth and Prior, 1993; Jeans, 1978).

Cropwell Bishop Formation

The Cropwell Bishop Formation (Charsley et al., 1990; Howard et al., in preparation) is equivalent to the Trent Formation and lower part of the Glen Parva Formation of Elliott (1961) and the Trent and Glen Parva Formations of Warrington et al. (1980). The lower boundary of this formation is the top of the Hollygate Sandstone Member and the upper is the base of the Blue Anchor Formation. The formation consists mainly of red-brown or brown silty mudstone, usually blocky but with some laminated beds. Grey-green beds of siltstone and silty mudstone become more common towards the top.

Gypsum occurs throughout the formation as veins, nodules and beds but may be absent near surface due to its removal in solution. The host rock may contain up to 40% gypsum. The Newark Gypsum contains both bedded and nodular gypsum. The dolomite content is consistently high and varies between about 10% and 30% and is generally more than 20% (Bloodworth and Prior; 1993, Jeans 1978).

The clay mineral composition shows an increase in illite with a proportional decrease in the mixed layer chlorite-smectite content from the bottom to the top of the formation. The percentage of smectite interlayers in the mixed layer clay decreases from 100% near the base to between 0% and 50% near to the top of the formation. Sepiolite is present near the base of the formation and is associated with zones with a higher proportion of mixed layer chlorite-smectite and with skerry bands (Taylor 1982).

The clay mineral composition of the Cropwell Bishop Formation near Newark, East Leake and in the Fauld mine shows a similar pattern to that found to the south of Nottingham (Taylor, 1982). At East Leake, sepiolite and palygorskite are associated with the main sulphate bed. Taylor (1982) separated the Cropwell Bishop Formation into a lower division, the Fauld Member, rich in authigenic clay minerals, which contained less than 85% illite and chlorite, and an upper division, the Hawton Member, which contained more than 85% illite and chlorite.

Blue Anchor Formation

The Blue Anchor Formation in the Nottingham area lies above the Cropwell Bishop Formation and was formerly considered to be the upper part of the Glen Parva Formation by Elliott (1961) but was renamed by Warrington et al. (1980). Its lower boundary is defined by the colour change of the mudstone from red-brown to pale greenish-grey. The upper boundary is a sharp disconformity marked by an uneven surface of grey-green silty mudstones and is overlain by the dark grey to black shaly mudstones (Westbury Formation) at the base of the Penarth Group. The Blue Anchor Formation is a pale greenish-grey, usually blocky, dolomitic, silty mudstone or siltstone with some darker, pyritic, laminae particularly near the base. There are scattered, coarse, aeolian quartz sand grains.

In the Nottingham area this formation has similar mineral characteristics to the top of the Cropwell Bishop Formation with a dolomite content, mainly greater than 20% (Jeans, 1978) and little or no gypsum. The clay mineral assemblage is dominated by illite with subordinate chlorite.

3.4.5 North and east of Newark

Geophysical logging of the Mercia Mudstone Group shows that the basal beds to the north and east of Newark, contain sufficient radioactive minerals, to act as a marker in the natural gamma ray log. To the north, in the Seaton Carew Formation, the grains of radioactive minerals are surrounded by bleached haloes. There are evaporites above the Seaton Carew Formation, the Esk Evaporites, and within or above the 'Green Beds' from North Nottinghamshire to Middlesborough. The evaporites consist of anhydrite and gypsum and may be up to 30 m thick in parts of north Yorkshire. Halite is present at depth in the Whitby area.

The Retford Formation in central and north Nottinghamshire, was formally called the 'Green Beds' by Warrington et al., (1980) and comprises in the north mainly green, grey or blue mudstone with thin bands of siltstone and sandstone but in the south it is a more sandy and rhythmically bedded sequence. At its base there is a pale-coloured conglomerate derived from the pebble beds of the Sherwood Sandstone. Gypsum and anhydrite are present as thin bands. The fine- to medium-grained quartz was probably derived from the Sherwood Sandstone. Fine micas (biotite, muscovite and chlorite) are concentrated on silty bedding planes. Calcite is sometimes present as a cement (Edwards, 1967).

The clay minerals at the base of the Retford Formation comprise illite with minor chlorite. However, mixed layer chlorite-smectite is present as corrensite or more smectite-rich mixed clays. This contrasts with the Sneinton Formation that contains no mixed layer clay minerals (Bloodworth and Prior, 1993).

Near East Retford the arenaceous members of the Sneinton Formation comprise well sorted, closely packed, coarse silt- to fine-sand sized, sub-angular to angular clastic grains (Smith et al., 1973). The quartz has secondary overgrowths. Feldspars are also present and show alteration with secondary overgrowths. The overgrowths do not appear to form a coherent cement. Where the rock is red, haematite form secondary coatings along joints. The detrital heavy minerals include zircon, apatite, tourmaline, rutile, garnet, leucoxene and anatase. The clay mineral composition is typical of the Sneinton Formation and comprises mainly illite with chlorite.

Between the Sneinton Formation and the Clarborough Beds the rocks comprise red mudstones with bands of silty micaceous mudstone that contain illite and minor chlorite. The skerries are laminated, usually dolomitic and are sometimes argillaceous and micaceous (Smith et al., 1973).

The Clarborough Beds consist of about 3 to 13 m of mudstone and silty mudstones with much gypsum and skerries. These beds are probably equivalent to the East Bridgford Gypsum at the base of the Gunthorpe Formation. The gypsum occurs as irregular bands and veins. The skerries are variable in composition. Some are very porous, greyish green, argillaceous, dolomitic siltstone with small cavities and consist of well-sorted, angular, fine sand size, quartz grains with plagioclase, orthoclase, mica and dolomite of coarse and very fine silt size. However, they can also be dense with fine sand-sized, roughly bedded aggregates of evenly sorted clastic quartz and feldspar scattered in a coarsely crystalline, sometimes interlocking gypsum matrix, with laminated fine-grained dolomite. Other skerries contain silt-sized quartz with scattered feldspars and mica with patches of intergranular fibrous gypsum and streaks of dolomite (Smith et al., 1973). Gypsum has been quarried from the Clarborough Beds in the East Retford area.

The Gunthorpe Formation above the Clarborough Beds, at Gringley-on-the-Hill, north Nottinghamshire, contains angular to sub-rounded, equant, irregular silt- to sand-sized quartz, slightly eroded potassium feldspar and calcite. Mica flakes up to 0.1 mm across are common. The porosity varies significantly from the silty areas to the more clayey areas that enclose them. In the siltier areas, the clay matrix and dolomite cement reduce the intergranular porosity. Dolomite and calcite commonly occur as granular to massive cements. Dolomite occasionally occurs as euhedral rhombs up to 0.01 mm across and shows no evidence of dissolution in the near-surface zone. The clay matrix is dominated by illite with minor amounts of chlorite and corrensite. Chlorite occasionally forms discrete but irregular patches up to several tenths of a millimetre across (Pearce et al., 1996).

The upper part of the red beds of the Mercia Mudstone Group comprises red mudstones with green bands and some skerries. Gypsum is common as bands and stringers.

The Blue Anchor Formation consists of light green, grey or greyish green mudstone or silty mudstone and is calcareous in some places. Grey, fine-grained bands of sandstone are also present. Pale greyish green dolomitic limestone has also been recorded.

4 Geotechnical literature review

4.1 INTRODUCTION

The Mercia Mudstone Group in the UK is characterised by a sequence of brown, red-brown, calcareous clays and mudstones, with occasional beds of impersistent green siltstone and fine-grained sandstone. In its unweathered state the Mercia Mudstone may be described as an intact, jointed, 'weak' rock (Figure 4.1), whereas in its fully weathered state it is a reddish-brown, 'very soft' to 'hard' silty clay, but frequently containing less-weathered mudrock clasts (Figure 4.2). The depth of weathering can be considerable, exceeding 30 m in some areas, however, it is more typically 10 to 15 m. The weathering profile is usually progressive, with strength and stiffness tending to increase with depth but may be influenced by lithological differences (Figure 4.3).

Early published work specifically on the geotechnical properties and classification of the Mercia Mudstone includes Birch (1966) and Chandler (1969). The former, described work supported by the Construction Industry Research Association (CIRIA) and carried out at Birmingham University, and covered a range of laboratory and field tests on samples from the UK.

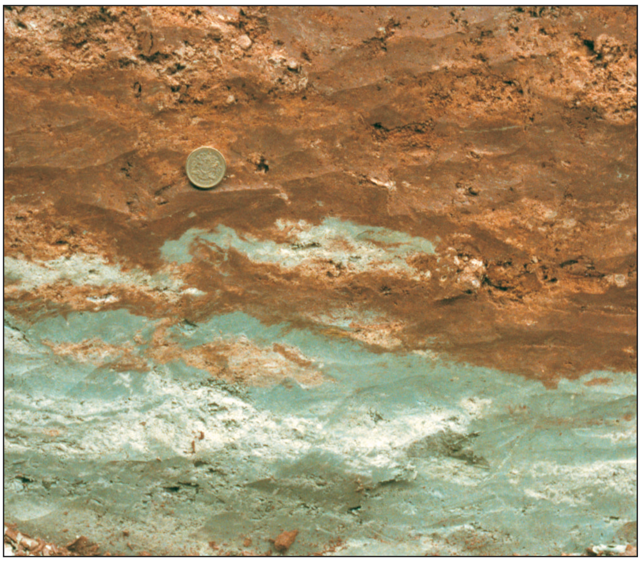


Figure 4.2 Fully weathered Mercia Mudstone (Zone 4b) reddish/brown and greenish/grey silty clay.

4.2 WEATHERING AND CLASSIFICATION

The primary classification of the Mercia Mudstone has, in the past, been by weathering zone. These classifications should not be used to derive quantities for strength and stiffness. The first of these was by Birch (1966). This was a simple division into 'weathered' and 'unweathered' zones. In most engineering applications the weathering classification attributed to Skempton and Davis (1966), and quoted by Chandler (1969) (Table 4.1), was used to classify the Mercia Mudstone prior to geotechnical testing; sometimes with minor modifications to suit local conditions (Chandler and Davis, 1973). In the literature, the weathering zone designation has traditionally been by Roman numerals (I–IV). Throughout this report, Arabic numbers have been used for convenience.

Figure 4.1 Unweathered (Zone I) jointed Mercia Mudstone (Cropwell Bishop Formation) classifiable as a 'weak rock'.

Bacciarelli (1993) re-assessed the weathering classification of Mercia Mudstone. He sub-divided Chandler's Zone 3, in a similar manner to Zone 4, and recognised the significant effect of alternating bands of 'weak' and 'strong' material. The re-assessment was based on bridge foundation work near Honiton in South Devon. The proposed subdivision of Zone 3 was as follows:

Zone 3a	lithorelict / particle dominant
Zone 3b	matrix dominant

An additional division for soil/rock with interbedded Zone 2 and 3 material was provided between Zones 2 and 3, as well as additional comments on permeability for Zone 4 material. The significance of alternating bands of different weathering zone was also discussed for a site at Ratcliffe-on-Soar, Nottingham by Seedhouse and Sanders (1993).

The problems inherent in devising a scheme to describe the weathering state of rock masses are due to the variety of physical and chemical processes that cause weathering and the wide range of mineralogical and structural characteristics of the rock masses being affected. The problems were addressed by the Engineering Group of the Geological Society's Working Party on *The description and classification of weathered rocks for engineering purposes* (Anon, 1995). They concluded that it was impractical to devise a single scheme to suit all the weathering processes that act on the full range of rock types and recommended a strategy that comprised five alternative approaches. The first approach is a factual description of

Figure 4.3 Weathered Mercia Mudstone near Honiton, Devon. 'Moderately weathered' material (Zone 3a) near surface becomes 'slightly weathered' (Zone 2) with depth, but is 'highly to fully weathered' (Zone 4a/4b) at the bottom of the section as shown by the smearing of material to the left of the spade.

weathering which is mandatory. The other four approaches are applicable to different situations where distinct zones and classes of a weathering sequence can be recognised unambiguously. Approach four is a prescriptive weathering classification incorporating material and mass features (Table 4.2) that is based on, and conforms with, existing formation-specific schemes such as Chandler's (1969) and its later developments. The five-fold approach to weathering description and classification has been adopted by BS 5930 (1999) with the suggestion that classes/zones may be more rigorously defined using local experience, site specific studies or reference to established schemes.

The weathering state of mudrocks has a significant effect on their strength and deformability when measured in both

Table 4.2 A weathering classification applicable to the Mercia Mudstone (after Anon., 1995).

APPROACH 4: CLASSIFICATION INCORPORATING MATERIAL AND MASS FEATURES		
Class	Classifier	Typical characteristics
A	Unweathered	Original strength, colour, fracture spacing
B	Partially weathered	Slightly reduced strength, slightly closer fracture spacing, weathering penetrating in from fractures, brown oxidation
C	Distinctly weathered	Further weakened, much closer fracture spacing, grey reduction
D	Destructured	Greatly weakened, mottled, ordered lithorelicts in matrix becoming weakened and disordered, bedding disturbed
E	Residual or reworked	Matrix with occasional altered random or 'apparent' lithorelicts, bedding destroyed. Classed as reworked when foreign inclusions are present as a result of transportation

Table 4.1 Weathering classification of Mercia Mudstone, after Skempton and Davis (1966).

State	Zone	Description	Comments
Fully weathered	4b	Matrix only	Can be confused with solifluction or drift deposits, but contains no pebbles. Plastic slightly silty clay. May be fissured
Partially weathered	4a	Matrix with occasional clay-stone pellets, usually about sand-size	Little or no trace of original(Zone 1) structure, although clay may be fissured
	3	Matrix with frequent lithorelicts becoming less angular with increasing weathering	Moisture content of matrix greater than that of lithorelicts
	2	Angular blocks of unweathered marl with virtually no matrix	Spheroidal weathering matrix starting to encroach along joints; first indications of chemical weathering
Non-weathered	I	Mudstone (often fissured)	Moisture content varies due to depositional variations

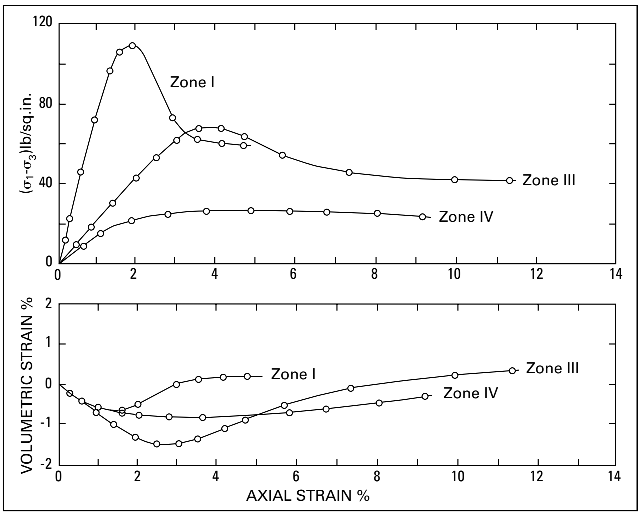


Figure 4.4 Stress vs strain graph for Mercia Mudstone Weathering Zones 1, 3 and 4 (drained, cell pressure 68.95 kN/m^2) showing change from brittle to plastic behaviour as weathering progresses (after Chandler, 1969).

the laboratory and in the field, thus it is important in the assessment of foundation suitability. This is particularly important in the case of the Mercia Mudstone (Chandler, 1969). The effect is seen in the shape of the stress vs. strain curve where essentially brittle behaviour for Weathering Zone 1 material becomes entirely plastic behaviour for Zone 4 material (Figure 4.4). Frequently, it is difficult to obtain undisturbed specimens to test for strength and deformability, and estimates are made from in situ standard penetration test N-value, cone penetrometer data, or more recently, self-boring pressuremeter results. Zone 4b material is typically ‘very soft’ to ‘firm’ and has widely varying geotechnical properties, in particular strength and stiffness. In some cases Zone 4 material is described as 'friable' and even ‘granular’. Zone 4b may be confused with head derived from Mercia Mudstone. The Mercia Mudstone is found to be ‘water-softened’ where its upper boundary acts as an aquiclude below sandstone or permeable fill. Here it can be expected to have low strength and high deformability. An undrained cohesion range of 12 to 600 kPa was reported for Zones 2 to 4 in the Coventry area (Old et al., 1989) with considerable overlap across the zones. Zone 1 material is rarely recorded in engineering site investigations. Zone 2 material may be subject to ‘spheroidal’ weathering.

Weathering tends to increase the measured plasticity of the Mercia Mudstone from ‘low’ to ‘intermediate’ or ‘high’ and reduce the beneficial mechanical effects of over-consolidation, for example, strength and stiffness. There is a notable increase in plasticity from Zone 3 to 4. In general Zones 1 to 3 have a ‘low’ to 'intermediate' plasticity whilst Zone 4 has an ‘intermediate’ to ‘high’ plasticity. Chandler (1969) suggests a boundary between weathering Zones 3 and 4 at a liquid limit of 38%. However, this is not borne out by Old et al. (1989). Chandler (1969) suggested that many properties attributed to over-consolidation were modified by weathering, leaving the soil in a pseudo-over-consolidated state similar to that obtained when soils are remoulded at water contents below the liquid limit. Natural moisture contents at depth are usually close to the plastic limit. Sometimes the Mercia Mudstone, and lithorelicts within it, is described as having a 'shaly' fabric. The siltstones within the Mercia Mudstone are usually well-cemented, fine-grained, and have a conchoidal fracture.

The various weathering systems do not fully distinguish between lithologies; for example, mudstone, siltstone and sandstone, or the relative proportions of them. Lithology is, however, important to the engineering behaviour of the formation. Grainger (1984) proposed a lithological classification for mudrocks (Figure 4.5). Bacciarelli (1993) proposed a lithological prefix to the zonal divisions where different lithologies are interbedded, and suggested that this would allow less conservative foundation designs to be used than were current at that time. Cragg and Ingman (1995) pointed out the limitation imposed by the depth dependence of weathering classification schemes, such as that of Chandler (1969), when disrupting factors such as evaporites, or regional variations in particle-size occur. Evaporite solution and re-precipitation result in contorted, brecciated and degraded material, often at depths where a more competent material might be anticipated. Birch (1966) reported the presence of ‘soft’ bands confined between ‘hard’ bands at depth, and attributed these to lithological variability (Figure 4.3).

The Mercia Mudstone was reported (Chandler et al., 1968; Birch, 1966) as having a two-stage structure, formed by the aggregation of clay-size particles into silt-sized peds, and the agglomeration of these weakly cemented by iron oxides. The primary ‘intra-ped’ structure is stronger than the secondary ‘inter-ped’ structure (Chandler et al., 1968). This implies that damage to the structure can be caused by sample disturbance associated with drilling. This has the effect of reducing deformation moduli and, to a lesser extent, strength values. This is demonstrated by the results of particle size analyses (PSA), where the per cent clay values obtained from British Standard (British Standards Institution, 1990) methods are significantly smaller than the value determined by mineralogical analysis (Dumbleton & West, 1966a, b; Davis, 1967). Davis (1967) quoted mineralogically determined values for % clay content of 60 to 100%, compared with particle size analysis determined values of 10 to 40%, and quoted values for aggregation ratio, Ar (ratio of clay content from mineralogical analysis to clay content from particle size analysis) of 1.4 to 10.0. This suggests that the measures employed to disaggregate samples in the BS1377 particle size analysis test (British Standards Institution, 1990) are unsuccessful in the case of the Mercia Mudstone. Chandler (1967) suggested that disaggregation is mainly a problem with unweathered Mercia Mudstone, and cited carbonate (cement?) content as one possible cause.

The Mercia Mudstone is often described as having an ‘affinity’ for moisture when used as an earthwork material. Therefore, this might imply that it has a tendency for swelling and shrinkage, and long-term degradation. The results of ‘moisture adsorption’ tests were described by Birch (1966). The intake of water by an unsaturated mudstone may result in softening (strength reduction) or slaking (strength reduction and structural breakdown), or both. However, slaking usually results from repeated cycles of wetting and drying. Few data on swelling, shrinkage, and slaking are available in the literature.

4.3 LITHOLOGICAL CONSIDERATIONS

The Mercia Mudstone is a heavily over consolidated and partially indurated clay/mudrock. It has been credited with ‘anomalous engineering behaviour’ and ‘unusual clay mineralogy’ throughout the literature (Davis, 1967). The former is usually attributed to aggregation of clay particles

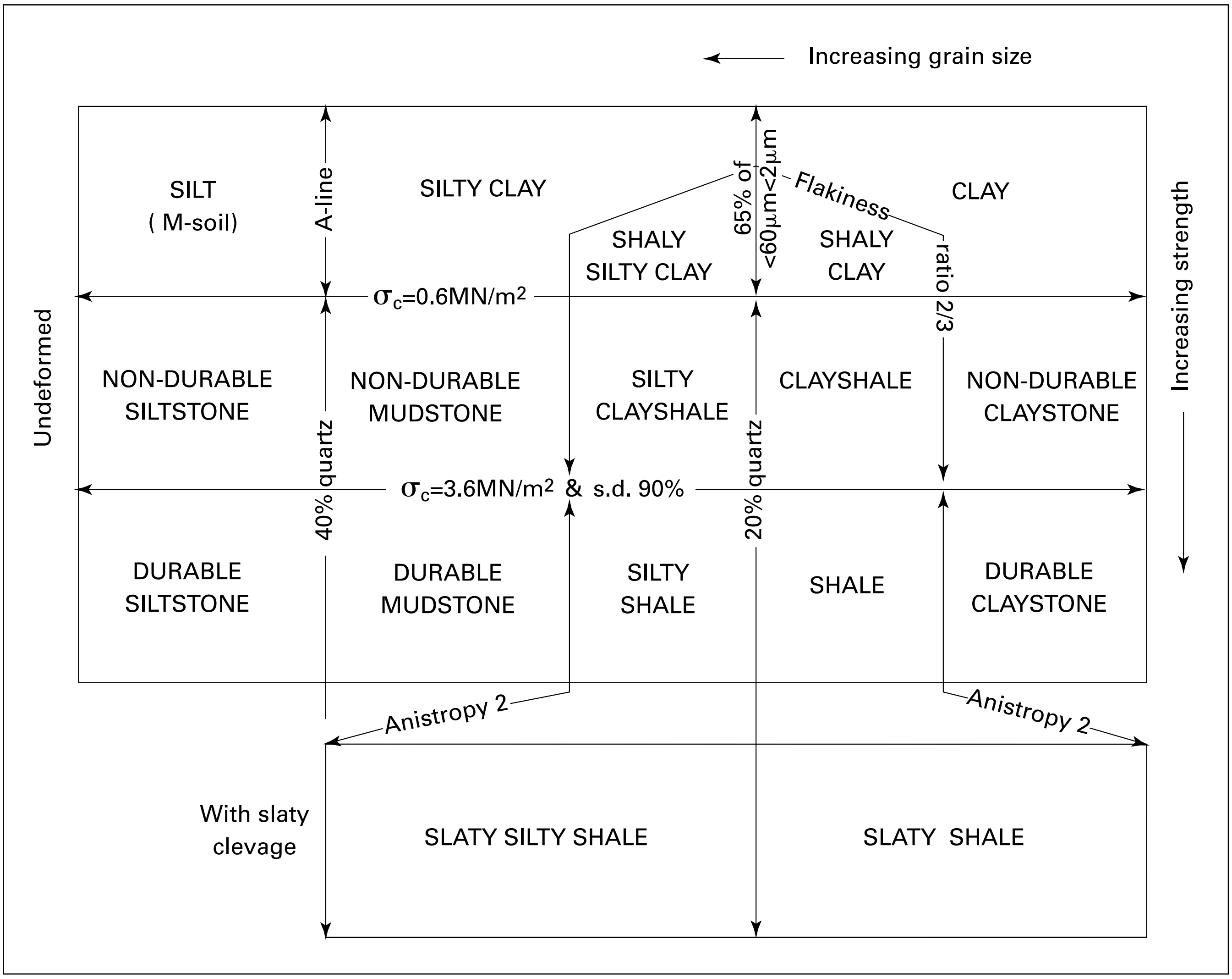


Figure 4.5 Classification of mudrocks suggested by Grainger, 1985.

into silt-sized peds or clusters. The clay mineral composition is dominated by illite (typically 40–60%), with additional mica, chlorite, swelling (mixed-layer) chlorite-smectite, and corrensite (mixed layer chlorite-smectite), with, less commonly, smectite, palygorskite and sepiolite (Bloodworth and Prior, 1993; Perrin, 1971; Dumbleton and West, 1966a, b). Other minerals found throughout the Mercia Mudstone include quartz, dolomite, and calcite. Cementing agents are important. These probably include secondary silica, haematite, and carbonates (Davis, 1967). Dumbleton and West (1966a, b) reported the presence of haematite, mainly in the fine particle size range, in all red coloured Mercia Mudstones but not in the grey. Keeling (1963) reported the presence of disordered kaolinite. Jeans (1978) recognised two distinct clay mineral assemblages: a) a detrital assemblage of mica with minor chlorite, and b) a neo-formed assemblage of magnesium-rich clays superimposed on the detrital sequence. Bloodworth and Prior (1993) found illite and chlorite throughout the Mercia Mudstone sequence in Nottingham, with magnesium-rich clays in the upper and middle parts modified by diagenesis. Mixed-layer clays (chlorite-smectite and illite-smectite) decline upwards being replaced by illite. Similar trends have been found in south-west England (Leslie et al., 1993). More details of the mineralogical composition of the Mercia Mudstone are given in Section 3.

The sulphate content of Mercia Mudstone ranges widely, depending on location and proximity to gypsiferous bands. All five sulphate classes, 1 to 5 (Building Research Establishment, 1991; British Standards Institution,1972) may be encountered, but typically, the Mercia Mudstone is placed in Class 1 (Forster et al., 1995). Carbonate contents range from 1 to 20% (Sherwood and Hollis, 1966; Chandler, 1969; Birch, 1966). Dolomite may substitute for calcite and be as high as 35% (Jeans, 1978). The Mercia Mudstone is, in the main, not classified as a marl, despite the former nomenclature Keuper Marl, according to the classification of Fookes and Higginbottom (1975). This classification, which requires that a ‘marl’ has a carbonate content of between 35 and 65%, describes the Mercia Mudstone as a ‘marly claystone’. However, Chandler (1967) described some Mercia Mudstone as ‘marl’. Many site investigation reports described large parts of the Mercia Mudstone as ‘siltstone’. As with many UK mudrock/clay formations the clay and silt sized fractions are often very similar, making the distinction between mudstone and siltstone difficult based purely on visual inspection. Isotropic, non-fissile argillaceous rocks are subdivided into mudstones, siltstones, and claystones by Grainger (1984) according to particle size and quartz content. The proposed boundary between mudstone and siltstone is at a quartz content of 40%, and the boundary

Table 4.3 Typical values for the engineering properties of Mercia Mudstone (after Chandler and Davis, 1973 and Cripps and Taylor, 1981).

	Chandler and Davis (1973)		Cripps and Taylor (1981)	
Property	Unweathered	Weathered	Unweathered	Weathered
Bulk density (Mg/m3)	2.480	1.840	–	–
Porosity (%)			1 – 50	
Natural water content (%)	5	35	5 – 15	12 – 40
Liquid limit (%)	25	60	25 – 35	25 – 60
Plastic limit (%)	17	33		
Plastic index (%)			10 – 35	
Undrained shear strength S_u (KPa)			130 – 2800 (from pressuremeter data)	
Young's modulus, E(MPa)	250	2	100 – 1200	10 – 100
Modulus of volume compressibility m_v (m^2/MN)	0.004	0.4	0.008	
Effective friction angle, ø' (°)	>40	25	⩾40	25 – 42

between mudstone and claystone at 20%. Grainger (1984) divided further according to 'durability', based on the compressive strength and the slake durability (2 cycles). Grainger's (1984) classification of mudrocks is shown in Figure 4.5.

4.4 INDEX PROPERTIES

Typical values for the engineering properties of Mercia Mudstone are shown in Table 4.3. In order to describe the aggregation of clay particles into peds or clusters, the aggregation ratio (Ar) has been used (Davis, 1967). The presence of aggregation is demonstrated in the results of particle size analyses, where % clay values obtained from British Standard methods test (British Standards Institution, 1990) are significantly smaller than the actual or so-called 'true' value obtained from mineralogical studies (Dumbleton, 1967; Dumbleton and West, 1966a, b; Davis, 1967). Davis (1967) quoted 'true' values for % clay-size content of 60 to 100%, compared with measured values of 10 to 40%.

The aggregation ratio (Ar) is defined as follows:

$$A_r = \frac{\text{\% clay mineral}}{\text{\% clay-size}}$$

where: % clay mineral is the % clay content (from mineralogical analysis)
% clay-size is the % clay-size fraction (from particle size analysis)

Davis (1967) quoted values of Ar ranging from 1.4 to 10.0; that is the mineralogically derived clay content was always larger than the particle-size derived clay content. This suggested that the measures employed to disaggregate samples in the BS1377 particle size analysis test (British Standards Institution, 1990) were, to a greater or lesser degree, unsuccessful. Birch (1966) showed that increased remoulding during sample preparation resulted in a higher % of clay-size contents. Chandler (1967) suggested that disaggregation was mainly a problem with unweathered Mercia Mudstone, and gave carbonate content as one possible cause. A significant positive relationship between (log) aggregation ratio and activity was given. Activity is defined as follows:

$$A_c = \frac{I_p}{\text{\% clay}}$$

where: I_p is plasticity index (i.e. liquid limit - plastic limit)
% clay is the percentage clay-size fraction

Davis (1967) found that there was a large rise in activity with decreasing clay-size fraction, and attributed this to the free surface area of aggregated clay particles being no different to that of disaggregated particles.

The determination of the plasticity of the Mercia Mudstone may be influenced by the methodology of the liquid limit and plastic limit tests. Birch (1966) reported that increased remoulding using a Hobart mixer during sample preparation resulted in higher values of liquid limit. He also reported that this effect was influenced by the moisture content of the mix, and that most of the increase in liquid limit was 'temporary'. The latter would imply that aggregations, having been destroyed, could reform with time. This has been shown for other, more highly aggregated soils, for example tropical red clays by Dumbleton (1967) and Northmore et al., (1993). The latter subjected tropical clay soils to non-standard preparation procedures involving mixing with a Seta grease worker (a tool which remoulds by repeated forced extrusion of the soil paste) for extended periods. This usually resulted in significant changes in the value of liquid limit obtained. In the case of one soil type (halloysitic) the liquid limit increased, and in the other (allophanic) it decreased. The standard procedure for the liquid limit test (British Standard Institution, 1990) employs hand-mixing of the soil sample 'for at least 10 minutes' prior to the test. This level of hand-mixing is adequate for most temperate climate soils, but becomes unreliable for highly aggregated soils. The BS1377 Part 2, Note 4.4.3.2 (British Standard Institution, 1990) says that care should be exercised when testing 'residual and highly plastic soils' and that these soils should be hand-mixed for 40 minutes, and that comparisons should be made between the two preparation techniques. Haider (1989) applied extended hand-mixing times (up to one hour) to Mercia Mudstone and found that there was no change from the standard ten minutes. He concluded that whilst the Mercia Mudstone was an aggregated clay its aggregations were broken down during the normal mixing time, unlike those of some tropical clays. He attributed this to differences in the cementing agent. The above means that the determination of activity potentially becomes doubly unreliable, i.e. from both the plasticity and the particle size term.

The plasticity of the Mercia Mudstone ranges from 'low'to 'high' in the Casagrande classification, but with the majority of data falling within the 'low' and 'intermediate' groups. Some silty Mercia Mudstone falls below the Casagrande A-line. Arithmetic means for liquid and plastic limit for the Coventry area were found to be 35% and 20%, respectively (Old et al., 1989). Weathering tends to increase the measured plasticity of the Mercia Mudstone from 'low' to either 'intermediate' or 'high'. Chandler (1969) suggested a boundary between weathering Zones 3 and 4 at a liquid limit of 38%. However, this was not borne out by Old et al. (1989).

Variations in natural moisture content within the Mercia Mudstone may be wide. Chandler (1967) quoted a range of 22 to 25% for a Mercia Mudstone profile at Kings Norton, Birmingham. Chandler et al. (1968) indicated that moisture content has a particularly important influence on all physical properties including geophysical, strength and compaction. The concept of 'critical degrees of saturation' (points of inflection obtained from plots of resistivity vs. saturation) (Chandler et al., 1968) is related to effective grain size, hardness, compaction, or cementation.

4.5 CONSOLIDATION

Generally, the Mercia Mudstone is described as having low compressibility and a high rate of consolidation, but is very variable (Birch, 1966). The consolidation settlement of unweathered Mercia Mudstone, under normal engineering loads, has been described as 'negligible' (Birch, 1966). The compressibility of the Mercia Mudstone, based on oedometer consolidation data for the Coventry area, was described as 'very low' to 'medium', and the rate of consolidation as 'low' to 'high' (Old et al., 1989). There is unlikely to be a clear relation between consolidation behaviour and maximum previous overburden (pre-consolidation stress) because the Mercia Mudstone has undergone some form of diagenesis. However, Chandler (1967) suggested that a likely 'pre-consolidation load' was equivalent to an overburden of between 230 and 610 m (assuming an overburden density of 1.12 Mg/m^3). Chandler (1967, 1969) described the Mercia Mudstone as 'heavily overconsolidated'. Standard laboratory consolidation testing equipment does not provide adequate stress levels to characterise fully the consolidation behaviour, including the over-consolidation ratio, of hard, unweathered Mercia Mudstone.

4.6 STRENGTH AND DEFORMABILITY

A considerable amount of work on the strength of Mercia Mudstone was carried out during the mid-1960's in the Midlands, particularly at Birmingham University. Chandler (1967) and Chandler et al. (1968) described the results of drained and undrained triaxial tests on specimens of 'Kings Norton marl' obtained from block samples in a brick pit in Birmingham, and discussed in general terms the geological factors influencing the strength of the Mercia Mudstone. Chandler (1967) saturated triaxial specimens by increasing the back pressure to around 275 kPa. The Mercia Mudstone is usually described as a heavily over-consolidated soil, showing considerable dilation at low effective stresses. Some stress-strain plots at low effective stresses appear to indicate a distinct yield point at around 1% axial strain that Chandler (1967) attributed to 'structural breakdown' and 'structural rigidity'. The yield point, which is not universally observed, coincides with the onset of dilation. This is reflected in load vs. settlement results for pile tests (Chandler et al., 1968). Results of tests carried out over a range of effective confining stresses showed the convex-upward shape of the Mohr envelope; the effective friction angle changing from 40.5° at low stresses to 20.9° at high stresses. A 'strength sensitivity' of 4.25 was quoted. Chandler (1967) attributed this to clay aggregations and calcite crystals. An increase in cohesion and a decrease in friction angle are noted with disaggregation (destructuring?) associated with decreasing moisture content at failure. In the Cheshire area the removal of gypsum in solution has resulted in what Marsland and Powell (1990) described as a broken fabric.

Strength, based on unconsolidated undrained (UU or QU) triaxial tests, standard penetration tests, and rock penetration tests, for the Mercia Mudstone in the Coventry area, are described by Old et al. (1989). Hobbs et al. (1994) obtained values for Mercia Mudstone near Gainsborough for c' and ø' from isotropically consolidated, undrained (CIU) triaxial tests of 14.7 kPa and 20.9°, respectively. These results agreed with those of Chandler (1967). The tendency to obtain unreliable results and positive values for $ø_u$ in the UU triaxial test, due to partial saturation, was highlighted by Chandler et al. (1968).

The rate of increase of strength with depth for the Mercia Mudstone was quoted as 37.5 kPa/m (Cripps and Taylor, 1981). This relatively high rate reflects the age and diagenetic changes of the Mercia Mudstone. Results from Marsland and Powell (1990) indicated an increase in ultimate bearing pressure with depth, derived from pressuremeter and plate bearing tests, of approximately 1.0 MPa/m for Mercia Mudstone near Warrington, Cheshire.

Weathering tends to reduce the shear strength of mudrocks to a common value irrespective of lithostratigraphy (Cripps and Taylor, 1981). Unweathered Mercia Mudstone (Zone 1) tends to exhibit brittle failure at low strains, whereas the weathered material (Zones 2 to 4) tends to exhibit a more plastic failure with a lower elastic modulus. The effect of weathering on strength and deformability has been investigated by Chandler (1969). Deformation behaviour, ranges from brittle for Zone 1 material to fully plastic for Zone 4 material. Effective strength parameters were reported as follows (Chandler, 1969; Cripps and Taylor, 1981):

Zone	Cohesion (kPa)	Friction angle (°)
1	28	40
3	17	42–32
4	17	32–25

Mercia Mudstone, in common with other 'hard' clays, is reported as being particularly susceptible to sample disturbance (Cripps and Taylor, 1981). All types of laboratory strength tests, and in particular deformation tests, are affected by disturbance.

Case histories involving pressuremeter testing of Mercia Mudstone were described by Mair and Wood (1987). Leach et al. (1976) reported in situ Menard pressuremeter tests on Mercia Mudstone from Kilroot, Co. Antrim, that gave undrained shear strength values up to 230% higher than values obtained from triaxial tests on samples from the same depth and the overall mean value was slightly more than double. Similar results were obtained for comparative elastic moduli obtained from pressuremeter, plate-loading, and oedometer tests (Meigh, 1976). These showed that pressuremeter results were highly variable but generally much higher than triaxial and oedometer results. The pressuremeter results from unload/reload tests were higher than those from initial loading by about the same factor. Marsland et al. (1983) found that pressuremeter test results gave elastic moduli twice the value of those obtained by either back-analysing bridge abutment settlements or from plate loading tests. Clarke and Smith (1993) referred to self-boring pressuremeter tests carried out in the Mercia Mudstone at West Burton. Shear strength was quoted as 0.13 to > 7 MPa, and shear modulus as 30 to 2685 MPa. Self-boring tests can be configured for either strength or deformation measurement. Seedhouse and Sanders (1993) discussed the results of a high pressure dilatometer used at Ratcliffe-on-Soar, Nottingham to determine deformability and strength.

Site investigation for the second Severn crossing and the M5 Avonmouth Bridge produced strength and deformation data for the Mercia Mudstone, both from laboratory and in situ tests (Maddison et al., 1996; Parry et al., 1996). At Avonmouth plate bearing tests gave vertical drained elastic moduli (assuming a Poisson's ratio of 0.2) in the range 62 to 92 MPa for initial loading, whilst pressuremeter tests gave equivalent horizontal moduli of 79 MPa. At the Severn crossing, in situ plate bearing tests typically gave drained vertical elastic moduli of 96 MPa, whilst laboratory tests gave 70 MPa, both at stresses < 3 MPa (Maddison et al., 1996). Plate bearing and pressuremeter tests indicated vertical to horizontal elastic moduli ratios of between 1.16 and 1.27 at the Severn crossing (Parry et al., 1996) and 1.4 at Avonmouth (Maddison et al., 1996). Unconfined compressive strength data from the second Severn crossing (Maddison et al., 1996) gave a median value of 16.6 MPa. Initial shear modulus was quoted as 25 MPa. Design values of shear strength for the Mercia Mudstone from triaxial tests and from pressuremeter tests were $c=0$, $ø=51°$, and $c_u=1.0$ MPa, respectively.

Cone penetration testing of over-consolidated clays was discussed by Meigh (1987), but without specific reference to the Mercia Mudstone. He stated that the macrofabric had a marked effect on the 'cone factor' results, thus making interpretation in terms of shear strength difficult.

Cyclic triaxial data were compared with static triaxial data by Little and Hataf (1990). These tests were strain-controlled, low frequency, cyclic tests carried out on undisturbed, reconstituted, and remoulded specimens. Different strengths were obtained for reconstituted and undisturbed materials at similar over-consolidation ratios, and a reduction in stiffness was found due to cyclic straining for both undisturbed and reconstituted specimens.

Residual strength is a function of both particle size distribution and particle shape. The residual strength, $ø_r'$, of the Mercia Mudstone is described as 'high' at 18 – 30° (Cripps and Taylor, 1981). This fitted well with an overall plasticity / residual strength classification for UK mudrocks in the same reference. Jones and Hobbs (1994) quoted values for $ø_r'$ of 22 – 30° for unsieved and grease-worked Zone IVa material. These values were similar to the effective stress values obtained from isotropically consolidated, undrained, triaxial tests; a result that did not suggest a significant strength sensitivity as indicated by Chandler (1969); although the relative size of the samples may have accounted for the difference in results.

4.7 SWELLING, SHRINKAGE AND DURABILITY

Swelling and shrinkage are the visible effects of the relationship between volume change and water content of clay soils. However, they are properties rarely determined in the course of routine site investigations in the UK, at least on undisturbed samples. This means that reliance has to be placed on estimates or correlations from other index parameters, such as liquid limit, plasticity index, and density. The reason for the lack of direct swell/shrink test data is that few engineering applications actually require these data for design or construction. Frequently, those structures most affected by swell/shrink, such as houses, pipelines and pylons, receive a minimal site investigation with little, if any, geotechnical testing. Such site investigations would tend to focus solely on strength, plasticity, and possibly consolidation. It is usually not until after construction is finished that problems associated with swelling and shrinkage become apparent, and the need for remedial measures is recognised. Swelling and shrinkage behaviour is also related to clay mineralogy, and to physico-chemical properties such as surface area or interplate distance. These properties may ultimately give better correlations with shrink/swell behaviour than index properties, but are more difficult to determine.

The Mercia Mudstone is generally considered to have a high 'affinity' for water, but a low swelling potential, due to its low content of recognised swelling clay minerals, and also perhaps to its aggregated structure. The dissolution of gypsum may result in large volume changes, irrespective of clay mineralogy. Swelling of compacted samples of Mercia Mudstone was found by Chandler et al. (1968) to be a function of placement moisture content and liquid limit.

The durability of mudrocks was discussed by Moon and Beattie (1995) and Hawkins and Pinches (1992). Birch (1966) described the reluctance of unweathered Mercia Mudstone at natural moisture content to break down in water even after months of immersion, albeit without mechanical abrasion, as compared with rapid breakdown when it was predried.

4.8 COMPACTION

Chandler et al. (1968) found that at low compactive efforts higher placement moisture contents resulted in higher dry density, whereas at high compactive efforts lower placement moisture contents resulted in higher dry density. They concluded that there was little to be gained from subjecting the wetter (weathered) Mercia Mudstone to heavy compaction, and that placement moisture content was crucial to the stability of compacted Mercia Mudstone fill. Chandler et al. (1968) also showed that there was a marked increase in California bearing ratio (CBR) with placement moisture content reduction, for example from 10 to 110% for a 5% moisture content reduction. The swelling of compacted samples of Mercia Mudstone was found to be a function of their placement moisture content and liquid limit. In the field, weathered Mercia Mudstone was easy to compact but 'hard' material of low moisture content was difficult.

The moisture condition value (MCV) test is increasingly used as a rapid indication of likely compaction behaviour. Typically, the Mercia Mudstone has specified moisture condition value ranges of 8 to 12 (Class 2A – wet) and 12 to 15 (Class 2B – dry) for general cohesive fill (Department of Transport, 1991). The moisture condition value may be correlated with undrained shear strength, California bearing ratio, and moisture content.

4.9 PERMEABILITY

The 'mass' permeability of highly indurated, mudrocks tends to be dominated by the presence of fissures that are capable of increasing the mass permeability by orders of magnitude over the 'intact' permeability. Permeability of 'intact' mudrock is a subject of some debate, owing to the likely non-Darcian nature of pore-water movement through clays. Bacciarelli (1993) describes Zones 4a and 4b as having lower permeability than underlying layers. Laboratory values for permeability were quoted by Tellam and Lloyd (1981) as 10^{-4}–10^{-6} m/day (10^{-9}–10^{-11} m/s), perpendicular to bedding, and field values 10^{-1}–10^{-3} m/day (10^{-6}–10^{-8} m/s), mainly parallel to bedding. Porosity was quoted as 20–40%. Locally the ability of the Mercia Mudstone to yield water is influenced by the proximity of sandy layers within it. Permeability through discontinuities may be influenced by the presence of infilling material such as halite or gypsum or by cavities left by solution. The effect of any ped-like structure within the Mercia Mudstone on 'intact' permeability is not clear. In theory a ped structure should impart a higher permeability to the undisturbed Mercia Mudstone compared with the reworked or destructured fabric.

4.10 GEOPHYSICAL PROPERTIES

Chandler et al. (1968) found that seismic compressional velocities ranged from 915 to 2750 m/s. Young's moduli, derived from shear wave tests, were between 207 and 1720 MPa, with Poisson's ratios between 0.3 and 0.5. Geophysical depth probes gave resistivity values of between 15 and 45 ohm m. Low resistivities were found to relate to low seismic velocities and low Young's Moduli, both in the field and in the laboratory. Pinches and Thompson (1990) described good correlations between seismic velocity and lithology for the Mercia Mudstone in north-east Nottinghamshire. The ratio of compressional to shear wave velocity (V_p/V_s) was recommended as a means of determining Poisson's ratio (σ_d). Values for the dynamic shear modulus (G_o) of Mercia Mudstone were given as 5 to 11 GPa.

Geophysical methods were used by Maddison et al. (1996) to determine dynamic deformation moduli for the second Severn crossing. These were at least an order of magnitude greater than the static elastic moduli obtained from laboratory, plate bearing, and pressuremeter tests. A typical value of 11.9 GPa was given for the elastic modulus of Mercia Mudstone.

4.11 ROCK MASS INDICES

Available rock mass data consist mainly of values of rock quality designation (RQD) and fracture index (FI). The mean RQD for Mercia Mudstone in the Coventry area was 36% (Old et al., 1989). This places it in the 'poor' category. Maddison et al. (1996) quoted an RQD of 40%, a solid core recovery (SCR) of between 46 and 53%, and an average FI of between 101 and 158 mm for Mercia Mudstone at the second Severn crossing. Care should be taken in extrapolating weathering or other classifications, obtained from core logs, to full-scale situations (Cragg and Ingman, 1995).

5 Drilling and sampling

5.1 INTRODUCTION

The Mercia Mudstone contrasts with many older more indurated and laminated mudstones, such as Carboniferous Coal Measures mudstones, that tend to have relatively thin weathering profiles, below which fresh rock is present at shallow depth and is amenable to rock sampling and testing techniques. It also contrasts with younger, relatively unindurated mudstones, such as Oxford Clay, where the structure is dominated by bedding and lamination, rather than jointing, which can be sampled and tested as an engineering soil in the depth range needed for most site investigations.

There is no other mudstone of comparable thickness, outcrop or importance in the UK that occupies the interface between soil and rock, and whose behaviour is predominantly influenced by weathering and jointing rather than by sedimentary discontinuities. Thus, it is not surprising that a specific weathering scheme should have been developed and refined over 30 years in order to understand and characterise Mercia Mudstone.

Chandler's original weathering scheme (1969) after Skempton and Davis (1966) (Table 4.1) put much of the weathering profile that is of practical concern, difficulty and interest to the construction industry into just one of five zones, that is Zone 3. This includes all the conditions between fresh or slightly weathered material (Zones 1 and 2) that is usually only encountered in deeper investigation and can be treated without much difficulty as a rock (Bacciarelli, 1993), and the highly or completely weathered material (Zones 4a and 4b) which can be treated as a soil.

The practical limitations of this scheme became evident from the practice of many contractors to amalgamate the more weathered Zones 4a and 4b, where the distinction is quite subtle, and divide Zone 3 according to the predominance of the lithorelics or the matrix. The problem is that this boundary is difficult to make in practice, being potentially dependant on the drilling and sampling technique, and the observer's expertise and experience. The approach was formalised by Bacciarelli (1993), who both subdivided Zone 3 and retained Chandler's subdivision of Zone 4. The evolution of the description of the weathering of Mercia Mudstone is described in more detail in section 4.2.

5.2 DRILLING

Soft ground boring and sampling techniques, with light cable percussion rigs and driven samplers, are as appropriate to Zone 4 Mercia Mudstone as they are to most other clay soils. The fresh or slightly weathered Mercia Mudstone of Zones 1 and 2 require the 'gentle' rotary flush coring techniques used for other weak mudstone rocks. The 'best practice' use of rotary coring in soft rocks and soils was discussed by Binns (1998) who stressed that the skill of the driller was of paramount importance and the need for drillers to be accredited by the British Drilling Association.

An air mist flush is most commonly used with rotary coring where it is not economic to set up a mud flush system. One could expect core quality to be enhanced by the use of 'low-torque' bit designs, rather than the saw-tooth pattern, and also by the use of the large diameter wireline coring systems.

Neither technique is wholly appropriate for the intervening Zone 3 material due to its inhomogeneous nature of 'clay' matrix and 'rock' lithorelics. Percussion boring and driven samples will only advance through the lithofragments by breaking them down, mainly to gravel size, with subsidiary fractions at cobble and sand size. On the other hand, rotary flush coring will preferentially erode the uncemented matrix fraction. Significant core loss is almost inevitable unless great care and the most gentle techniques are used. The difficulty arises much more from the disparity between the lithorelics and the matrix, than from the matrix alone. Since there is no ideal method for drilling and sampling Zone 3 Mercia Mudstone it must be drilled by a combination of both soft ground boring and rotary flush coring. If weathering profiles exhibited a consistent and progressive decrease of weathering with depth, one might seek the optimum point at which to change from soft ground boring to rotary coring. In practice, weathering grade is related to discontinuities and lithology as well as depth. Consequently weathering of more susceptible beds or fractures cause locally increased degrees of weathering within the more normal pattern of decreasing weathering with increasing depth. The profile can be further complicated where distinctly different lithologies such as siltstones and sandstones are interbedded with the mudstones. Thus, for Mercia Mudstone, an optimum point at which to change technique will not exist.

In practice, the more appropriate technique will also be dependent on several factors in addition to the weathering grade itself. Amongst these are the purpose of the investigation, the requirement for 'undisturbed' samples, their quality for deriving design parameters, the relative cost and availability of the two drilling and sampling techniques, and the required depth in relation to the weathering profile.

The safest approach is to overlap the two techniques. Soft ground boring and sampling is utilised in the first borehole to its economic limit, where the rate of advance is slow and the samples are of doubtful value. Rotary coring is then employed in an adjacent borehole, the coring to commence at the shallowest depth that will achieve a worthwhile core recovery. Ideally, this would provide an overlap of several metres. The overlap between the two adjacent boreholes enables the borehole logs from the two contrasting techniques to be reconciled. In the great majority of logs that have been seen, a stratum boundary is recorded at the depth at which the method was changed in a single borehole. The probability of these being 'true' boundaries is remote. Unfortunately, even when this overlap was achieved by two boreholes, the results were most often portrayed on separate and incompatible logs, compiled at different times by different staff. A single seamless log should be made by one individual, albeit with an interval in which the sampling/coring is duplicated.

5.3 SAMPLING

The shallowest taper angle and sharpest edge practicable should be used and maintained on the cutting shoe for taking driven samples. However, thin wall sampling tubes, driven by continuous pushing rather than hammering, are unlikely to penetrate material in which there is a significant content of lithofragments.

Samples taken by rotary coring methods may be taken using semi-rigid plastic core liners or more sophisticated triple tube core barrels both of which afford protection to the core once it is cut by the drill bit. The removal of the core from the barrel should be done in the horizontal position and its subsequent handling, transport and storage must also be treated with care in order to maintain the integrity and quality of the sample. Particular care is necessary to stop the core drying out and, for high quality testing, the logging and selection of samples for testing should be done soon after coring in order to minimise the effects of the flushing medium and stress relief (Binns, 1998).

Sampling from trial pits offers the possibility of high quality, undisturbed, block samples or tube samples in the weaker material. Block samples may be taken by hand excavation and, if testing is not to be done immediately, preserved by wrapping in cling film, foil and waxing. Transport to the laboratory should be in boxes with the samples suitably padded and protected from mechanical damage. In the harder material the ability to obtain block samples may be limited by natural discontinuities such as bedding jointing and listric fractures.

In this study, block samples of hard, fractured material were taken by pushing a 300 mm by 300 mm open ended steel cutter frame 150 mm deep with its lower end sharpened to form a cutting edge down over a slightly oversized pre-prepared square pillar of material. The pit was dug and the pillar prepared carefully by hand to avoid sample disturbance. As the box was pushed down the pillar was trimmed to size and the final cut was made by the cutter frame. The box was separated at its base from the base of the soil pillar and surplus material was trimmed from the open ends of the cutter frame which were then sealed with cling film, aluminium foil and adhesive plastic tape. The samples so taken were transported to the laboratory taking care to avoid mechanical damage and drying. The samples were suitable for unconfined three dimensional swell, swelling pressure, one dimensional swell, index tests, scanning electron microscope examination and mineralogical analysis to be carried out after specimen preparation in the laboratory.

Cylindrical samples were taken in a similar manner by lowering a plastic sample tube 100 mm in diameter over a pre-prepared oversized cylindrical pillar with the aid of a tripod frame which guided the tube accurately as it was lowered (Culshaw et al. 1991; Northmore and Culshaw, 1992). The cylindrical samples were used for oedometer testing at the sampling diameter of 100 mm.

6 Database design and method of analysis

6.1 DATA SOURCES AND COVERAGE

Data for the Mercia Mudstone Group have been compiled for ten areas (Figure 6.1), reflecting the depositional basins and present outcrop, the extent of current and potential development, and the availability of data sources. Particular emphasis has been given to those areas in which formations within the Mercia Mudstone Group have been mapped, namely the northern part of the East Midlands (Nottinghamshire and south Derbyshire)(Area 8), the Worcester Basin (Area 3), and the Cheshire Basin (Area 1) where the older Keuper Marl divisions were mapped from deep borehole data. Areas 2 (the Stafford Basin), 6 (Warwickshire), and 7 (Leicester) cover other parts of central England where mapping has not as yet divided the Mercia Mudstone Group. Further north, site investigations have rarely penetrated the thicker drift that obscures the Carlisle area (Area 11) and the complex of basins in west Lancashire (Area 12). In the West Country, Areas 4 and 5 comprise data for the Severn Estuary and east Devon, respectively. To the east of the Pennines, modest amounts of data have been obtained for Humberside and Teesside (Areas 9 and 10, respectively).

The majority of the data have been taken from investigations for the motorway and trunk road network, as these provide an abundance of good quality data, often across a major part of the outcrop. All the selected reports are for investigations since 1985, and include weathering grades for the Mercia Mudstone Group. Those with data available in digital format were chosen wherever possible. These criteria were relaxed for the Teesside area, due to a paucity of available data, and the results for this area should be treated with greater caution.

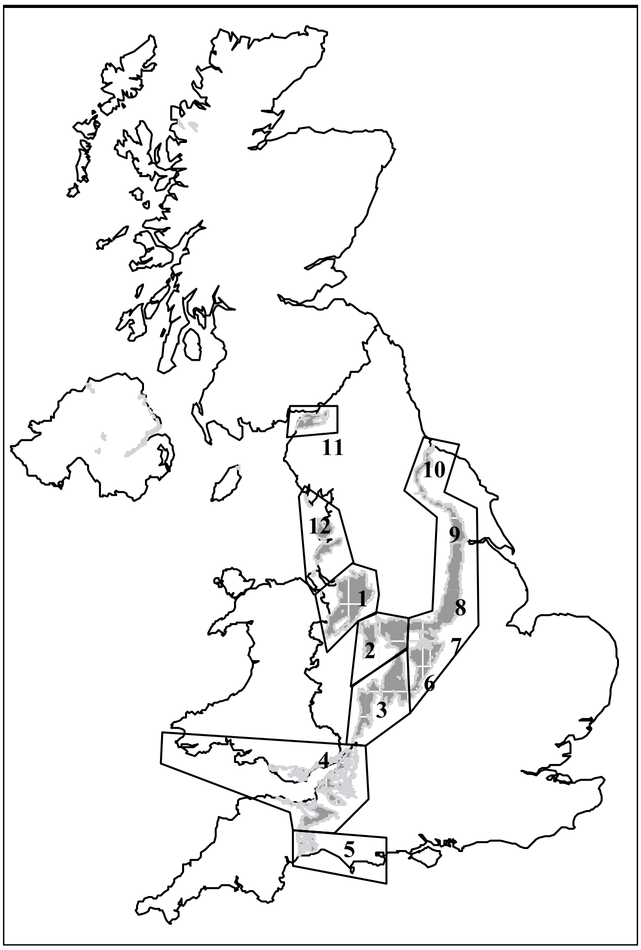


Figure 6.1 Outcrop of the Mercia Mudstone Group showing areas used for the statistical analysis of the geotechnical database. The numbered areas refer to:
1. Cheshire Basin, 2. Staffordshire Basin, 3. Worcester Basin
4. Severn Estuary, 5. East Devon, 6. South Midlands,
7. Leicestershire, 8. East Midlands (Nottingham and south Derbyshire), 9. North Humberside, 10. Teeside, 11. Carlisle Basin, 12. West Lancashire. [Boxes refer to the lithostratigraphical summary in Table 2.1and Figure 2.4].

6.2 DATABASE STRUCTURE

The structure of the relational database for this study was amended and expanded early in the work, to facilitate the entry of digital data in the Association of Geotechnical Specialists' format (Association of Geotechnical Specialists, 1992) and make fuller use of this data medium. This amended structure is shown in Figure 6.2. The database tables are generally equivalent to AGS 'groups' and, wherever practicable, the same fields are used. The more significant differences are as follows:

GEOL table: separate fields are included for chronostratigraphy, lithostratigraphy at the group and formation level, weathering zone and summary lithology.

GRAD table: each record comprises a summary particle size analysis, with fields for the ten particle sizes, from 0.002 mm to 60 mm, that define the boundaries between the fine, medium and coarse divisions of silt, sand and gravel. Values that were not available from digital source data were interpolated manually from the particle size graph.

CONS table: consolidation data from oedometer testing is recorded with fields for the final voids ratio, m_v , and c_v values for each loading stage, together with the initial voids ratio. To ease the data analysis, only those tests in which the pressure increments were doubled (or approximately so) for each successive stage were used.

6.3 DATA ENTRY

Where reports were available only in hard-copy form, data were abstracted and keyed in directly by one person. The data selection was generally restricted to that for the Mercia Mudstone, and in most cases excluded trial pits and shallower holes with little data.

Digital data, whether in AGS or other earlier formats, were first examined and processed in spreadsheet software. This enables the content and range of each field to be examined,

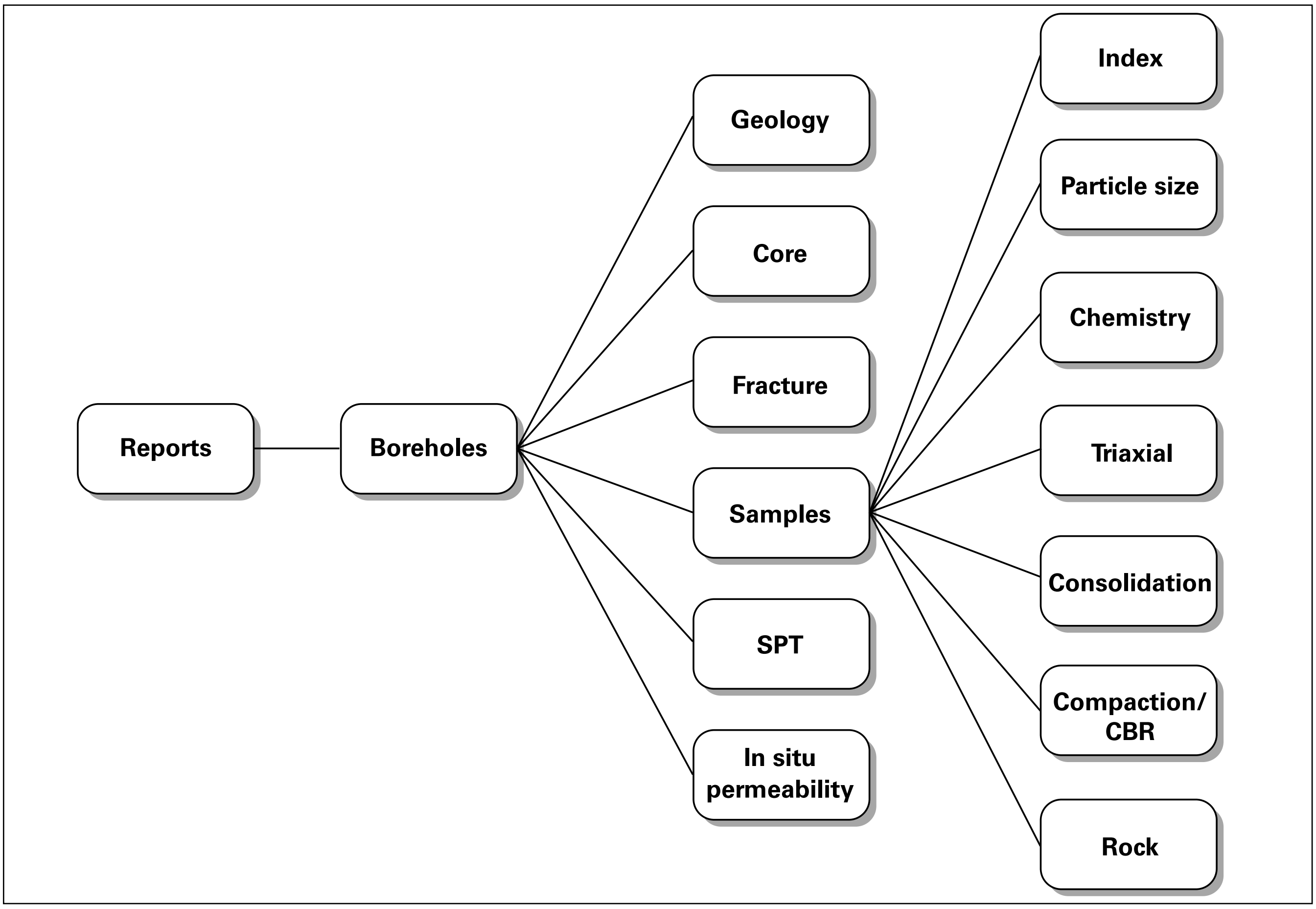


Figure 6.2 Table structure for the geotechnical database.

arithmetic to be checked within and between data records, standard codes to be applied to appropriate data fields and additional geological and key fields added (a significant amount of error was found in all digital source data). The data were only then transferred to the database, which enforces a strict referential integrity between the data tables.

The total data set for the Mercia Mudstone comprised values for approximately 6500 samples and 3600 SPT tests from over 1400 boreholes and test pits, abstracted from the reports for 32 investigations.

6.4 DATA QUALITY

The data sources comprised recent contracts carried out by four of the leading ground investigation contractors for the Highways Agency or its predecessors with the exception of the Teesside area in which the identification, description and logging of the Mercia Mudstone appeared to be of a high standard. Source data in digital format were used wherever possible and subjected to extensive checking before entry, otherwise data were abstracted and entered directly from hard-copy by one person. The extreme values in each data field were examined, and those that appeared to be gross errors were deleted. Nevertheless, it has to be recognised that much of the data, as in other geoscience fields, was potentially 'dirty' in the statistical sense. The values in the database are often the final result from a succession of field, laboratory and transcription procedures, during which one must expect errors to occur, however small or infrequent. Some data, such as stratigraphy and weathering zone, are interpretative and hence subjective.

Fracture indices were initially entered into the database. However, it soon became apparent that there was a wide disparity in the manner in which these indices had been determined. Some were recorded as fractures per metre, and others, in the opposite sense, as the average length between fractures. Whilst the text of the original definition (Franklin et al., 1971) could have been stated with more precision, the accompanying figure showed the index was to be used in the latter sense, and expressed in millimetre units. Where the indices have been recorded as fractures per metre, they can readily be converted to the correct form. However, the basis for determining the indices does need to be consistent. The index, as defined, should be given for a core interval in which the frequency of natural fractures is generally constant, and should not in any way be related to individual core runs. The limits of these intervals would normally be coincident with the changes in stratum, and where there is a clear change of fracture frequency within a stratum. This issue was most evident in the data from one major investigation, in which the core logging had been undertaken by two people. It appeared that one had recorded fracture indices much in accordance with the definition. However, the other recorded values for each metre interval within each core run (and without regard to stratum boundaries). The level of the values, furthermore, suggested that there had been a distinct difference in the identification of fractures, as ‘natural’ or ‘drilling-induced’. Fracture logging of the Mercia Mudstone is clearly difficult to achieve with the consistency and objectivity needed to justify statistical analysis, and entry of this parameter was discontinued.

6.5 DATA ANALYSIS

The data should be regarded as potentially 'dirty' when it is considered from a statistical viewpoint, as mentioned earlier. Furthermore, in analysing the frequency of geotechnical data values, one should not assume there to be a normal (Gaussian) or other mathematically simple frequency distribution. In these circumstances the conventional summary statistics, such as the mean and standard deviation, can be very misleading and fail to portray the real distribution of the values. This is particularly likely if there is more than one factor controlling the magnitude of the value, which is frequently the case. Such descriptive statistical measures (and particularly the more rarely quoted skewness and kurtosis) are especially sensitive to atypical and possibly erroneous values.

The summary and analysis of the data has been achieved using a 'robust' method, based on percentiles, rather than 'classical' or population statistics. A percentile is the value below which a given percentage of the data falls. For example, if the 10th percentile of a set of data values is 57 then 10% of the values will be less than 57, and 90% will be greater. The median, i.e. the 50th percentile, is the most commonly quoted, as the central measure of a distribution. The 25th and 75th percentiles are also widely reported, as the lower quartile and the upper quartile respectively. A commonly used measure of the spread of a distribution is the interquartile range (IQR), which is the difference between the upper and lower quartiles.

However, such measures of the data are unable to distinguish between the natural spread of values and the impact of uncertainties arising from errors due to measurement, detection or sampling. They are also unable to describe the spatial distribution of variability, for which the specialist technique of geostatistics is required.

6.6 DATA SUBDIVISION AND PRESENTATION

Data in the statistical tables and plots are subdivided according to a location (Figure 6.1, Areas 1 to 10), weathering zone (Zones 1 to 4b), and lithostratigraphy (where available). In the case of some areas and zones few data were available, and may not be shown. The areas do not have any significance outside the database, and are not represented by uniformly distributed data. Weathering zones are not shown in Roman numerals but as arabic numbers for the sake of clarity. The samples from any general location identified should not necessarily be considered as representative of that area as a whole. The area codes represent the following general locations:

Table 6.1 Area codes 1–10 used for database analysis.

Area	Location
1	Cheshire
2	Staffordshire
3	Worcestershire
4	Severn Estuary
5	East Devonshire
6	Warwickshire
7	Leicestershire
8	Nottinghamshire and south Derbyshire
9	Humberside
10	Teesside

Table 6.2 Weathering zones codes used in database analysis.

Zone	Description
1	Unweathered (no matrix)[rock]
2	Slightly weathered (matrix in joints) [rock]
3	Moderately weathered (undifferentiated) [soil]
3a	Moderately weathered (matrix / frequent lithorelicts) [soil]
3b	Moderately weathered (matrix / some lithorelicts) [soil]
4	Highly weathered (undifferentiated) [soil]
4a	Highly weathered (occasional clay stones) [soil]
4b	Fully weathered (matrix only) [soil]
GRw	Glacially reworked

The weathering zones selected reflect the descriptions given in the original source material. Combinations of weathering zones (for example, '3/4a') in the database usually indicate either uncertainty in the original classification or a borderline zone, but may also indicate interbedded strata of contrasting weathering zone. It should be noted that weathering does not necessarily decrease, or appear to decrease, with depth. Samples in the database that were reported as crossing stratigraphical or weathering zone boundaries were excluded from the data interpretation. Data sets with less than five members have not been included in the statistical presentations.

Where stratigraphical subdivisions of the Mercia Mudstone Group are mapped and recorded these are given in the database. Only Areas 1 (Cheshire), 3 (Worcestershire) and 8 (Nottinghamshire and south Derbyshire) have such subdivisions. In Area 1 the subdivisions have been revised recently as described in Chapter 4 and the bulk of the geotechnical data that indicate a subdivision use the former, obsolete, nomenclature. This has been kept in the analysis since it was not possible to assign modern subdivisions in retrospect without detailed examination of the lithology of the boreholes. The subdivisions in these areas are shown in Table 6.3.

A basic statistical analysis of the data is given in the form of tables. A variety of plots are used to display the data. These include 'box', 'scatter', 'line', and 'bubble' plots. These attempt to show distribution and correlations of various key geotechnical parameters (Chapter 7). The structure of the box plots (Appendix), depicting the median quartiles and other percentiles, is described in Section 6.7. The bubble plot is a form of scatter plot where the size of the point is proportional to the number of data having common values. For example, if there are five samples with identical liquid and plasticity indices the graph point will be proportionately larger than one representing a single sample. This gives a clearer indication of data concentration than a simple scatter plot in which coincident points are simply overwritten.

Selected geotechnical parameters are plotted against depth or against one another, in order to determine variations

Table 6.3 Stratigraphical subdivisions for Areas 1, 3 and 8.

AREA 1	LKM	Lower Keuper Marl
	MKM	Middle Keuper Marl
	LKSB	Lower Keuper Saliferous Beds
	UKSB	Upper Keuper Saliferous Beds
AREA 3	TwM	Twyning Mudstone Formation
	Eld	Eldersfield Mudstone Formation
AREA 8	Cbp	Cropwell Bishop Formation
	Edw	Edwalton Formation
	Gun	Gunthorpe Formation
	Hly	Hollygate Sandstone
	Rdc	Radcliffe Formation
	Snt	Sneinton Formation

caused by depth, and other, related factors, and to characterise engineering behaviour at deep and shallow levels (Figures 7.2 to 7.18). Weathering may be related in a general sense to depth below ground level, but this is not a simple relationship of decreasing weathering with increasing depth in the case of the Mercia Mudstone. Moisture content, density, permeability, and strength may also relate to depth. A large proportion of the database was assembled from highway site investigations. Many of these have been carried out on embankments or in cuttings, for example where existing roads are to be widened. This means that ground levels reported in the site investigation are not necessarily original natural ground levels. *Plots of parameters with depth should therefore be treated with some caution as they contain random errors, and only give a general trend. Depth relationships shown here should not be used in design calculations.*

6.7 BOX PLOTS

The box plot (Figure 6.3) is a simple, compact, graphical method of summarising a frequency distribution based on the robust median and quartiles. The alternative term 'box and whisker' plot is also in use. The ends of the box are drawn at the lower and upper quartiles (25 and 75 percentiles) with an internal division at the median value. Lines or 'whiskers' are conventionally drawn from these ends to the lowest and highest data values that are not 'outliers'. Outliers, as described below, are usually represented by individual crosses beyond the whisker ends. Simple summaries of the frequency distributions of several batches of data may be compared by drawing parallel box plots to a common data scale.

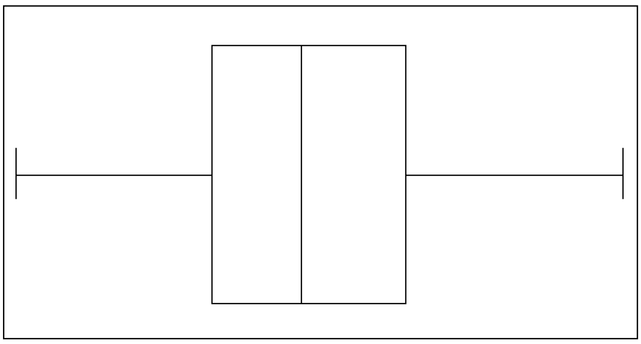


Figure 6.3 Standard box and whisker plot.

It is possible to grasp the major characteristics of a distribution at a glance by using box plots. The centre of the distribution is shown by the median crossbar within the box. An indication of spread, the interquartile range is shown by the length of the box. The whiskers illustrate the tail lengths of the distribution. The relative position of the median crossbar within the box and the relative lengths of the whiskers indicate the skewness of the distribution.

To a first approximation the confidence with which the parameters of an actual distribution can be used to infer those of the total population increases as the square root of the number of data values. Thus if the width of the boxes is drawn in proportion to the square root of the size of each data set, the relative significance of each can be compared.

The box plot has two particular limitations as a summary of a geotechnical property distribution. There is a simple convention to determine whether a value will fall within a tail whisker or be classed as an outlier. The lower and upper cut-offs are 1.5 x IQR below the lower and above the upper quartiles respectively. However, this approach is rather too simplistic where the distribution is appreciably non-Gaussian. In these cases reasonable tail values will be classed as outliers and vice versa. It would be preferable to determine the two cut-offs separately, with regard to the distribution in each tail area. This would also help in determining a realistic spread or 'range' within which the great bulk of the data distribution falls.

The second limitation is again concerned with the tail areas. By far the greatest distinction between the many distributions encountered is to be found in the tail areas. The central part of a distribution is usually very well defined by just the median and quartiles. The conventional box plot gives minimal information beyond the quartile box.

6.8 EXTENDED BOX PLOTS

A refinement of the box plot was devised by Hallam (1990) to provide a more comprehensive representation of the frequency distribution of geotechnical data sets' distributions particularly in the tail areas. This is referred to as the 'extended box plot' (Figure 6.4) and is used here to summarise statistical data for most of the geotechnical parameters of the Mercia Mudstone.

These plots are constructed from the 0.5th, 2.5th, 10th, 25th, 50th, 75th, 90th, 97.5th and 99.5th percentiles of the data sets. The selected percentiles have been chosen as a compromise between practical geotechnics and statistical rigour. For the former, the simple percentages should be readily recognisable and useful. From the point of view of the latter, the selection is such that the percentages plot at approximately equal intervals for normally distributed data.

The 25th, 50th and 75th percentiles are used to construct a central box with a median division, as for the standard box plot. The remaining percentiles are used to define a series of subsidiary boxes to either side of the central box. In order to distinguish between, and readily recognise, the successive boxes, they are shaded alternately from the centre in complimentary pairs. Thus the outer limits of the shaded boxes will fall at the 0.5th, 10th, 90th and 99.5th percentiles.

An indication of the skewness, and even the kurtosis, of the data distributions may be obtained by comparing the relative width of the boxes, as they will be of almost equal width for a normal distribution where the data scale is drawn arithmetically. Logarithmic scaling is used for those parameters that generally have distributions that are approximately log-normal. Various measures of the spread or

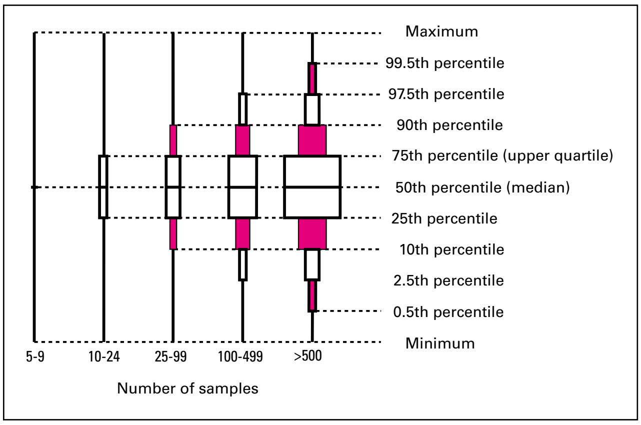


Figure 6.4 Structure of extended box plots for 'normal' distribution of data values.

variability of the data can be determined from symmetrical pairs of the percentiles. For example 95% of the data will fall between 2.5th and 97.5th percentiles.

Typically, most actual data sets will be of insufficient size to calculate the outer percentiles and will have only perhaps one or two data values 'contained' within the outermost boxes. Therefore, to ensure that the plot is reasonably meaningful, it is necessary to relate the number of subsidiary boxes to the size of the data set. In order that the outermost box, at each end, should contain a minimum of three values and that at least two further values should fall beyond this box, the following relationship is used:

Number of samples	Parameter values shown
⩾ 5	50th percentile (Median)
⩾ 10	25th and 75th percentiles (lower & upper quartiles)
⩾ 25	10th and 90th percentiles
⩾ 100	2.5th and 97.5th percentiles
⩾ 500	0.5th and 99.5th percentiles

The number of available data values is statistically very important. To a first approximation, the statistical significance of the data summary is proportional to the square root of this number. The width of each box within the plots should therefore be drawn in direct proportion to the square root of the number of data values that fall within it. Limitations of the graphics software did not permit this to be achieved, but a series of box widths are used which approximate to the required effect for sets of an average size within each of the above categories. The statistical significance that can be given to each data summary is therefore reflected in both the width of the plot and the number of boxes that it contains. The lines drawn beyond the outer boxes extend to the minimum and maximum values in the data set. As the outer boxes of any plot are necessarily based on a minimal number of data values, the quantitative information that they portray should be treated with great caution. The tail lines beyond these boxes will have virtually no statistical significance.

Extended box plots offer the following advantages:

a) Compact graphical displays are used to compare the distributions of several data sets.
b) The distribution centre and several measures of its spread are shown.
c) The width of each display and the number of subsidiary boxes indicate the significance that should be given to each data set.
d) Being based on percentiles, the box plot is resistant to any major disturbance by gross outliers and is not dependent on any underlying frequency distribution. It emphasises the structure of the bulk of the data.
e) The outermost boxes indicate the rough limits to which any statements concerning the distribution tails are justified by the data as being at all meaningful (the outermost limit shown should always be treated with considerable caution). Thus it may be of practical use to say that 90% of the actual data have values above 'x', or 95% fall between 'y' and 'z', whereas the conventional range (between the most extreme values) is essentially meaningless.

This graphical form of statistical presentation was devised to provide the reader with a rapid summary of the 'centre' and spread of each data. The summaries of the geotechnical data are useful guides to the engineering properties of the Mercia Mudstone provided that the limitations in the quantity and quality of the source data are realised and undue reliance is avoided.

It is stressed that the summary geotechnical values should be used as a general guide only and not as a substitute for adequate site investigation, or in detailed design calculations.

7 Geotechnical database — results of analysis

7.1 GENERAL

The geotechnical properties of Mercia Mudstone, as collected for the database, are described in this section. Geotechnical data are derived in the main from routine laboratory testing using either British Standards (British Standards Institution, 1990), American Standards (ASTM) or recommended international procedures (e.g. International Society for Rock Mechanics, 1988). In addition, a small number of tests have been carried out in the British Geological Survey laboratories and are referred to in the text.

In general, research data are not included unless stated otherwise. Geotechnical tests on soils and rocks may be broadly subdivided into 'index' and 'mechanical' property tests. The term 'index' implies a simple, rapid test, the equipment and procedure for which are recognised internationally (e.g. point load index) and which can be repeated in any laboratory; or a test which measures a fundamental physical property of the material (e.g. density). A mechanical property test may be more complex, time consuming, and measure a particular behaviour of the material under certain imposed conditions (e.g. a triaxial strength test). If these conditions are changed the result of the test will be different. Equipment and methods for these tests tend to vary internationally, and note should be taken of the test methodology, particularly where no standard exists. Mechanical property tests tend to require carefully prepared specimens. Index tests tend to be used to characterise a formation and to plan further testing, whereas mechanical property tests may be used for design calculations. For mechanical properties where little or no data are available (e.g. swelling, shrinkage, durability), index tests are often used as a guide if correlations have been established elsewhere. In some cases, however, such correlations may not be appropriate.

Geotechnical tests may also be subdivided into 'soil' and 'rock' tests. This distinction is solely a function of the equipment used and the method of specimen preparation. Larger stresses are generally required when determining mechanical properties of rock, compared with soil. The Mercia Mudstone is a material that spans the interface between 'soil' and 'rock' by geotechnical definition, and as such may have both 'soil' and 'rock' type tests applied to it, depending on its condition and weathering state. Mechanical property tests on rock usually require machined specimens. If the material is incapable of being machined the test cannot be carried out. *Test data in the database may be biased towards strong material in the case of the 'rock' tests and weak material in the case of the 'soil' tests, purely as the result of the need to match the test method to the sample.* Test data in the database consist mainly of clay and mudstone lithologies, rather than sandstone and evaporite. An assessment of the general geotechnical properties of Permo-Triassic anhydrite and gypsum is found in Bell (1994).

7.2 DENSITY AND MOISTURE CONTENT

The database contains few values for bulk density (452). The density and natural moisture content of the Mercia Mudstone are affected by cementation, aggregation, weathering and other lithological changes with depth. Considerable variations on a scale of metres and millimetres are seen. These changes also affect strength. Bulk density (γ_b or BD), or wet unit weight, for undisturbed samples is recorded in units of Mg/m^3. Values of bulk density range from 1.47 to 2.47 Mg/m^3. The trend of bulk density with increased weathering is negative in the case of Areas 4 and 5 (that is, bulk density reduces with increased weathering) but indeterminate in other areas. The median value of bulk density for Area 4 (2.27 Mg/m3) is notably higher than for other areas. Individually, each of Area 4's weathering zones is high except for 4a. Overall median values for the areas lie between 1.96 and 2.27 Mg/m^3. The highest values were obtained for Area 4, Weathering Zone 1/2, at 2.47 Mg/m^3. The lowest value was obtained for Area 2, Weathering Zone 4a at 1.47 Mg/m^3.

The dry density, or dry unit weight, γ_d is the density of the oven-dried soil, i.e. with no 'free' water contained in the voids. Dry densities in the database comprise 536 values representing Areas 1, 2, 3, 8, and 10, and for which the overall median dry density is 1.68 Mg/m^3. Areas 1, 2, and 3 have medians close to the overall median. In Area 8 the Edwalton Formation has a distinctly low median dry density and the Sneinton Formation a distinctly high median dry density.

There are 3429 natural moisture contents in the database. The overall natural moisture content medians for Areas 1 to 11 are within the range 18 to 20% with the exceptions of Area 5 (23%), Area 9 (26%), and Area 10 (12%). The Edwalton Formation (Area 8) has a high median value of 25%. This compares with 17% common to other formations in Area 8. The full range of values is very large, as might be expected. However, some very high values ($w > w_L$) are possibly erroneous. These may have been obtained from poorly executed or flooded cable percussion boreholes or from highly reworked material. These result in unfeasibly high values for liquidity index (section 7.4).

Particle density is poorly represented in the database. Area 2 gives an overall particle density median of 2.69 Mg/m^3. The Cropwell Formation (Area 8) gives a median value of 2.74 Mg/m^3. Maximum and minimum values are 2.86 and 2.42 Mg/m^3, respectively. The particle density of gypsum is 2.32 Mg/m^3.

Under SEM examination Zone 4 Mercia Mudstone samples from Gringley-on-the-Hill (Area 8) were found to have more porous, less compact textures than Zone 2 material from Cropwell Bishop (Area 8). Deformation structures are observed in the vicinity of gypsum bodies (Pearce et al., 1996). Meigh (1976) notes that total carbonate content may have an important effect on density, and hence on mechanical properties.

7.3 PARTICLE SIZE

Particle size data for soils are usually obtained by combining the results of sieving and sedimentation analyses (British Standards Institution, Part 2, 1990; Head, 1992). The *coarse* fraction (>0.060 mm) is determined by dry or wet sieving and the *fine* fraction (< 0.060 mm) by sedimentation using the hydrometer or pipette methods (automated indirect methods may also be used such as the X-ray Sedigraph™). The results are usually shown as grading curves which have 'percentage passing' (0 to 100%) on the Yaxis and particle size as a log scale (0.002 to 60mm) on the X axis, where particle size categories are as shown in Table 7.1.

Table 7.1 Particle size categories.

	Particle size (mm)	Designation	
Coarse fraction	20 – 60 6.0 – 20 2.0 – 6.0	coarse medium fine	gravel
	0.6 – 2.0 0.2 – 0.6 0.06 – 0.2	coarse medium fine	sand
Fine fraction (fines)	0.02 – 0.06 0.006 – 0.02 0.002 – 0.006	coarse medium fine	silt
	<0.002		clay

A total of 208 particle size grading curves are contained in the database. Most of these are from Areas 1 and 2. There are no data for Areas 3, 9 and 10. Particle size data are shown as percentile plots in Figure 7.1. It is clear from the grading curves' distribution that a very wide range of gradings is represented. The range is from a silty clay to a silty, sandy gravel. The median grading line for all data (Figure 7.1), whilst not representing an actual grading curve, gives the equivalent of a reasonably well-graded clayey, sandy silt with fine gravel. Bearing in mind that these soils are all described in the database as clays or mudstones, there is clearly a problem with the concept of particle size as applied to the Mercia Mudstone. This is perhaps a more serious failing than incomplete disaggregation resulting in an error of a few percent in the grading. This may indicate that these data are the result of either incorrect test procedures or inaccurate sample description. However, it is possible that a mudrock contains clasts or lithorelicts of perhaps stronger mudrock which are either not broken down or are incapable of being broken down, during particle size analysis, in which case the sample description of 'mudrock' or 'clay' is misleading and should be qualified. Mudrock may be defined, in terms of particle size, as having a fine fraction (combined clay and silt) content (< 0.060 mm) of greater than 35%. This is the value, above which the fine particles are believed to dominate the mechanical behaviour of the material (Grainger, 1984). Sedimentological classifications tend to use 50% as a cut-off value (Stow, 1981). If the former definition is applied to the database, it is clear that about 15% of the data are not mudrocks. If the latter definition is applied this becomes 25%. However, the classification scheme for Mercia Mudstone (Bacciarelli, 1993) is based partly on a 'matrix' vs. 'lithorelicts' assessment and describes proportions and sizes of lithorelicts for Weathering Zones 3a, 3b and 4a.

Clay-size content in the database ranges from 1 to 70%. Sherwood & Hollis (1966) described clay contents derived from particle size analyses as being less than those derived from X-ray analysis. Davis (1967) quoted so-called 'true' values for % clay-size content of 60 to 100% from X-ray diffraction analysis (XRD), compared with 'measured' values of 10 to 40% obtained from particle size analysis.

The grading curves show a marked change of gradient at the silt / sand size boundary (0.06 mm). This may indicate a form of gap-grading due to the predominance of silt and gravel compared with fine sand, or it may be due to poor matching of the sieving and sedimentation parts of the analysis, or to incorrect adjustment of the grading curve owing to the need to sieve subsamples in the case of coarse grained soils (Head, 1992). However, the discrepancy appears to apply across the grading range. A good illustration of this is shown for Area 1, Lower Keuper Marl (Figure 7.2). Here, a clear change of slope is seen at 0.06 mm irrespective of the Y-axis value.

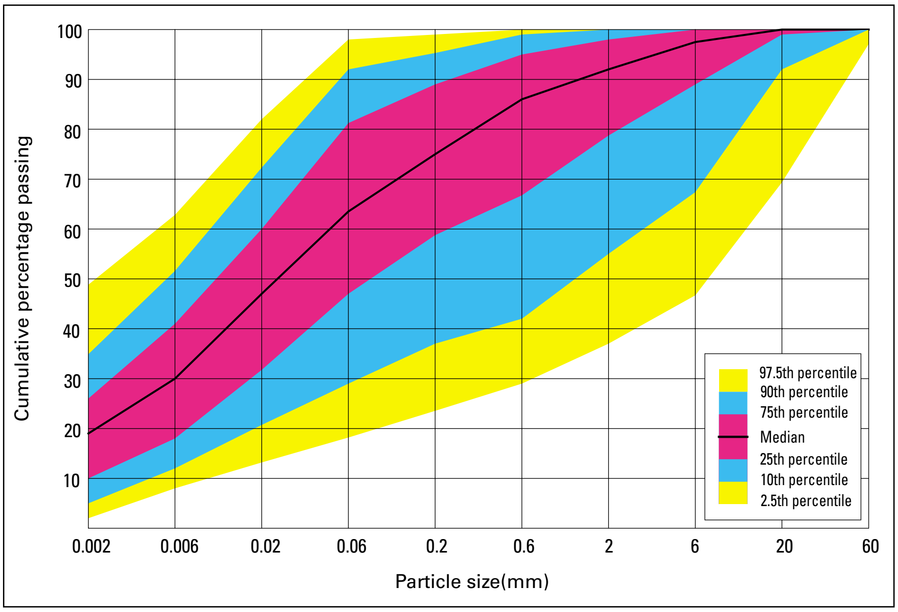


Figure 7.1 Particle size grading envelopes (all data).

It would seem likely that with increased weathering the particle size grading should become finer overall, as the clasts, lithorelicts, and bonds are progressively broken down. Whilst this does appear to be the case, there is not a good correlation. A trend is seen, for example, for Area 2 Weathering Zones 2, 3 and 4a, where the particle size grading becomes finer with increasing weathering (Figure 7.3). For other areas the trend is similar, less clear, or non-existent. The correlation between particle size grading and stratigraphy is somewhat better. The data for Area 1 (Figures 7.2) allow comparison to be made between local stratigraphic units: Lower Keuper Marl (LKM), Lower Keuper Saliferous Beds (LKSB), and Middle Keuper Marl (MKM); the LKM showing the coarsest, the MKM the finest, and the LKSB an intermediate grading. The compari-

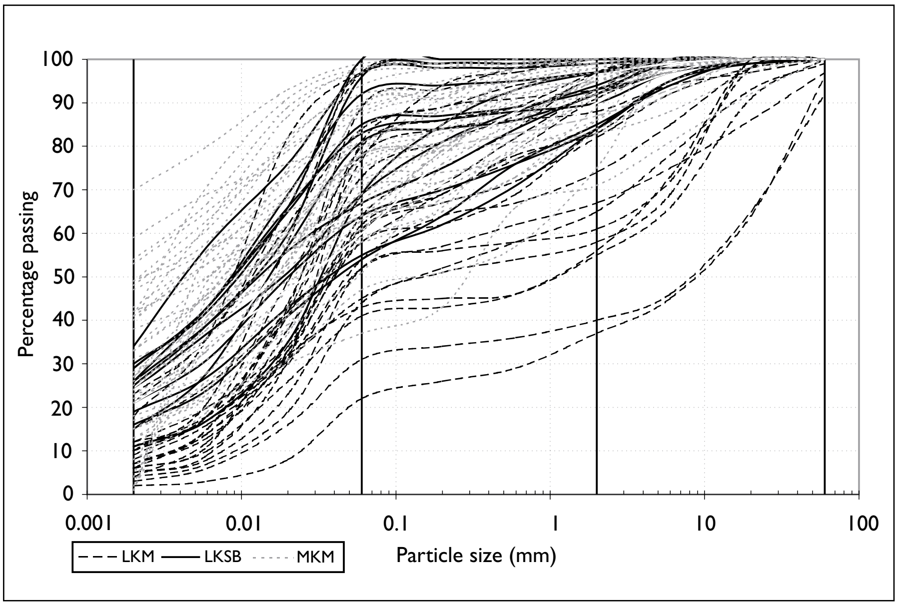


Figure 7.2 Particle size grading curves (Area 1, subdivided by formation).

son of particle size gradings from one area to another is hampered by a shortage of data in many areas. The general rule seems to be that the greater the number of data, the greater its scatter. For example, the scatters for Areas 1 and 2 data are as large as for all data combined. However, Area 1 does tend to be finer overall than Area 2. This is also reflected in the higher plasticity results for Area 1 (section 7.4). Other areas tend to be intermediate between Areas 1 and 2 in terms of grading.

It has been clearly demonstrated in the database, and in the literature (Chandler et al., 1968), that a large proportion of particle size data are misleading; dispersion (or disaggregation) during sample preparation may have been inadequate and the fine fractions reported are lower than they should be. Davies (1967) defined the aggregation ratio, A_r as follows:

$$A_r = \frac{\%\ \text{clay mineral}}{\%\ \text{clay size fraction}}$$

The % clay mineral content is determined from mineralogical analysis, whereas the % clay fraction (particles < 0.002 mm) derives from particle size analysis. Both percentages are expressed as weight proportions of the whole sample. Sherwood and Hollis (1966), Dumbleton and West (1966a, b), Davis (1967), and Chandler et al. (1968) gave values for A_r of between 1.39 and 9.35. The implication of these figures is that either the clay minerals exist as particles larger than 0.002 mm, or that the particle size fraction is incorrect. Chandler et al. (1968) gave a positive correlation between aggregation ratio and activity. Clay size fraction was also introduced in Skempton's definition of Activity (Skempton, 1953). This is discussed in section 7.4.

The problem appears to stem in part from the inadequacy of the British Standard (British Standards Institution, 1990) mixing method and its duration with respect to the Mercia Mudstone. This was touched on by Birch (1966). Experiments carried out at the BGS have shown that extended periods (2 to 24 hours) of disaggregation using the normal chemicals, as specified in BS1377, in shaking flasks has resulted in the 'correct' gradings. Consistent 'particle size analysis' grading plots with clay-sizes (%<0.002 mm) of between 22 and 40% were reported by Entwisle (1996) for Area 8. The Skempton Activity plot is shown in Figure 7.4. This demonstrates a wide scatter of activity values from 'inactive' to 'very active', both overall and when subdivided by area or formation.

It may be argued that the conventional particle size analysis is unsuited to the Mercia Mudstone, at least in Weathering Zones 1, 2, and 3a. Rocks are not usually subjected to what is essentially a soils test. Instead they are examined petrographically or in terms of a prescribed fabric classification depending on lithological type. This is a further illustration of the problems caused by a material that is mid-way between a soil and a rock, at least in engineering geological terms. It may be that an index test such as the slake durability test is more suited to the Mercia Mudstone. Whilst this test is not a particle size test it gives an indication of liability to breakdown under conditions of mechanical abrasion and swelling, and may be indicative of the breakdown taking place during disaggregation or the wet sieving process. The slake durability test is not commonly carried out on weak mudrocks and clays, and no data for the test exists in the database. However, tests were successfully carried out on Oxford and Weald clays (Franklin and Chandra, 1972). The

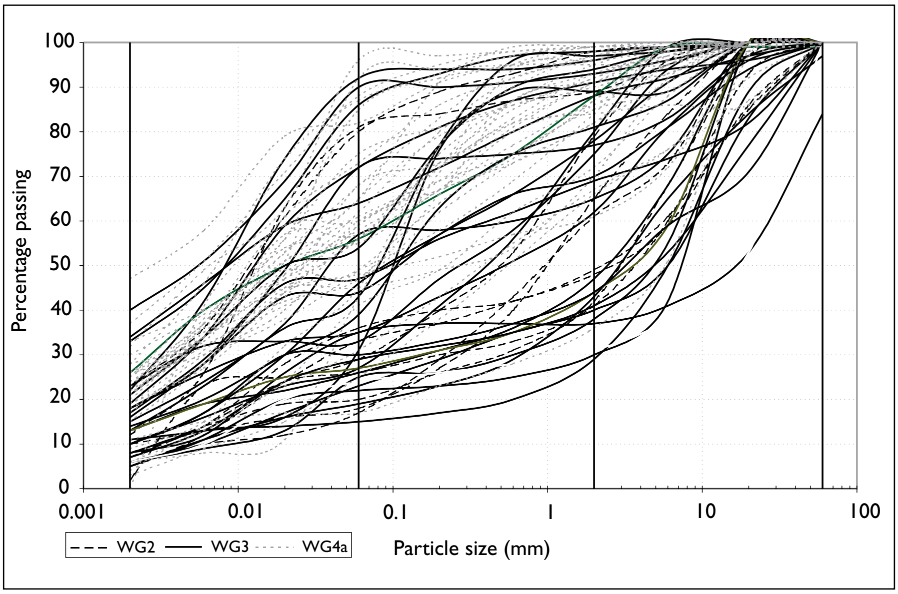


Figure 7.3 Particle size grading curves (Area 2, subdivided by weathering zone, WG).

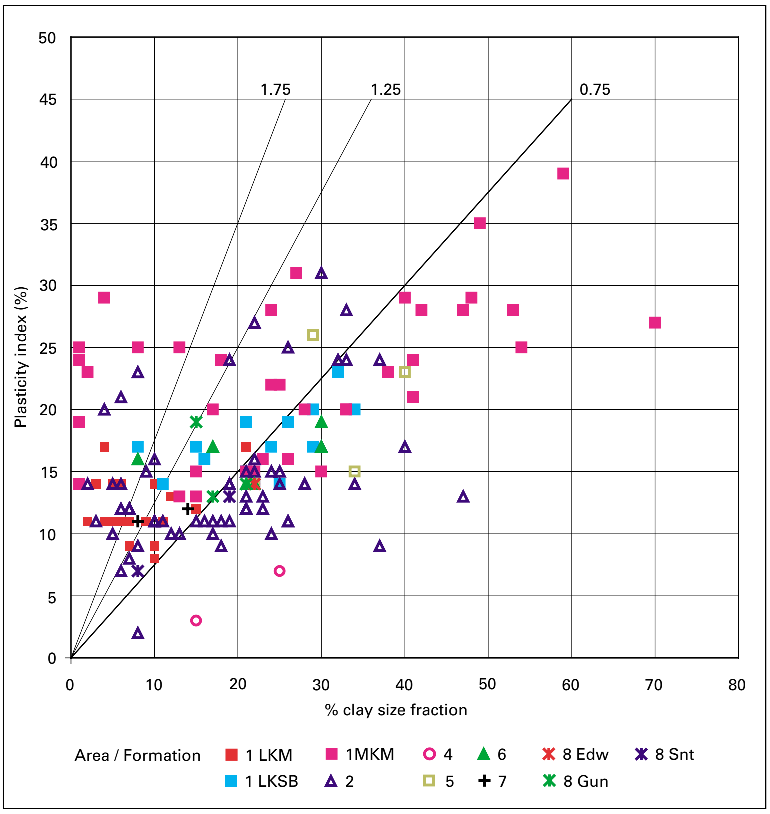


Figure 7.4 Activity plot, %<0.002 mm vs. plasticity index I_p (subdivided by formation).

slake durability test was recommended by Grainger (1984) for the classification of mudrocks into 'durable' and 'non-durable'. Birch (1966) suggested a simple moisture adsorption test to characterise mineralogy and surface area.

The British Standard for particle size analysis (British Standards Institution, 1990) Part 2, Test 9 notes that standard dispersion techniques may not be successful with 'certain highly aggregated soils' and that other methods of dispersion may be required. If we consider Mercia Mudstone (Weathering Zones 1 and 2) as essentially a mudrock this note presumably applies. It may be that the duration of dispersion during sample preparation is more important than the chemical dispersing agent used. The problem of particle disaggregation described for Weathering Zone 3 and 4 Mercia Mudstone clay soil may be distinct from that of mudrock breakdown, discussed above, characteristic of Weathering Zone 1 to 3 material. Nevertheless, the effect may be similar in terms of the particle size grading results. Chandler (1967) suggested that disaggregation is mainly a problem with unweathered Mercia Mudstone, and cites carbonate (cement?) content as one possible cause. Other sources suggest iron oxide (Kolbuszewski and Shojobi, 1965) or silica (Sherwood and Hollis, 1966) as a primary cementing agent, or that there is no cementing agent (Birch 1966).

Sherwood and Hollis (1966) suggested that particle size discrepancies in particle size data using different methods may in part be due to silt-sized clay minerals. Scanning electron microscopy of samples from Zone 4 Mercia Mudstone from Gringley-on-the-Hill and Zone 2 from Cropwell Bishop (Area 8) suggested that the proportion of clay minerals present at silt-size is low (Pearce et al., 1996).

The apparent problems inherent in disaggregation and determining particle size gradings render the accuracy of particle size analyses in the database open to doubt and hence also the activity data.

7.4 PLASTICITY

Plasticity is a property of clay soils which is largely dependent on clay mineralogy and particle size. If a clay contains enough water to form a slurry it behaves as a viscous fluid (liquid state). If the clay begins to dry out it reaches a point where it is capable of withstanding a shear stress (plastic state). On further water loss the clay becomes stronger and brittle (semi-solid state). Plasticity is usually expressed in terms of the Atterberg (or consistency) limits: liquid limit (w_L or LL) and plastic limit (w_p or PL). The plasticity index (Ip or PI) is defined as follows:

$I_p = w_L - w_P$

This is the range of moisture contents over which the clay soil's behaviour is plastic. Liquid and plastic limits are universally recognised empirical values on the moisture content scale, as is shrinkage limit (section 7.11). In addition, the liquidity index, I_L or LI, is defined as follows:

$$I_L = \frac{(w - w_L)}{I_P}$$

where: w = natural moisture content
I_P = plasticity index

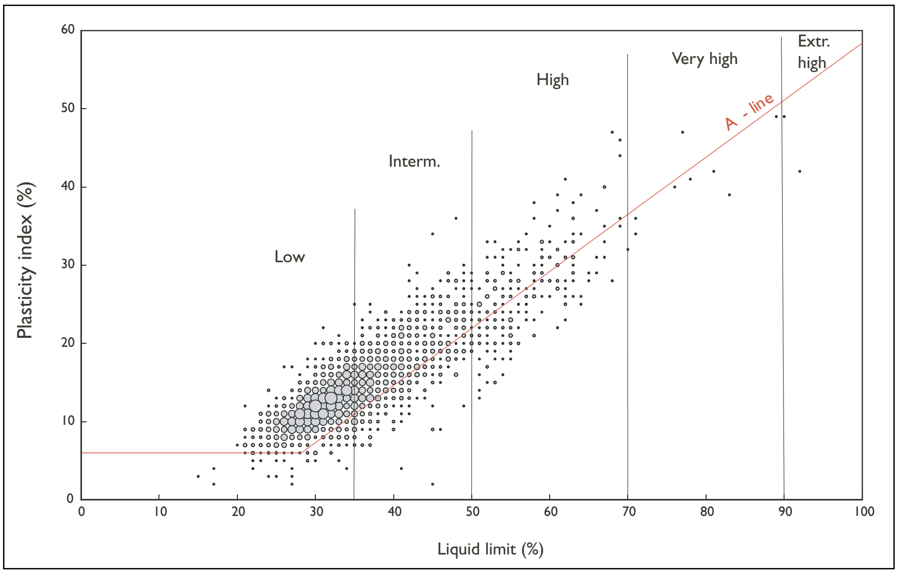


Figure 7.5 Casagrande plasticity plots — liquid limit w_L vs. plasticity index I_P (all data).

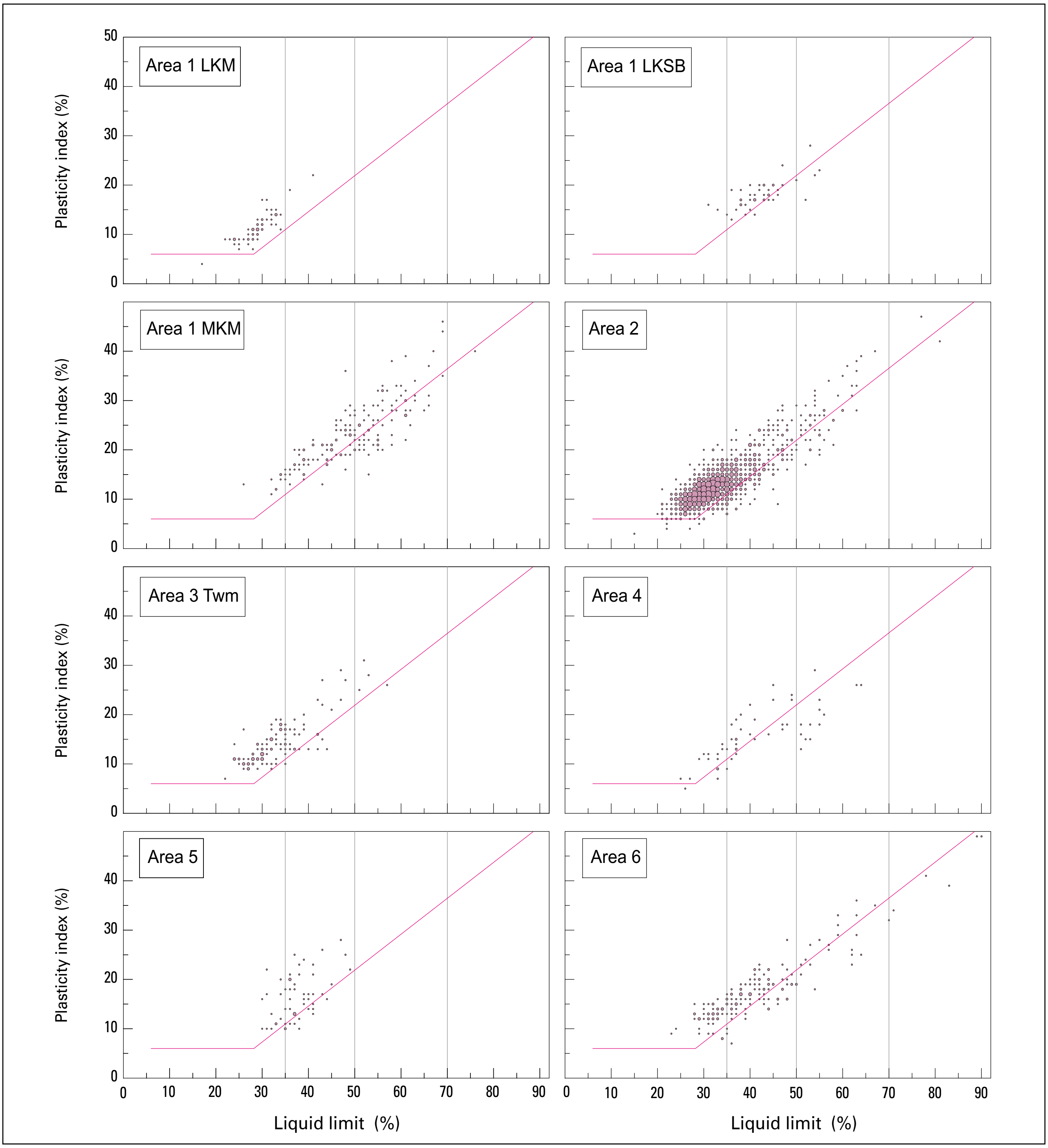


Figure 7.6 *(above and opposite)* Casagrande plasticity plots — liquid limit, w_L vs. plasticity index I_P (subdivided by area).

The results of liquid and plastic limit tests are shown in Figures 7.5 and 7.6 as traditional Casagrande plasticity plots (liquid limit, w_L vs. plasticity index, I_P), and in Figure 7.7, 7.8 and 7.9 as special plasticity plots of plastic limit, w_P vs. plasticity index, I_P. The latter attempts to display the data as independent, rather than partially dependent, relationships as is the case with the former. This results in non-linear relationships that in some cases show groupings according to area or formation. Also, the whole of the plot area is available, unlike the normal Casagrande plot where only half of the plot is available due to the fact that plasticity index cannot exceed liquid limit.

A total of 2598 liquid limit results are contained in the database. Values for liquid limit range from 11 to 133%. Overall medians for the ten areas range from 30 to 52%. Areas 1 and 9 have notably higher liquid limits than the other areas. The respective overall medians for these two areas are 44 and 52%. Samples with liquid limits greater than 70% (that is 'very high' or 'extremely high' plasticity) represent less than 0.5% of all data. There is a general trend of increasing liquid limit with increased weathering (i.e. higher weathering zone), although this increase does not appear to be 'linear'. For example, whilst significant change is seen from Zone 2 to 2/3 or from 4a/4b to 4b, little or no change is seen between 3a and 4a. The highest value recorded (133%) is for glacially reworked material

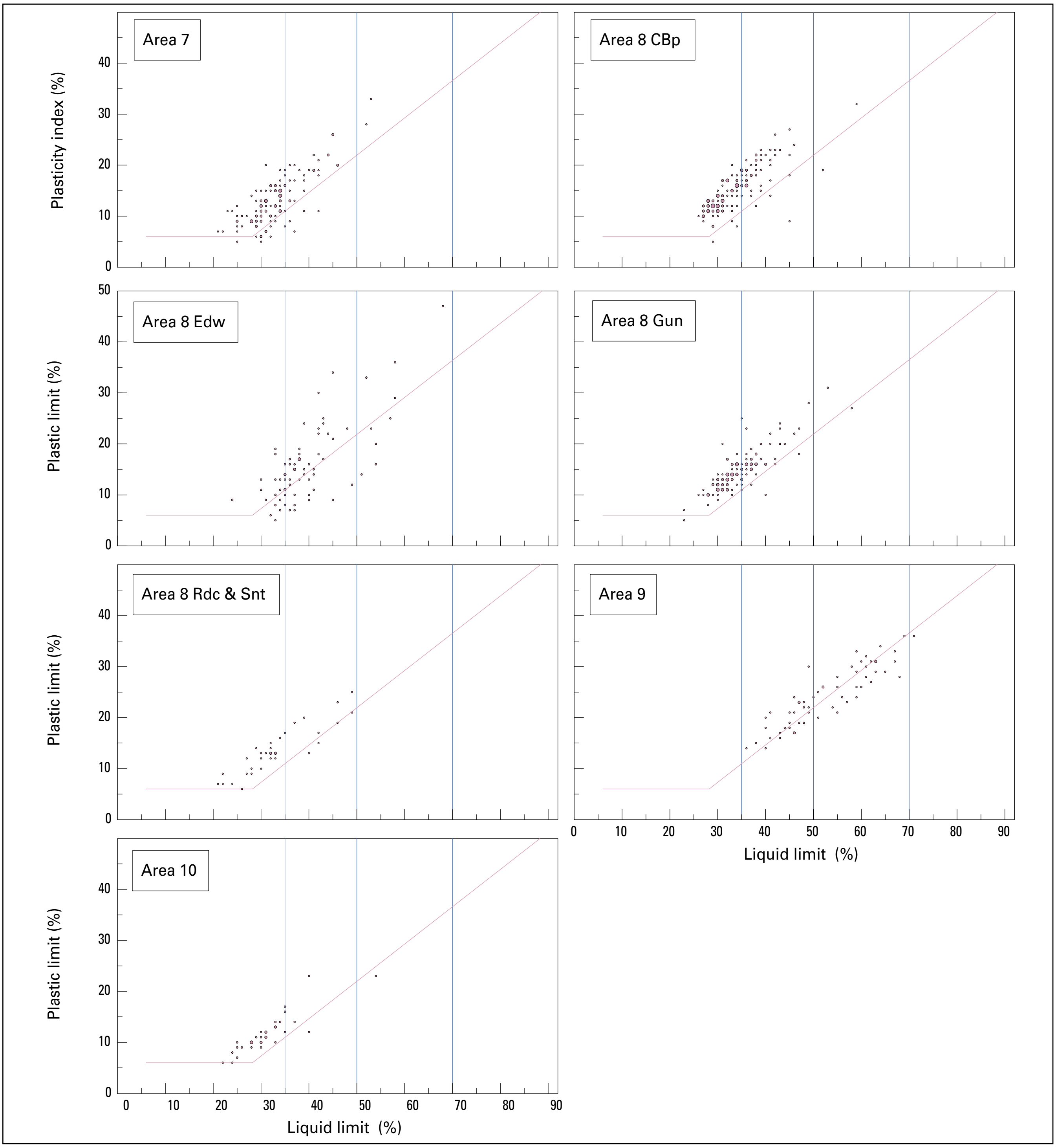


Figure 7.6 *(continued from previous page).*

from Area 2. The highest value for unreworked material is for Area 2, Zone 2/3, at 106%. Lithostratigraphic subdivisions have been applied to Areas 1, 3 and 8 only. All data from Area 3 are from the Twyning Mudstone Formation. In Area 1 the Middle Keuper Marl and Lower Keuper Saliferous Beds have higher medians than the Lower Keuper Marl. The Edwalton Formation in Area 8 (Nottinghamshire and south Derbyshire) has higher medians than the other formations in this area.

A total of 2511 plastic limit results are contained in the database. Values for plastic limit range from 9 to 50%. Overall medians for the ten areas range from 18 to 28%. Area 9 (Humberside) has the highest overall median, and Area 3 the lowest. There is a general trend of increasing plastic limit with increased weathering, but this is often slight and most notable at the extremes of the weathering zone scale. In Area 1 the Middle Keuper Marl and Lower Keuper Saliferous Beds have higher medians (> 20 %) than the Lower Keuper Marl (< 20 %). The Edwalton Formation in Area 8 (Nottinghamshire and south Derbyshire) has higher medians than the other formations in this area.

A total of 2509 plasticity index results are contained in the database. Values for plasticity index range from 2 to 49%, with a ‘reworked’ maximum of 79%. Overall medians for the ten areas range from 11 to 24%. Area 9 (Humberside) has the highest overall median, and Area 10 (Teeside) the lowest. There is a general trend of increasing plasticity index with increased weathering (i.e. higher

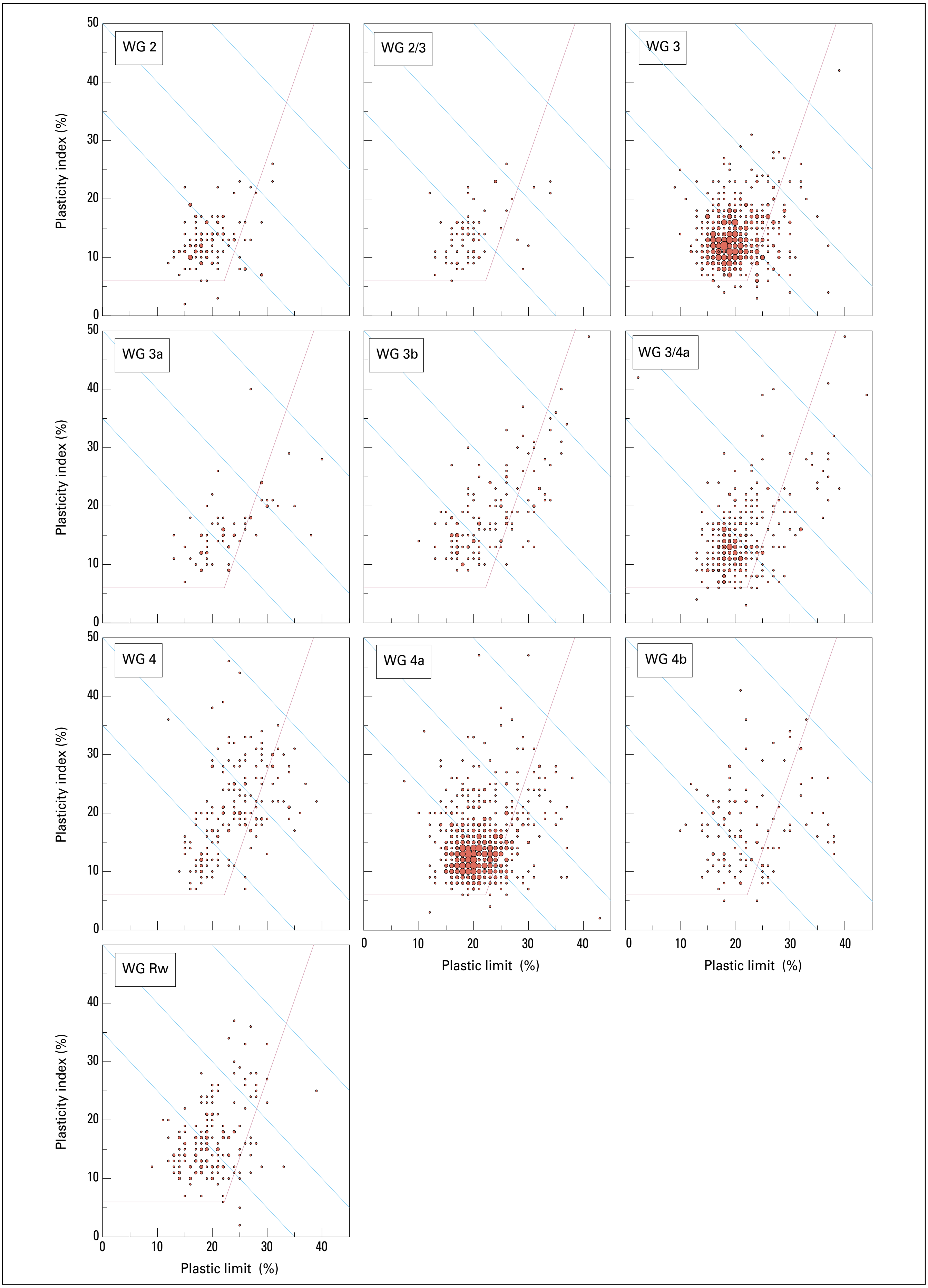


Figure 7.7 Plot of plastic limit, w_P vs. plasticity index I_P, (subdivided by weathering zone, WG).

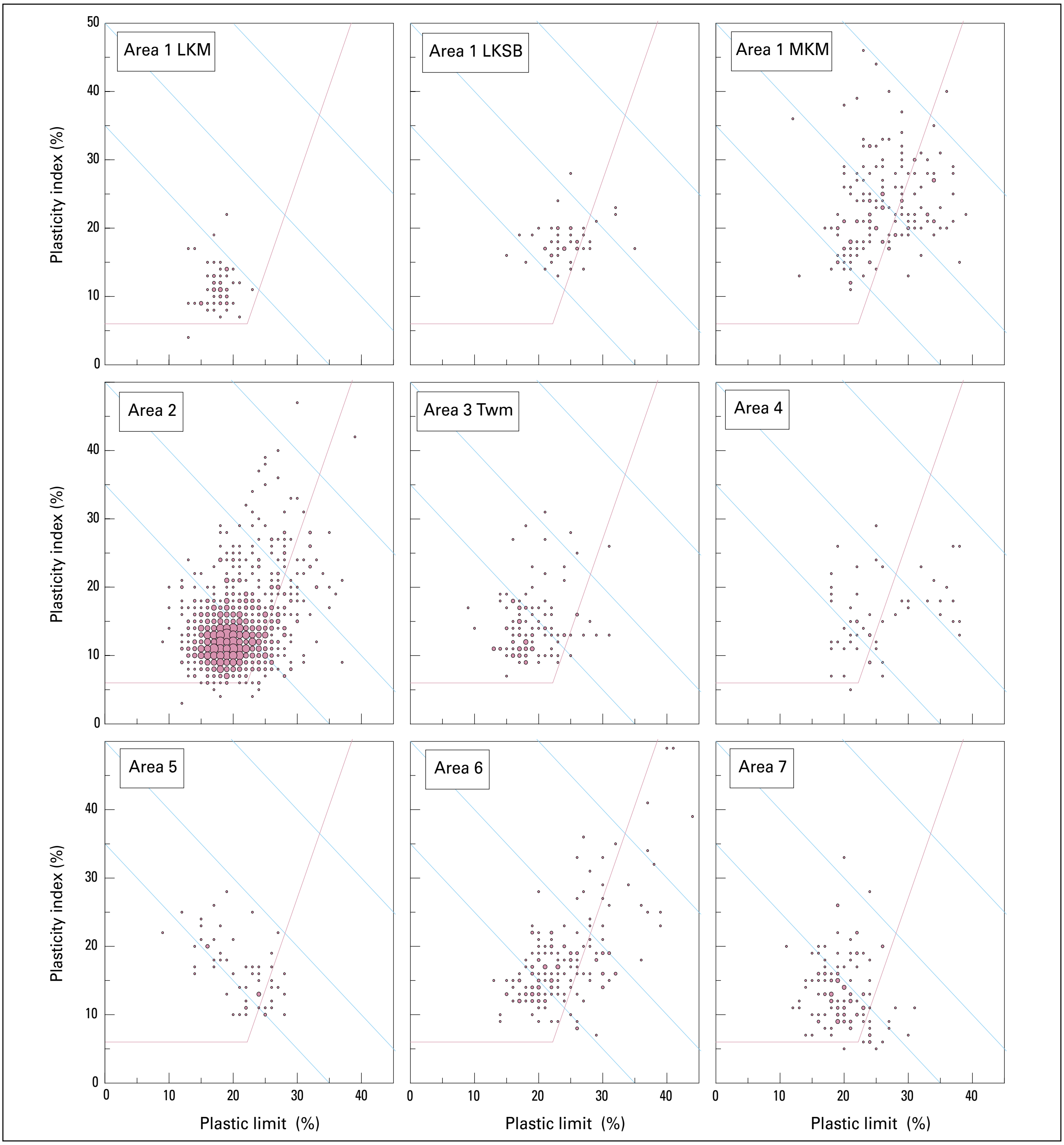


Figure 7.8 *(above and overleaf)* Plot of plastic limit, w_P vs. plasticity index I_P, (subdivided by area).

weathering zone), but this is not universal, and is not always seen from one weathering zone to the next. Area 2, for which there is the largest number of data, shows that plasticity index increases by 5% from Weathering Zones 2 to 4b, but only by 1% from Zones 2 to 4a/4b. In contrast to the liquid and plastic limit results, the plasticity index data for the Edwalton Formation of Area 8 (Nottinghamshire and south Derbyshire) are not significantly higher than those for the other formations in this area. The plasticity plot for this formation (Figure 7.8) also shows considerable scatter compared with the other formations, also with many data points lying below the A line.

The Casagrande plot (Figure 7.6) and special bubble plots subdivided by area and formation (Figures 7.7 and 7.8, and key Figure 7.9), show different distributions of data on the plots and a wide range of plasticity classes from low to high. Area 1 has a particularly wide range with a clear trend of increasing plasticity from 'low plasticity' for the Lower Keuper Marl (LKM), through 'intermediate' for the Lower Keuper Saliferous Beds (LKSB), to 'intermediate' and 'high' for the Middle Keuper Marl (MKM). Area 2 has a similar shape but, albeit with a much larger dataset, shows a dense concentration at the 'low plasticity' end, and without the highest Area 1, MKM values. Area 8 shows a distinction between the Edwalton and other formations, the former having a tendency for greater scatter and overall higher plasticities. Area 9 has a tendency for 'high' plasticity and an almost total absence of data points in the 'low plasticity'

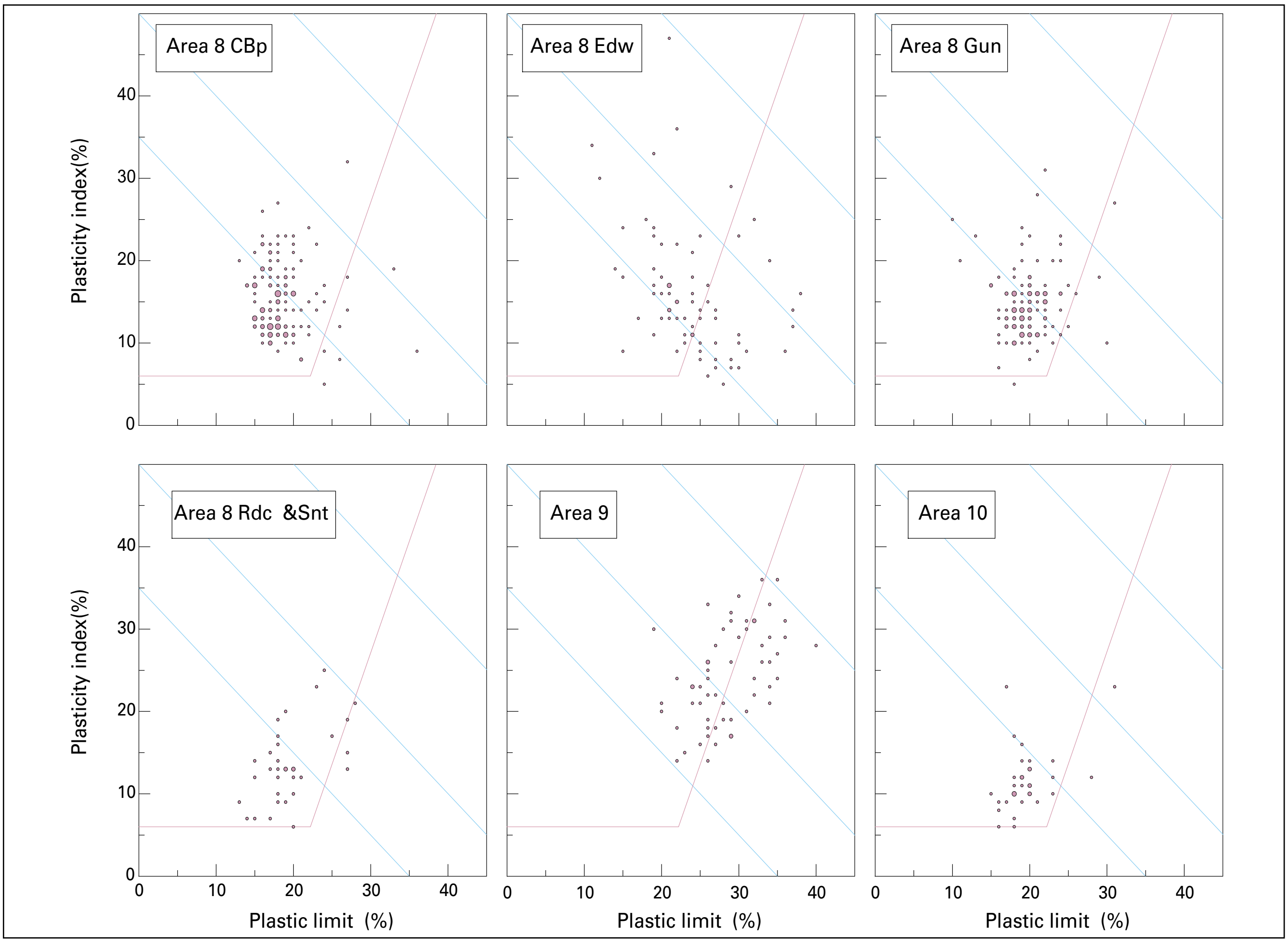


Figure 7.8 *(continued from previous page).*

zone. The only points not shown on the Casagrande bubble plots (Figure 7.6) are a very small number from Areas 2 and 6. These have liquid limits in excess of 90% and are thus classed as 'extremely high plasticity' soils. There are also very few samples having a liquid limit between 70 and 90% ('very high plasticity'). Samples with liquid limits greater than 70% represent less than 0.5% of all data. The plot subdivided by weathering zone (Figure 7.7) shows little distinction between zone, apart from a general broadening of scatter up the A line with increased weathering from Zone 2 to 4. Scatter tends to increase with increasing numbers of data. Data lie mainly above the A line, but may fall below it, particularly for $w_L > 50\%$.

Liquidity index is a ratio (defined above) which allows 'location' of the in situ condition of a soil in its consistency range related to the Atterberg limits. Values of liquidity index may be used as a guide to desiccation, or where equilibrium moisture content is established, the degree of over-consolidation of a soil. There are 2400 liquidity indices in the database. These range from -2.00 to +0.94, with an overall median of -0.07. A value of +1.00 indicates that the natural moisture content equals the liquid limit. A value of 0 indicates that the natural moisture content equals the plastic limit. The overall medians for Areas 1, 2, 6, and 7 are -0.21, 0, -0.15, and 0, respectively. There does not appear to be any relationship within these areas between weathering zone and liquidity index, except for Area 2 (the largest sub-set) where there is a general increase in liquidity index from Zone 2/3 to Zone 4b. The Edwalton Formation in Area 8 has a high liquidity index median of +0.14, compared with other formations and other areas which are negative or zero with the exceptions of Area 5 (+0.11) and the Sneinton Formation, Area 8 (+0.07). In Area 1 the liquidity index medians increase upward from the LKM (-0.35), through the LKSB (-0.21) to the MKM (-0.19). The Area 10 median is particular low (-0.67). The correlation between liquidity index and weathering grade is unclear. Whilst there is an overall trend of increasing liquidity index with increased weathering, individual grades may not follow the trend. An example is Weathering Zone 4 (-0.17) which, unlike Zones 4a (+0.06) and 4b (+0.04), has a positive liquidity index median. Reworked Mercia Mudstone has a liquidity index median of +0.09. Despite the fact that Mercia Mudstone plasticity indices are low, some of the very low values (<5%) contained in the database are suspect. When liquidity index is calculated these low values contribute to very high values for I_L, although the main cause appears to be unfeasibly high natural moisture contents.

Chandler et al. (1968) gave ranges of liquid limit and plasticity index (for borehole core samples from a variety of locations) of 27 to 39% and 8 to 15%, respectively (with the exception of a sample from West Burton with 50 and 20%, respectively).

Activity, A_c, was defined (Skempton, 1953) as follows:

$$A_c = \frac{I_p}{\%\ \text{clay}}$$

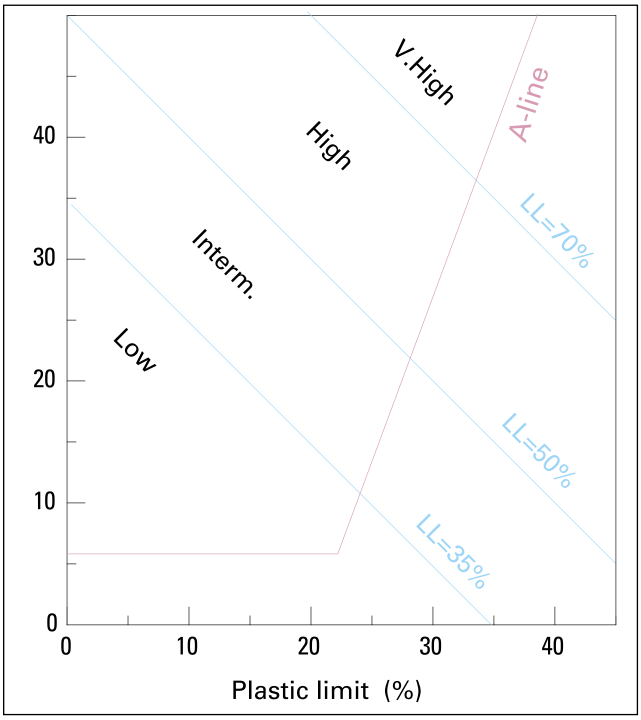


Figure 7.9 Key to plots of plastic limit, w_P vs. plasticity index I_P (Figures 7.7 and 7.8).

where: Ip = plasticity index
% clay = % by weight passing 0.002 mm sieve

Activity describes the significance in terms of swell/shrink and other engineering behaviour, of the clay fraction within the soil. For example, a soil with a low clay-size content, but where that fraction consists mainly of the clay mineral sodium smectite, will produce a high activity whereas a soil with a high clay-size content consisting mainly of illite will not. The accuracy of the activity data in the database is subject to doubt due to problems with the sample preparation and determination of particle size (Section 7.3). There is also some doubt about the concept of activity when applied to clays with low activity. The data contained in this and other BGS databases, suggest that silt-sized particles (i.e. >0.002 mm) can result in measurable liquid and plastic limits, and hence plasticity indices. For such materials an activity value of infinity is obtained.

Whilst a large proportion of the data fall into the 'inactive' category (A_c < 0.75), there are many data with unfeasibly large values of activity, A_c. Samples with the same plasticity index have activities ranging from 'inactive' to 'very active'. Values for A_c of 30 and 40 are not uncommon, and some values of infinity are obtained. Given the mineralogy of the Mercia Mudstone such activities are highly unlikely. Davies (1966) explains this by pointing out the ability of clay to absorb water, and hence exhibit plasticity, is not confined to dispersed clay particles but is equally applicable to aggregated particles. Chandler et al. (1968) and Davies, (1966) gave activities of between 0.3 and 0.8 for Mercia Mudstone from Area 8 and between 0.15 and 1.13 for the Midlands generally. This compares with values for clay-size fraction of between 2 and 32%, and for activities of between 0.56 ('inactive') and 2.11 ('very active'), from the database for Area 8. There appears to be no relation between activity and weathering zone or area. Results from Davies (1966) suggested that the 'true' activity of Mercia Mudstone might typically be around 0.2. Work carried out at the BGS has also shown the importance of clay surface area determinations to augment XRD data which on their own may be inadequate to distinguish some clay mineral types (see Section 3).

Activity plots (plasticity index vs. % clay-size fraction) for thousands of test results from BGS databases on a variety of UK soil types, including Mercia Mudstone, produce regression lines which intercept the plasticity index axis at some positive value. *The regression line may not in fact be straight (as shown in Skempton, 1953), but rather a gentle curve, thus explaining the apparent deviation away from an intercept at the origin.* It is unlikely that the particle size sample preparation problems discussed in Section 7.3 affect all of these data or that these problems are as significant with other UK soils as they appear to be with the Mercia Mudstone.

Certain clay minerals may exist at sizes larger than 0.002 mm. It should be noted also that the sample preparation procedure for the Atterberg limit tests is different from that of the particle size test. The use of dispersing agents is not permitted prior to the 0.425 mm sieving of Atterberg samples. Analysis of the data reveals large discrepancies between % <0.425 mm reported form Atterberg tests and equivalent data calculated from particle size analyses. The tendency is for the <0.425 mm data to be equal to, or higher than, the particle size analysis data (by a factor of up to 10). The reason for this is unclear, but is unlikely to lie

Table 7.2 British Standard sample preparation procedures for Atterberg limit and particle size tests.

Atterberg limits (BS1377:1990) (Sieved specimen)	**Particle size analysis (BS1377:1990) (Wet sieving/sedimentation method)**
1. partially (air) dry if required	1. partially (air) dry if required
2. disaggregate with rubber pestle, if required	2. disaggregate with rubber pestle
3. add distilled water & stir to slurry	3. subdivide (e.g. riffle)
4. wet sieve 0.425 mm mesh	4. oven dry (105 – 110 °C), if soil suitable
5. mature for 24 hours, if clay	5. sieve 20 mm mesh and above
6. hand mix paste (10 to 40 minutes)	6. soak & stir >1 hour in dispersant
	7. wet sieve 2 & 0.063 mm mesh
	8. soak & shake > 4 hours in dispersant
	9. wet sieve 0.063 mm mesh
	10. sedimentation test on <0.063 mm fraction

solely with dispersion. Head (1992) recommends that the clay-size fraction used in the calculation of activity should be corrected to be the proportion of soil passing the 0.425 mm sieve rather than the proportion of the whole sample. A comparison of the British Standard (BS1377:1990) sample preparation procedures for Atterberg limit and particle size testing is shown in Table 7.2.

The above highlights the contrasting energy inputs and drying procedures for each test. The British Standards Institution (1990) states that disaggregation (without chemicals) for the Atterberg limit tests should be such that only individual particles are left on the 0.425 mm sieve.

Plasticity data are commonly used as a guide or index to determine other soil properties, which in some cases are more difficult to determine. Examples of these are swelling and shrinkage (Section 7.11), standard penetration test (SPT), strength (Section 8.5), and compressibility (Section 7.7). In assessing volume change potential (swell and shrink) the Building Research Establishment (Building Research Establishment, 1993) used a plasticity index, I_P', corrected for the proportion of the sample passing the 0.425mm sieve (Section 7.11). Examination of this quantity for the Mercia Mudstone indicated that some medium to low plasticity soils are significantly reduced in volume change potential whereas high plasticity soils are largely unaffected.

Scanning electron microscopy and X-ray diffraction studies have shown that the clay fraction of parts of the Mercia Mudstone sequence for Area 8 is dominated by illite, corrensite, with minor chlorite (Section 3, Pearce et al., 1996; Bloodworth and Prior, 1993). Illite typically accounts for between 40 and 60% of the Mercia Mudstone by weight (Davies, 1966) and corrensite (regularly inter-stratified chlorite / smectite) between 5 and 35%; the ratio between them being reasonably constant. Illite is generally considered as a mineral of low to medium plasticity and low volume change potential (Birch, 1966; Shaw, 1981). Clay mineral composition and regional variation are discussed in detail in Section 3. The presence of illite and smectite is described for a sample near Leicester, Area 8 (Birch, 1966). It is suggested that this sample may have been affected by glacial activity. This may equate with the high plasticity zone within the Edwalton Formation that was described by Atkinson et al. (1998) in their work on destructured Mercia Mudstone from Edwalton Hill which had caused problems during a full face TBM tunnel drive near Leicester (Myers and Sindle, 1994).

Work has been carried out on the effect of varying energy input to the reworking of Atterberg samples (Entwisle, 1996). This work followed the work at the Transport Research Laboratory (TRL) by Newill (1961), Sherwood (1967), and Sherwood and Hollis (1966). Entwisle (1996) showed, for samples from Gringley-on-the-Hill and Cropwell Bishop (Nottinghamshire, Area 8), that whilst some aggregations were apparently broken down by extra reworking (for example by using a grease-worker, Kolbuszewski and Shojobi, 1965), resulting in a higher % clay and higher Atterberg limits, the effect was by no means universal and in many cases was slight. Entwisle (1996) concluded from this that the aggregation was not as pronounced as indicated in Davis (1967) and suggested that the inclusion of silt-sized mica and chlorite in the clay mineral content figures was a possible explanation. However, Sherwood and Hollis (1966) pointed out that the presence or absence of aggregations did not appear to affect the results of Atterberg tests as it did particle size tests. They also suggested that some clay mineral particles may be larger than 0.002 mm. Their work was based on samples obtained from Worcestershire and Gloucestershire (Area 3), and Leicestershire (Area 7). Clearly, the reworking energy applied to normal Atterberg test preparation exceeds that of particle size test preparation, and is sufficient to break down most, or all, aggregations. However, the energy input to reworking during Atterberg preparation is partly dependent on the operator, and it is unclear whether the standard (British Standards Institution, 1990) procedure is always sufficient to break down all aggregations (Kolbuszewski and Shojobi, 1965).

Sherwood and Hollis (1966) used the relationships of % clay-size fraction with Atterberg limits and with 'loss on ignition' to demonstrate that the 'X-ray mineralogical analysis' derived clay-size fractions are correct and the 'particle size test' derived fractions are incorrect. In fact the discrepancies reported between the two methods were very large but inconsistent; the aggregation ratio, A_r, varying from 1.6 to 6.4. Sherwood and Hollis (1966) suggested that a significant component of the discrepancy was due to silt-sized clay minerals, and used the low Atterberg results.

7.5 SULPHATE, PH AND OTHER CHEMICAL TESTS

A small group of relatively simple chemical tests for soils is usually included in geotechnical testing. These are: total sulphate content, aqueous extract sulphate content, pH, carbonate content, and organic content (Head, 1992). In addition, there is a test for the sulphate content of ground water. These tests are carried out to British Standard procedures (British Standards Institution, 1990). In each of these cases there are alternative, and usually more rigorous, methods of analysing soil chemistry by geochemical and mineralogical laboratories. However, these are often assumed to be complex, expensive, or simply unnecessary by engineers and are seldom carried out as part of routine site investigations. Even the basic British Standard (British Standards Institution, 1990) chemical tests are infrequently carried out and are thus poorly represented in the database. X-ray diffraction (XRD) techniques, the scanning electron microscope (SEM), and surface-area techniques may also be used to examine soil chemistry and mineralogy (Pearce et al., 1996).

Groundwater containing sulphate can attack concrete and other materials containing cement. A reaction takes place between the sulphate and aluminium compounds in the cement, causing crystallisation of complex compounds. This process causes expansion and internal damage. A classification for sulphate in soils, specified by the Building Research Establishment (BRE, 1981; 1991) is given in Table 7.3.

Excessive acidity or alkalinity of groundwater can have detrimental effects on concrete below ground level. Even moderate acidity can corrode metals. Some soil stabilisa-

Table 7.3 Classification of total sulphate content (BRE, 1991).

Total sulphate content (%)	Class	
< 0.2	1	increasing potential
0.2 – 0.5	2	for attack
0.5 – 1.0	3	↓
1.0 – 2.0	4	
> 2.0	5	

tion agents may be unsuited to alkaline conditions. The pH also affects the solubility of some ions.

The Mercia Mudstone includes evaporite sequences that contain sulphate, largely in the form of gypsum as a *primary* constituent, in sufficient quantities to merit quarrying and mining for industry. *Data from evaporite sequences in the Mercia Mudstone are not included in the database.* The Mercia Mudstone may have near-surface zones leached of sulphates (Forster et al., 1995). Proximity to major gypsum layers may raise sulphate values in groundwater locally.

Results from three 'chemical' laboratory test parameters are contained in the database: total (soil) sulphate, aqueous extract (soil) sulphate, and pH. 'Total sulphate' is the acid-soluble sulphate content, whilst 'aqueous extract sulphate' is the water soluble sulphate content. Both are obtained from liquid extracts but indicate the sulphate content of the soil itself rather than of the groundwater, and are expressed as a percentage. There are two recommended British Standard test methods (British Standards Institution, Part 3, 1990), the gravimetric and the titration methods.

Total sulphates overall range from 0.002% (Area 2) to 9.47 % (Area 1). This covers the entire range of sulphate classes (1–5) shown above (BRE, 1991). Areas 2 and 8 are the best represented in the database, and have medians of 0.08 and 0.15% (both Class 1), respectively. Areas 1, 2, and 8 have a wider range of values than Area 3 (other areas have few data). Data from Area 8 suggest that variations across the stratigraphical subdivisions may be discernible. For example, total sulphate values for the Gunthorpe Formation are higher than for the Cropwell Bishop Formation.

Aqueous extract sulphates range from 0.001% (Area 8) to 2.3% (Area 10). Again, Areas 2 and 8 have the largest representation, and have medians of 0.21 and 0.05%, respectively. Overall, the trend is for Areas 2 and 7 to have higher values than Area 8.

Head (1992) suggested that if the predominant sulphate in the soil is calcium sulphate (gypsum or its well-crystallised form, selenite) the 'total sulphate' value is likely to give a pessimistic indication of potential sulphate attack. He also stated that an 'aqueous extract sulphate' value in excess of 0.12% is indicative of sulphates other than gypsum; these being potentially more aggressive than gypsum.

Excessive acidity or alkalinity of the groundwater in soils can have a very detrimental effect on buried metals and reinforced concrete. Acidity and alkalinity is quantified in terms of the pH value. This is a measure of the 'active' acidity rather than the acid content and is a logarithmic scale. The test is usually carried out in tandem with the sulphate content test (Head, 1992). Results of pH tests in the database show that values generally lie between 7 and 8, i.e. slightly alkaline, with the median values of several subdivisions lying at, or close to, 8. In none of the areas do acid values (pH < 7) account for more than the 10th percentile of the data. Areas 2 and 8 are well represented in the database and have medians of 7.9 and 7.7, respectively. Subdivisional trends within areas are difficult to discern. However, the Cropwell Bishop Formation from Area 8 may be slightly lower than the other formations. Area 4 has a high median value at 8.5. The weathering subdivisions in Areas 2 and 8 do not show marked differences in pH.

Carbonates, either in the form of dolomite or calcite, are important constituents of the Mercia Mudstone. However, carbonate contents, organic contents, and other chemical/geotechnical test data are not represented in the database. Sherwood and Hollis (1966) gave carbonate contents of between 0.4 and 14% (Areas 3 and 7). Calcite is absent from one of the two mineral suites suggested by Davis (1966), whereas dolomite is almost ubiquitous. Total carbonate contents (calcite + dolomite) from Davis (1966) and Meigh (1976) were typically between 5 and 25%. Meigh (1976) placed particular emphasis on the importance of carbonate content to density and deformability. The results of mineralogical analyses are described in Pearce et al. (1996) and Section 3.

Sherwood and Hollis (1966) gave a value for organic content between 0.01 and 0.9 %, and for 'loss on ignition' between 7.5 and 17.9% for Area 3 and 7 material. They also gave values for cation exchange capacity (CEC) between 9.5 and 44.5 me/100 g the great majority of which was accounted for by exchangeable calcium and magnesium. Pearce et al. (1996) found that samples from Cropwell Bishop and Gringley-on-the-Hill had surface areas of about 60 and 145 m^2/g, respectively.

7.6 STRENGTH

The strength of a soil or rock is a measure of its capability to withstand a stress (or stresses) in a particular direction or configuration. Strength is not a fundamental property of a soil or rock, but is dependent on the condition of the soil/rock and the type of stresses applied to it. The strength of soils is particularly sensitive to the drainage conditions during the test, and the duration of the test. If full drainage is allowed the test measures *effective* strength parameters. If the conditions are undrained the test measures *total* strength parameters. Strength is usually determined as a compressive, shear, or tensile strength. Strength is usually determined on intact laboratory specimens but may be determined by tests on the soil/rock mass in the field, either at the surface, in trial pits, or in boreholes.

There are a variety of tests that measure strength. In both laboratory and field the methods differ from soils to rocks although the principles are the same. The most common tests for rock are the uniaxial (unconfined) compression test (UCS), and the point load index test (PL), whilst for soils it is the triaxial test of which there are several versions, and which, for a cohesive soil, determines the parameters cohesion, c, and the internal friction angle, ϕ. Shear strength is defined by the Coulomb equation as follows:

$$\tau = c + \sigma \tan \phi$$

where: σ = normal (perpendicular to shearing) stress

One important difference between the rock and soil tests is the specimen preparation. Rock specimens for UCS testing require machining and in common with PL test specimens are in an undisturbed state. Soil specimens may be undisturbed, remoulded, or compacted. Details of the testing of soils may be found in Head (1998).

It is difficult to give typical or average values of strength for the mudstones of the Mercia Mudstone Group, as a whole or for its component formations, because of the variation in fabric, structure, cementation aggregation and the heavy over-consolidation it has undergone due to post Triassic deposition and erosion. This results in very variable profiles of intact strength with depth on a scale of metres or millimetres, whether these are determined in situ or in the laboratory. This is also reflected in the moisture content and density profiles. Such variability can affect individual test specimens. Soft bands may underlie hard bands. Birch (1966) noted that 'soft' bands, 1.0 to 1.5 m thick, had been recorded at depths of 6 m, below 'unweath-

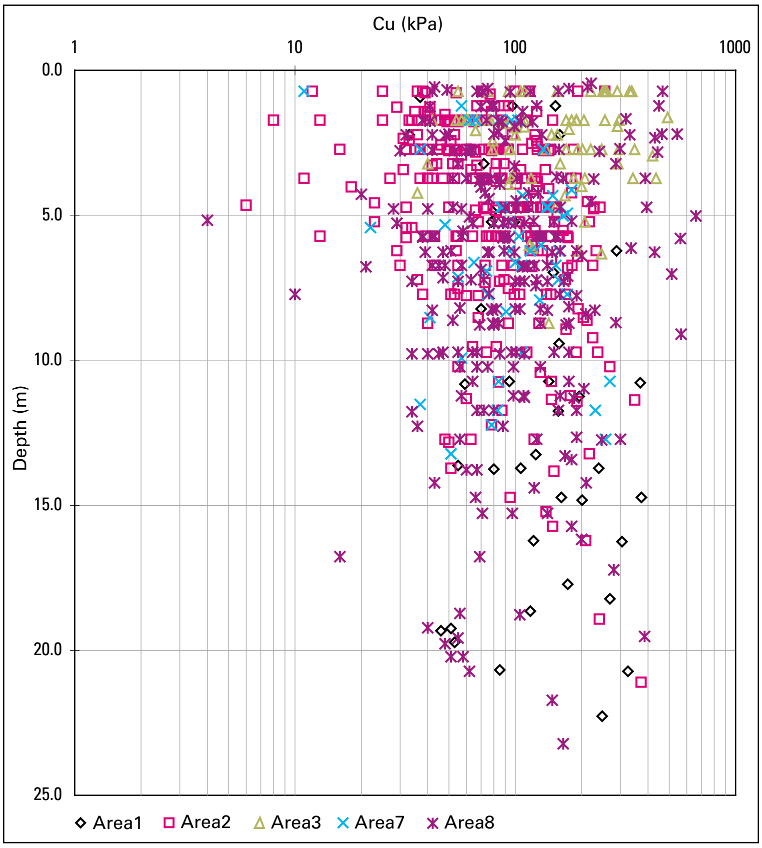


Figure 7.10 Plot of undrained cohesion c_u vs. depth (subdivided by area).

ered' rock, at the first Severn crossing site, (Area 4). This is due to the essentially tropical or subtropical hypersaline depositional environment of the group where leaching and redeposition are important factors in the development of inhomogeneity, and in the processes of chemical bonding and alteration that they engender. Chandler et al. (1968) pointed to high values of strength sensitivity; that is, a significant decrease in strength from the 'peak' to the fully 'remoulded' states. Factors of about four are quoted. The mass strength is also variable due to the pervasive jointing and fissuring within the Group. There is a general lack of high quality triaxial strength data for the low and intermediate weathering grades because of the difficulty of obtaining undisturbed specimens in this very stiff, fissured material. The result of this is difficulty in formulating design strength parameters based solely on laboratory data, and the consequent tendency to under-estimate strength, and to use direct field strength tests or indirect field tests from which strength may be inferred.

The strength of the Mercia Mudstone is represented in the database by the following parameters: undrained cohesion (c_u), uniaxial compressive strength (UCS), axial point load index ($I_{s(PLA)}$), and diametral point load index ($I_{s(PLD)}$). The standard penetration test (SPT) is also used as a guide to strength, and is discussed in section 8.5. Undrained cohesion is derived from *soil* triaxial tests while the remaining strength parameters are derived from rock tests. This is an example of the borderline nature of the Mercia Mudstone between 'soil' and 'rock'. The uniaxial compressive strength (UCS) test is usually considered to be an 'index' test, despite the need for a machined cylindrical specimen. The point load index test is an 'index' test for which machining is not mandatory. However, machined specimens may be used in addition to un-machined borehole core. Both these variants allow two types of test, diametral and axial. To some extent the test data may be biased towards strong material in the case of the 'rock' tests and weak material in the case of the 'soil' tests, purely as the result of the need to match method to sample. For example, skerries (sandstone) bands or cemented bands within the Mercia Mudstone tend to be subject to 'rock' tests rather than 'soil' tests. Both the uniaxial compressive strength and the point load index tests may have corrections applied to them (Broch and Franklin, 1972). These are usually in order to normalise results from a non-standard sized test specimen. Data may also be unreliable and open to misinterpretation (Farmer and Kemeny, 1992) particularly where insufficient data preclude statistical treatment.

Strength data obtained from quick undrained (soil) triaxial strength tests are quoted in the database as values of undrained cohesion, c_u.

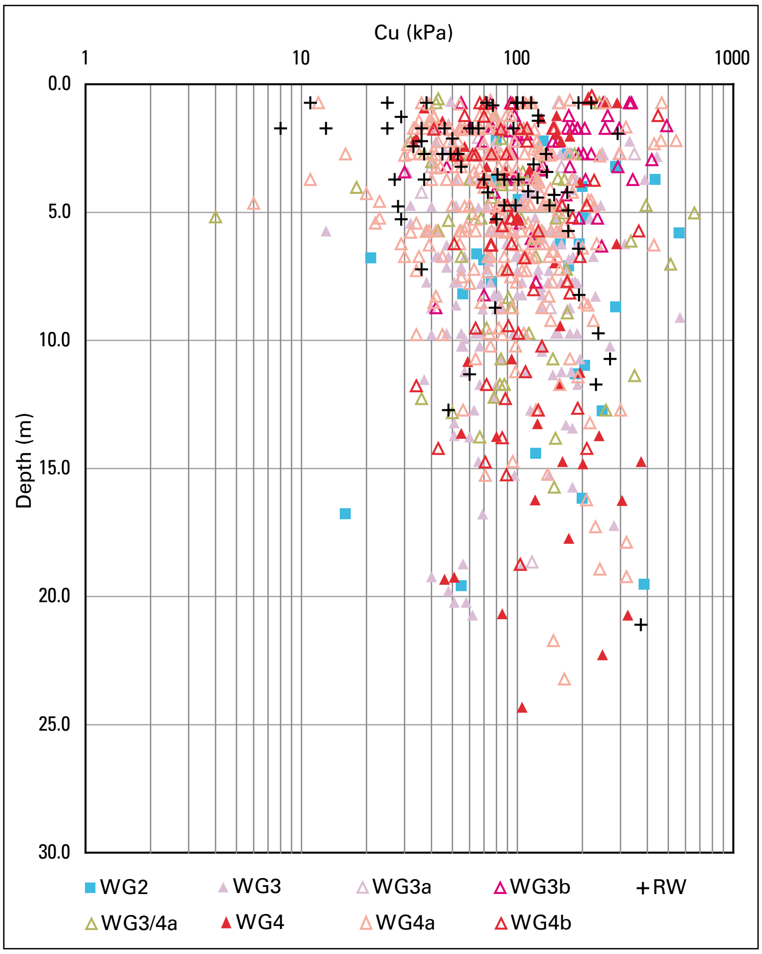


Figure 7.11 Plot of undrained cohesion c_u vs. depth (subdivided by weathering zone, WG).

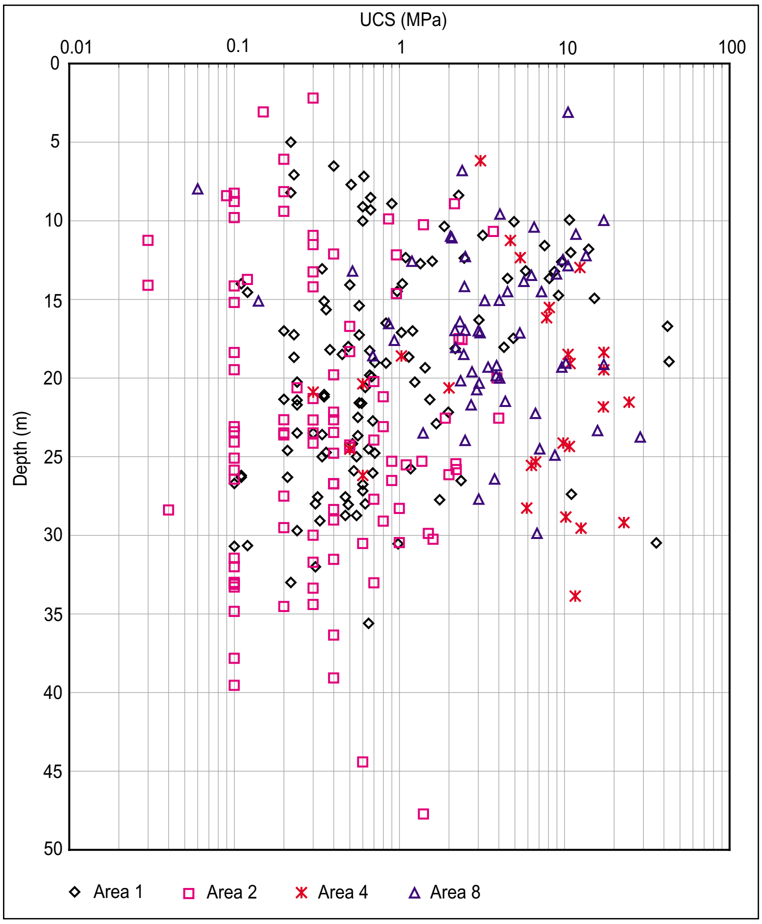


Figure 7.12 Plot of uniaxial compressive strength, UCS vs. depth (subdivided by area).

The assumption made in this test is that the undrained angle of internal friction, $ø_u$, is zero as indicated in effective stress theory (Head, 1998). However, in reality the value of $ø_u$ may be greater than zero, for example where saturation is incomplete, or where the specimen is highly fissured. Therefore, for an *ideal* undrained soils triaxial strength test the undrained cohesion, c_u, is equal to the undrained (total) shear strength, s_u. The overall undrained cohesion, c_u, median values range from 82 (Area 2) to 155 kPa (Area 3). Individual subdivision medians range in Area 1 from 72 (Lower Keuper Marl) to 141 kPa (Middle Keuper Marl), and in Area 8 from 73 (reworked Cropwell Bishop Formation) to 220 kPa (Sneinton Formation Zone 4a). In Area 1 the Middle Keuper Marl has higher strength than the Lower Keuper Marl. This agrees with the trend in SPT (Section 8.5). However, in Area 8 the Edwalton Formation does not stand out as the strongest formation with respect to c_u, albeit based on few data, as it does with SPT. Rather, the Sneinton Formation gives the highest c_u. The c_u strength data do not show the same trends overall as the UCS strength data.

Chandler (1969) described modifications to the stress-strain curve in triaxial tests related to weathering. He showed brittle behaviour for 'Zone 1' material and plastic behaviour for 'Zone 4' material (Cripps and Taylor, 1981); the latter accounting for the reduction in effective shear strength parameters. The weathering zones show little correlation with undrained cohesion, c_u. In some cases there is a decrease in strength, as might be expected, from a low weathering zone to the next higher (e.g. Gunthorpe Formation, Area 8) and in other cases the reverse is seen (e.g. Area 7 and Cropwell Bishop, Area 8). However, in both cases, where Zone 2 is represented, there is a corresponding high strength. Frequently, Zone 4 or 4b produces unexpectedly high strengths. Taking a consistency classification based on median c_u values there is a range from 'stiff' to 'very stiff', with the majority of data falling within 'stiff'. Area 3 (Twyning Mudstone Formation) is notable in having high c_u values. The Gunthorpe Formation (Zones 2 and 3) and Sneinton Formation (Zone 4a) medians from Area 8 are also within the 'very stiff' class. It is likely that lithological variations cause greater scatter of the data values than weathering alone. Mercia Mudstone described as 'reworked' in the database tends to show lower strength, and where present, these data will tend to reduce the overall median for that Area. Mercia Mudstone strength values in the database support the conclusions of Chandler (1969) that there appears to be a marked reduction in cohesion from Zone 1 to 3, then little or no reduction from Zone 3 and a continuous decrease in friction angle from Zones 1 through

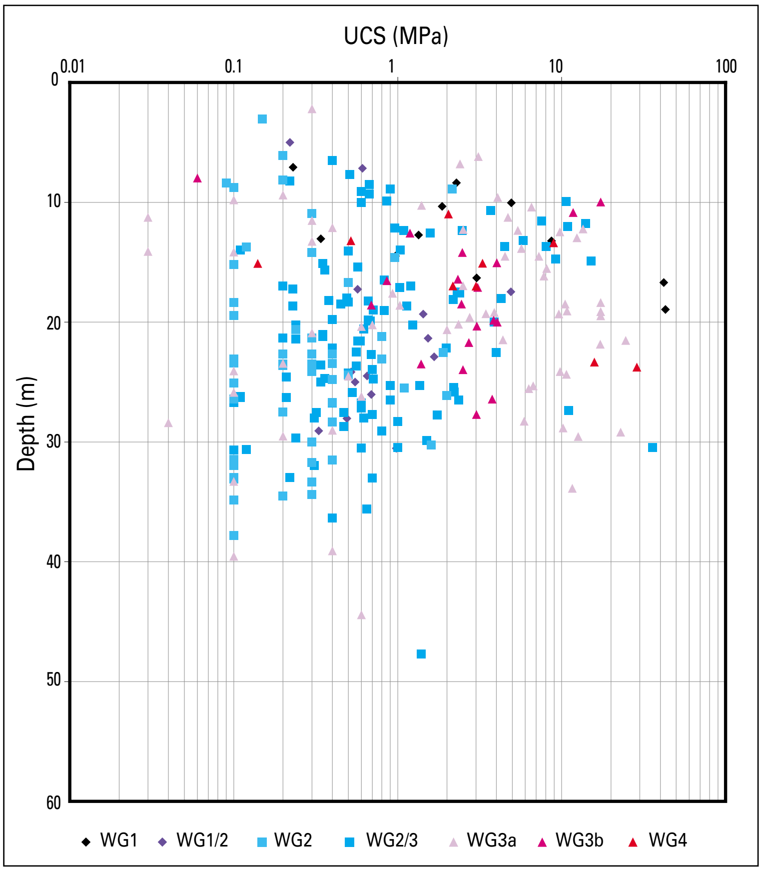


Figure 7.13 Plot of uniaxial compressive strength, UCS vs. depth (subdivided by weathering zone, WG).

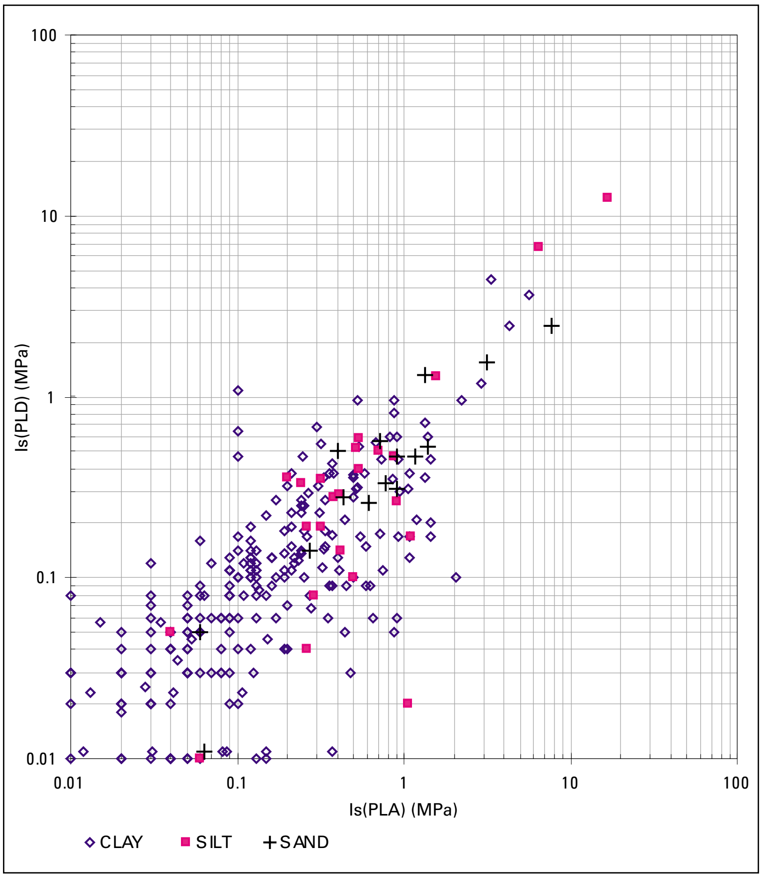


Figure 7.14 Plot of point load (axial) $I_{S\ (PLA)}$ vs. point load (diametral) $I_{S\ (PLD)}$ (all data).

4. For the second Severn river crossing project (Area 4) Maddison et al. (1996) quoted a design c_u value of 1.0 MPa for undrained shear strength.

The profile of c_u with depth is highly scattered (Figures 7.10, 7.11). Strength (c_u) data are available for all areas; Areas 2 and 8 having the larger datasets. However, it should be noted that the depth assigned to samples in the database may be subject to error due to the fact that borings do not necessarily start from original ground level. There is a slight discernible increase in strength with depth between 0 and 25 m, particularly at the depth interval 3 to 5 m. There is also a slightly higher strength near to ground surface, above 2 m. This may be attributable to desiccation. Cripps and Taylor (1981) quoted a rate of increase of undrained shear strength, s_u with depth for the Mercia Mudstone of 37.5 kPa/m but Parry et al. (1996) quoted values of 771 kPa/m using pressuremeter data and 440 kPa/m using the SPT correlation (s_u = 5N) of Stroud (1989) in Area 4 (depth calculated below rockhead rather than below ground level).

Residual shear strength is the minimum strength of a soil reached after continuous shearing along a predetermined shear plane, usually within a remoulded sample, in the laboratory. The results are expressed in terms of the residual angle of internal friction, ϕ_r, obtained from a plot of effective normal stress vs. shear stress. No data for residual strength are contained in the database. However, results given by

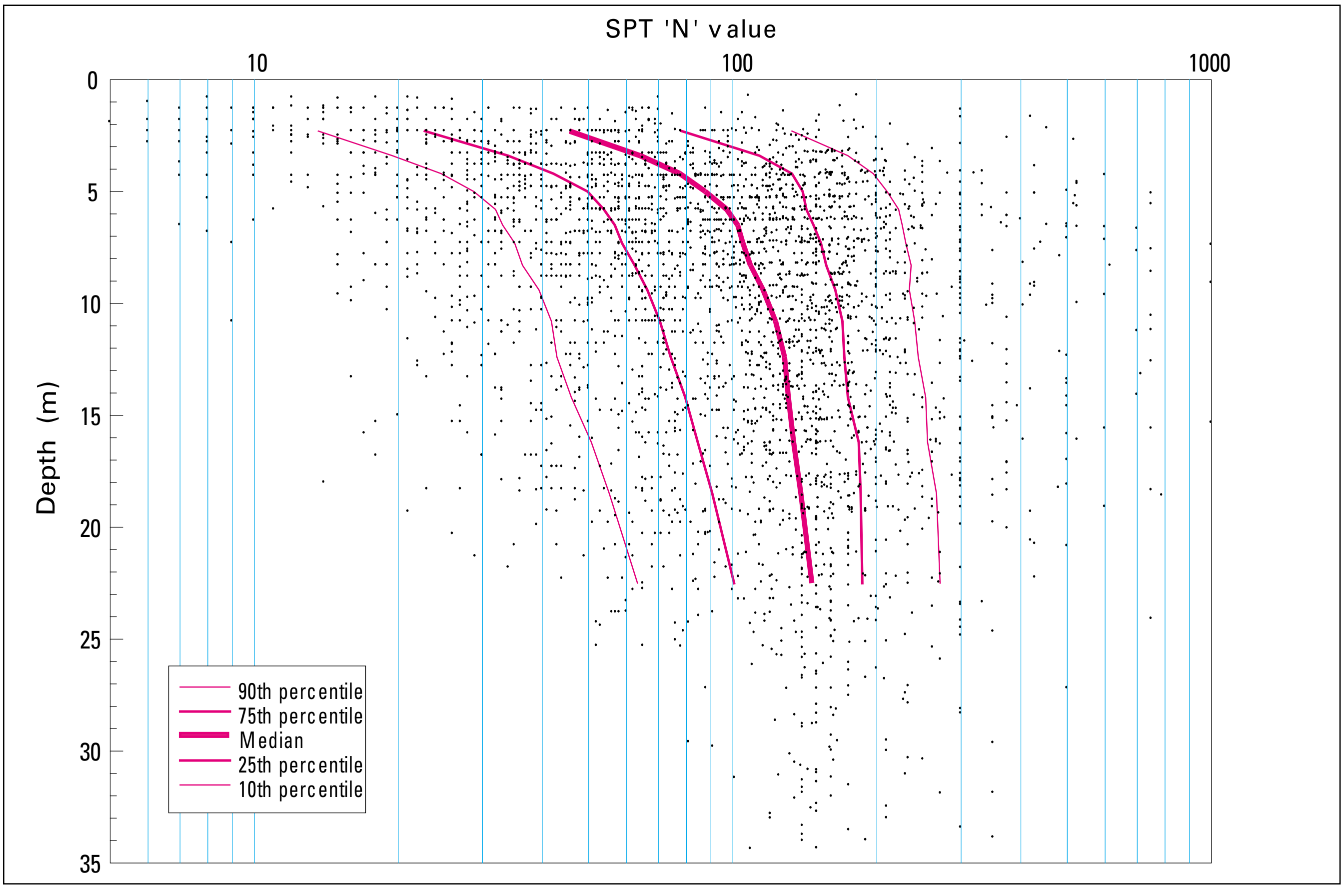


Figure 7.15 Plot of standard penetration test SPT ‘N’ value vs. depth, showing percentiles (all data).

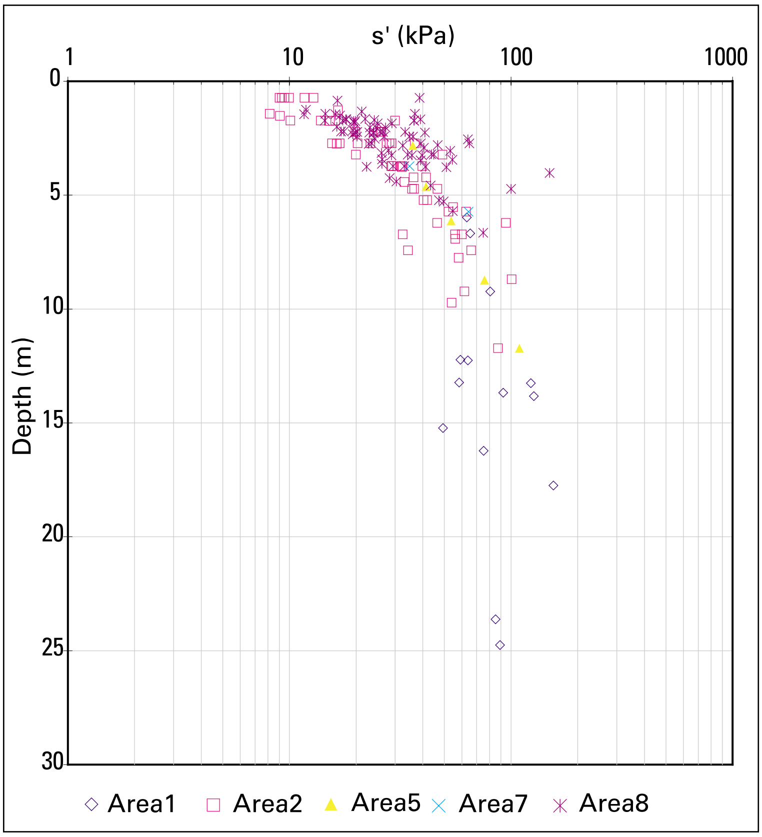


Figure 7.16 Plot of estimated effective shear strength s' vs. depth (subdivided by area).

Entwisle (1996), Jones and Hobbs (1994) and Hobbs et al. (1994) showed similar results for Weathering Zone 1 and 4a soils from Area 8. Values for $ø_r$ range from 22 to 30° and are, to a limited extent, stress dependent. These data also fall within the bounds suggested by Lupini et al. (1981) when plotting $ø_r$ against plasticity index and per cent clay-size. Cripps and Taylor (1981) suggested that mudrocks have characteristically high $ø_r$ values (> 25°) compared with overconsolidated clays (< 25°).

The uniaxial compressive strength (UCS) test determines the peak strength of a machined cylinder of rock under unconfined conditions (i.e. zero lateral stress). The UCS rock test data give overall median values ranging from 0.3 (Area 2) to 8.1 MPa (Area 4); that is, within the 'very weak' to 'moderately weak' classes (Anon, 1970). The minimum and maximum are 0.03 (Area 2) and 141 MPa (Area 8, Gunthorpe Formation, Zone 3); that is, classes 'very weak' to 'very strong'. It is clear that many of the lower values represent material unsuitable for this 'rock' test, and should have been tested with a soils method such as the triaxial test. The stronger values probably represent desiccated clay or claystone. The ranges of values within a particular subdivision or weathering zone are generally very large, frequently spanning two orders of magnitude. Median UCS values for Areas 1 and 2 are notably lower than for Areas 4 and 8. In Area 1 there is a decrease in UCS from Weathering Zone 2 to 3 for the Middle Keuper Marl but an increase for the Lower Keuper Marl. In Area 8 the Cropwell Bishop Formation UCS decreases from Zone 1 to 2. The trends of the UCS data are not the same as those for the undrained cohesion data. This is probably due to the differing suitability criteria (dependent mainly on specimen preparation) of samples for each test, and the different test methodologies. Plots of UCS show considerable scatter even on a log scale and show little correlation with either area (Figure 7.12) or weathering zone (Figure 7.13). Where UCS data are available for siltstones, sandstones and gypsum, these tend to give higher results than the mudstones with values typically between 2 and 20 MPa. Maddison et al. (1994) quoted a median UCS for Mercia Mudstone at the second Severn crossing (Area 4) of 16.6 MPa. These values were presumably obtained from considerable depth.

The *axial* point load index ($I_{s(PLA)}$) overall median values range from 0.10 (Area 2) to 0.33 MPa (Area 8), and the *diametral* point load index ($I_{s(PLD)}$) from 0.07 (Areas 1 and 2) to 0.25 MPa (Area 3). The $I_{s(PLA)}$ results are generally higher than the $I_{s(PLD)}$. This is to be expected if the former are assumed to have been taken perpendicular to the bedding and the latter parallel to it. The plot of $I_{s(PLA)}$ vs. $I_{s(PLD)}$ shows considerable scatter (Figure 7.14) but a broadly linear trend on a log-log scale.

The linear regression for 253 tests on claystone (all areas) is as follows:

$$I_{s(PLD)} = 0.58\ I_{s(PLA)}$$

$$(r^2 = 0.66)$$

The linear regression for 293 tests on all lithologies (all areas) is as follows:

$$I_{s(PLD)} = 0.73\ I_{s(PLA)}$$

$$(r^2 = 0.79)$$

Where r^2 is the regression coefficient

Figure 7.14 suggests that in the higher range of claystone values there is better agreement between axial and diametral. Forster (1983) found that diametral tests on sedimentary rocks were unreliable in terms of uniaxial strength correlations. As with the other strength parameters there is not a good correlation with weathering zone, except in some cases where a decrease in value is seen from Zone 1, or Zones 1 and 2, to higher zones. The point load index, I_s, has been related to UCS by a factor ranging from 15 to 29 (Broch and Franklin, 1972; Bieniawski, 1974, 1975; Forster, 1983; Chau and Wong, 1996). These factors have usually been produced from tests on a wide variety of rock types, the great majority of them strong, nonsedimentary rocks. For sedimentary rocks Read et al. (1980) found a factor of 16. There are no discrete sampling points having both UCS and I_s results within the database. Therefore, a conversion factor cannot be established. However, if medians for each area are compared a ratio of UCS to $I_{s\,(PLD)}$ of between 4.3 and 57.9 is found, with Area 8 giving an overall factor of 15.7 (all lithologies).

The poor correlation of undrained cohesion, c_u, with both weathering and depth is in contrast to SPT data (section 8.5) which show a good correlation with weathering but a poor correlation with depth. The trend is for increasing SPT N value with reduction in weathering and with increase in depth (Figure 7.15). This may in part be due to the relatively small number of data available for c_u. Stroud (1974) suggested a relationship between undrained cohesion, c_u, and SPT 'N' value that showed an increase in

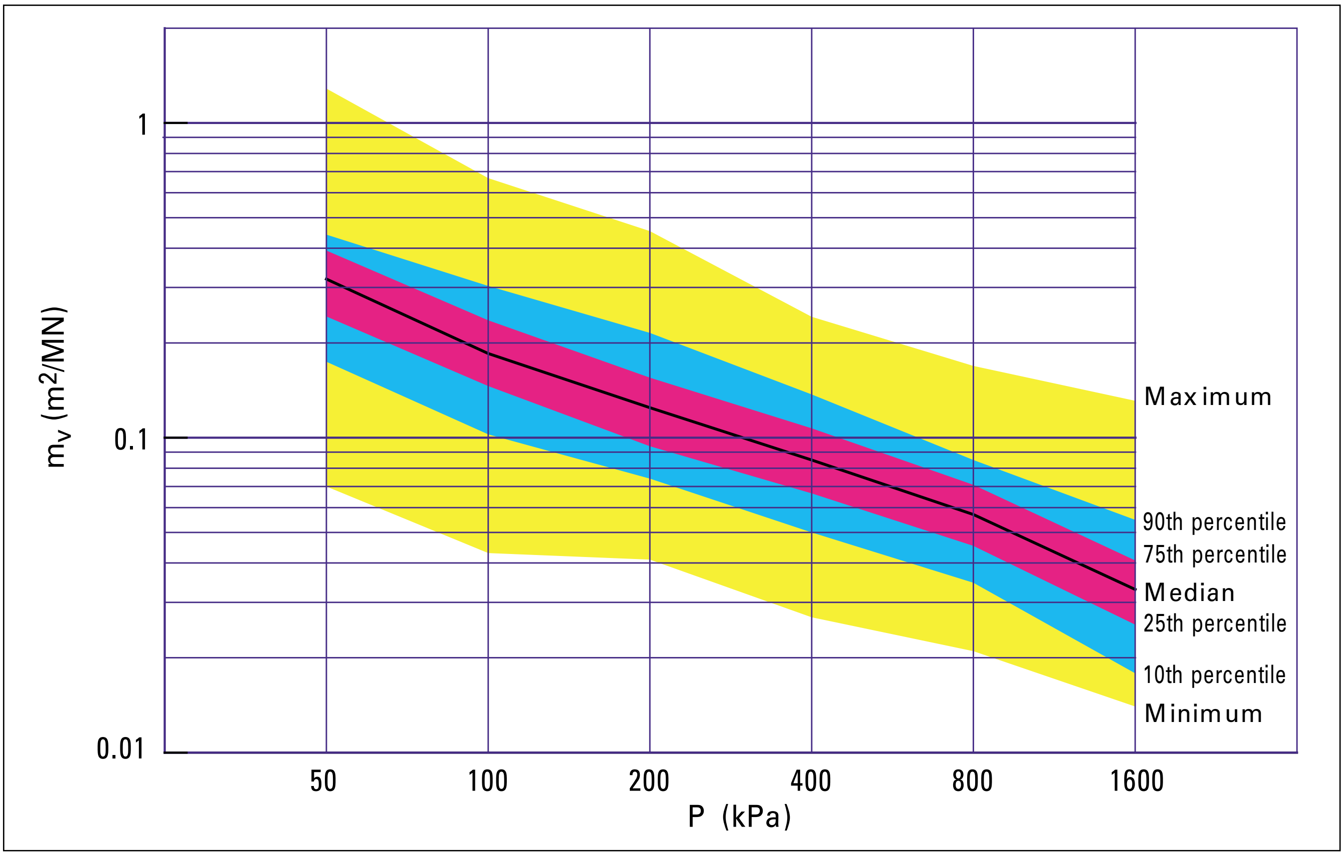


Figure 7.17 Plot of percentiles, m_v vs. (log) P (oedometer consolidation) (all data).

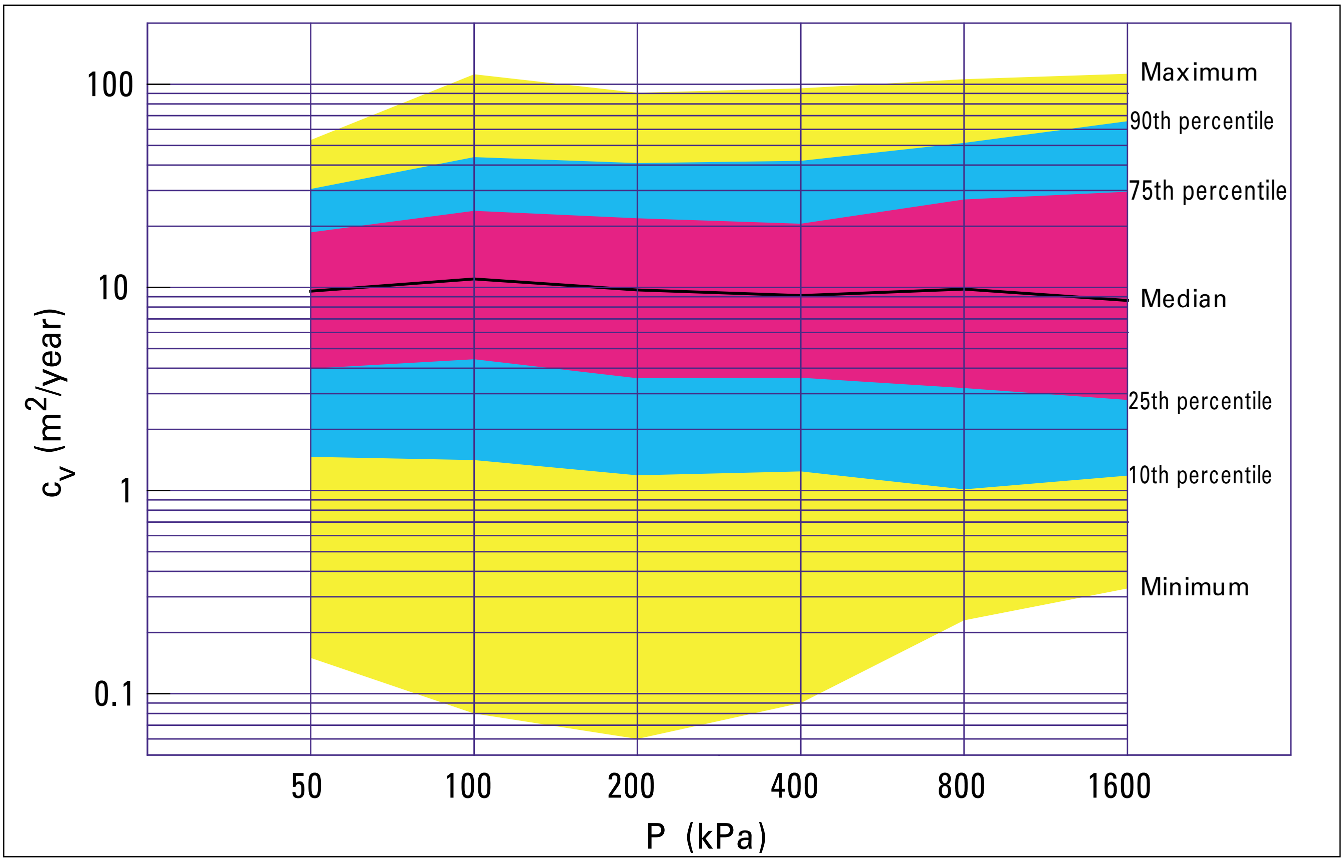


Figure 7.18 Plot of percentiles, c_v vs. (log) P (oedometer consolidation) (all data).

the ratio c_u / N with decreasing plasticity index, I_p particularly where $I_p < 40\%$.

Few effective strength data are in the database. A plot of (log) estimated effective shear strength vs. depth is shown in Figure 7.16. The effective strengths were calculated from the Coulomb equation (see above) using an estimated effective overburden stress. The plot shows a good correlation; strength increasing with depth to about 7 m, below which little increase in strength is discernible. Results of effective stress triaxial tests were quoted by Chandler (1969) and Jones and Hobbs (1994).

7.7 CONSOLIDATION

Consolidation is the process whereby pore water is expelled from a soil as the result of applied, static, external stresses, resulting in structural densification of the soil. For most purposes, the external stress is considered to be unidirectional, and usually vertical. Swelling strain data may also be obtained from the oedometer test. The oedometer is a simple laboratory apparatus that applies a vertical, deadweight load via a lever to a small disc-shaped soil specimen, laterally confined in a ring. The consolidation test is normally carried out by doubling the load at 24 hour intervals, and measuring the resulting consolidation deformation (British Standards Institution, 1990; Head, 1994). The test is normally carried out on undisturbed specimens. The rate at which the consolidation process takes place is characterised by the coefficient of consolidation, c_v, and the amount of consolidation by the coefficient of volume compressibility, m_v. Consolidation data, derived from the oedometer test on undisturbed specimens are used in the calculation of likely foundation settlement, and may also provide information on the stress history, geological history, state of disturbance, permeability, and elastic moduli of clay soils.

Consolidation data in the database are confined to oedometer tests where loading increments are doubled, in accordance with British Standard recommendation (British Standards Institution, 1990). Nevertheless, statistical comparisons remain difficult. There are a total of 350 data points in the database. Statistical treatment of, for example, the coefficients of volume compressibility, m_v, and consolidation, c_v, at specific stresses may be misleading if the overall trend across all increments is not also shown. Part of the reason for this is that test data do not all have a common initial stress increment. A sample of Mercia Mudstone from depth in a borehole will tend to be tested starting at a higher initial increment than a shallower sample. The properties at the lower stress are therefore unknown. The voids ratio vs. (log) applied stress (e-logP) curves tend to be 'flat' with no clear indication of a yield point, or the capability for calculating the compression index, C_c, within the normal range of stress for the typical laboratory apparatus, i.e. 25 to 1800 kPa. It would appear that this normal range is inadequate for undisturbed partially weathered Mercia Mudstone, in terms of defining a compression index, and hence correlating with index properties. The yield point is either not reached or is poorly defined in conventional tests. Yield points could also be obscured by sample disturbance.

The median values for coefficient of consolidation, c_v, do not vary greatly for increments between 25 and 1600 kPa. Overall the range is remarkably narrow: 5.6 to 6.5 m^2/yr. The overall minimum and maximum are 0.1 and 68.2 m^2/yr. These results place the (overall median) Mercia Mudstone in the 'medium' c_v class, representative of medium plasticity soils (Lambe and Whitman, 1979). The equivalent median values for coefficient of volume compressibility, m_v, reduce consistently with increasing stress from 0.32 to 0.03 m^2/MN. The overall minimum and maximum are 0.01 and 1.29 m^2/MN. These results place the Mercia Mudstone in the 'low' to 'medium' compressibility group of soils, comparable with London Clay (Head, 1998).

There is an overall similarity in the shapes of e-logP plots, with those samples having higher initial voids ratio giving steeper curves, i.e. higher m_v values overall. When plotted together the e-logP curves do not merge, at least at the stresses applied, and probably would not do so below stresses of between 5000 and 10 000 kPa. However, Entwisle (1996) identified an indistinct yield stress at about 1000 kPa for a Weathering Zone 4a soil from Area 8, using a special high stress oedometer. Nevertheless, such a yield point would probably not be definable using a normal stress-range oedometer test or a disturbed test specimen.

Figures 7.17 and 7.18 summarise m_v and c_v data but it is important to recognise that *these plots do not represent individual test curves, but are simply a visual representation of the statistics at each stress increment.* The (log) m_v vs. (log) P plot clearly indicates the overall decrease in m_v with increasing applied stress in terms of percentiles. Note: the decrease rate lessens with increasing stress on an arithmetic scale. The (log) c_v vs. (log) P plot is widely scattered over three orders of magnitude, and the expected trend of decreasing c_v with applied stress is not seen. Overall the c_v median remains constant with stress. This trend may also continue to higher stresses (Entwisle, 1996). The tendency is for samples with low overall c_v values (<10 m^2/yr) to have a moderate decrease in value with stress, whereas samples with higher values unexpectedly show an increase in value with increasing applied stress. If data are plotted for individual areas they tend to show almost as much scatter as for the whole data set. Insufficient data are available with which to gauge the influence of weathering zone.

The state of consolidation (i.e. normally, over, or underconsolidated) of a soil in its current natural condition, and hence its maximum previous overburden stress, can be estimated from oedometer consolidation tests, where a yield point can be identified. Chandler and Davis (1973) described the state of weathered Mercia Mudstone as 'normally consolidated' or 'lightly overconsolidated', and that of unweathered Mercia Mudstone as 'heavily overconsolidated'. The Mercia Mudstone, in general terms, has been described as having low compressibility and a high rate of consolidation, but variability is high (Birch, 1966). The consolidation settlement of unweathered Mercia Mudstone, under normal engineering loads, has been described as 'negligible' (Birch, 1966). Chandler et al. (1968) described the Mercia Mudstone tested as isotropic in terms of consolidation properties.

Clays are often classified or discussed in terms of their degree of consolidation in their natural state, i.e. the natural, geological stress history. The overconsolidation of a clay is an important engineering descriptor, particularly where the degree of overconsolidation is high. Overconsolidation affects undrained shear strength, lateral stress, pore water response, and allowable bearing pressure and settlement (Borowczyk and Szymanski, 1995). An overconsolidated clay is one in which the maximum previous overburden exceeds the present overburden, resulting in a denser, stronger, and less deformable soil. It is possible to estimate the degree of overconsolidation from oedometer test data. The overconsolidation ratio (OCR) is commonly defined as follows:

$$OCR = \frac{P'_c}{P'_o}$$

where: P'_c = preconsolidation (maximum previous) effective stress
P'_o = present effective overburden stress

Indications are that the Mercia Mudstone behaves as a ‘lightly’ to ‘moderately’ overconsolidated clay; the apparent degree of overconsolidation decreasing with increased weathering (Chandler et al., 1968). The determination of the degree of overconsolidation of the Mercia Mudstone is hampered to some extent by the lithological variability of the formation and, as described above, the insufficient level of applied stress for most test data in the database. On a larger scale, considering the soil mass in the field, the presence of siltstone and sandstone bands affects the drainage paths for consolidation, and affects the transfer of overburden stress to underlying strata. Such factors are probably not modelled by the smaller scale laboratory test. Geological assessment of the overconsolidation ratio of the Mercia Mudstone is difficult, and was not included in the review of the engineering properties of mudrocks by Cripps and Taylor (1981). The distinction between a mud rock and a heavily overconsolidated clay soil is unclear (Taylor and Spears, 1981). Inherent in the estimation of overconsolidation is the assumption that the soil is responding to stress in a linear, unchanging manner. It may be that the laboratory estimation of overconsolidation becomes impossible once the soil becomes a rock. In addition, the processes of weathering tends to obliterate the evidence of overconsolidation.

7.8 DEFORMABILITY

Deformability (the terms compressibility and stiffness may also be used) is a measure of the strain undergone by a soil or rock subjected to a particular stress amount and direction. This strain may be unidirectional or volumetric. Deformability may be measured in both laboratory (intact) and field (rock or soil mass). Field deformability testing methods and results are discussed in Section 8. Usually, test data are interpreted from stress-strain plots, with several parametric variants of deformability available. The elastic properties of a material are defined by the fundamental properties: bulk modulus, K, and shear modulus, G. Bulk modulus represents the change in all-round stress per unit change in volume, whereas shear modulus represents the change in shear stress per unit change in shear strain. The simplest form of deformability measurement is that of Young’s modulus, E, which is derived from a uniaxial compression test and is defined as follows:

$$E = \frac{\sigma_1}{\varepsilon_1}$$

where: σ_1 = major principal stress
ε_1 = strain in direction of major principal stress

The relationship between strain in the direction of stress and strain at right angles to it is defined by the Poisson’s ratio, ν, as follows:

$$\nu = \frac{\varepsilon_{2,\,3}}{\varepsilon_1} = \frac{E\varepsilon_{2,3}}{\sigma_1}$$

where: σ_1 = major principal stress
ε_1 = strain in direction of major principal stress
$\varepsilon_{2,3}$ = strain at right angles to major principal stress
E = Young’s modulus

Deformability data are usually confined to unweathered or partially weathered Mercia Mudstone, and may be obtained from either laboratory or field tests. *However, preparation of undisturbed test specimens for the laboratory is difficult in the case of unweathered Mercia Mudstone.* No deformation data are included in the database. Meigh (1976), in a comprehensive work on the deformability of Mercia Mudstone in the Midlands and Wales, described the derivation of drained (constrained) modulus from the coefficient of compression, m_v, using the following relationship:

$$m_v = \frac{0.9}{E'} \quad \text{for Poisson's ratio, } \nu' = 0.2$$

where: E’ = drained Young’s modulus of elasticity
ν’ = drained Poisson’s ratio

Normal oedometer tests are not suitable for unweathered Mercia Mudstone, but become increasingly practical with increased weathering (Hobbs, 1975). This fact further highlights the borderline nature of Mercia Mudstone between a soil and a rock. Meigh (1976) and Marsland (1977) gave

Table 7.4 Deformation moduli of Mercia Mudstone from the second Severn crossing (Maddison et al., 1996).

E'_{vi} (stress 0–3MPa)	E'_v (stress >3MPa	E'_{vi} / E'_v	E'_{hi}	E'_h	E'_{vi}/ E'_{hi}	G_i	G_{ur}
96	328	0.29	70	34	1.4	25	125

Where, E'_{vi} = initial drained vertical Young's modulus
E'_v = drained vertical Young's modulus
E'_{hi} = initial drained horizontal Young's modulus
E'_h = drained horizontal Young's modulus
G_i = initial shear modulus
G_{ur} = unload/reload modulus

Table 7.5 Typical permeabilities of main soil types.

Soil type	Permeability (m/s)
Gravels	$1 - 10^{-2}$
Clean sands	$10^{-2} - 10^{-5}$
Very fine or silty sands	$10^{-5} - 10^{-8}$
Silt, loess	$10^{-5} - 10^{-9}$
Fissured & weathered clays	$10^{-4} - 10^{-8}$
Intact clays	$10^{-8} - 10^{-13}$
Glacial till	$10^{-6} - 10^{-12}$

some deformation modulus profiles with depth, derived from in situ test pile and plate loading tests, laboratory data, and back analyses from foundation settlements. These profiles (from Areas 1 and 10) show considerable variability, both within each profile and between test methods. Shear moduli tend to increase significantly moving from Weathering Zone 2 to 1, though data for the latter are limited. Marsland (1977) stated: 'Most weathering zones are capable of supporting higher loads than are commonly used at present'. Oedometer derivations and plate-loading data tend to give much lower values than pressuremeter data within weathered Mercia Mudstone (see section 8.3). Shear modulus, G, is defined as:

$$G = \frac{E}{2(1 + \nu)}$$

where: E = Young's modulus
ν = Poisson's ratio

Also: $E' = 2G(1 + \nu')$

where: G = shear modulus
E' = drained Young's modulus
ν' = drained Poisson's ratio

Shear modulus may be measured in a variety of ways from the stress vs. strain plots. The most commonly quoted are the initial shear modulus, G_i, and the unload/reload modulus, G_{ur}. Marsland et al. (1983) gave values of shear modulus, G, of between 10 and 100 MPa for Weathering Zone 4 to 2 Mercia Mudstone in Lymm, Cheshire (Area 1) to a depth of 9 m for both pressuremeter tests and back analysis of plate loading tests. They gave a rate of increase for G with depth of 5 MPa per metre. It was also noted that most settlement occurred during construction.

Maddison et al. (1996) described the results of deformation tests carried out for the Second Severn Crossing project. These were derived from plate-bearing tests in boreholes and trial pits onshore, pressuremeter tests offshore and onshore, and from laboratory tests on core samples. Values for Young's moduli and shear moduli in units of MPa for Mercia Mudstone are shown in Table 7.4.

Unload/reload loops were carried out over cavity strains of 0.05 to 0.2 and good agreement was obtained between different methods for obtaining Young's modulus. Dynamic deformation moduli obtained for Mercia Mudstone from geophysical data were found to be between one and two orders of magnitude greater than those from the static determinations described above (Maddison et al., 1996).

Meigh (1976) stated that it is the initial shear modulus that is most likely to represent rock mass behaviour. The use of load / unload moduli, whilst erring on the conservative side, may result in over-costly engineering solutions in some cases. This was confirmed by Smoltczyk et al. (1995).

In the case of lightly overconsolidated clays a relationship was suggested (Skempton and Bjerrum, 1957) between the coefficient of volume compressibility, m_v derived from oedometer consolidation test, (section 7.7) and the N value from the standard penetration test (SPT), as follows:

$$m_v = f_2.N$$

Clayton (1995) stated that heavily overconsolidated clays tend to exhibit deformability anisotropy. Bedding and soil structure can have a strong influence on deformability. Data from Nuremberg, Germany gave elastic moduli for similar Triassic mudstone material of between 23 and 57 MPa from back analysis of foundation settlements (Smoltczyk et al., 1995). Good agreement was obtained between constrained modulus, E' and Young's modulus of elasticity, E. Laboratory tests provided Young's moduli of between 9 and 139 MPa, with a mean of 42 MPa.

The importance of avoiding sample disturbance was emphasised by Meigh (1976); in particular, the overestimation of rock mass fracture density as a consequence of drill-core fracturing, and laboratory test disturbance due to drilling method, desiccation, and stress relief. The weaker Mercia Mudstone materials tend to suffer the greatest disturbance, but probably have the greatest influence on mass deformability beneath a structure. Meigh (1976) suggested that the leaching of gypsum was an important factor in the reduction of expected deformability moduli.

Chandler (1969) described the effect of weathering on the modulus of elasticity. Generally the modulus reduces with weathering. However, the relationship is probably not linear. Davies (1972) described a threshold pressure (or yield point) beyond which deformation increases rapidly. This point reduces with increasing weathering (Cripps and Taylor, 1981).

7.9 PERMEABILITY

Permeability, or hydraulic conductivity, in the geotechnical context, is a measure of the ability of soil or rock to allow the passage of a liquid subject to a pressure gradient. The permeability measured on intact specimens in the laboratory (k_{LAB}) is usually distinct from that measured in the field, as a result of the huge scale difference, and hence the involvement in the field tests of discontinuities and lithological variations. No permeability data are held in the database.

Bacciarelli (1993) described Zone 4a and 4b as having lower permeability than underlying (less weathered) layers. Tellam and Lloyd (1981) gave laboratory values for the (intact) permeability of Mercia Mudstone between 10^{-4} and 10^{-6} m/day ($10^{-9} - 10^{-11}$ m/s), perpendicular to bedding, and field values of between 10^{-1} and 10^{-3} m/day ($10^{-6} - 10^{-8}$ m/s), mainly parallel to bedding. These figures illustrate the large increase in permeability from the essentially *intact* laboratory test specimen to the *fissured* rock mass in the field. The permeability of Proctor compacted Mercia Mudstone was reported in Chandler et al. (1968) as between 10^{-8} and 10^{-10} m/s depending on placement moisture content. These values may be compared to the general ranges of permeabilities for different soil types shown in Table 7.5.

Marsland et al. (1983) and Chandler and Davis (1973) noted that a large proportion of excess pore pressure dissipation and ultimate consolidation settlement took place during construction. They attributed this to the high mass-permeability of the Mercia Mudstone. This was mainly due to the intensity of open discontinuities in the rock mass, particularly for Weathering Zones 1 and 2 exposed in excavation.

Permeability, k_{OED}, may be measured indirectly from oedometer consolidation tests (Section 7.7) using the following relationship:

$$k_{OED} = 0.31.m_v.c_v.\gamma_w.10^{-9} \text{ m/s}$$

where: m_v = coefficient of volume compressibility (m^2/MN)
c_v = coefficient of consolidation (m^2/year)
γ_w = density of water

Entwisle (1996) gave indirect (oedometer) values of between 3 x 10^{-11} and 1.1 x 10^{-10} m/s for Zone 3 or 4b material from Gringley-on-the-Hill, Nottinghamshire (Area 8). Sandstones (skerries) within the Mercia Mudstone Group have higher mass permeabilities than the mudstones and may act as pathways for water flow and generate spring lines on slopes.

7.10 COMPACTION

Compaction is the process whereby soil is densified, usually after reworking and usually in layers, in order to produce an engineering fill of known properties. This is achieved by applying dynamic forces, using special plant, such as rollers, vibratory rollers, rammers, or by special ground improvement processes. The densification is achieved by the solid soil particles packing closer together and producing a strong soil mass. The moisture content of the placed fill and the amount of energy input are critical to the density that can be produced. The process is not the same as consolidation (section 7.7). Mercia Mudstone is frequently utilised as compacted fill.

Compaction properties may be measured in the field and in the laboratory. Field methods are often indirect measures of density, for example using a nuclear probe or a dynamic penetrometer. Laboratory methods are standardised and usually employ the Proctor test where layers of a disturbed soil sample are compacted into a mould and sub-samples taken for moisture content determination (British Standards Institution, 1990). The results are shown in the form of a dry density vs. moisture content plot, from which the maximum dry density (MDD) and corresponding optimum moisture content (OMC) are calculated. The California bearing ratio test (CBR) measures the penetration of a plunger into a compacted sample, compared with the penetration into a ‘standard’ material. It is a combined compaction / bearing capacity test designed for flexible road pavements.

A small dataset of compaction and moisture condition values is included in the appendix. This includes both ‘light’ and ‘heavy’ test data. Area 2 contains the largest data set in which the median OMC and MDD values are 19.0% and 1.71 Mg/m^3, respectively. The median CBR value for Area 8 is 6.5%. There are insufficient data for subdivision by weathering zone. Chandler et al. (1968) showed that for ‘typical’ Mercia Mudstone, using a low compactive effort, a high placement moisture content (16%) gave the highest density, whereas for a high compactive effort a low moisture content (8%) gave the highest density. Thus little was to be gained by subjecting wet marls to heavy compaction, and that placement moisture content significantly affects the long term stability of compacted marl. OMC values of between 12 and 14% were indicated with MDD values of between 1.8 and 2.2 Mg/m^3. In one example (low plasticity sample) the CBR dropped from 140 to 17% for a placement moisture content increase from 8 to 15%. Minimum (saturated triaxial) permeability was reported at compacted moisture contents near the plastic limit. This was 3% above the optimum moisture content. Birch (1966) stated that, when compacted in a state drier than optimum, the Mercia Mudstone suffered large expansions due to residual negative pore pressures, whereas at optimum there should not be undue expansion. Current engineering practice suggests that for the Proctor test fresh sub-samples should be used at each stage of the test.

The moisture condition value (MCV) is a test capable of being used in laboratory or field, and is becoming an increasingly popular means of selection, classification, and specification of fill material (British Standards Institution, 1990; Department of Transport, 1991; Caprez and Honold, 1995). The test aims to determine the minimum compactive effort required to produce near-full compaction of a <20mm sample. The test differs from the traditional Proctor test in that the compaction energy is applied across the entire sample surface, and compaction energy can be assessed as an independent variable.

Median MCV values for Areas 6 and 7 are 10.1 and 14.4 respectively. Data from the MCV data correlate well with undrained cohesion, California bearing ratio (CBR), and moisture content. MCV values less than seven tend to result in very poor trafficability. The Mercia Mudstone is usually capable of fulfilling the requirements of a Grade 2A or 2B ‘general cohesive fill’ material (Department of Transport, 1991). Long term degradation may be a problem if poorly compacted, and strength loss a problem if over-compacted. A CBR test should be carried out at equilibrium (Proctor) moisture content. The moisture content is critical to the CBR result.

Inadequate compaction tends to result in long term degradation and settlement of the Mercia Mudstone when used as fill. This is probably due to bulking of discontinuity-bound blocks and subsequent breakdown at block contact points under engineering stresses.

7.11 SWELLING AND SHRINKAGE

Swelling and shrinkage are two mechanical properties of a soil which, though driven by related physico-chemical mechanisms, are usually treated separately in the laboratory. Swelling sensu stricto is mainly a function of the clay minerals present in the soil or rock. The engineering phenomenon of *heave* may be caused by factors other than swelling of clay; for example, by stress relief. Assessment of swelling and shrinkage usually does not involve direct measurement, but rather indirect estimation of volume change potential from index tests on reworked samples.

The geological processes affecting swelling and shrinkage were described by Gostelow (1995). A wide variety of available methods for measuring swelling and shrinkage were described by Hobbs and Jones (1995). Laboratory tests may be carried out on *undisturbed* or *disturbed* samples. Undisturbed samples are as near to their in situ condition as possible, whereas disturbed samples may be reworked, reconstituted, or compacted depending on the engineering application.

The tests usually either measure the *strain* resulting from swelling resulting from access of a sample to water, or the *pressure (or stress)* produced when the sample is restrained from swelling. Swelling strain samples may be disc-shaped oedometer types for 1-D testing of soils and slaking rocks, or cubes for 3-D testing of non-slaking rocks. The 1-D samples are laterally restrained. Swelling pressure samples are usually oedometer discs and may be mounted in a normal oedometer or a special swelling pressure apparatus. There are two shrinkage tests specified by British Standard 1377 (British Standards Institution, 1990). These are the shrinkage limit test, carried out on undisturbed or disturbed samples, and the linear shrinkage test, carried out on reworked soil paste (prepared as for Atterberg limits). *It should be noted that the shrinkage limit is a specific moisture content below which little or no volumetric shrinkage occurs, whereas the linear shrinkage is a percentage reduction in length (strain) on oven drying.*

No swelling or shrinkage data are held in the database. The Mercia Mudstone is generally considered to be of low swell/shrink potential, due to the low content of swell/shrink susceptible clay minerals and the presence of intergranular cements. Tests were carried out at the BGS on samples from for Weathering Zone 3 and 4b Gunthorpe Formation from Gringley-on-the-Hill (Area 8). Jones (1998) quoted values for shrinkage limit (SL, or w_s) of between 10 and 12%, and for linear shrinkage at Gringley-on-the-Hill and Zone 1 Cropwell Bishop Formation at Cropwell Bishop (Area 8) of between 8 and 15%. Kadir (1997) quoted values for shrinkage limit and linear shrinkage, LS, of 12.6% and 8.6%, respectively for Gringley-on-the-Hill. Taylor and Smith (1986) indicated that illite-rich clays, such as the Mercia Mudstone, have a volume change response intermediate between the purely physico-chemical and the purely mechanical (stress-relief). They further indicated that indurated mudrocks with small expandable clay mineral contents, such as the Mercia Mudstone, required the application of suctions of over 10 kPa before air entry, and hence shrinkage, began.

Jones and Hobbs (1998a) examined the shrink swell behaviour of each formation of the Mercia Mudstone in Area 8 using samples from seven quarries in Nottinghamshire and Derbyshire. Swelling pressures and strains were found to be low overall. The swelling data were of reasonably good quality, with well-defined swelling pressure and swelling strain curves, developing identifiable peaks for the most part. The 3-D (unconfined) swelling strain test showed clearly anisotropic behaviour in relation to bedding. A good positive correlation was obtained between swelling pressure and volumetric swelling strain. The shapes of the 1-D swelling strain curves proved to be characteristic of the formations. However, the 1-D swelling strain test results (peak strain) did not correlate with other parameters. Commonly applied relationships between swelling and plasticity index were not successful, probably due to the small variation in plasticity index throughout.

The Edwalton Formation sample from Hemington Quarry [SK 4620 3050] had the greatest rate of swelling and the greatest 3-D swell strain anisotropy, but the lowest amount of swell strain and the lowest swell pressure. It also had the highest clay surface area (130 m^2/g) but the lowest free-swell, the lowest density, and the highest compression index, (C_c, oedometer test). The Gunthorpe Formation samples were prone to slaking. The Sneinton Formation sample from Heather Quarry [SK 3910 0970] showed high swelling behaviour throughout despite comparatively low clay content and plasticity, and a lack of corrensite (a regular chlorite-smectite mixed-layer clay). There appeared to be a general negative correlation between natural moisture content and swelling.

Shrinkage data were limited to the Edwalton, Gunthorpe, and Radcliffe formations. The Edwalton Formation sample had the highest shrinkage limit (18.2%) and the lowest volumetric shrinkage strain. It also had the highest linear shrinkage (10%). The Radcliffe Formation had the lowest shrinkage limit (10.2%). Shrinkage limit tests were particularly difficult to perform because of the tendency of the samples to disintegrate during air drying, and the adhesion of mercury to the silty partings and fissures. A procedure to estimate shrinkage limit from the position relative to the A-line on the Casagrande plasticity plot appeared to compare well with the test results. A high value of shrinkage limit is associated with low shrinkage and swelling strains, and hence low volume-change potential. This applied to the Edwalton Formation sample. The converse did not appear to apply to the Radcliffe Formation sample. A good positive correlation was obtained between shrinkage limit and linear shrinkage.

The Casagrande plasticity plot showed that the samples tested were closely grouped, and fell within the 'low' to 'intermediate' plasticity categories. The Skempton/Williams and Donaldson (1980) plot showed that all the samples tested fell within the 'medium' expansive potential class, despite an apparently wide range of Activities (0.32 to 0.93). This type of plot was discussed, with respect to other UK soil formations, by Taylor and Smith (1986).

Swelling test data showed a common pattern across the swelling tests on the samples, with the exception of the 1-D swelling strain test. Particularly good correspondence was obtained between free swell and swelling pressure. Comparison of the shrinkage test data showed similar patterns for shrinkage limit and linear shrinkage, but not for volumetric shrinkage strain (from the shrinkage limit test). The latter may be explained, in part, by the variations in initial moisture content. The correspondence between shrinkage limit and linear shrinkage was unexpected, because Yong and Warkentin (1975) considered there to be an inverse relationship between these parameters.

Various 'volume change potential' classification schemes were applied to the results from the Mercia Mudstone samples. These placed the Mercia Mudstones in the 'low' volume change potential category, with only minor exceptions. The swelling potential classification scheme for mudrocks proposed by Sarman et al. (1994), placed the Mercia Mudstones tested in the low end of the 'very low' category. The classification schemes of Vijayvergiya and Sullivan (1974) Snethen et al. (1977), and the Building Research Establishment (1993) produced 'low' categories for the Mercia Mudstone.

It was observed during sample collection that water contents and densities varied considerably within an outcrop or pit section, and even within a block sample in the laboratory. This may have caused different swell/shrink behaviour from one sub-sample to another.

Table 7.6 shows a scheme adopted by the Building Research Establishment (BRE, 1993) for assessing susceptibility to volume change (i.e. swelling or shrinkage) of overconsolidated clays in terms of a modified plasticity index, I_p', expressed as:

$$I_p' = I_p \frac{\% <0.425 \text{ mm}}{100\%}$$

The purpose of the modified plasticity index is to take account of the proportion of fines in relation to the total sample and to reduce the measured plasticity index in proportion. Much Atterberg data in the database did not include <0.425 mm results. This may be because the sample did not require sieving, or that a small number of coarse particles were removed by hand, without sieving. Examination of the limited data containing both reported %<0.425 mm from the Atterberg test preparation stage and equivalent particle size data, showed very wide discrepancies; the particle size data tending to give similar or lower values (i.e. coarser grain size).

Entwisle (1996) reported that measured laboratory 1-D swelling strains and swelling pressures on undisturbed soil specimens were greater than predicted from plasticity and density. Values for plasticity index ranged from 2 to 49%, with the exception of reworked samples, some of which were higher. Less than 2.5% of all samples tested gave a I_P >40 % and hence may be categorised as having a 'high' volume change potential using the Building Research Establishment (1993) classification. Overall, plasticity index medians for the ten areas ranged from 11 to 24%, thus placing the Mercia Mudstone in the 'low' to 'medium' categories.

Table 7.6 Classification of volume change potential (BRE, 1993).

Modified plasticity index I_p'	Volume change potential
>60	very high
40 – 60	high
20 – 40	medium
<20	low

The Building Research Establishment (1993) classification did not indicate the actual volumetric shrinkage to be expected for each of the volume change potential categories. Net volume changes depend on the initial saturation condition of the test sample. In the case of the shrinkage limit test this is usually natural moisture content, whereas in the case of the linear shrinkage test it is close to the liquid limit. Volume change for the former was reported as 6.7% and a linear strain for the latter as 8.6% (Kadir, 1997), for samples from Nottinghamshire (Area 8). These compare with values of 13 to 27% for shrinkage limit and 17 to 20% for linear shrinkage, for the Gault clay (Jones and Hobbs, 1998b).

Chandler et al. (1968) reported 1-D swelling strain data for Proctor compacted Mercia Mudstone as between 0 and 6% depending on placement moisture content. Such data are difficult to use for classification because of the dependence of the results on test conditions (e.g. surcharge load applied) and pre-test moisture content. It would be preferable to use a common swell test procedure irrespective of sample condition. Chandler et al. (1968) showed an overall trend of increasing Proctor swell strain with increasing liquid limit, and also reported the difficulties experienced in achieving air-voids targets in compacting unweathered Mercia Mudstone of low moisture content. Heavy compaction is almost certainly required.

A useful classification of swelling potential for mudrocks was given by Shakoor and Sarman (1992). This was based on a log-log plot of swelling (volumetric) strain vs. swelling pressure. Unfortunately insufficient swelling data are available to make use of it. The clay fraction of the Mercia Mudstone is dominated by illite, corrensite (a mixed layer clay), and chlorite. A detailed description is found in Jeans (1978) and Section 4. Illite was considered to be a 'non-swelling' clay mineral by Shaw (1981). Corrensite is probably a 'moderately swelling' clay mineral. Shaw (1981) gave an 'expandable clay mineral' content for the Mercia Mudstone of about 18 per cent.

8 In situ testing

8.1 INTRODUCTION

Considerable difficulties are experienced in the determination of the mass strength and mass stiffness of weak rocks such as Mercia Mudstone (Thompson et al., 1993). This is due to the fissured nature of the unweathered rock and problems encountered when sampling and during testing in the laboratory.

Over the past three decades, in situ geotechnical testing equipment has been developed in the UK. In the last decade, in addition to refinements to the long-established standard penetration test (SPT) and plate-bearing test (PBT), new techniques have been developed in the form of the pressuremeters and the static and dynamic penetrometers. Recently, work on a combined pressuremeter/penetrometer has been carried out (Zuidberg and Post, 1995). The more sophisticated of these methods do not, as yet, have standards defining the procedure for their use. The self-boring pressuremeter (SBPM) is a relatively recent development.

Traditional and new in situ tests have particular importance for the Mercia Mudstone, which as a fissured soft-rock/hard-soil material may be difficult to characterise using traditional undisturbed sampling and laboratory testing methods, particularly in the unweathered state. As a result, considerable use has been made of penetrometers and, to a lesser extent, pressuremeters in characterising the Mercia Mudstone. The principal advantage of these methods is their ability to test for the mass properties of strata when compared with traditional laboratory testing methods. The principal disadvantage of the methods is that, in most cases, a sample for visual inspection, and hence geological identification, is not obtained. Consequently, as with geophysical methods, some form of ‘control’ is required. This may take the form of operator experience, a cored borehole for lithological description or the use of test sites typifying, for example, over-consolidated clays or soft clays.

8.2 STATIC AND DYNAMIC PENETRATION TESTS

Static and dynamic probing or penetration tests are made using a wide range of techniques. The history of the cone penetration test (CPT) was described by Marsland and Powell (1988). Recent developments of the cone penetration test include the piezocone (Powell et al., 1988) and seismic, thermal, and environmental cones of various types. The cone penetrometer may also be referred to as the Dutch cone or the electric cone. A workshop on the subject in May 1995 at Loughborough University, (Price et al., 1996) made use of a previously drilled test site on Mercia Mudstone overlain by alluvium. The main advantage of these techniques is that they are either continuous or semi-continuous, unlike traditional laboratory techniques which deal only with discrete, intact specimens which have to be selected from core or other samples. Hence, a large number of data points may be obtained, usually recorded by an on-site computerised data logger, enabling a ‘profile’ of geotechnical properties to be obtained. This has the capability of identifying subtle changes in lithology, characterising the formation, and enabling further investigations on the site to be planned. The main disadvantage of current static and dynamic penetration methods is their inability to penetrate thick sequences of soft-rock/strong-soil such as the Mercia Mudstone. This is because resistance to penetration builds with depth whereas the applied force is finite, provided in the case of static tests by reaction against ground anchors or by dead weight, and in the case of dynamic tests by a falling weight.

Whilst the prime role of penetration testing is to determine strength and deformability, recent developments have enabled a variety of parameters to be measured directly or to be derived. These include geophysical and geochemical parameters. The results of static and dynamic penetration tests tend to be displayed as continuous traces rather than as discrete numbers. As such they may be difficult to deal with statistically, and are not easy to enter into a database.

The dynamic penetration test is a simple and rapidly executed test which takes several forms, but is usually carried out by a small rig which applies a repeated impact force to the drill string at the surface. The output is in terms of penetration resistance which may be correlated with undrained shear strength or compactness of the material penetrated and it is particularly useful in the assessment of the compaction of fill. The problems associated with the analysis of these data are discussed in section 8.5.

8.3 PRESSUREMETER TESTS

The pressuremeter is a cylindrical device that may be expanded against the walls of a borehole. There are broadly three types of pressuremeter, the self-boring type (e.g. ‘Camkometer’), the push-in type (e.g. the Building Research Establishment’s ‘PIP’), and the original type which required a pre-formed borehole (e.g. ‘Menard pressuremeter’)(Mair and Wood, 1987). These are all able to measure undrained strength and deformability simultaneously, and to determine horizontal stress (Clough et al., 1990). The method has been hampered by difficulties in interpretation due to complex boundary conditions, disturbance when cutting the hole, and the bias toward measurement of properties in a horizontal direction.

Accounts of the borehole type pressuremeter’s use in Mercia Mudstone were given by Meigh (1976), Marsland et al. (1983), Leach et al. (1976, 1979), Maddison et al. (1996), and Parry et al. (1996). Leach et al. (1976) gave a detailed comparison of pressuremeter data and laboratory triaxial data. The pressuremeter test tends to give a much higher value for undrained shear strength, compared with the laboratory test; the difference increasing with depth. Marsland et al. (1983) also compared pressuremeter test data with back-analysed foundation displacements. These and other references suggest that both the true strength and the true deformation moduli of the soil or rock mass lie between the traditional triaxial test values and the pressurementer test values. Large differences in the interpretation of the pressuremeter test are obtained depending on whether the initial or the unload/reload cycle results are used. The unload/reload elastic moduli are between two and three times the initial values. Modern small-strain stiffness triaxial test techniques narrow the gap between laboratory and field to some extent.

The self-boring pressuremeter is believed to overestimate the undrained strength of clays by a factor of about two (Shuttle and Jefferies, 1996). However, the self-boring pressuremeter (and also the cone pressuremeter) have an advantage in that they fit, by definition, closely to the hole. A recent development has been the ‘weak rock self-boring pressuremeter’, which is capable of dealing with rocks such as the Mercia Mudstone (Clarke and Allen, 1989; Clarke et. al., 1989; Thompson et al., 1993).

Conventional analyses of the pressuremeter test are the Gibson-Anderson (1971) method and the Palmer method (1972), The former uses a two-stage ideal elastic / perfectly plastic (Tresca) analysis where yielding occurs when the cavity pressure equals the undrained cohesion. The undrained shear strength is the gradient of the pressure vs. log volumetric strain line. Rigidity and shear modulus can also be obtained from this plot. The Palmer method utilises the actual stress/strain response. Shuttle and Jefferies (1996) recommended that self-boring pressuremeter parameters are determined in a synthesised ‘iterative forward modelling’ method, and gave results which are independent of disturbance and comparable with high quality triaxial testing. Oversized cutting shoes are sometimes used for self-boring pressuremeter tests in weak mudrocks such as Mercia Mudstone. This means that the test is not strictly ‘self-bored’ and a different method is necessary to interpret the results.

The results of selected pressuremeter tests from four site investigations in the East and West Midlands are shown as depth profiles, A to E, on a log scale in Figure 8.1. The undrained cohesion values from pressuremeter data show an overall trend of increase with depth, but with a wide scatter of data, particularly at depths shallower than 12 m. Shear modulus values derived from pressuremeter data show little or no increase with increasing depth below 8 m deep. Weathering zones have been omitted as some data did not have this information, and others were not compatible. Comparison of initial and first unload/reload shear moduli show a median increase in the latter over the former of 186%. Most first unload/reload (G_{ur1}) data agree with data quoted by Marsland et al. (1983) for Mercia Mudstone in Cheshire. No values of Young’s Modulus (E) derived from pressuremeter tests are present in the database. Values of between 350 and 820 MPa are quoted for Weathering Zone 3 material in Area 8 (East Midlands). Meigh (1976) discussed results of pressuremeter, plate bearing, pile loading tests, and back-analyses, carried out in the Midlands and South Wales, in terms of Young’s modulus and its relationship with depth. Young’s modulus may also be derived from laboratory oedometer tests using elastic theory, with coefficient of volume compressibility (m_v) and Poisson’s ratio (ν’) as inputs (Meigh, 1976):

$E' = 0.9/m_v$ (assuming $\nu' = 0.2$ for Mercia Mudstone)

8.4 PLATE-BEARING TESTS (PBT)

The in situ plate-bearing test is a well-established, but relatively expensive and little used test. It was developed (in

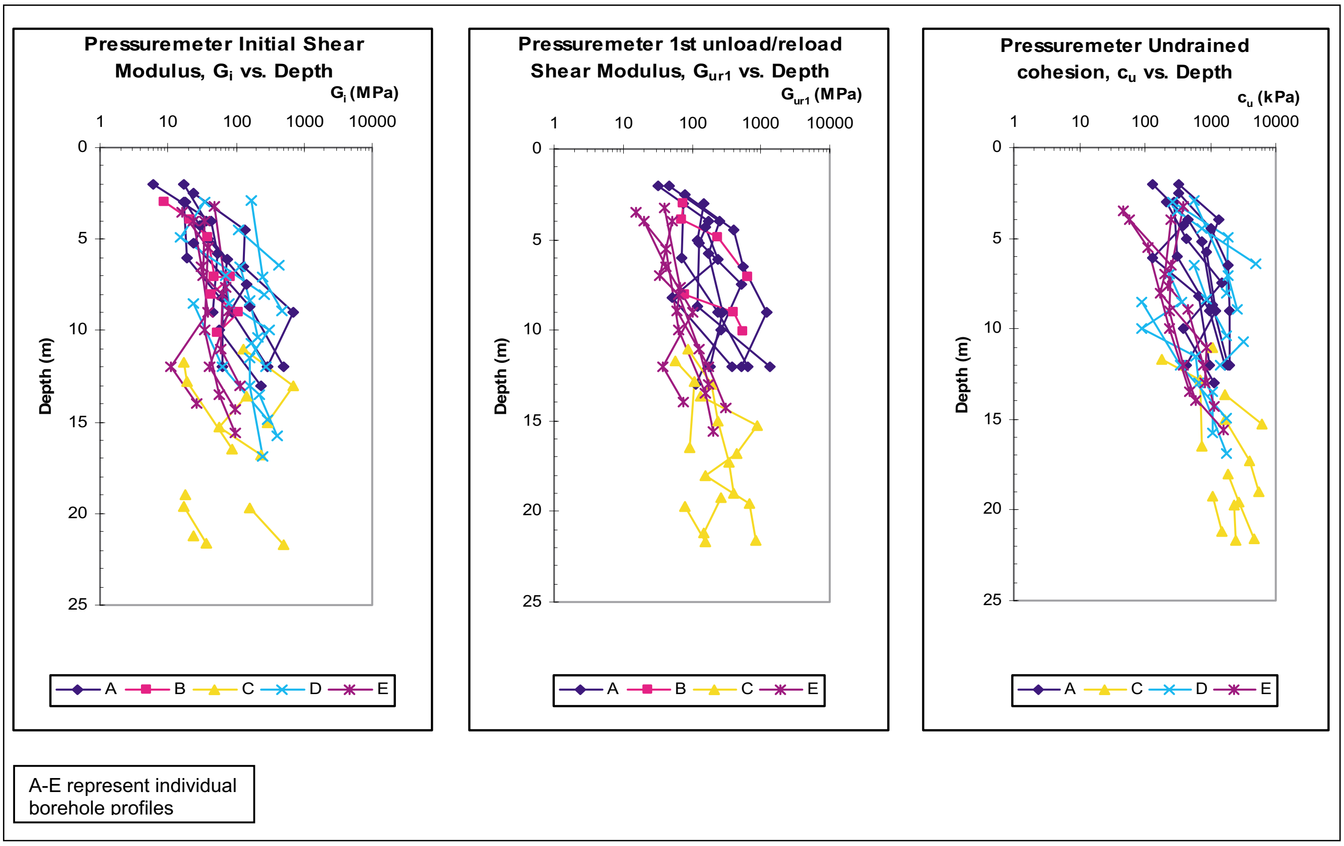


Figure 8.1 Pressuremeter test results for the East and West Midlands.

the UK) by the Building Research Establishment. The possible exception to this lies in its use for bridge abutments in strong clay formations, such as the Mercia Mudstone. One such use, for the M56 motorway between Manchester and Chester, was described by Marsland et al. (1983); a good agreement was found between shear modulus results from plate bearing tests and back-analysed foundation displacements. However, shear moduli values from pressuremeter tests were significantly higher. Although plate-bearing tests vary in the size of plate and the method of application of the load they usually require the use of heavy plant, and the preparation of a purpose-made trial pit or a large diameter borehole.

Settlements of 30 to 33 mm for 250 to 275 kN applied loads for 300 mm diameter plate tests in the West Midlands were reported by Meigh (1976) who also discussed the results of the plate and pile loading tests in terms of elasticity modulus.

8.5 STANDARD PENETRATION TEST (SPT)

The standard penetrometer test (SPT) is a long-established, 'founding method' of in situ geotechnical testing. This dynamic method employs a falling weight to drive a split-sampler and cutting shoe (or solid 60° cone in the case of coarse soils or soft rock) 300 mm into the ground from a position 150 mm below the base of a borehole; the initial 150 mm being the 'seating' drive. The use of the test is described in British Standard 5930 (British Standard Institution, 1999) and the methodology in British Standard 1377: Part 9: Clause 3.3 (British Standard Institution, 1990). There has been much discussion concerning the test method, test apparatus, and test interpretation (Stroud and Butler, 1975; Stroud, 1989). International variations in practice have been a feature of its use.

It was recommended (Clayton, 1995; British Standard Institution, 1990; International Society for Soil Mechanics and Foundation Engineering, 1988) that test results are reported in the form of six 75 mm penetration increments; the first two representing the 'seating' drive and the final four the 'test' drive, the sum of the latter providing the SPT 'N' value. This is often not the case in site investigation reports, though it does form part of the Association of Geotechnical Specialists' (AGS) format for the electronic transfer of geotechnical data. The difficulties inherent in databasing and analysing SPT data are discussed below.

The standard penetration test (SPT) may be regarded as rather crude, but it has the virtue of being an inexpensive in situ test that can and has been carried out across the full range of weathering zones in the Mercia Mudstone. It could be argued that it is unique in this respect, given the difficulties in applying most other test procedures to this formation. Thus it is perhaps not surprising to see how often it has been deployed between core runs in relatively deep boreholes. This somewhat inconvenient procedure must have been regarded as worthwhile, despite the fact that such tests very rarely achieve the full test penetration. If the data from these tests are to be compared and analysed, and not simply dismissed as incomplete, then some extrapolation or other normalisation is required.

An abundance of SPT data was available, in most cases with a record of the incremental blows and penetrations. The advent and availability of the data in digital format, means that it was practical to input this detailed information into the geotechnical database for analysis. The summaries presented for the SPT are derived from over 3500 tests. The data from these tests were processed in several stages:

1 *Seating blows and penetration.* The current test standard (British Standard 1377) has since 1990 specified that the seating drive is complete after an initial penetration of 150 mm or 25 blows, whichever is first achieved. This recognises that, in harder soils and weak rocks, the test equipment can be regarded as adequately seated with a penetration of significantly less than 150 mm. Thus it is no longer permissible to report tests as 'seating blows only'. None of the investigations used for this study, including those carried out well after the introduction of the standard, had complied with this requirement. This is surprising in view of the fact that the total penetration for many of the deeper tests was very limited. It is more remarkable that some drillers, from the evidence of the incremental data, had carried out the test correctly, and yet the formal report records these tests as incomplete.

   Where the blow count to 150 mm was greater than 25, the data within this interval was examined. The seating penetration was taken at the increment for which the total blow count was proportionately closest to 25. In the cases where this occurred at the first increment, all the subsequent data was shifted to the right and the next four increments taken as the main test drive. Tests in which data had only been recorded for a single increment were discarded, as they left no scope whatever to distinguish a seating drive and an even minimal test drive.

2 *Variability of the incremental blows.* The purpose in recording the SPT test in 75 mm increments is not clear, either in the British Standard or in the otherwise comprehensive report by Clayton (1995). In this study, the incremental data were analysed on the premise that in each test an attempt is made to derive a measure of resistance for a single and, at least locally, consistent material. Thus, when the test interval crosses between two materials of markedly differing resistance, the result will reflect the properties of neither, nor the overall properties of the two materials when considered together at the macro scale.

   Data from the final increment of each test was examined. Where the penetration for this increment had been recorded as zero, the test was discarded, irrespective of the blow and penetration history in the preceding increments. It was taken that the test interval had reached a second material of very much higher resistance, for which the available data indicated an infinite N value. For the remaining tests, the penetration rate (blows/mm) for the final increment was compared to the rate for the first increment of the main test drive. Where this ratio was higher than about 4:1, the tests were again discarded. The limit was entirely subjective and arbitrary, set with the purpose of eliminating a small proportion of the data where it was most likely that two contrasting materials were being tested. This procedure was applied progressively, from those tests having the greatest penetrations to those having the least (and hence fewer increments).

For a small proportion of tests neither digital nor incremental data were available. In these cases, tests giving a full N value were accepted, together with those in which a partial main test drive could be distinguished from a seating drive. In total, rather less than 10% of the original test data was discarded. For the remainder, extrapolated N values were calculated from the main test drive penetration (where less than 300 mm) and the corresponding blow count. The very small number of N values in excess of 1000 were given a ‘high default’ value of 9999, on the basis that the value must be very high but the degree of extrapolation was so great that the computed value was worthless.

In this study, an attempt has been made to derive extrapolated N values on a consistent basis. There is an inevitable bias, in that the higher the value, the greater will be both the degree of extrapolation, and the probability that the ‘real’ value’ would be higher still. Much of the discarded data almost certainly represents high but unquantifiable N values. In most instances these could have been determined if there were a modest amendment to the test procedure. This would define the main test drive in a similar manner to the revised seating drive, as 300 mm penetration or 100 blows, recorded in four increments of 75 mm or 25 blows (in both cases, whichever is achieved first, but allowing the driller a modest latitude). Thus all tests could be carried to a clear conclusion, and provide the same amount of incremental data, from which to assess the consistency of the test drive and thence base an extrapolation, if required. Whilst this could readily be recorded within the AGS digital format, representation on the printed log would be a little lengthier.

Results of SPT tests held on the database number over 3500. Taking all areas together, the median values for Weathering Zones 2, 2/3, 3, 3/4a, and 4a are N = 161, 146, 126, 117, and 59, respectively. This confirms the expected trend of a reducing N value with increasing weathering. Median N values are highest in Area 2, with a median N value of 122, and decrease towards the south-west and east with a minimum median N value of 50 for Area 5. A plot of the median, and associated percentile, values of SPT with depth is given in Figure 7.15. This shows a clear increase in median value of N = 40 to 100 between 2 and 7 m. Below this a similar increase is only achieved below 25 m depth. The full statistical results are given in the Appendix.

Strictly, the correlation of SPT with strength values determined in the laboratory is not possible from the database because data were not obtained from the same sampling interval or depth. Stroud (1989) and Clayton (1995) give log-log correlations between N value (derived from SPT, pressuremeter, and pile tests) and unconfined compressive strength data for various clay and mudrock formations including Mercia Mudstone, obtained from a variety of sources. From this Clayton (1995) quoted the following relationship for ‘clays’:

$$C_u = 5N_{60} \text{ kPa}$$

where: N_{60} = equivalent SPT resistance corrected to 60% of energy

8.6 PERMEABILITY TESTS

There are only two site investigation reports in the dataset containing in situ permeability data. (There are no laboratory permeability data). These are both from the East Midlands. Permeability values for the Mercia Mudstone ranged from 3.42×10^{-7} to 1.4×10^{-4} m/s (falling head, Weathering Zone 4a), from 3×10^{-7} to 1.0×10^{-6} m/s (falling head, Weathering Zone 3), and from 1.17×10^{-10} to 1.44×10^{-7} m/s (reduced constant head, Weathering Zone 4).

9 Conclusions

9.1 GEOLOGY

The Mercia Mudstone Group is dominated by reddish-brown mudrocks that accumulated under hot, seasonally wet climatic conditions in basins with intermittent, restricted connection to the sea. It is characterised primarily by a monotonous sequence of brown, red-brown, calcareous clays and mudstones, with occasional beds of impersistent green mudstone siltstone and fine-grained sandstone (skerries), often forming the high ground features. Evaporite deposits of halite, gypsum and anhydrite are significant in parts of the sequence but the thick halite deposits are confined to the centres of former basins and are not present at the surface due to their solution by groundwater.

The outcrop of the Mercia Mudstone extends northwards from Lyme Bay through Somerset and on to both sides of the Severn Estuary. It continues northwards through Hereford and Worcester before broadening out to underlie much of the central Midlands. The outcrop bifurcates around the Pennine Anticline, with the eastern limb running through Nottinghamshire into the Vale of York, before eventually reaching the North Sea coast at Teesside. The western limb underlies northern Shropshire, Cheshire and Merseyside and much of the Formby and Fylde peninsulas, passing offshore below the Irish Sea before extending onshore again on the northern side of the Lake District near Carlisle. In Cheshire, Warwickshire, Formby, Fylde, the Vale of York and the Carlisle area, large parts of the outcrop are masked by thick Quaternary deposits (mainly glacial till), with more patchy cover of superficial deposits elsewhere. Thick sequences of the group dip below younger Mesozoic rocks in Dorset, Hampshire, north-east England and the Southern North Sea, In south-east England, the group pinches out in the subsurface around the margins of the London Brabant Massif.

Detailed geological mapping to identify characteristic formations has not been carried out in all the basins of the Mercia Mudstone outcrop and detailed correlations within or between basins that would be useful for indicating the engineering behaviour of the Mercia Mudstone for site investigation purposes are limited.

9.2 MINERALOGY

An appreciation of the mineral composition, diagenesis and structure of the Mercia Mudstone Group can aid an understanding of its engineering behaviour. The plasticity of clays and mudstones depends on the type of clay minerals present, particularly those of the less than 0.002 mm grain-size fraction, and the percentage of clay minerals in the mineral composition. The nature and distribution of intergranular cement will affect its strength, deformation and susceptibility to weathering and the nature of the weathered material.

The main non-clay minerals present in Mercia Mudstone are quartz, calcium carbonate, magnesium carbonate, calcium sulphates, micas, iron oxides, and halite. Feldspar may also be present and several heavy minerals occur in very small quantities. The major clay minerals are illite, chlorite, mixed layer illite-smectite or chlorite-smectite and, in some horizons, smectite. Predominance of illite and chlorite indicate a detrital origin in low salinity conditions associated with wet climatic conditions. Where high salinity, arid conditions prevailed the authigenic clays, illite-smectite, chlorite-smectite and smectite are found to be dominant. The determination of the proportion of clay minerals in a sample by conventional particle size analysis may be different to the value determined by X-ray diffraction due to difficulties in disaggregating the clay minerals, the presence of silt-size detrital clay minerals (mica and chlorite) and the assumption that X-ray diffraction is a quantitative method of analysis

9.3 SAMPLING AND TESTING

The Mercia Mudstone is different to many older more indurated and laminated mudstones, such as Carboniferous, Coal Measures mudstones, which tend to have relatively thin weathering profiles, below which fresh rock is present at shallow depth which is amenable to normal rock sampling and testing techniques. It is also different to younger, relatively unindurated mudstones, such as Oxford Clay, which can be sampled and tested as an engineering soil in the depth range needed for most site investigations. There is no other mudstone of comparable thickness, outcrop or importance in the UK which occupies the interface between soil and rock, and whose behaviour is predominantly influenced by weathering and jointing rather than by sedimentary discontinuities.

In its unweathered state the Mercia Mudstone may be described as an intact, jointed, 'weak' rock whereas in its fully weathered state it is a reddish-brown, 'very soft' to 'hard' silty clay, but frequently containing less-weathered mudrock clasts. The depth of weathering can be considerable, exceeding 30 m in some areas. However, the depth of weathering is more typically 10 to 15 m. The weathering profile is usually progressive, with strength and stiffness tending to increase with depth but may show reversal with more weathered material below less due to lithological variation in the sequence.

Soft ground boring and sampling techniques, with light cable percussion rigs and driven samplers, are as appropriate to Weathering Zone 4 Mercia Mudstone as they are to most other clay soils. The shallowest taper angle and sharpest edge practicable should be used and maintained on the cutting shoe for taking driven samples. The fresh or slightly weathered Mercia Mudstone of Zones 1 and 2 require the 'gentle' rotary flush coring techniques used for other weak mudstone rocks. Samples may be taken using semi-rigid plastic core liners or triple tube core barrels both of which afford protection to the core once it is cut by the drill bit. Neither technique is wholly appropriate for the intervening Zone 3 material due to its inhomogeneous nature of 'clay' matrix and 'rock' lithorelics and both techniques may need to be used in close proximity with an overlap through a suitable depth range, ideally, of several metres. The overlap enables the borehole logs from the two contrasting techniques to be reconciled. Although not without difficulties, sampling from trial pits offers the possibility of high quality, undisturbed, block samples or tube samples in the weaker material.

Considerable difficulties are experienced in the determination of the mass strength and mass stiffness of a weak rock such as Mercia Mudstone due to the fissured nature of the unweathered rock and problems encountered when sampling and during testing in the laboratory. In situ geotechnical testing equipment has been developed in the form of pressuremeters and static and dynamic penetrometers to circumvent these problems and refinements made to the long established standard penetration test (SPT) and plate-bearing test (PBT) have been made in recent years.

9.4 GEOTECHNICAL DATABASE

A geotechnical database for the Mercia Mudstone Group has been compiled for ten areas that reflect the original depositional basins, the present outcrop, the extent of current and potential development, and the availability of data sources. Particular emphasis has been given to those areas in which the Mercia Mudstone has been mapped and subdivided stratigraphically, namely the northern part of the East Midlands, the Worcester Basin and the Cheshire Basin. In the Stafford Basin, Warwickshire and Leicester mapping has not as yet divided the group. Further north, site investigations rarely penetrated the drift that obscures the Carlisle area and the complex of basins in west Lancashire. In the West Country, areas comprise the Severn Estuary and east Devon. To the east of the Pennines, modest amounts of data have been obtained for Humberside and Teesside.

The majority of the data were taken from investigations for the motorway and trunk road network, as these provided an abundance of good quality data, often across a major part of the outcrop. All the selected reports were for more recent investigations (post 1985), and included weathering zones.

In addition to basic statistical analysis of the data using scatter and line plots, a non-standard approach has been applied to displaying geotechnical data graphically. This involved the use of box plots and the bubble plots. In addition, a variation of the familiar Casagrande plasticity plot has been produced. This plot substitutes plastic limit for liquid limit on the abscissa, resulting in a cluster of data rather than the more familiar linear scatter parallel, or subparallel, with the A-line. A feature of the plot is that the entire plotting area is utilised, as opposed to half of it as is the case with the Casagrande plot. The box plot enables a visual assessment of statistical percentiles to be made, and many boxes, each representing a subdivision of data, may be placed on one diagram. The use of rigorous statistics with geotechnical databases has been discussed in Hallam (1990). The bubble plot is a means of indicating the concentration of data at one co-ordinate. This is particularly suited to geotechnical index data which may be reported to one decimal place or the nearest whole number as specified by British Standard procedure (British Standards Institution, 1990), and as a result many data points have the same values.

The analysis showed the distribution and correlations of various key geotechnical parameters with regard to geography and stratigraphy. Selected geotechnical parameters were plotted against depth or against one another, in order to determine variations caused by depth, and other, related factors, and to characterise engineering behaviour at deep and shallow levels. Weathering may be related in a general sense to depth below ground level, but this is not a simple relationship of decreasing weathering with increasing depth in the case of the Mercia Mudstone. Moisture content, density, permeability, and strength may also relate to depth.

9.5 ENGINEERING BEHAVIOUR

Comments on the engineering behaviour are largely based on the geotechnical properties of mudstones of the Mercia Mudstone Group recorded in the geotechnical database or in the published literature. The material being considered was undisturbed or remoulded material in a fresh or weathered condition. However, in some areas the Mercia Mudstone strata have been disrupted by the dissolution of soluble evaporite minerals, gypsum or halite, or by the volume increase that occurs when anhydrite converts to gypsum in the presence of water. Large volumes of strata have been transformed to breccia by these processes. In these areas the in situ behaviour of Mercia Mudstone will be very different to its undisturbed state.

The analysis of the geotechnical database, described in Section 7.2, revealed some trends in the properties and engineering behaviour of the Mercia Mudstone. Data have been analysed and correlated by lithostratigraphical division (where available), geographic areas, weathering zone, and depth. The trends appeared in general to depend on stratigraphic subdivision and area rather than weathering zone. For example, clear trends were seen in several index properties between the three main stratigraphic subdivisions of Area 1 (Cheshire). This was partly due to the fact that the Mercia Mudstone is lithologically varied, and stratigraphical subdivisions each have characteristic lithologies and mineralogies which correlate with most geotechnical properties.

Some areas gave contrasting strength or plasticity values compared with others. However, the data were not equally distributed across the areas; Areas 1, 2, and 8 together accounted for about 75% of the data. Variation or scatter was in many cases the same within a single area as it was across the areas. This applied to particle size data in particular and, to a lesser extent, plasticity data.

Median values of liquid limit for each area ranged from 30 to 52%. Areas 1 and 9 had notably higher values than other areas. Samples with a plasticity classification greater than ‘high’ represented less than 0.5% of the data. There was a general trend of increasing liquid and plastic limits with increased weathering. The Edwalton Formation in Area 8 had higher liquid and plastic limit medians than the other formations in the area. Area 9 had the highest plastic limit median with few values below ‘medium’ plasticity. Area 10 the lowest plasticity. There was no clear correlation between liquidity index and weathering zone, with the possible exception of Area 2 which showed an increase from Zone 2/3 to 4b. Again, the Edwalton Formation (Area 8) had high liquidity indices. Few data were available for swelling and shrinkage. All indications were that the Mercia Mudstone had a low swelling and shrinking potential (Building Research Establishment, 1993). Large differences were reported between laboratory and field permeabilities. Permeabilities were reported of between 10^{-8} and 10^{-11} m/s for intact laboratory samples and between 10^{-6} and 10^{-8} for field tests (Tellam and Lloyd, 1981). The differences in the reported values are due to the scale of the tests and discontinuities in the rock mass.

Chemical tests were sparsely represented in the database. Sulphate contents are important in view of the gypsum within the Mercia Mudstone Group and the potential for concrete and steel attack beneath ground level. A wide range of sulphate contents was found, resulting in classes from 1 to 5 (Building Research Establishment, 1991). The pH values typically lay between 7 and 8, that is, slightly alkaline, with the Sneinton Formation highest and the Cropwell Formation the lowest. The pH varied across stratigraphical subdivisions in Area 8. Carbonates, either in the form of dolomite or calcite, are important constituents of the Mercia Mudstone. However, carbonate contents, organic contents, and other chemical test data were not represented in the database.

The aggregation of Mercia Mudstone has been widely discussed (Chandler et al., 1968; Dumbleton and West, 1966; Davis, 1967). Chandler et al. (1968) explained the wide range in activity observed in terms of the unchanging free surface area of clays compared with the change in particle size. They quoted values of activity for disaggregated material of between 0.15 and 1.15. A good positive correlation was also suggested (by the above) between activity, A_c, and aggregation ratio, A_r. Data from the database, described in section 7.2, showed a much wider range of activities (0.38 to 25). These may be, in many cases, erroneous due to incorrect clay-size contents derived from particle size analyses. If the percentage clay size fraction used to calculate activity, was taken as a proportion of the percentage passing the 0.425 mm sieve, instead of the whole sample, the activity values drop by a factor of up to three. It was clear that complete dispersion had not being completed in many tests, resulting in aggregations of mudrock being graded as sand, gravel, and cobbles. At the same time these samples were described as mudrock or clay. Whilst it is the case that some weathering grades are characterised by clay matrix and lithorelics of mudrock, and that it is possible to break-down these lithorelics, the correct grading of these materials is open to question. Clearly, lithorelics of any rock type other than mudrock, would normally be considered intact and no attempt made to break them down. It may be that conventional particle size analysis is unsuited to the Mercia Mudstone, at least in Weathering Zones 1, 2, and 3a and it may be that an index test such as the slake durability test is more suited to the Mercia Mudstone. Whilst this test is not a particle size test it gives an indication of liability to breakdown under conditions of mechanical abrasion and swelling, and may be indicative of the breakdown taking place during the wet sieving process. The slake durability test is not commonly carried out on weak mudrocks and clays, and no data for the test exists in the database.

The '% clay mineral' in the aggregation ratio formula is the percentage of clay minerals as determined by X-Ray diffraction (XRD) or chemical analyses, whereas the '% clay size' (proportion of particles < 0.002 mm) is determined from conventional particle size (grading) analyses. The latter may *include* non-clay mineral material, and may *exclude* aggregations of clay minerals. XRD analyses are not routinely carried out as part of site investigations, and the data required to calculate aggregation ratio are thus not contained in the database. Chandler et al., (1968) quoted values for A_r of between 1.4 and 10. Such high values may point to poor disaggregation in the particle size analysis. It has been shown that by means of a minor modification to the BS1377 preparation procedure, successful aggregation can be carried out using an extended mixing time (Entwisle, 1996). He also pointed out that mica and chlorite are present as silt-sized particles, and may have been included in earlier work as 'clay minerals' that were assumed to be of clay size.

It may be the case that a distinction needs to be made between naturally occurring particle size and disaggregated particle size for a material such as the Mercia Mudstone. It may be that standard testing procedures can be used to evaluate this rather than XRD analysis. Clearly, if the mechanical properties of the clay in its natural, undisturbed state are required, then disaggregated properties are inappropriate (Dumbleton and West, 1966), except in the context of an index or reference point. Other properties influenced by the aggregation state are permeability, density, and strength.

Activity data for the Mercia Mudstone are generally unreliable, and may be inappropriate to define the formation. It would appear that positive values of plasticity index can be obtained for a soil with zero clay size fraction (% < 0.002mm). This then gives activity values of infinity. This may not be wholly attributable to poor disaggregation in particle size analysis preparation, but may be a feature of activity when applied to soils of low plasticity. It has been shown from the database that particle size data may be unreliable in many cases, and that there is widespread disagreement between % < 0.425mm data from the Atterberg limit preparation stage and the equivalent particle size data.

Strength data showed some trends with area, stratigraphy (Areas 1 and 8), and with depth, though little correlation with weathering zone was seen. Laboratory strength samples of Zone 1, 2, and 3 Mercia Mudstone are difficult to prepare, and the scatter of undrained strength data (C_u and UCS) is considerable. This partly explains the popularity of in situ test methods in the Mercia Mudstone (section 8). The SPT results (N values) showed a good correlation with weathering grade and stratigraphy for Area 8; the N-values decreasing with increased weathering. Residual (soil) strength data were few, but indicated high values (>25°) for residual friction angle, $ø'_r$. There was wide scatter of point load test data values. True correlations of point load and SPT with other strength parameters were not possible due to non-coincidence of sample interval. Depth profiles of strength parameters generally showed an increase with depth, to a depth of about 10 m, below which little further increase was apparent. However, depths below true ground level were difficult to determine accurately in the database. This contributed to the scatter of data.

Deformability of Zone 1, 2, and 3 Mercia Mudstone is difficult to determine in the laboratory, it being difficult to prepare specimens and to avoid sample disturbance and it is usually measured in situ using large-scale tests (Section 8). Deformability is strongly influenced by lithology, geological structure, and sample disturbance. The consensus of opinion at a meeting on *The engineering geology of Mercia Mudstone in highways* (Barber 1996) was that the deformability of Mercia Mudstone was often overestimated. The selection of deformation modulus from laboratory and field tests is difficult. For the more weathered Mercia Mudstone (Zones 3b, 4) the use of oedometer consolidation tests is feasible, though the normally applied stresses (up to 2000 kPa) may be inadequate for interpretation of overconsolidation or yield stress. There was a wide scatter of consolidation data, particularly for the coefficient of consolidation, c_v.

Marsland et al. (1983) concluded that shallow mass foundations are 'perfectly adequate for many bridges constructed on weathered Keuper Marl'. It may be that piles are specified unnecessarily in many cases. Remoulded strength data from laboratory tests may be one reason for this. Creep may be a significant factor in settlement calculations. This may be caused by dissolution of sulphates. Effective stress triaxial testing should be used in preference to 'quick undrained' or 'unconsolidated undrained' triaxial testing. Mercia Mudstone in the engineering zone is typically partially saturated. This results in negative pore pressures in the triaxial test.

Slope stability in the Mercia Mudstone is not solely a function of the intact strength. Slope angles are dependent on lithology, bedding and jointing, seepage, and the state of weathering. The strength of joints, and other discontinuities, plays an important part, particularly as a large reduction in effective cohesion takes place along them. In unweathered Mercia Mudstone, joints may be planar, undulose, or listric; spaced typically at between 0.1 and 0.5 m (Forster and Hobbs, 1995). The result of undulose or listric jointing is that intact blocks are rarely cuboid in shape, but rather lenticular or flaggy. Engineered slopes in Mercia Mudstone are typically graded at 1:2 (27°), whilst natural slope angles are very variable.

References

AMBROSE, K. 1989. Geology of the Lowdham district, 1:10 000 sheet SK64NE: part of 1:50 000 sheet 126 – Nottingham. *British Geological Survey Technical Report,* WA/89/14.

ANON. 1970. The logging of rock cores for engineering purposes. Report by the Engineering Group of the Geological Society's Working Party. *Quarterly Journal of Engineering Geology*, Vol. 3, 1–24.

ANON. 1995. The description and classification of weathered rocks for engineering purposes. Report by the Engineering Group of the Geological Society's Working Party. *Quarterly Journal of Engineering Geology*, Vol. 28, 207–242.

ARTHURTON, R S. 1980. Rhythmic sedimentary sequences in the Triassic Keuper Marl (Mercia Mudstone Group) of Cheshire, north-west England. *Geological Journal,* Vol. 15, 43–58.

ASSOCIATION OF GEOTECHNICAL AND ENVIRONMENTAL SPECIALISTS. 1992. Electronic transfer of geotechnical data from ground investigations. *Association of Geotechnical and Environmental Specialists*. 1st Edition.

ATKINSON, J H, PETTIFER, G S, and FOOKES, P G. 1998. Geotechnical properties of destructured Mercia Mudstone. *Proceedings of the Construction Industry Research and Information Association seminar on the engineering properties of the Mercia Mudstone Group*, Pride Park, Derby, November 1998, pp. 7/1–7/5.

BACCIARELLI, R. 1993. A revised weathering classification for Mercia Mudstone (Keuper Marl). 169–174 *in* CRIPPS et al. (eds.). The Engineering Geology of Weak Rock. *Engineering Geology Special Publication,* No.8. (Rotterdam: Balkema).

BARBER, L. 1996. The engineering geology of Mercia Mudstone in highways. *Geoscientist*, Vol. 6, No. 6, 24–26.

BELL, F G. 1994. A survey of the engineering properties of some anhydrite and gypsum from the north and midlands of England. *Engineering Geology*, Vol. 38, 1–23.

BIENIAWSKI, Z T. 1974. Estimating the strength of rock materials. *Journal of the South African Institute of Mining and Metallurgy*. Vol. 74, 312–320.

BIENIAWSKI, Z T. 1975. The point load test in geotechnical practice. *Engineering Geology*, Vol. 9, 1–11.

BINNS, A. 1998. Rotary coring in soft rocks and soils for geotechnical engineering. *Proceedings of the Institution of Civil Engineers,* Vol. 131, 63–74.

BIRCH, N. 1966. Keuper Marl. *Proceedings of the Midland Soil Mechanics & Foundation Engineering Society*, Vol. 6, 41–84.

BLOODWORTH, A J, and PRIOR, S V. 1993. Clay mineral stratigraphy of the Mercia Mudstone Group in the Nottingham area. *British Geological Survey Technical Report,* WG/93/29.

BOROWCZYK, M, and SZYMANSKI, A. 1995. The use of in situ tests for determination of stress history. *Proceedings of the XI European Conference on Soil Mechanics and Foundation Engineering – The Interplay between Geotechnical Engineering and Engineering Geology, Copenhagen.* Vol. 1, 17–22.

BRITISH STANDARDS INSTITUTION. 1972. Code of practice for foundations CP:2004. (London: British Standards Institution.)

BRITISH STANDARDS INSTITUTION. 1990. British standard methods of test for soils for civil engineering purposes BS: 1377. (London: British Standards Institution.)

BRITISH STANDARDS INSTITUTION. 1999. Code of practice for site investigations BS: 5930. (London: British Standards Institution.)

BROCH, E, and FRANKLIN, J A. 1972. The point-load strength test. *International Journal of Rock Mechanics and Mining Science,* Vol. 9, 669–697.

BUILDING RESEARCH ESTABLISHMENT. 1981. Concrete in sulphate bearing soils and groundwaters. *Building Research Digest,* No. 250.

BUILDING RESEARCH ESTABLISHMENT. 1991. Sulphate and acid resistance of concrete in the ground. *Building Research Digest,* No. 363 (second edition, 1996).

BUILDING RESEARCH ESTABLISHMENT. 1993. Low rise buildings on shrinkable clay soils: Part 1. *Building Research Digest,* No. 240.

CAPREZ, M, and HONOLD, P. 1995. Moisture condition as a basis for compaction. *Proceedings of the XI European Conference on Soil Mechanics and Foundation Engineering — The Interplay between Geotechnical Engineering and Engineering Geology, Copenhagen,* Vol. 3, 25–30.

CHADWICK R A, and EVANS D J. 1995. The timing and direction of Permo-Triassic extension in southern Britain. 161-192 *in* BOLDY, S A R (editor). Permian and Triassic Rifting in Northwest Europe. *Geological Society Special Publication,* No. 91.

CHARSLEY, T J, RATHBONE, P A, and LOWE, D J. 1990. Nottingham: A geological background for planning and development. *British Geological Survey Technical Report,* WA/90/1.

CHANDLER, R J. 1967. The strength of a stiff silty clay. *Proceedings of the Geotechnical Conference Oslo,* Vol. 1, 100–108.

CHANDLER, R J. 1969. The effect of weathering on the shear strength properties of Keuper Marl. *Geotechnique*, Vol. 19, 321–334.

CHANDLER, R J, BIRCH, N, and DAVIES, A G. 1968. Engineering properties of Keuper Marl. *Construction Industry Research and Information Association Report,* No. 13.

CHANDLER, R J, and DAVIS, A G. 1973. Further work on the engineering properties of Keuper Marl. *Construction Industry Research and Information Association Report,* No. 47.

CHAU, K T, and WONG, R H C. 1996. Uniaxial compressive strength and point load strength of rocks. *International Journal of Rock Mechanics, Mining Science & Geomechanics,* Vol. 33, No. 2, 183–188.

CLARKE, B G, and ALLEN, P G. 1989. A self-boring pressuremeter for testing weak rock. *XII International Conference on Soil Mechanics and Foundation Engineering, Brazil.* Vol. 1, 211–214.

CLARKE, B G, and SMITH, A. 1993. Self-boring pressure meter tests in weak rocks. 233–241 *in* CRIPPS J C et al. (eds.). The Engineering Geology of Weak Rock. *Engineering Geology Special Publication,* No. 8. *(*Rotterdam: Balkema.)

CLARK, B G, NEWMAN, R L, and Allan, P G. 1989. Experience with a new high pressure self boring pressuremeter in weak rock; Part II. *Ground Engineering,* Vol. 22, Pt.6, 45–52.

CLAYTON, C R I. 1995. The Standard Penetration Test (SPT): Methods and use. *Construction Industry Research and Information Association Report,* No. 143.

CLOUGH, G W, BRIAUD, J L, and Hughes, J M O. 1990. The development of pressuremeter testing. *Proceedings of the 3rd. International Symposium on Pressuremeters, Oxford,* 25–45.

CRAGG, D J, and INGMAN, J. 1995. Rock weathering descriptions: current difficulties. *Quarterly Journal of Engineering Geology,* Vol. 28, 277–286.

CRIPPS, J C, and Taylor, R K. 1981. The engineering properties of mudrocks. *Quarterly Journal of Engineering Geology,* Vol. 14, 325–346.

CULSHAW, M G, NORTHMORE, K J, and HOBBS, P R N. 1991. Undisturbed pit sampling of tropical red clay soils. 485–490 *in* FORSTER, A. et al. (editors). *Engineering Geology Special Publication,* No.7.

DAVIS, A G. 1967. The mineralogy and phase equilibrium of Keuper Marl. *Quarterly Journal of Engineering Geology,* Vol. 1, 25–38.

DAVIS, A G. 1972. The settlement of structures founded on weathered soft rocks with particular reference to the Keuper Marl. *Proceedings of the symposium on the interaction between structures and foundations. Midlands Soil Mechanics and Foundation Engineering Society,* 18–28

DEPARTMENT OF TRANSPORT. 1991. *Manual of contract documents for highway works. Vol. 1: Specification for highway works.* (London: HMSO for Department of Transport.)

DUMBLETON, M J, 1967. Origin and mineralogy of African red clays and Keuper Marl. *Quarterly Journal of Engineering Geology,* Vol. 1, 39–45.

DUMBLETON, M J, and West, G. 1966a. Studies of the Keuper Marl: Mineralogy. *Road Research Laboratory. Ministry of Transport,* Report No. 40, 1–25.

DUMBLETON, M J, and WEST, G. 1966b. Some factors affecting the relation between the clay minerals in soils and their plasticity. *Clay Mineralogy,* Vol. 6, Pt.3, 179–193.

EDWARDS, W N. 1967. Geology of the Country around Ollerton. *Memoir of the Geological Survey of Great Britain,* Sheet 113 (England and Wales).

ELLIOTT, R E. 1961. The Stratigraphy of the Keuper Series in Southern Nottinghamshire. *Proceedings of the Yorkshire Geological Society,* Vol. 33, 197–234.

ENTWISLE, D C. 1996. Geotechnical laboratory determinations of samples from the Cropwell Bishop Gypsum Pit and Gringley-on-the-Hill, Nottinghamshire. *British Geological Survey, Engineering Geology & Geophysics Group Laboratory Report,* No. 96/9.

ENTWISLE, D C. 1997. The mineralogy of the Mercia Mudstone Group. *British Geological Survey Technical Report,* WN/97/15.

EVANS, D J, REES, J G, and HOLLOWAY, S. 1993. The Permian to Jurassic stratigraphy and structural evolution of the central Cheshire Basin. *Journal of the Geological Society of London,* Vol. 150, 857–870.

FARMER, I W, and KEMENY, J M. 1992. Deficiencies in rock test data. Rock Characterisation. 298–303 *in* HUDSON, J. (editor) *Proceedings of the International Society for Rock Mechanics Symposium: Eurock '92,* (British Geotechnical Society).

FOOKES, P G, and HIGGINBOTTOM, I E. 1975. The classification and description of near-shore carbonate sediments for engineering purposes. *Geotechnique*, Vol. 25, No.2, 406–411.

FORSTER, A, CULSHAW, M G, and BELL, F G. 1995. The regional distribution of sulphate in rocks and soils of Britain. 83–100 *in* EDDLESTONE, S WALTHALL, J C CRIPPS, M G CULSHAW (eds). *Geological Society Engineering Group Special Publication,* No. 10.

FORSTER, A, and HOBBS, P R N. 1995. Cropwell Bishop Quarry sampling report. *British Geological Survey Engineering Geology and Geophysics Group project note,* No. 95/27.

FORSTER, I R. 1983. The influence of core sample geometry on the axial point load test. *International Journal of Rock Mechanics, Mining Science & Geomechanics,* Vol. 20, 291–295.

FORSTER, S C, and WARRINGTON, G. 1985. Geochronology of the Carboniferous, Permian and Triassic. 99–113 *in* SNELLING, N J (editor). The chronology of the geological record. *Geological Society Memoir,* No.10.

FRANKLIN, J A, and CHANDRA, R. 1972. The slake-durability test. *International Journal of Rock Mechanics and Mining Science,* Vol. 9, 325–341.

FRANKLIN, J A, BROCH, E, and WALTON, G. 1971. Logging the mechanical character of rock. *Transactions of the Institute of Mining and Metallurgy*, Vol. 80, Pt. A, 1–9.

GIBSON, R E and ANDERSON, W F. 1971. In situ measurements of soil properties with the pressuremeter. *Civil Engineering and Public Works Review*, Vol. 56, 615–618.

GOSTELOW, T P. 1995. Some geological aspects of clay swelling and shrinkage. *British Geological Survey Technical Report,* WN/95/16.

GRAINGER, P. 1984. The classification of mudrocks for engineering purposes. *Quarterly Journal of Engineering Geology,* Vol. 17, 381–387.

HAIDER, M J. 1989. Effects of changes in pre-treatments and method of soil testing. Unpublished MSc thesis, University of Nottingham.

HALLAM, J R. 1990. The statistical analysis and summarisation of geotechnical databases. *British Geological Survey Technical Report,* WN/90/16.

HAWKINS, A B, and PINCHES, G M. 1992. Engineering description of mudrocks. *Quarterly Journal of Engineering Geology,* Vol. 25, 17–30.

HEAD, K H. 1992. *Manual of soil laboratory testing. Vol. 1: Soil classification and compaction tests.* 2nd edition. (London: Pentech Press.)

HEAD, K H. 1994. *Manual of soil laboratory testing. Vol. 2: Permeability, compressibility, and shear strength tests.* 2nd edition. (London: Pentech Press.)

HEAD, K H. 1998. *Manual of soil laboratory testing. Vol. 3: Effective stress tests.* 2nd edition (London: Wiley.)

HOBBS, N B. 1975. The factors affecting the prediction of the settlement of structures on rock with particular reference to the Chalk and Trias. Conference on Settlement of Structures, 579–610 (London: Pentech Press.)

HOBBS, P R N, JONES, L D, and CULSHAW, M G. 1994. Effective strength testing and slope stability analysis of a landslip at Gringley-on-the-Hill, Nottinghamshire. *British Geological Survey Technical Report,* WN/94/43C.

HOBBS, P R N, and JONES, L D. 1995. Methods of testing for swelling and shrinkage of soils. *British Geological Survey Technical Report,* WN/95/15.

HOWARD, A S, WARRINGTON, G, AMBROSE, K, and REES, J G. 1998. Lithostratigraphy of the Mercia Mudstone Group of England and Wales. Discussion document for the BGS Stratigraphy Committee by the BGS Permo-Trias Stratigraphical Framework Committee.

HOWARD, A S, YOUNG, S R, WARRINGTON, G, and PHAROAH, T C. In preparation. Geology of the Country around Nottingham. Sheet memoir 126. *Memoir of the British Geological Survey Sheet 126 (England and Wales).*

INSTITUTION OF CIVIL ENGINEERS. 1994. *Site investigation in construction : without site investigation ground is a hazard.* Report of the Site Investigation Steering Group of the Institution of Civil Engineers. (London: Thomas Telford.)

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND FOUNDATION ENGINEERING. 1988. International Reference Test Procedure. Proc. ISOPT-1 Standard Penetration Test (SPT*). International Society for Soil Mechanics and Foundation Engineering,* Vol. 1, 3–26.

JEANS, C V. 1978. The origin of the Triassic clay assemblages of Europe with special reference to the Keuper Marl and Rhaetic of parts of England. *Philosophical Transactions of the Royal Society,* Series A, Vol. 289, 549–639.

JONES, L D. 2000. Results of a user survey into the needs for a greater understanding of shrink swell behaviour. *British Geological Survey Coastal and Engineering Geology Group Project Note,* 2000/03.

JONES, L D. 1998. Determination of the shrinkage and swelling properties of the Mercia Mudstone. *British Geological Survey*

Coastal and Engineering Geology Group Laboratory Report, No. 98/3.

JONES, L D, and HOBBS, P R N. 1994. Triaxial and ring shear testing of samples from Gringley-on-the-Hill, Nottinghamshire, *British Geological Survey, Engineering Geology and Geophysics Group, Laboratory Report,* 94/10.

JONES, L D, and HOBBS, P R N. 1998a. The shrinkage and swelling behaviour of UK soils: Mercia Mudstone. *British Geological Survey Technical Report,* WN/98/14.

JONES, L D, and HOBBS, P R N. 1998b. The Shrinking and swelling properties of the Gault Clay. *British Geological Survey Technical Report,* WN/98/13.

KADIR, A ABD. 1997. The determination of shrinkage limit for clay soils using a travelling microscope with comparison to the established definitive method (TRRL). Unpublished MSc dissertation, University of Leeds.

KEARY, P, and VINE, F. 1990. *Global Tectonics,* (Oxford: Blackwell Scientific Publishers.)

KEELING, P S. 1963. *The geology and mineralogy of British clays.* (Nottingham: Thomas Forman and Sons Ltd for the Brick Development Association.)

KELLAWAY, G A, and WELCH, F B A. 1993. Geology of the Bristol District. *Memoir of the British Geological Survey,* 1: 63 360 geological special sheet (England and Wales).

KOLBUSZEWSKI, J, and SHOJOBI, J O. 1965. Chemical analysis of Keuper Marl — influence of iron oxides on index properties. *Surveyor,* Vol. 125, 3793, 30–33.

LAMBE, T W, and WHITMAN, R V. 1979. *Soil mechanics. SI version.* (New York: Wiley.)

LEACH, B A, MEDLAND, J W, and SUTHERLAND, H B. 1976. The ultimate bearing capacity of bored piles in weathered Keuper Marl. *Proceedings of the 6th European Conference on Soil Mechanics and Foundation Engineering, Vienna,* 1976, Vol. 1.2, 507–514.

LEACH, B A, and THOMPSON, R P. 1979. The design and performance of large diameter bored piles in weak mudstone rocks. *Proceedings of the 7th European Conference on Soil Mechanics and Foundation Engineering, Brighton,* 1979, Vol. 3, 101–108.

LESLIE, A B. 1989. Sedimentology and geochemistry of the Upper Triassic Mercia Mudstone Group and marginal deposits, south-west Britain. Unpublished PhD thesis, University of Durham.

LESLIE A B, SPIRO, B, and TUCKER, M E. 1993. Geochemical and mineralogical variations in the upper Mercia Mudstone Group (Late Triassic), south-west Britain; correlation of outcrop sequences with borehole geophysical logs. *Journal of the Geological Society of London,* Vol. 150, Pt. 1, 67–75.

LITTLE, J A, and HATAF, N. 1990. Some monotonic and cyclic properties of weathered undisturbed and reconstituted Keuper Marl. 303–310 *in* CRIPPS, J C et al. (editors). The Engineering Geology of weak rock. *Engineering Geology Special Publication* No.8 (Rotterdam: Balkema.)

LUPINI, J F, SKINNER, A E, and VAUGHAN, P R. 1981. The drained residual strength of cohesive soils. *Geotechnique,* Vol. 31, No. 2, 181–213.

MADDISON, J D, CHAMBERS, S, THOMAS, A, and JONES, D B. 1996. The determination of deformation and shear strength characteristics of Trias and Carboniferous strata from in situ and laboratory testing for the Second Severn Crossing. 598–609 in *Advances in Site Investigation Practice.* (London: Thomas Telford.)

MAIR, R J, and WOOD, G M. 1987. Pressuremeter testing — methods and interpretation. *Construction Industry Research and Information Association, Ground Engineering Report.* (Butterworths.)

MARSLAND, A. 1977. In situ measurement of the large-scale properties of Keuper Marl. *The Geotechnics of Structurally Complex Formations, Capri,* Vol. 1, 335–344.

MARSLAND, A, BUTCHER, A P, and TAFFS, F H. 1983. The behaviour of a bridge abutment foundation on Keuper Marl during and after construction. *Proceedings of the Institution of Civil Engineers,* Vol. 74, Pt.1, 917–944 .

MARSLAND, A, and POWELL, J J M. 1988. Investigation of cone penetration tests in British clay carried out by the Building Research Establishment 1960–86. 83–88 in *Penetration testing in the UK.* (London: Thomas Telford.)

MARSLAND, A, and POWELL, J J M. 1990. Pressuremeter tests on stiff clays and soft rocks: factors affecting measurements and their interpretation. 91–110 in BELL, F G, et al. (editors). *Field Testing in Engineering Geology. Engineering Geology Special Publication* No. 6. (Rotterdam: Balkema.)

MAYALL, M J. 1981. The late Triassic Blue Anchor Formation and the initial Rhaetic marine transgression in south-west Britain. *Geological Magazine,* Vol. 118, 377–384.

MEIGH, A C. 1976. The Triassic rocks, with particular reference to predicted and observed performance of some major foundations. *Geotechnique,* Vol. 26, Pt.3, 391–452.

MEIGH A C. 1987. Cone penetration testing methods and interpretation. *Construction Industry Research and Information Association, ground engineering report*: *In-situ testing,* (Butterworths.)

MILODOWSKI, A E, STRONG, G E, SPIRO B, KEMP, S J, HYSLOP, E K, LENG, M J, and HASLAM, H. 1994. The diagenesis of the Permo-Triassic rocks of the Cheshire Basin. *British Geological Survey Technical Report,* WG/94/34R.

MOON, V G, and BEATTIE, A G. 1995. Textural and microstructural influences on the durability of Waikato Coal Measures mudrocks. *Quarterly Journal of Engineering Geology,* Vol. 28, 303–312.

MYERS, A, and SINDLE, A. 1994. Abbey Sewer. *World Tunnelling,* February, 3–8.

NEWILL, D. 1961. A laboratory investigation of two red clays from Kenya. *Geotechnique,* Vol. 11, Pt. 4, 302–318.

NORTHMORE, K J, and CULSHAW M G. 1992. Red soils in the sunset. *Earthworks,* Vol. 3, (Keyworth: British Geological Survey.)

NORTHMORE, K J, ENTWISLE, D C, HOBBS, P R N, and CULSHAW, M G. 1993. Engineering geology of tropical red clay soils: geotechnical characterisation: index properties and testing procedures. *British Geological Survey Technical Report,* WN/93/12.

OLD, R A, SUMBLER, M G, and AMBROSE, K. 1987. The geology of the country around Warwick. *Memoir of the British Geological Survey,* Sheet 184 (England and Wales).

OLD, R A, BRIDGE, D McC, and REES, J G. 1989. Geology of the Coventry Area. *British Geological Survey Technical Report,* WA/89/29.

OLD, R A, HAMBLIN, R J O, AMBROSE, K, and WARRINGTON, G. 1991. Geology of the country around Redditch. *Memoir of the British Geological Survey,* Sheet 183, (England and Wales).

PALMER, A C. 1972. Undrained plane strain expansion of a cylindrical cavity in clay: a simple interpretation of the pressuremeter test. *Geotechnique,* Vol. 22, Pt. 3, 451–457.

PARRY, N V, JONES, A J, and DYER, M R. 1996. M5 Avonmouth bridge strengthening — in situ in testing of Mercia Mudstone. 610–622 in *Advances in Site Investigation Practice*. (London: Thomas Telford.)

PEARCE, J M, KEMP, S J, and Hards, V L. 1996. A petrographical and mineralogical study of clay minerals in the Mercia Mudstone. *British Geological Survey Technical Report,* WG/96/22R.

PERRIN, R M S. 1971. *The clay mineralogy of British Sediments*. (London: The Mineralogical Society.)

POWELL, J H. 1998. A guide to British stratigraphical nomenclature. *Construction Industry Research and Information Association Special publication,* No. 149.

POWELL, J J M, QUARTERMAN, R S T, and LUNNE, T. 1988. Interpretation and use of the piezocone test in UK clays. 47–52 in *Penetration testing in the UK*. (London: Thomas Telford.)

PRICE, R D, HOBBS, P R N, and ROGERS, C D F. 1996. Report on a half-day workshop which examined the relative performance of probing and penetration test equipment. *Ground Engineering,* April, 39–40.

RATHBONE, P A. 1989. Geology of the East Bridgford district, 1:10 000 sheet SK64SE: part of 1:50 000 sheet (Nottingham). *British Geological Survey Technical Report,* WA/89/16.

READ, J R L, THORNTON, P N, and REGAN, W H. 1980. A rational approach to the point load test. *Proceedings of the 3rd Australia and New Zealand Conference on Geomechanics*, Wellington, Vol. 2, 35–39.

SARMAN, R, SHAKOOR, A, and PALMER, D F. 1994. A multiple regression approach to predict swelling in mudrocks. *Bulletin of the Association for Engineering Geology*, Vol. 31, No.1, 107–121.

SEEDHOUSE, R L, and SANDERS R L. 1993. Investigations for cooling tower foundations in Mercia Mudstone at Ratcliffe-on-Soar, Nottinghamshire. 465–472 *in* CRIPPS, J C, et al. (editors). The engineering geology of weak rock. *Engineering Geology Special Publication,* No. 8. (Rotterdam: Balkema).

SHAKOOR, A, and SARMAN, R. 1992. Swelling potential classification of mudrocks based on geotechnical properties. Rock Characterisation. 75–80 *in* HUDSON, J (editor). Proceedings of the International Society for Rock Mechanics Symposium: Eurock '92. (British Geotechnical Society).

SHAW, H F. 1981. Mineralogy and petrology of the argillaceous sedimentary rocks of the UK. *Quarterly Journal of Engineering Geology.* Vol. 14, 277–290.

SHEARMAN, D J, MOSSOP, G, DUNSMORE, H, and MARTIN, H. 1972. Origin of Gypsum veins by hydraulic fracture. *Transactions of the institute of Mining and Metallurgy. Section B Applied Earth Sciences*, Vol. 81, 149–55.

SHERWOOD, P T. 1967. Classification tests on African red clays and Keuper Marl. *Quarterly Journal of Engineering Geology* Vol. 1, Pt.3, 47–55 and 207–212 [discussion].

SHERWOOD, P T, and Hollis, B G. 1966. Studies of the Keuper Marl: chemical properties and classification tests. *Ministry of Transport, Road Research Laboratory (TRL) Report,* No. 41.

SHUTTLE, D A, and JEFFERIES, M G. 1996. Reliable parameters from imperfect SBP tests in clay. 571–585 in *Advances in Site Investigation Practice*. (London: Thomas Telford.)

SKEMPTON, A W. 1953. The colloidal activity of clays. *Proceedings of the 3rd International Conference on Soil Mechanics*, Vol. 1. 57–61.

SKEMPTON, A W, and BJERRUM, L. 1957. A contribution to the settlement analysis of foundations on clay. *Geotechnique*, Vol. 7, 168–178.

SKEMPTON and DAVIS 1966 personal communication in CHANDLER, R J, 1969. The effect of weathering on the shear strength properties of Keuper Marl. *Geotechnique,* Vol. 19, Pt.3, 321–334.

SMITH, E G, RHYS, G H, and GOOSENS, R F. 1973. Geology of the Country around East Retford, Workshop and Gainsborough. *Memoir of the British Geological Survey*, Sheet 101 (England and Wales).

SMOLTCZYK, U, HILMER, K, and WEISSMANTEL, R. 1995. Back analyses of pad foundation settlements on hard soil. *XI European Conference on Soil Mechanics and Foundation Engineering - The Interplay between Geotechnical Engineering and Engineering Geology, Copenhagen,* Vol. 1, 253–258.

SNETHEN, D R, JOHNSON, L D, and PATRICK, D M. 1977. An evaluation of expedient methodology for identification of potentially expansive soils. *US Army Engineer Waterways Experiment Station, USAEWES, Vicksburg,* Mis. Report No. FHWA-RD-77-94.

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

STRONG, G E. 1976. Petrology of some Keuper 'skerries' from the Atherstone area (1" Sheet 155). *British Geological Survey, Petrology Unit Internal Report.* No. 101.

STRONG, G E. 1979. Petrology of some Triassic and Jurassic sediments from localities in Warwickshire (1:50 000 Sheet 184). *British Geological Survey, Petrology Unit Report,* No. 171.

STRONG, G E. 1983. Petrology of Triassic and Jurassic specimens from localities in Warwickshire and Worcestershire (1:50 000 sheet 183). *British Geological Survey, Petrology Internal Unit Report,* No. 238.

STRONG, G E. 1992. Petrography of Mercia Mudstone Breccias from the M556 ((M56–M6) improvement area, near Knutsford, Cheshire. *British Geological Survey Technical Report,* WG/92/2R.

STROUD, M A. 1974. The Standard Penetration Test in insensitive clays and soft rocks. *Proceedings of the European Symposium on Penetration Testing*, ESOPT 1, 367–375.

STROUD, M A. 1989. The standard penetration test - its application and interpretation. 29–49 in *Proceedings of the Symposium on Penetration Testing in the UK*. University of Birmingham. (London: Thomas Telford.)

STROUD, M A, and BUTLER, F J. 1975. The standard penetration test and the engineering properties of glacial materials *Proceedings of the Symposium on the behaviour of glacial materials,* University of Birmingham, 124–135

TAYLOR, B J, PRICE, R H, and TROTTER, F M. 1963. Geology of the Country around Stockport and Knutsford. *Memoir of the British Geological Survey,* Sheet 98 (England and Wales).

TAYLOR, R K, and SPEARS, D A. 1981. Laboratory investigation of mudrocks. *Quarterly Journal of Engineering Geology,* Vol. 14, 291–309.

TAYLOR, R K, and SMITH, T J. 1986. The engineering geology of clay minerals: swelling, shrinking and mudrock breakdown. *Clay Minerals*, Vol. 21, 235–260.

TAYLOR, S R. 1982. Clay mineralogy and dolomite oxygen isotope geochemistry; a new approach to lithostratigraphic correlation of fine-grained unfossiliferous red beds. *Proceedings of the Eleventh International Congress on Sedimentology, Hamilton, Ontario,* 22–27.

TELLAM, J H, and LLOYD, J W. 1981. Hydrogeology of British onshore non-carbonate mudrocks. *Quarterly Journal of Engineering Geology*, Vol. 14, 347–355.

TERZAGHI, K. 1936. Presidential address — the relationship between soil mechanics and foundation engineering. *Proceedings of the first International Conference on Soil Mechanics and Foundation Engineering, Harvard University,* Vol. 3, 13–18.

THOMAS, I A. 1973. Celestite. *Institute of Geological Sciences Mineral Dossier,* No. 6.

THOMPSON, R P, NEWMAN, R L, and DAVIS, P D. 1993. Advances in the in situ testing of weak mudstone. 303–310 *in* CRIPPS, J C et al. (editors). The engineering geology of weak rock. *Engineering Geology Special Publication,* No. 8. (Rotterdam: Balkema.)

VIJAYVERGIYA, V N, and SULLIVAN, R A. 1974. Simple technique for identifying heave potential. *Bulletin of the Association for Engineering Geology,* Vol. 11, Pt. 4, 277–292.

WARRINGTON, G, and IVIMEY-COOKE, H C. 1992. Triassic. 97–106 *in* COPE, J C W, INGHAM, K K, and RAWSON, P F. (editors). Atlas of Palaeogeography and Lithofacies. *Geological Society Memoir,* No. 13.

WARRINGTON, G, AUDLEY-CHARLES, M G, ELLIOT, R E, EVANS, W B, IVIMEY-COOK, H C, KENT, P E, ROBINSON, P, SHOTTON, F W, and TAYLOR, F M. 1980. A correlation of Triassic rocks in the British Isles. *Geological Society Special Report,* No. 13.

WATERS, R A, and LAWRENCE, D J D. 1988. Geology of the South Wales Coalfield, Part III, the country around Cardiff. Third edition. *Memoir of the British Geological Survey,* Sheet 263 (England and Wales).

WILLIAMS, A A B, and DONALDSON, G W. 1980. Building on expansive soils in South Africa, 1973–1980. *Proceedings of the 4th International Conference on Expansive Soils, ASCE, Denver,* Vol. 2, 834–844.

WILSON, A A. 1993. The Mercia Mudstone Group (Trias) of the Cheshire Basin. *Proceedings of the Yorkshire Geological Society*, Vol. 49, 171–188.

WORSSAM, B C, and OLD, R A. 1988. Geology of the Country around Coalville. *Memoir of the British Geological Survey*, Sheet 155, (England and Wales).

YONG, R N, and WARKENTIN, B P. 1975. Soil properties and behaviour. *in Developments in Geotechnical Engineering,* No. 5. (Amsterdam: Elsevier.)

ZUIDBERG, H M, and POST, M L. 1995. The cone pressuremeter: an efficient way of pressuremeter testing. *Proceedings of the 4th International Symposium on The Pressuremeter and its New Avenues, Sherbrooke, Canada.*

Appendix — Statistical summary of geotechnical data

Key

GEOTECHNICAL DATA

Index tests

NMC	Natural moisture content
BD	Bulk density
DD	Dry density
LL	Liquid limit
PL	Plastic limit
PI	Plasticity index
LI	Liquidity index

Chemical tests

TS	Total sulphate content (soil)
AS	Aqueous sulphate content
pH	pH value (soil)

Strength tests

PLA	Point load (axial)
PLD	Point load (diametral)
UCS	Uniaxial (unconfined) compression test
CU	Undrained cohesion

Consolidation tests

c_v	Coefficient of consolidation
m_v	Coefficient of volume compressibility

Compaction tests

OMC	Optimum moisture content
MDD	Maximum dry density
CBR	California bearing ratio
MCV	Moisture condition value

In situ tests

SPT	Standard penetration test

AREAS

Area 1	Cheshire
Area 2	Staffordshire
Area 3	Worcestershire
Area 4	Severn estuary
Area 5	East Devonshire
Area 6	Warwickshire
Area 7	Leicestershire
Area 8	Nottinghamshire and south Derbyshire
Area 9	Humberside
Area 10	Teeside

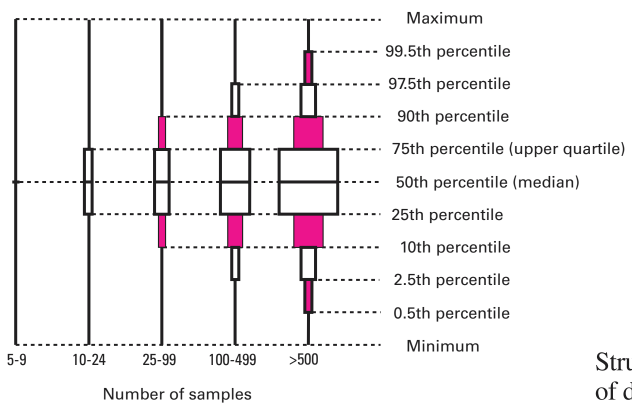
STRATIGRAPHY

LKM	Lower Keuper Marl [Area 1]
LKSB	Lower Keuper Saliferous Beds [Area 1]
MKM	Middle Keuper Marl [Area 1]
ElM	Eldersfield Mudstone Formation [Area 3]
TwM	Twyning Mudstone Formation [Area 3]
CBp	Cropwell Bishop Formation [Area 8]
Edw	Edwalton Formation [Area 8]
Gun	Gunthorpe Formation [Area 8]
Rdc	Radcliffe Formation [Area 8]
Snt	Sneinton Formation [Area 8]
Rw	*Glacially reworked*

(The Mercia mudstones in areas other than 1, 3 and 8 are not subdivided stratigraphically in this statistical review)

WEATHERING ZONES

1	Unweathered (no matrix) [rock]
2	Slightly weathered (matrix in joints) [rock]
3	Moderately weathered (undifferentiated) [soil]
3a	Moderately weathered (matrix/frequent lithorelicts) [soil]
3b	Moderately weathered (matrix/some lithorelicts) [soil]
4	Highly weathered (undifferentiated) [soil]
4a	Highly weathered (occasional claystones) [soil]
4b	Fully weathered (matrix only) [soil]



Structure of extended box plots for 'normal' distribution of data values.

INDEX TESTS — Natural moisture content

Natural moisture content (NMC, w %) — AREA 1

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*447*	3	6	11	15	**20**	24	28	34.9	61
LKM 1	*18*	3			6.3	**8**	10.8			14
LKM 2	*8*	4				**7**				13
LKM 3/4a	*6*	7				**13.5**				18
LKM 3a/3b	*7*	6				**11**				14
LKM 3a/4	*9*	11				**14**				20
LKM 3b	*14*	6			11.8	**15.5**	17.8			28
LKM 3b/4	*14*	9			12.3	**13.5**	15			35
LKM 4	*38*	4		8	10	**13.5**	15.8	21		35
LKSB 3a	*7*	6				**16**				34
LKSB 3b	*23*	14			18	**22**	28.5			37
LKSB 3b/4	*10*	17			18.8	**23**	26			42
LKSB 4	*28*	8		16	17	**19**	24	26.3		46
MKM 3/4	*11*	17			18	**20**	23			32
MKM 3a	*25*	11		14.4	16	**20**	25	29.6		44
MKM 3b	*19*	18			19	**22**	25			32
MKM 3b/4	*48*	7		15	19.8	**21.5**	24	26		47
MKM 4	*138*	13	14.4	16.7	20	**22**	25	29	33	61

LKM Lower Keuper Marl
LKSB Lower Keuper Saliferous Beds
MKM Middle Keuper Marl

Natural moisture content (NMC, w %) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*1310*	2	8	12	16	**20**	24	28	34	46
2	*31*	7		9	11.5	**16**	19	24		30
2/3	*46*	7		10.5	13	**15**	19	21.5		30
3	*367*	2	7	12	14	**18**	22	26	31	37
3/4a	*151*	6	10.8	13	15	**19**	24	28	34	41
4a/4b	*6*	18				**21.5**				32
4b	*14*	11			19	**21**	22.8			33
Rw	*134*	4	10	13	17	**21**	25	30	36.4	41

Rw = Reworked

Natural moisture content (NMC, w %) — AREA 3

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*139*	9	10	12	15	**18**	22	25	29	48
TwM 2	*42*	9		11.1	13	**16**	19	24.9		
TwM 3a	*25*	12		13	14	**17**	19	23		27
TwM 4	*6*	13				**18.5**				

TwM Twyning Mudstone Formation

Natural moisture content (NMC, w %) — AREA 4

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*107*	3	4	6	10.5	**19**	25	29.4	36.1	48
1/2	*11*	5			6.5	**8**	9.5			12
2	*11*	4			6.5	**8**	22.5			25
2/3	*8*	7				**21.5**				34
3	*24*	3			12	**18.5**	23.3			31
3/4a	*11*	7			11.5	**15**	20			25
4a	*20*	11			20.8	**22.5**	32			48
4b	*15*	8			24	**26**	28.5			33

Natural moisture content (NMC, w %) — AREA 5

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*63*	14	15.6	18	20.5	**23**	26	29	30	31
3	*21*	14			19	**22**	23			
4a	*22*	16			22.3	**25**	29			30
4b	*18*	18			20.3	**22**	24.8			31

Natural moisture content (NMC, w %) — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*220*	10	12	14	17	**20**	26	33	39.5	48
2	*11*	12			15	**16**	18.5			19
3	*40*	12		14.9	17	**18**	20	23		29
3a	*9*	10				**18**				36
3a/4	*7*	13				**18**				33
3b	*42*	10		15	17	**19.5**	26	18.9		39
3b/4	*39*	17		18	20	**27**	33	40.8		48
4	*39*	13		14	18	**21**	27	29.6		36
4a	*7*	17				**24**				29
Rw	*19*	12			15.5	**20**	26.5			41

Natural moisture content (NMC, w %) — AREA 7

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*222*	9	9.5	12	15	**19**	22	24	27	35
2	*9*	10				**15**				27
2/3	*12*	12			12.8	**14.5**	16			20
3	*73*	9		11	14	**19**	22	24		31
3/4a	*51*	9		12	16.5	**19**	23	26		29
4a	*40*	11		14	16	**19**	23	24.1		35
4b	*7*	14				**20**				27
Rw	*30*	9		12.8	14.3	**17**	20	22.2		27

Rw = Reworked

Natural moisture content (NMC, w %) — AREA 8

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*663*	4	10	12	15	**18**	23	28	34.5	74
CBp 1	*10*	8			11	**11.5**	13.8			16
CBp 2	*38*	10		11	13	**15**	17	20.3		22
CBp 3	*139*	9	10.5	13	15	**17**	21.5	24.2	31.1	35
CBp 4a	*47*	8		14.6	17	**20**	25	32.4		40
CBp 4b	*28*	11		12.7	15.8	**20**	24.5	28.3		37
CBp Rw	*10*	7			16	**19**	20.8			23
Edw 2	*9*	13				**19**				74
Edw 3	*12*	13			21	**16**	30.3			36
Edw 3/4a	*6*	17				**25.5**				38
Edw 4a	*26*	16		17	22.3	**25**	28.8	31.5		34
Edw 4b	*29*	12		19.6	23	**27**	32	35.6		58
Gun 2	*19*	11			14	**17**	20.5			25
Gun 2/3	*8*	14				**15**				21
Gun 3	*57*	10		12.6	14	**16**	19	22.4		33
Gun 3/4a	*48*	10		13.7	15	**17**	21	25		31
Gun 4a	*46*	6		14	16	**19**	21.8	24		32
Gun 4b	*12*	11			14.5	**17.5**	21.3			34
Rdc 4a	*8*	10				**17.5**				24
Snt 3	*7*	12				**14**				20
Snt 3/4a	*10*	13			16.5	**19.5**	20.8			22
Snt 4a	*7*	14				**17**				20

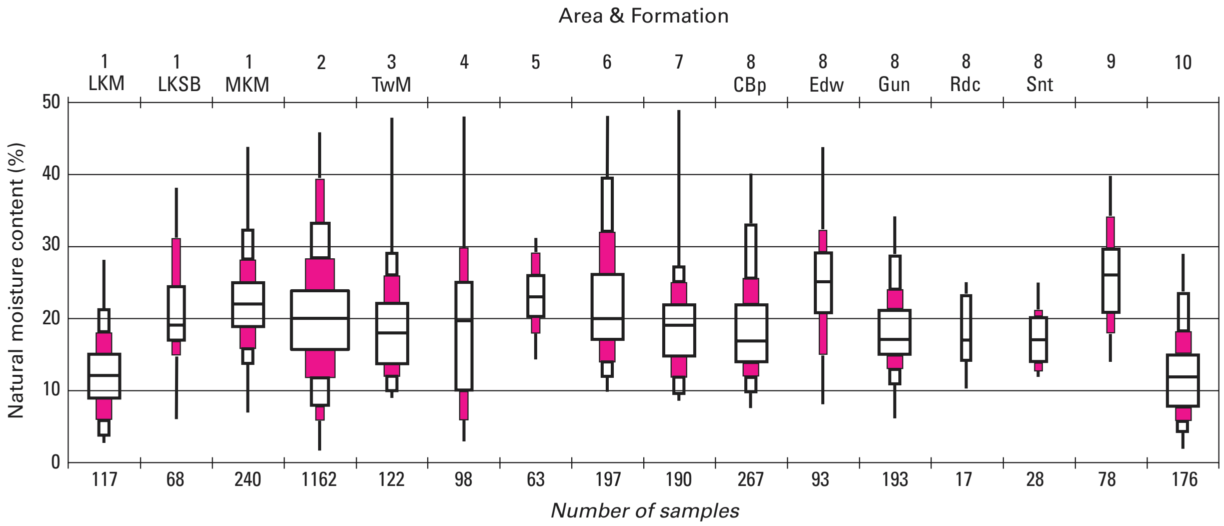
CBp	Cropwell Bishop Formation	Gun	Gunthorpe Formation
Edw	Edwalton Formation	Rdc	Radcliffe Formation
Snt	Sneinton Formation	*Rw*	*Reworked*

Natural moisture content (NMC, w %) — AREA 9

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*79*	14		18	21	**26**	30	34.2		69
2	*6*	21				**24.5**				69
2/3a	*13*	14			19	**27**	29			37
3a	*5*	18				**21**				40
3a/3b	*7*	18				**22**				28
4a	*33*	16		18	22	**26**	30	34.4		37
4b	*8*	21			23.8	**27.5**	31			35

Natural moisture content (NMC, w %) — AREA 10

	No.	Min.	2.5	10	25	**50**	75	90	97.5	
Stratig. &/or weath. zone										
All data	*179*	2	4.5	6	8	**12**	15	18	23	28
1	*24*	3			9	**10**	15.3			19
2	*28*	2		6	8	**9**	13	15		19
3	*52*	3		6	7	**9**	11	12.9		19
3/4a	*6*	4				**12**				21
4a	*45*	4		8.4	11	**14**	17	19.6		28
4b	*20*	10			13.8	**15**	18			26



Extended box plots showing graphical summary of moisture content data.

INDEX TESTS — Bulk density

Bulk density, BD (Mg/m³) — AREA 1

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*43*	1.90		1.92	1.96	**2.01**	2.06	2.1		2.14
LKM 4	*6*	1.92				**2.04**				2.14
MKM 4	*26*	1.92		1.94	1.96	**2.03**	2.05	2.08		2.13

LKM Lower Keuper Marl
MKM Middle Keuper Marl

Bulk density, BD (Mg/m³) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*165*	1.47	1.75	1.84	1.92	**2.01**	2.07	2.13	2.20	2.31
3	*17*	1.91			1.98	**2.02**	2.04			2.10
3/4a	*31*	1.85		1.91	1.98	**2.04**	2.09	2.16		2.23
4a	*87*	1.47		1.80	1.89	**1.99**	2.06	2.12		2.20
Rw	*24*	1.86			1.95	**2.03**	2.09			2.31

Bulk density, BD (Mg/m^3) — AREA 3

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*83*	1.74		1.91	1.98	**2.04**	2.10	2.16		2.35
TwM 2	*7*	1.93				**2.06**				2.21
TwM 3a	*14*	1.97			1.98	**2.03**	2.10			2.16
TwM 3b	*43*	1.78		1.87	1.98	**2.04**	2.10	2.14		2.28
TwM 4	*6*	1.81				**1.99**				2.15

TwM Twyning Mudstone Formation

Bulk density, BD (Mg/m^3) — AREA 4

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*41*	1.74		1.99	2.03	**2.27**	2.42	2.44		2.47
1/2	*9*	2.28				**2.42**				2.47
2	*10*	2.01			2.06	**2.36**	2.42			2.46
3	*6*	2.01				**2.30**				2.42
4a	*6*	1.95				**2.01**				2.05

Bulk density, BD (Mg/m^3) — AREA 5

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*22*	1.83			2.02	**2.07**	2.10			2.21
3	*9*	1.83				**2.08**				2.11
4a	*5*	2.01				**2.03**				2.08
4b	*8*	2.02				**2.11**				2.21

Bulk density, BD (Mg/m^3) — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*6*	1.78				**2.12**				2.19

Bulk density, BD (Mg/m^3) — AREA 7

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*70*	1.75		1.82	1.92	**2.01**	2.08	2.15		2.36
3	*23*	1.75			1.87	**2.01**	2.06			2.17
3/4a	*10*	1.92			2.00	**2.01**	2.03			2.14
4a	*19*	1.78			1.91	**2.04**	2.07			2.16
Rw	*11*	1.8			1.94	**2.08**	2.15			2.36

Bulk density, BD (Mg/m³) — AREA 8

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*415*	1.37	1.78	1.85	1.95	**2.03**	2.10	2.16	2.26	2.52
CBp 2	*12*	1.98			2.01	**2.09**	2.21			2.21
CBp 3	*111*	1.79	1.81	1.92	1.98	**2.04**	2.10	2.14	2.17	2.18
CBp 4a	*36*	1.74		1.87	1.93	**2.01**	2.07	2.12		2.17
CBp 4b	*21*	1.81			1.92	**1.97**	2.01			2.17
CBp Rw	*8*	1.97				**2.04**				2.26
Edw 3	*10*	1.64			1.84	**1.94**	2.03			2.11
Edw 4a	*18*	1.84			1.87	**1.91**	2.00			2.09
Edw 4b	*27*	1.37		1.72	1.82	**1.86**	1.99	2.05		2.11
Gun 2	*7*	2.03				**2.12**				2.16
Gun 3	*25*	1.87		2.01	2.05	**2.12**	2.19	2.32		2.41
Gun 3/4a	*29*	1.84		1.95	2.00	**2.06**	2.12	2.16		2.30
Gun 4a	*33*	1.83		1.94	2.00	**2.07**	2.17	2.22		2.52
Snt 4a	*6*	1.97				**2.11**				2.18

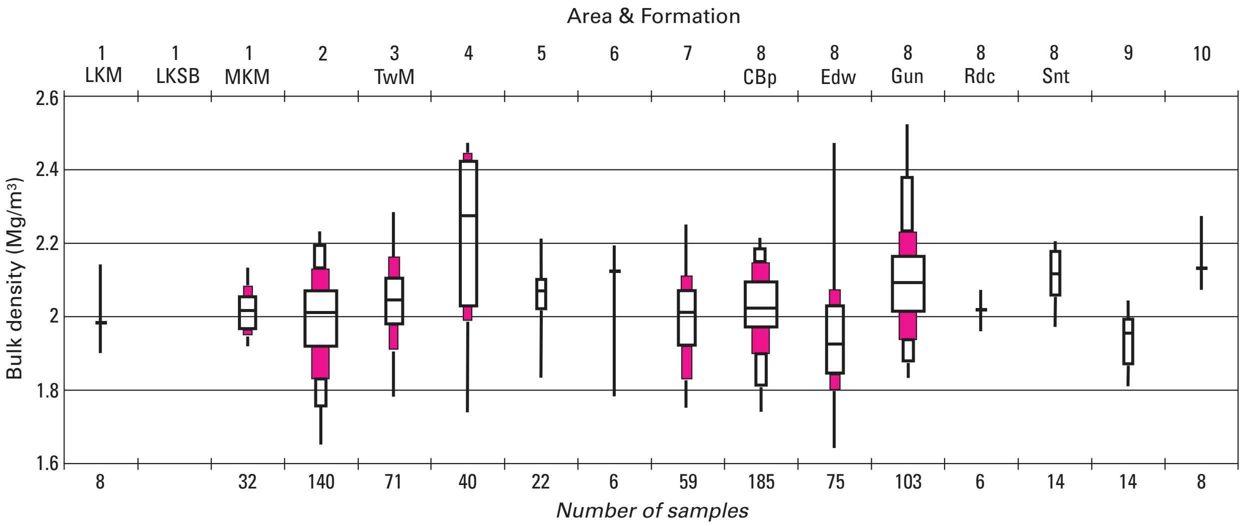
CBp Cropwell Bishop Formation
Edw Edwalton Formation
Gun Gunthorpe Formation
Snt Sneinton Formation
Rw *Reworked*

Bulk density, BD (Mg/m³) — AREA 9

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*14*	1.82			1.87	**1.96**	1.99			2.04
3b	*9*	1.85				**1.99**				2.04

Bulk density, BD (Mg/m³) — AREA 10

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*8*	2.07				**2.13**				2.27



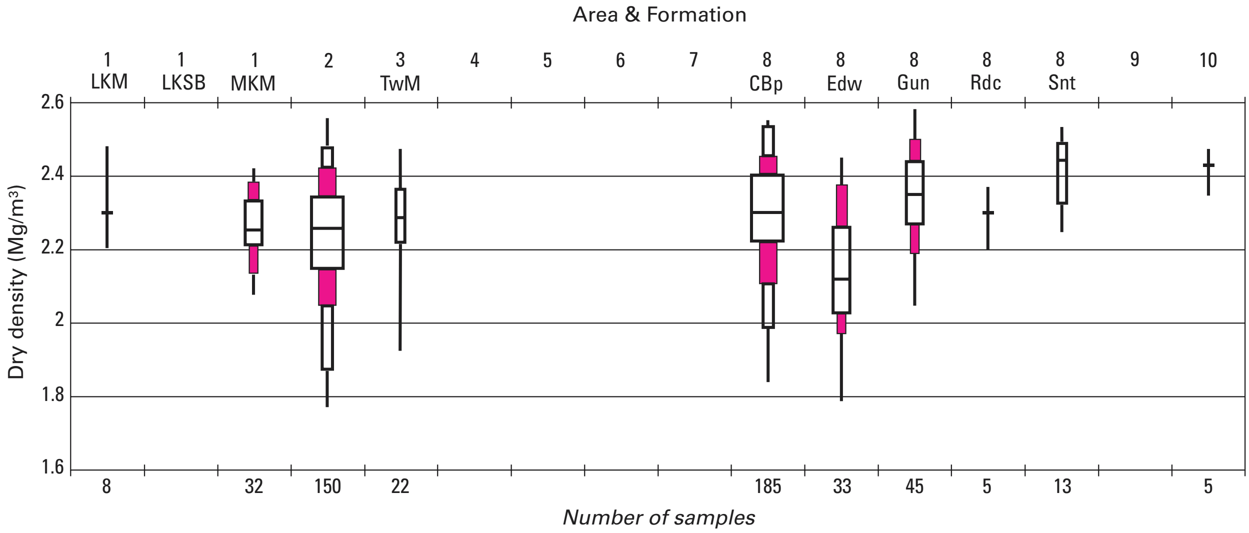
Extended box plots showing graphical summary of bulk density data.

INDEX TESTS — Dry density

Dry density, DD, γ_d (Mg/m^3) — All data

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*536*	1.05	1.32	1.47	1.60	**1.68**	1.78	1.84	1.93	2.06
Area 1 LKM	*8*	1.60				**1.70**				1.88
Area 1 MKM	*33*	1.48		1.54	1.61	**1.66**	1.73	1.78		1.82
Area 2	*176*	1.17	1.26	1.44	1.55	**1.65**	1.74	1.82	1.92	2.06
Area 3 TwM	*22*	1.32			1.62	**1.69**	1.76			1.87
Area 8 CBp	*195*	1.24	1.39	1.51	1.62	**1.70**	1.79	1.85	1.93	2.02
Area 8 Edw	*34*	1.05		1.37	1.43	**1.52**	1.68	1.81		1.85
Area 8 Gun	*45*	1.45		1.59	1.67	**1.75**	1.84	1.90		1.98
Area 8 Rdc	*5*	1.60				**1.70**				1.77
Area 8 Snt	*13*	1.65			1.73	**1.85**	1.89			1.93
Area 10	*5*	1.75				**1.83**				1.87

LKM Lower Keuper Marl
MKM Middle Keuper Marl
TwM Twyning Mudstone Formation
CBp Cropwell Bishop Formation
Edw Edwalton Formation
Gun Gunthorpe Formation
Rdc Radcliffe Formation
Snt Sneinton Formation



Extended box plots showing graphical summary of dry density data.

INDEX TESTS — Liquid limit

Liquid limit (LL) — AREA 1

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*274*	17		28	34	**44**	52	59		76
LKM 3/4a	*6*	17				**23.5**				24
LKM 3a/3b	*7*	25				**28**				33
LKM 3a/4	*7*	28				**31**				36
LKM 3b	*8*	27				**29.5**				34
LKM 3b/4	*11*	25			27.5	**29**	30.5			33
LKM 4	*14*	24			28.3	**29**	30			41
LKSB 3a	*7*	33				**38**				50
LKSB 3b	*16*	36			38.8	**43**	44.3			55
LKSB 3b/4	*5*	41				**43**				53
LKSB 4	*16*	31			40	**42.5**	45.3			54
MKM 3/4	*8*	33				**44.5**				65
MKM 3a	*22*	34			39	**46**	52			67
MKM 3b	*17*	26			45	**51**	55			76
MKM 3b/4	*24*	32			41	**47**	50.5			66
MKM 4	*88*	26		38	45	**51**	58	61		69

LKM Lower Keuper Marl
LKSB Lower Keuper Saliferous Beds
MKM Middle Keuper Marl

Liquid limit (LL) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*1271*	11	23	26	29	**32**	36	43	54.3	133
2	*31*	17		21	24	**27**	31	37		45
2/3	*41*	20		25	26	**31**	34	40		106
3	*356*	11	23	26	28	**31**	35	41	51.1	81
3/4a	*147*	21	24	26	29	**32**	35	37.4	47.7	67
4a/4b	*6*	27				**32**				46
4b	*12*	26			29	**36**	39			47
Rw	*132*	17	24	26	29.8	**34.5**	41	46.9	56.7	133

Liquid limit (LL) — AREA 3

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*126*	22	24	26	29	**32**	36	42	50.6	57
TwM 2	*40*	24		26	27.8	**30**	35	40.2		57
TwM 3a	*22*	22			30	**31.5**	33.8			43
TwM 4	*5*	24				**35**				53

TwM Twyning Mudstone Formation

Liquid limit (LL) — AREA 4

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*61*	20		28	33	**37**	49	54		64
3	*15*	25			31	**34**	45			49
3/4a	*11*	20			28.5	**33**	37			41
4a	*13*	33			37	**37**	40			64
4b	*15*	33			47.5	**51**	54.5			63

Liquid limit (LL) — AREA 5

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*57*	30		32	35	**37**	40	43		49
3	*18*	30			35	**37**	38.8			45
4a	*21*	32			36	**39**	41			49
4b	*16*	31			34.8	**36**	37			47

Liquid limit (LL) — AREA 6

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*170*	23	28	31	34	**40**	46.8	59	76.4	92
2	*10*	32			33.3	**34**	36			37
3	*39*	28		32	35.5	**39**	42	43.2		47
3a	*5*	28				**31**				37
3a/4	*6*	23				**30.5**				45
3b	*30*	29		30.8	32	**39.5**	49.8	58.4		92
3b/4	*32*	31		36	40.3	**45**	59.8	69.3		89
4	*24*	24			31	**38.5**	45.5			56
4a	*7*	35				**47**				49
Rw	*15*	33			35.5	**47**	56			64

Liquid limit (LL) — AREA 7

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*138*	17	21	25	29	**32**	35	41	45.6	53
2/3	*8*	24				**30**				35
3	*46*	21		25	29.3	**31**	33.8	35.5		41
3/4a	*34*	17		26	30	**32**	34	37		42
4a	*23*	28			31.5	**36**	42			53
4b	*5*	31				**41**				45
Rw	*18*	17			25.8	**30.5**	34			52

Liquid limit (LL) — AREA 8

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*409*	17	24.4	28	31	**34**	38	43	52.8	68
CBp 2	*7*	28				**35**				35
CBp 3	*80*	27		28	30	**33**	36	39.1		45
CBp 4a	*24*	27			30	**36**	39.5			52
CBp 4b	*20*	27			29	**30.5**	35.3			59
CBp Rw	*9*	26				**31**				41
Edw 3	*11*	33			35	**38**	42.5			53
Edw 4a	*23*	30			35	**38**	44			68
Edw 4b	*23*	33			36.5	**41**	46.5			58
Gun 2	*11*	28			29.5	**31**	35			38
Gun 2/3	*5*	31				**33**				37
Gun 3	*39*	28		30	30.5	**34**	36	38.2		47
Gun 3/4a	*27*	17		30.6	32	**34**	37	42.4		44
Gun 4a	*28*	26		30.4	32	**34**	40.3	46.3		58
Gun 4b	*9*	23				**35**				53
Snt 3	*6*	22				**31**				34
Snt 3/4a	*9*	26				**32**				37

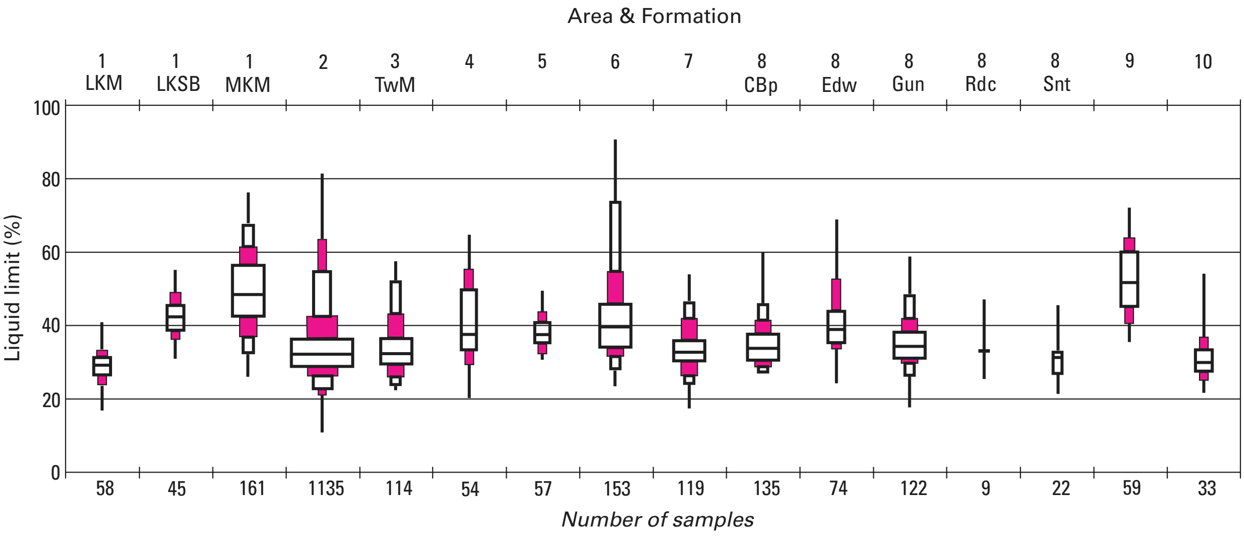
CBp	Cropwell Bishop Formation
Edw	Edwalton Formation
Gun	Gunthorpe Formation
Snt	Sneinton Formation
Rw	*Reworked*

Liquid limit (LL) — AREA 9

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*59*	36		41	46	**52**	60.5	64.2		71
2/3a	*7*	40				**47**				57
3a	*5*	36				**45**				68
3a/3b	*5*	38				**50**				55
3b	*23*	41			47.5	**55**	61			71
4a	*5*	51				**59**				62
4b	*8*	40				**61.5**				69

Liquid limit (LL) — AREA 10

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*33*	22		25	28	**30**	33	36.6		54
3	*13*	22			26	**28**	30			35
4a	*13*	28			30	**33**	33			40



Extended box plots showing graphical summary of liquid limit data.

INDEX TESTS — Plastic limit

Plastic limit, PL (%) — AREA 1

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*272*	12	14.8	17	19	**23**	28	32	36	39
LKM 3/4a	*6*	13				**14.5**				15
LKM 3a/3b	*6*	17				**18.5**				19
LKM 3a/4	*7*	14				**17**				20
LKM 3b	*8*	13				**17**				20
LKM 3b/4	*11*	16			17	**18**	19			21
LKM 4	*14*	16			17.3	**18**	19			23
LKSB 3a	*7*	18				**22**				29
LKSB 3b	*16*	19			23	**24.5**	26			32
LKSB 3b/4	*5*	23				**24**				28
LKSB 4	*16*	15			22	**25**	27			35
MKM 3/4	*8*	21				**23.5**				37
MKM 3a	*22*	19			22.3	**26.5**	30			38
MKM 3b	*17*	13			23	**27**	33			36
MKM 3b/4	*24*	18			21	**24**	28.3			37
MKM 4	*87*	12		20	23	**26**	29	33.4		39

KM Lower Keuper Marl LKSB Lower Keuper Saliferous Beds MKM Middle Keuper Marl

Plastic limit, PL (%) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*1206*	9	13	16	18	**20**	23	26	30	35
2	*27*	12		14.6	15	**17**	19.5	22.2		29
2/3	*38*	12		14.7	16	**19**	20	21.3		36
	332	10	14	15	17	**19**	22	26	29	39
3/4a	*142*	13	15	16.1	18	**19**	22	24.9	28	30
4a/4b	*6*	18				**20.5**				26
4b	*12*	10			15.8	**19.5**	21.5			28
Rw	*125*	9	12.1	14	17	**20**	23	26.6	28.9	55

Plastic limit, PL (%) — AREA 3

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*124*	9	13	15	17	**18**	21	24	27.9	31
TwM 2	*40*	9		14.9	16.8	**18**	22	24.1		31
TwM 3a	*22*	13			18	**19**	21.5			28
TwM 3b	*44*	10		15	16	**17.5**	21	24		31

TwM Twyning Mudstone Formation

Plastic limit, PL (%) — AREA 4

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*58*	18		18	21	**24**	28.8	36.3		38
3	*15*	18			20	**21**	24.5			29
3/4a	*9*	18				**22**				26
4a	*13*	18			21	**24**	24			38
4b	*14*	25			30	**34**	37			38

Plastic limit, PL (%) — AREA 5

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*57*	9		15	17	**22**	24	26		28
3	*18*	9			20	**23.5**	24.8			28
4a	*21*	15			19	**22**	24			28
4b	*16*	12			15.8	**18**	22			26

Plastic limit, PL (%) — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*169*	13	15	18	20	**23**	27	31	39	50
2	*10*	18			20	**22**	25.3			29
3	*39*	16		19	20	**22**	25	27.2		30
3a	*5*	13				**19**				23
3a/4	*6*	14				**20**				26
3b	*30*	16		17	20	**21**	29.5	31.6		50
3b/4	*31*	18		19	22	**26**	35	38		44
4	*24*	14			18	**21.5**	26.5			32
4a	*7*	20				**25**				30
Rw	*15*	17			19	**24**	27.5			39

Rw = Reworked

Plastic limit, PL (%) — AREA 7

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*129*	11	13.2	16	18	**20**	22	24	28	34
2/3	*8*	13				**18**				20
3	*42*	12		16	17	**20**	22.8	25.8		30
3/4a	*30*	14		16	17.3	**19**	21	24		27
4a	*23*	16			20	**22**	23			31
4b	*5*	17				**19**				22
Rw	*17*	11			15	**19**	24			34

Rw = Reworked

Plastic limit, PL (%) — AREA 8

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*404*	10	14	15	17	**19**	22	26	31	43
CBp 2	*7*	16				**16**				19
CBp 3	*80*	15		15	16.8	**18**	19	20.1		24
CBp 4a	*24*	13			16	**18.5**	21.3			33
CBp 4b	*20*	15			17	**18.5**	21.3			27
CBp Rw	*9*	14				**17**				19
Edw 3	*9*	19				**27**				37
Edw 4a	*22*	11			19.3	**24**	25.8			43
Edw 4b	*23*	15			21	**24**	26.5			38
Gun 2	*11*	17			17.5	**19**	20			24
Gun 2/3	*5*	17				**20**				21
Gun 3	*39*	10		15.8	18	**19**	20.5	22.2		30
Gun 3/4a	*26*	15		18	19	**20**	21.8	23.5		26
Gun 4a	*28*	16		17.4	18	**19.5**	22	24.3		31
Gun 4b	*9*	16				**19**				23
Snt 3	*6*	13				**18**				20
Snt 3/4a	*9*	15				**19**				20

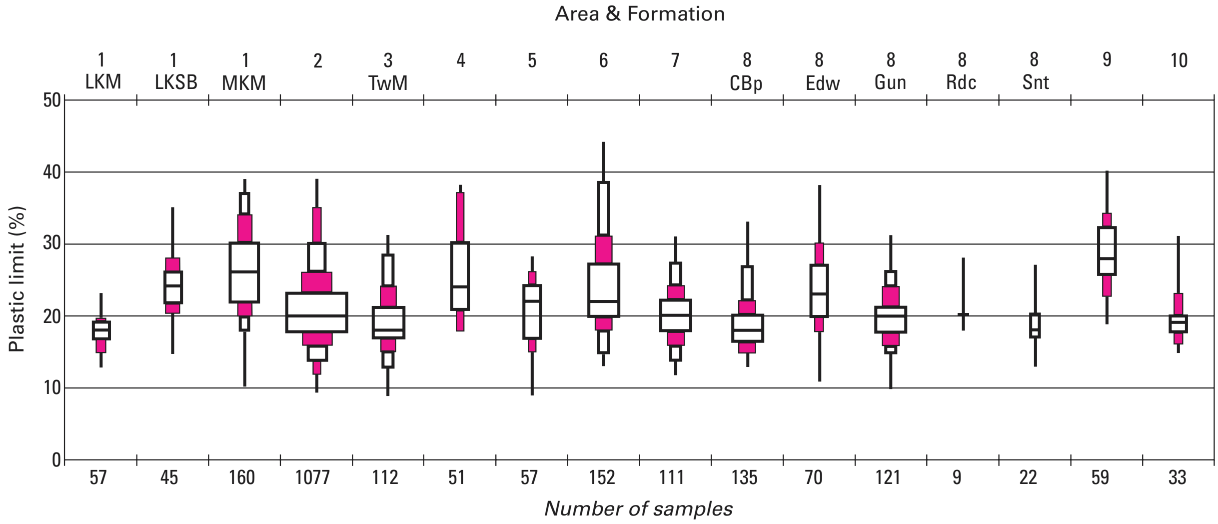
CBp Cropwell Bishop Formation
Edw Edwalton Formation
Snt Sneinton Formation
Gun Gunthorpe Formation
Rdc Radcliffe Formation
Rw Reworked

Plastic limit, PL (%) — AREA 9

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*59*	19		22.8	26	**28**	32	34.2		40
2/3a	*7*	20				**24**				34
3a	*5*	22				**27**				40
3a/3b	*5*	23				**27**				32
3b	*23*	19			26	**29**	32			36
4a	*5*	26				**32**				35
4b	*8*	22				**31**				34

Plastic limit, PL (%) — AREA 10

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*33*	15		16.2	18	**19**	20	23		31
3	*13*	16			17	**18**	19			23
4a	*13*	17			19	**20**	20			23



Extended box plots showing graphical summary of plastic limit data.

INDEX TESTS — Plasticity index

Plasticity index, PI (%) — AREA 1

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*272*	4	8	10.1	14	**19**	24	29	36.2	46
LKM 3/4a	*6*	4				**9**				9
LKM 3a/3b	*6*	7				**10**				14
LKM 3a/4	*7*	11				**14**				19
LKM 3b	*8*	9				**14**				17
LKM 3b/4	*11*	7			9	**11**	13			14
LKM 4	*14*	8			10.3	**11**	12			22
LKSB 3a	*7*	14				**16**				21
LKSB 3b	*16*	13			16.8	**17.5**	19.3			24
LKSB 3b/4	*5*	17				**19**				28
LKSB 4	*16*	14			17	**18**	20			22
MKM 3/4	*8*	12				**21**				28
MKM 3a	*22*	13			15.3	**18**	20.8			40
MKM 3b	*17*	13			20	**23**	25			40
MKM 3b/4	*24*	14			18	**21.5**	23.3			32
MKM 4	*87*	12		17.6	20	**25**	29	32.4		46

LKM Lower Keuper Marl
LKSB Lower Keuper Saliferous Beds
MKM Middle Keuper Marl

Plasticity index, PI (%) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*1206*	2	7	9	10	**13**	15	20	27	78
2	*27*	2		7.6	9.5	**11**	13	14.8		16
2/3	*38*	6		9	10	**13**	15	21		70
3	*332*	4	7	8	10	**12**	14	17	25	42
3/4a	*142*	3	6	8	10	**12**	14	16.9	22	40
4a/4b	*6*	9				**12**				20
4b	*12*	8			12.8	**16**	17.3			28
Rw	*125*	2	9	11	12	**15**	19	25.6	32.7	78

Rw = reworked

Plasticity index, PI (%) — AREA 3

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*124*	7	9	10	11	**13**	17	20.7	27	31
TwM 2	*40*	9		10	11	**12**	16	17		26
TwM 3a	*22*	7			10.3	**12**	14.8			20
TwM 3b	*44*	9		10.3	13	**14**	17.3	21.8		27

TwM Twyning Mudstone Formation

Plasticity index, PI (%) — AREA 4

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*58*	3		8.4	12	**15**	18.8	23.3		29
3	*15*	3			10	**13**	20.5			26
3/4a	*9*	7				**12**				19
4a	*13*	9			14	**15**	18			26
4b	*14*	9			15	**17.5**	19.5			29

Plasticity index, PI (%) — AREA 5

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*57*	10		10.6	13	**16**	20	23		28
3	*18*	10			11.3	**16**	17.8			22
4a	*21*	10			14	**16**	21			26
4b	*16*	10			11.8	**18.5**	20.3			28

Plasticity index, PI (%) — AREA 6

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*169*	7	9	12	14	**17**	20	27	38.4	49
2	*10*	7			9.3	**13**	14			15
3	*39*	12		13	14	**16**	18	19		20
3a	*5*	9				**13**				15
3a/4	*6*	9				**11**				19
3b	*30*	11		12	13.3	**17**	21.8	27.7		49
3b/4	*31*	9		15	16	**19**	24	32		49
4	*24*	9			13	**16.5**	19.3			35
4a	*7*	10				**20**				28
Rw	*15*	12			16	**23**	26			36

Rw = Reworked

Plasticity index, PI (%) — AREA 7

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*127*	5	6	8	10	**12**	16	19.4	25.4	33
2/3	*8*	8				**11.5**				16
3	*41*	5		7	9	**11**	13	17		19
3/4a	*30*	6		8	11	**13.5**	15	19		20
4a	*23*	6			10.5	**13**	20			33
4b	*5*	13				**22**				26
Rw	*16*	5			10	**14.5**	17.3			28

Rw = reworked

Plasticity index, PI (%) — AREA 8

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*404*	2	7	10	12	**14**	18	22	28	47
CBp 2	*7*	12				**17**				19
CBp 3	*80*	9		11	12	**15.5**	18	21		27
CBp 4a	*24*	10			12	**14.5**	19.3			26
CBp 4b	*20*	5			10.8	**12**	15.5			32
CBp Rw	*9*	10				**15**				23
Edw 3	*9*	4				**12**				23
Edw 4a	*22*	2			10.3	**13**	18			47
Edw 4b	*23*	8			14.5	**16**	22			36
Gun 2	*11*	10			12.5	**14**	14			16
Gun 2/3	*5*	11				**13**				16
Gun 3	*39*	9		10	12	**14**	16	18.4		25
Gun 3/4a	*26*	10		11	12	**14.5**	16	19		23
Gun 4a	*28*	8		11	13	**15.5**	18	22.6		28
Gun 4b	*9*	5				**12**				31
Snt 3	*6*	7				**12**				16
Snt 3/4a	*9*	6				**13**				19

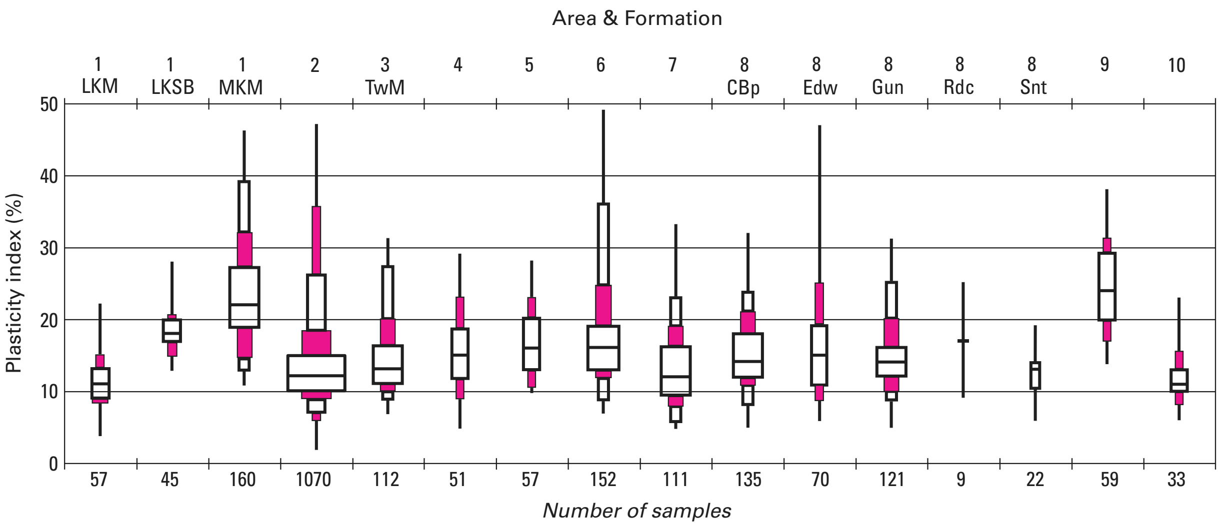
CBp	Cropwell Bishop Formation	Rdc	Radcliffe Formation	Gun	Gunthorpe Formation
Edw	Edwalton Formation	Snt	Sneinton Formation	*Rw*	*Reworked*

Plasticity index, PI (%) — AREA 9

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*59*	14		17	20	**24**	29	31.2		36
2/3a	*7*	18				**23**				26
3a	*5*	14				**18**				29
3a/3b	*5*	15				**22**				28
3b	*23*	16			21	**28**	30.5			36
4a	*5*	24				**26**				31
4b	*8*	14				**28.5**				36

Plasticity index, PI (%) — AREA 10

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*33*	6		8.2	10	**11**	13	15.6		23
3	*13*	6			9	**10**	12			16
4a	*13*	9			10	**12**	14			23



Extended box plots showing graphical summary of plasticity index data.

INDEX TESTS — Liquidity index

Liquidity index (LI) — AREA 1

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*245*	-1.63	-0.99	-0.59	-0.39	**-0.21**	0.00	0.25	0.75	0.93
LKM 3/4a	*6*	-1.50				**-0.06**				0.33
LKM 3a/3b	*5*	-1.63				**-0.55**				-0.43
LKM 3a/4	*7*	-0.46				**-0.12**				0.20
LKM 3b	*5*	-0.21				**0.08**				0.88
LKM 3b/4	*9*	-1.00				**-0.36**				0.00
LKM 4	*13*	-0.64			-0.55	**-0.33**	-0.09			0.60
LKSB 3a	*6*	-0.50				**-0.27**				0.93
LKSB 3b	*16*	-0.69			-0.24	**0.06**	0.27			0.76
LKSB 4	*15*	-0.65			-0.50	**-0.35**	-0.08			0.90
MKM 3/4	*8*	-0.36				**-0.25**				-0.07
MKM 3a	*19*	-0.80			-0.53	**-0.22**	0.01			0.88
MKM 3b	*13*	-0.60			-0.25	**-0.11**	0.12			0.65
MKM 3b/4	*22*	-1.25			-0.28	**-0.12**	-0.06			0.19
MKM 4	*81*	-0.80		-0.47	-0.32	**-0.18**	0.00	0.17		0.81

LKM Lower Keuper Marl — LKSB Lower Keuper Saliferous Beds — MKM Middle Keuper Marl

Liquidity index (LI) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*1169*	-1.56	-0.88	-0.50	-0.25	**0.00**	0.25	0.44	0.66	0.94
2	*24*	-1.00			-0.47	**0.00**	0.18			0.89
2/3	*35*	-1.17		-0.57	-0.35	**-0.18**	-0.07	0.36		0.48
3	*324*	-1.40	-0.93	-0.60	-0.33	**-0.10**	0.18	0.40	0.61	0.83
3/4a	*137*	-1.25	-0.85	-0.56	-0.36	**-0.08**	0.25	0.42	0.58	0.94
4a/4b	*6*	-0.17				**0.13**				0.30
4b	*11*	-0.36			-0.24	**0.11**	0.31			0.83
Rw	*120*	-1.50	-1.17	-0.34	-0.08	**0.14**	0.30	0.47	0.63	0.77

Rw = reworked

Liquidity index (LI) — AREA 6

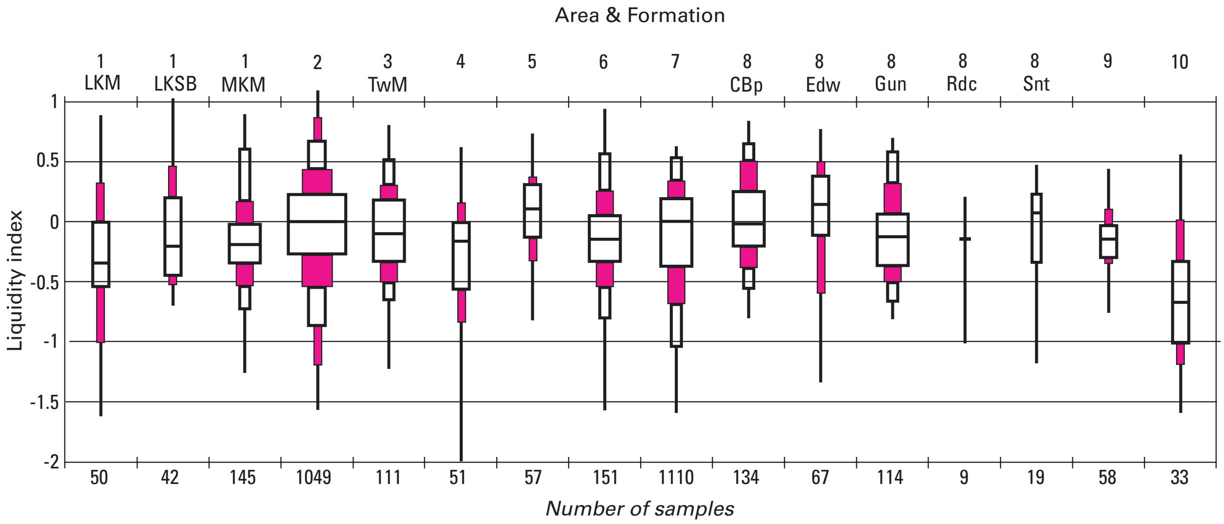
	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*167*	-1.57	-0.78	-0.54	-0.31	**-0.15**	0.04	0.25	0.55	0.94
2	*10*	-1.57			-0.81	**-0.43**	-0.32			-0.20
3	*39*	-0.75		-0.54	-0.41	**-0.25**	-0.15	-0.05		0.25
3a	*5*	-0.56				**-0.07**				0.42
3a/4	*6*	-0.78				**0.02**				0.60
3b	*29*	-0.78		-0.39	-0.29	**-0.19**	-0.06	0.25		0.92
3b/4	*31*	-0.69		-0.21	-0.13	**0.00**	0.17	0.47		0.94
4	*23*	-0.37			-0.18	**-0.07**	0.02			0.44
4a	*7*	-0.80				**0.06**				0.10
Rw	*15*	-0.63			-0.25	**-0.04**	0.02			0.28

Rw = reworked

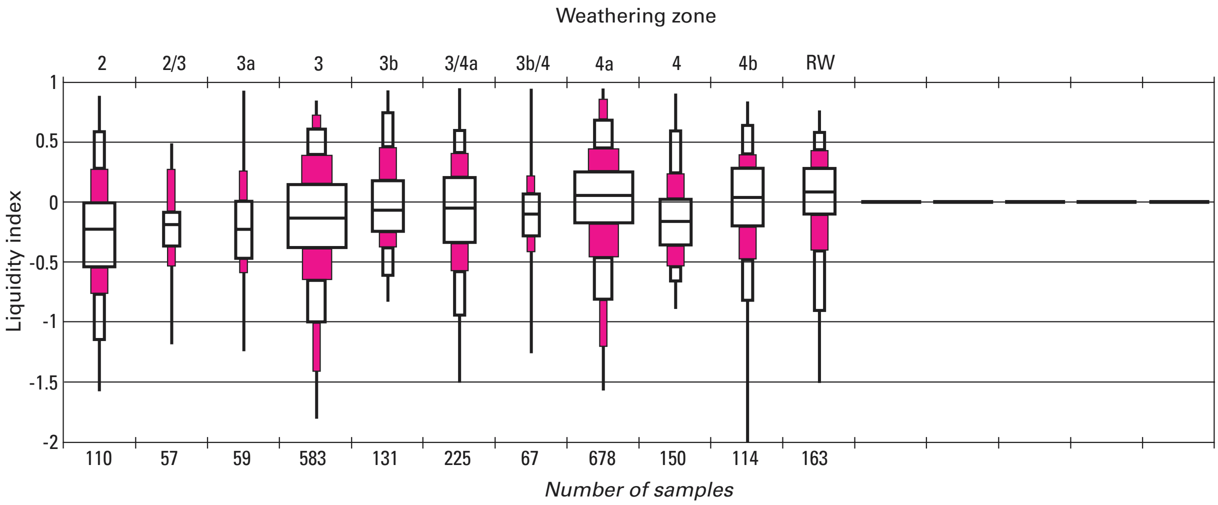
Liquidity index (LI) — AREA 7

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*126*	-1.60	-0.98	-0.62	-0.37	**0.00**	0.19	0.33	0.53	0.63
2/3	*8*	-0.56				**-0.21**				0.27
3	*40*	-1.60		-0.66	-0.50	**-0.16**	0.11	0.33		0.46
3/4a	*30*	-0.88		-0.27	0.00	**0.15**	0.26	0.50		0.55
4a	*23*	-1.17			-0.36	**0.00**	0.18			0.36
4b	*5*	0.00				**0.09**				0.63
Rw	*16*	-0.57			-0.28	**-0.07**	0.13			0.40

Rw = Reworked



Extended box plots showing graphical summary of liquidity index data related to areas and formation.



Extended box plots showing graphical summary of liquidity index data related to weathering zone.

CHEMICAL TESTS — Total sulphate content

Total sulphates, TS (%) — AREA 1

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*11*	0.01			0.17	**0.39**	1.15			9.47
MKM 4	*6*	0.23				**0.63**				1.63

MKM Middle Keuper Marl

Total sulphates, TS (%) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*186*	0.002	0.01	0.03	0.05	**0.08**	0.15	0.27	7.09	8.13
2/3	*7*	0.07				**0.25**				1.05
3	*41*	0.01		0.04	0.05	**0.08**	0.17	0.27		4.43
3/4a	*14*	0.03			0.06	**0.08**	0.24			8.13
Rw	*34*	0.01		0.02	0.03	**0.07**	0.15	0.24		7.3

Rw = Reworked

Total sulphates, TS (%) — AREA 3

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*22*	0.008			0.01	**0.02**	0.04			0.27
TwM 2	*9*	0.008				**0.04**				0.27
TwM 3a	*6*	0.008				**0.015**				0.14

TwM Twyning Mudstone Formation

Total sulphates, TS (%) — AREA 5

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*5*	0.01				**0.06**				0.11

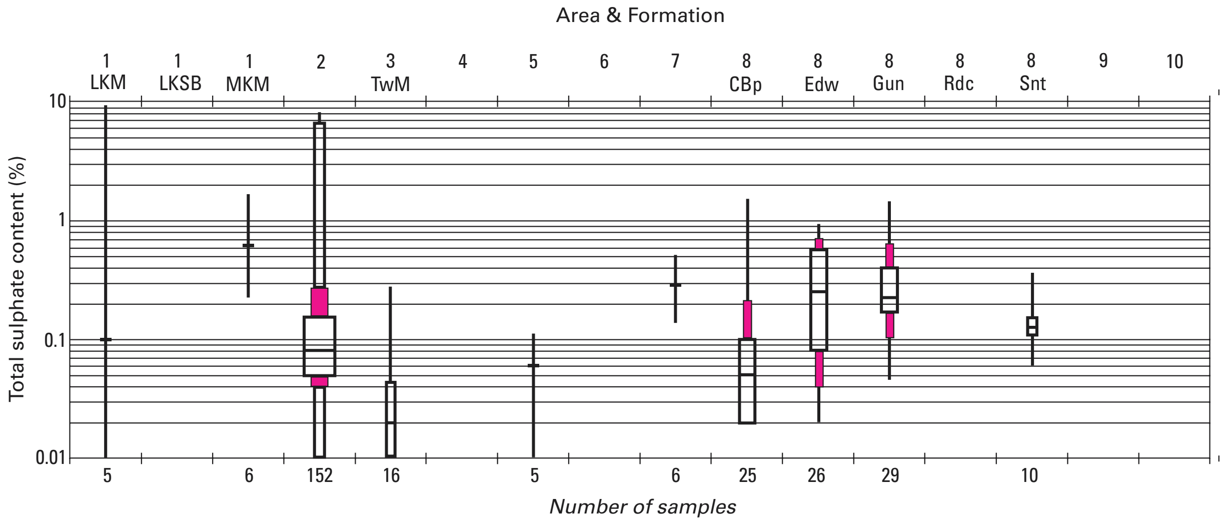
Total sulphates, TS (%) — AREA 7

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*6*	0.14				**0.29**				0.5

Total sulphates, TS (%) — AREA 8

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*97*	0.02		0.03	0.05	**0.15**	0.3	0.62		1.5
CBp 3	*14*	0.02			0.02	**0.05**	0.05			1.5
CBp 4a	*5*	0.02				**0.05**				0.1
CBp 4b	*5*	0.02				**0.10**				0.25
Edw 3	*5*	0.11				**0.37**				0.92
Edw 4a	*8*	0.03				**0.53**				0.88
Edw 4b	*10*	0.02			0.05	**0.07**	0.13			0.49
Gun 3	*8*	0.11				**0.20**				1.41
Gun 3/4a	*9*	0.14				**0.21**				0.61

CBp Cropwell Bishop Formation
Edw Edwalton Formation
Gun Gunthorpe Formation



Extended box plots showing graphical summary of total sulphate content data.

CHEMICAL TESTS — Aqueous sulphates

Aqueous sulphates, AS (%) — AREA 1

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*7*	0.09				**0.54**				1.64
MKM 4	*5*	0.09				**0.50**				1.29

MKM Middle Keuper Marl

Aqueous sulphates, AS (%) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*32*	0.03		0.06	0.09	**0.21**	1.01	1.28		1.53
3	*7*	0.03				**0.09**				0.97
3/4a	*5*	0.05				**0.44**				8.13
4a	*9*	0.06				**0.22**				1.28
Rw	*5*	0.09				**0.99**				1.49

Aqueous sulphates, AS (%) — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*17*	0			0.01	**0.02**	0.05			1.3
4	*6*	0.01				**0.02**				1.3

Aqueous sulphates, AS (%) — AREA 7

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*26*	0.24		0.25	0.31	**0.36**	0.38	0.45		0.56
3	*9*	0.24				**0.35**				0.45
3/4a	*7*	0.25				**0.36**				0.56

Aqueous sulphates, AS (%) — AREA 8

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*52*	0.001		0.01	0.03	**0.05**	0.08	0.13		0.54
Edw 4a	*5*	0.007				**0.02**				0.22
Gun 2	*6*	0.050				**0.07**				0.10
Gun 3	*9*	0.001				**0.05**				0.34
Gun 3/4a	*6*	0.005				**0.05**				0.16
Gun 4a	*11*	0.014			0.04	**0.05**	0.08			0.13

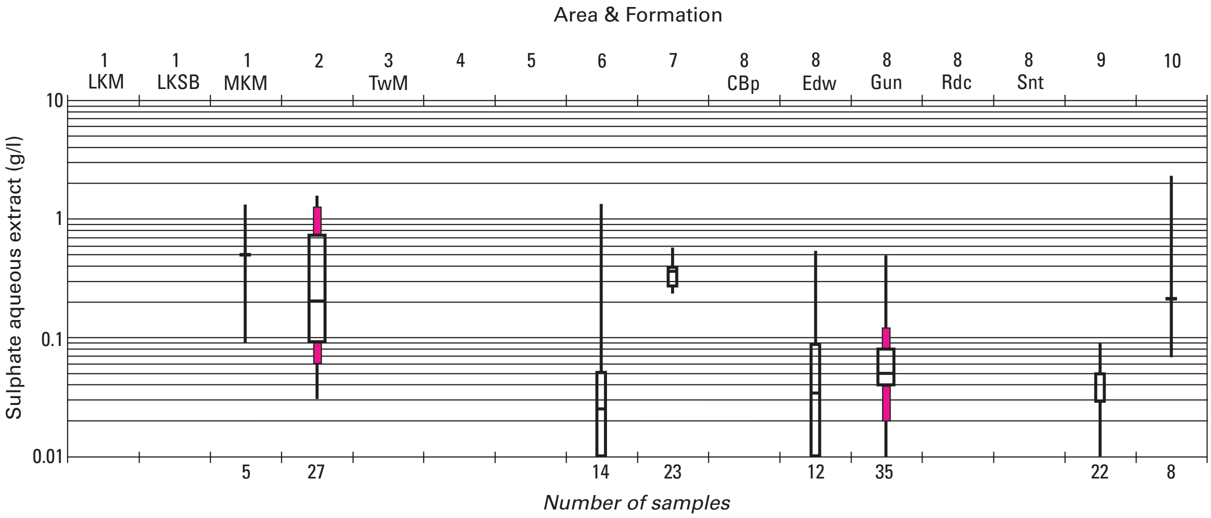
Edw Edwalton Formation Gun Gunthorpe Formation

Aqueous sulphates, AS (%) — AREA 9

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*22*	0.01			0.03	**0.03**	0.05			0.09
3b	*7*	0.02				**0.05**				0.08

Aqueous sulphates, AS (%) — AREA 10

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*8*	0.07				**0.22**				2.3



Extended box plots showing graphical summary of aqueous sulphate content data.

CHEMICAL TESTS — pH

pH — AREA 1

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*15*	7.7			7.9	**8.0**	8.4			8.5
MKM 4	*8*	7.8				**8.1**				8.5

MKM Middle Keuper Marl

pH — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*241*	5.3	6.5	7	7.6	**7.9**	8.2	8.5	8.8	10.6
2	*6*	7.7				**8.1**				9.0
2/3	*8*	7.7				**8.1**				8.8
3	*61*	6.5		7.2	7.7	**8.0**	8.3	8.7		10.6
3/4a	*22*	6.6			7.5	**7.7**	8.0			8.5
4a	*101*	6.1	6.6	7.0	7.6	**7.9**	8.1	8.4	8.6	9.0
4b	*5*	7.8				**7.9**				8.5
Rw	*37*	5.3		6.4	7.0	**7.6**	8.0	8.3		8.6

Rw = Reworked

pH — AREA 3

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*22*	7.0			7.3	**7.4**	7.7			8.3
TwM 2	*9*	7.2				**7.7**				8.2
TwM 3a	*6*	7.3				**7.5**				8.3

TwM Twyning Mudstone Formation

pH — AREA 4

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*11*	7.4			7.9	**8.5**	8.7			9.0

pH — AREA 5

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*5*	6.9				**7.6**				8.1

pH — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*18*	7.0			7.5	**7.7**	7.9			8.3
4	*6*	7.1				**7.7**				7.9

pH — AREA 7

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*33*	6.8		7.2	7.7	**8.0**	8.2	8.4		8.4
3	*12*	7.1			7.6	**8.0**	8.2			8.4
3/4a	*9*	7.6				**7.9**				8.4

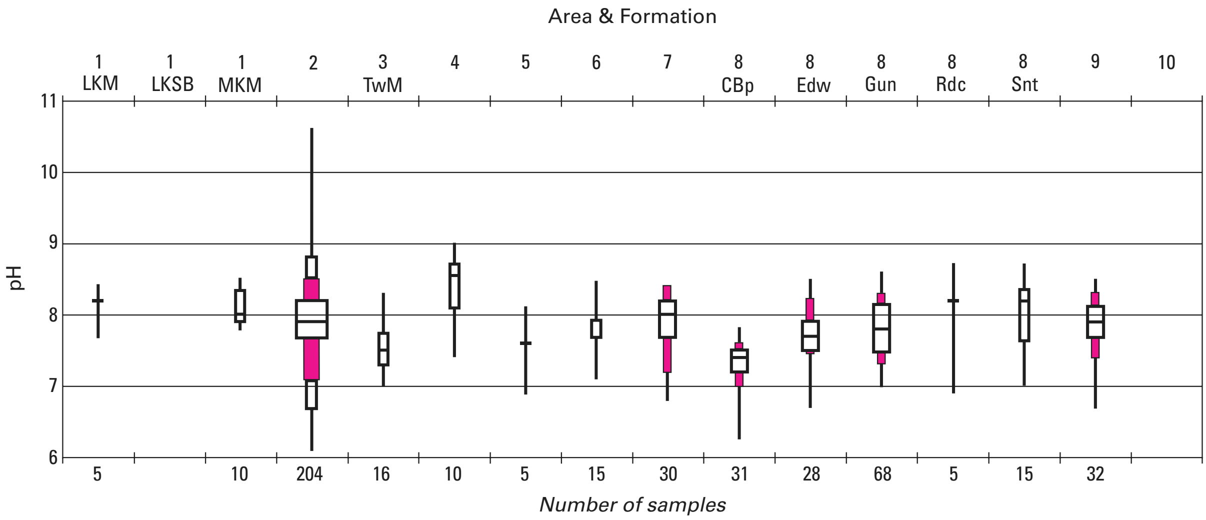
pH — AREA 8

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*152*	6.3	6.9	7.2	7.5	**7.7**	8.0	8.3	8.5	8.7
CBp 3	*17*	6.3			7.3	**7.4**	7.5			7.8
CBp 4a	*5*	6.9				**7.6**				7.6
CBp 4b	*7*	7.0				**7.5**				7.6
Edw 3	*5*	7.7				**8.0**				8.5
Edw 4a	*9*	7.5				**7.7**				8.5
Edw 4b	*10*	7.1			7.5	**7.6**	7.8			8.2
Gun 3	*21*	7.3			7.5	**7.8**	8.0			8.6
Snt 3/4a	*6*	7.3				**8.0**				8.7

CBp Cropwell Bishop Formation
Edw Edwalton Formation
Gun Gunthorpe Formation
Snt Sneinton Formation

pH — AREA 9

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*32*	6.7		7.4	7.7	**7.9**	8.1	8.3		8.5
2/3a	*8*	6.8				**8.1**				8.3
3b	*8*	7.4				**8.0**				8.5



Extended box plots showing graphical summary of pH data.

STRENGTH TESTS — Point load (axial)

Point load (axial), PLA (MPa) — AREA 1

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*462*	0	0.03	0.04	0.07	**0.11**	0.21	0.55	1.33	2.92
LKM 1	*18*	.37			0.84	**1.00**	1.34			1.46
LKM 2	*56*	0.00		0.05	0.10	**0.19**	0.44	1.02		2.92
LKM 2/3a	*12*	0.03			0.12	**0.18**	0.28			0.62
LKM 2/3b	*5*	0.03				**0.06**				0.30
LKM 3a	*66*	0.03		0.04	0.07	**0.14**	0.30	0.44		1.15
LKM 3a/3b	*39*	0.01		0.04	0.07	**0.11**	0.21	0.79		1.62
LKM 3b	*15*	0.03			0.04	**0.13**	0.30			2.60
LKM 3b/4	*6*	0.04				**0.07**				0.45
LKSB 2/3a	*12*	0.05			0.10	**0.19**	0.34			1.70
LKSB 3a	*35*	0.01		0.04	0.06	**0.07**	0.14	0.62		2.44
MKM	*14*	0.01			0.04	**0.07**	0.12			0.21
MKM 2	*47*	0.00		0.04	0.07	**0.09**	0.17	0.32		0.52
MKM 2/3a	*9*	0.04				**0.08**				0.18
MKM 3a	*39*	0.04		0.05	0.07	**0.10**	0.15	0.16		0.40
MKM 3a/3b	*21*	0.03			0.07	**0.11**	0.14			0.19
MKM 3b	*49*	0.03		0.04	0.06	**0.07**	0.10	0.12		0.15
MKM 4	*16*	0.04			0.07	**0.07**	0.10			0.15

LKM Lower Keuper Marl   LKSB Lower Keuper Saliferous Beds   MKM Middle Keuper Marl

Point load (axial), PLA (MPa) — AREA 2

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*161*	0.01	0.01	0.03	0.05	**0.10**	0.21	0.50	1.20	3.31
2	*43*	0.02		0.04	0.07	**0.12**	0.27	0.52		3.31
2/3	*73*	0.01		0.03	0.05	**0.12**	0.21	0.45		2.05
3	*35*	0.02		0.02	0.04	**0.06**	0.11	0.19		0.87
3/4a	*6*	0.02				**0.05**				0.36

Point load (axial), PLA (MPa) — AREA 3

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*37*	0.05		0.07	0.13	**0.25**	0.39	0.59		5.61
ElM 1/2	*8*	0.06				**0.15**				0.56
ElM 2	*9*	0.13				**0.23**				0.39
TwM 1/2	*6*	0.09				**0.48**				0.76
TwM 2	*7*	0.05				**0.08**				0.40

ElM Eldersfield Mudstone Formation   TwM Twyning Mudstone Formation

Point load (axial), PLA (MPa) — AREA 4

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*102*	0.01	0.01	0.04	0.09	**0.21**	0.41	0.68	1.40	1.88
1/2	*18*	0.09			0.20	**0.26**	0.49			1.88
2	*49*	0.01		0.04	0.09	**0.26**	0.46	0.81		1.52
2/3	*19*	0.02			0.05	**0.07**	0.18			0.60
3	*11*	0.01			0.10	**0.14**	0.20			0.46

Point load (axial), PLA (MPa) — AREA 8

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*652*	0.00	0.00	0.04	0.16	**0.33**	0.55	0.90	1.52	17.73
CBp 1	*61*	0.00		0.16	0.26	**0.45**	0.58	0.78		17.73
CBp 2	*331*	0.00	0.00	0.03	0.17	**0.33**	0.52	0.79	1.19	2.85
Edw 2	*35*	0.00		0.03	0.06	**0.14**	0.39	0.59		3.43
Gun/Sk 3	*5*	0.02				**0.52**				0.62
Gun 1	*7*	0.03				**0.27**				1.08
Gun 1/2	*11*	0.08			0.16	**0.27**	0.36			0.57
Gun 2	*83*	0.01		0.05	0.12	**0.26**	0.45	1.07		16.61
Gun 2/3	*26*	0.00		0.13	0.20	**0.30**	0.46	1.12		2.20
Gun 3	*13*	0.00			0.25	**0.34**	0.63			0.90
N	*6*	0.14				**0.36**				0.90
Snt 2	*8*	0.40				**0.89**				7.69
T	*14*	0.31			0.75	**0.97**	1.21			1.63

CBp Cropwell Bishop Formation N Newark gypsum
Gun Gunthorpe Formation T Tutbury gypsum Snt Sneinton Formation

STRENGTH TESTS — Point load (diametral)

Point load (diametral), PLD (MPa) — AREA 1

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*323*	0.00	0.00	0.01	0.04	**0.07**	0.13	0.22	0.56	1.64
LKM 1	*12*	0.09			0.19	**0.40**	0.49			0.60
LKM 2	*39*	0.00		0.00	0.03	**0.07**	0.23	0.46		1.26
LKM 2/3a	*14*	0.00			0.03	**0.04**	0.06			0.32
LKM 2/3b	*6*	0.00				**0.01**				1.64
LKM 3a	*42*	0.00		0.01	0.03	**0.06**	0.13	0.20		0.62
LKM 3a/3b	*8*	0.01				**0.21**				0.82
LKSB 3a	*6*	0.01				**0.04**				0.06
MKM	*12*	0.01			0.03	**0.06**	0.09			0.14
MKM 2	*40*	0.00		0.03	0.04	**0.07**	0.09	0.11		0.26
MKM 2/3a	*15*	0.03			0.04	**0.07**	0.08			0.19
MKM 3a	*60*	0.01		0.04	0.06	**0.10**	0.14	0.19		0.36
MKM 3a/3b	*14*	0.04			0.07	**0.10**	0.12			0.18
MKM 3b	*31*	0.03		0.04	0.04	**0.07**	0.11	0.13		0.15
MKM 4	*5*	0.06				**0.10**				0.15

LKM Lower Keuper Marl LKSB Lower Keuper Saliferous Beds MKM Middle Keuper Marl

Point load (diametral), PLD (MPa) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*159*	0.00	0.01	0.02	0.03	**0.07**	0.13	0.25	0.52	4.48
2	*42*	0.00		0.02	0.04	**0.10**	0.14	0.37		4.48
2/3	*75*	0.00		0.02	0.04	**0.08**	0.13	0.20		0.65
3	*33*	0.00		0.01	0.02	**0.04**	0.06	0.15		0.40
3/4a	*5*	0.02				**0.05**				0.13

Point load (diametral), PLD (MPa) — AREA 3

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*14*	0.07			0.16	**0.25**	0.39			3.64

Point load (diametral), PLD (MPa) — AREA 4

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*101*	0.01	0.01	0.02	0.06	**0.14**	0.26	0.62	0.91	1.30
1/2	*17*	0.06			0.12	**0.23**	0.26			1.30
2	*50*	0.01		0.03	0.07	**0.18**	0.26	0.62		1.14
2/3	*18*	0.01			0.04	**0.07**	0.21			0.71
3	*11*	0.01			0.06	**0.09**	0.18			0.66

Point load (diametral), PLD (MPa) — AREA 8

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*339*	0.00	0.01	0.02	0.09	**0.23**	0.51	1.00	2.48	16.33
CBp 1	*15*	0.13			0.33	**0.60**	0.91			1.02
CBp 2	*58*	0.04		0.11	0.20	**0.33**	0.68	0.95		1.40
Edw 2	*14*	0.01			0.01	**0.03**	0.08			0.22
Gun/Sk 3										
Gun 1	*7*	0.03				**0.23**				0.27
Gun 1/2	*14*	0.01			0.14	**0.20**	0.26			0.44
Gun 2	*106*	0.00	0.01	0.01	0.03	**0.10**	0.23	0.47	5.19	16.33
Gun 2/3	*29*	0.01		0.01	0.09	**0.15**	0.25	0.41		0.95
Gun 3	*16*	0.01			0.12	**0.14**	0.28			1.32
N	*17*	0.75			0.88	**0.97**	1.08			1.62
Snt 2	*14*	0.26			0.43	**0.49**	1.24			15.38
T	*9*	0.41				**1.00**				2.74

CBp	Cropwell Bishop Formation	Snt	Sneinton Formation	N	Newark gypsum
Gun	Gunthorpe Formation	T	Tutbury gypsum		

STRENGTH TESTS — Uniaxial compressive strength

Uniaxial compressive strength, UCS (MPa) — AREA 1

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*116*	0.10	0.11	0.22	0.34	**0.61**	1.54	7.83	17.80	43.00
LKM 2	*7*	0.22				**2.28**				9.59
LKM 3a	*8*	0.60				**4.15**				14.00
LKSB 3a	*6*	0.11				**0.35**				2.18
MKM	*5*	0.12				**0.24**				1.17
MKM 2	*17*	0.34			0.57	**1.34**	1.87			43.00
MKM 3a	*24*	0.10			0.29	**0.57**	0.74			36.00
MKM 3a/3b	*8*	0.20				**0.32**				1.20
MKM 3b	*17*	0.12			0.34	**0.57**	1.04			11.00
MKM 4	*6*	0.11				**0.58**				1.09

LKM Lower Keuper Marl LKSB Lower Keuper Saliferous Beds MKM Middle Keuper Marl

Uniaxial compressive strength, UCS (MPa) — AREA 2

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*89*	0.03		0.10	0.10	**0.30**	0.70	1.42		4.00
2	*35*	0.09		0.10	0.20	**0.40**	0.90	1.98		4.00
2/3	*34*	0.03		0.10	0.10	**0.30**	0.40	1.01		2.00
3	*14*	0.03			0.10	**0.30**	0.40			1.40

Uniaxial compressive strength, UCS (MPa) — AREA 4

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*27*	0.30		0.60	3.90	**8.10**	12.00	17.30		24.60
1/2	*9*	1.03				**10.80**				24.60
2	*10*	0.30			0.95	**3.90**	9.50			22.90
3	*5*	6.30				**10.50**				17.30

Uniaxial compressive strength, UCS (MPa) — AREA 8

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*60*	0.00		0.92	2.39	**3.61**	7.13	11.92		140.50
CBp 1	*10*	0.93				**4.30**				17.30
CBp 2	*26*	1.39		2.27	2.56	**3.87**	6.58	9.26		10.50
Gun 3	*5*	2.17				**8.93**				140.50

CBp Cropwell Bishop Formation Gun Gunthorpe Formation

STRENGTH TESTS — Undrained cohesion

Undrained cohesion, CU (kPa) — AREA 1

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*39*	33		53	79	**121**	184	291		374
LKM 4	*5*	33				**72**				159
MKM 4	*24*	46			83.8	**141**	211			374

LKM Lower Keuper Marl MKM Middle Keuper Marl

Undrained cohesion, CU (kPa) — AREA 2

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*276*	6	18	35	52	**82**	127	179	234	373
2										
2/3										
3	*56*	13		41	59	**91**	145	189		269
3/4a	*26*	18		52	76	**116**	148	170		349
4a	*148*	6	21	35	53	**82**	123	166	226	255
4b										
Rw	*40*	8		27	37	**60**	118	192		373

Undrained cohesion, CU (kPa) — AREA 3

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*76*	36		64	94	**155**	220	296		492
TwM 2	*5*	170				**200**				435
TwM 3a	*12*	36			76	**151**	200			348
TwM 3b	*41*	42		61	93	**152**	207	296		492
TwM 4	*6*	57				**216**				290

TwM Twyning Mudstone Formation

Undrained cohesion, CU (kPa) — AREA 4

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*10*	40			77	**103**	125			240

Undrained cohesion, CU (kPa) — AREA 5

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*27*	35		72	82	**126**	175	201		365
3	*9*	79				**155**				315
4a	*8*	35				**74**				150
4b	*10*	85			116	**154**	189			365

Undrained cohesion, CU (kPa) — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*31*	30		50	89	**129**	174	195		262
3b	*11*	30			122	**131**	184			262
4	*8*	34				**101**				195

Undrained cohesion, CU (kPa) — AREA 7

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*51*	11		41	64	**94**	137	182		269
3	*16*	37			57	**80**	126			180
3/4a	*9*	37				**84**				257
4a	*10*	22			91	**107**	150			172
Rw	*10*	11			71	**119**	166			269

Rw *Reworked*

Undrained cohesion, CU (kPa) — AREA 8

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*248*	4	29	42	60	**90**	153	228	461	660
CBp 3	*75*	40		47	57	**80**	135	173		280
CBp 4a	*34*	34		42	55	**96**	130	164		429
CBp 4b	*16*	34			72	**105**	138			210
CBp Rw	*7*	28				**73**				125
Edw 2	*6*	55				**117**				386
Edw 4a	*6*	38				**90**				140
Edw 4b	*11*	41			63	**76**	92			227
Gun 2	*11*	56			91	**185**	267			562
Gun 3	*9*	42				**158**				566
Gun 3/4a	*14*	4			47	**81**	146			395
Gun 4a	*18*	30			77	**105**	169			543
Snt 4a	*5*	70				**220**				463

CBp Cropwell Bishop Formation; Edw Edwalton Formation; Gun Gunthorpe Formation
Snt Sneinton Formation; *Rw* *Reworked*

Undrained cohesion, CU (kPa) — AREA 9

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*12*	42			65	**89**	103			125
3b	*8*	42				**83**				122

Undrained cohesion, CU (kPa) — AREA 10

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*9*	14				**103**				357

CONSOLIDATION TESTS — Coefficients of consolidation (c_v) and volume compressibility (m_v)

Coefficient of consolidation, c_v (m^2/yr) — All data

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Oedom. load										
25 – 50 kPa		0.2		1.3		**5.6**		11		22.7
50 – 100 kPa		0.1		1.3		**6.5**		19.6		68.2
100 – 200 kPa		0.1		1.1		**6.1**		18.7		49.9
200 – 400 kPa		0.1		1.2		**5.5**		21.4		53.5
400 – 800 kPa		0.2		0.8		**6.5**		24.3		54.4
800 – 1600 kPa		0.3		0.9		**5.8**		34.4		46.9

Coefficient of volume compressibility, m_v (m^2/MN) — All data

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Oedom. load										
25 – 50 kPa		0.07		0.17	0.24	**0.32**	0.39	0.44		1.29
50 – 100 kPa		0.04	0.06	0.10	0.15	**0.19**	0.24	0.03	0.38	0.67
100 – 200 kPa		0.04	0.05	0.07	0.09	**0.12**	0.16	0.22	0.28	0.45
200 – 400 kPa		0.03	0.04	0.05	0.07	**0.08**	0.11	0.14	0.18	0.24
400 – 800 kPa		0.02	0.03	0.03	0.05	**0.06**	0.07	0.09	0.11	0.17
800 – 1600 kPa		0.01		0.02	0.03	**0.03**	0.04	0.05		0.13

COMPACTION TESTS — Optimum moisture content (OMC) & maximum dry density (MDD)

Compaction, OMC (%) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*30*	11	11	13	16	**19**	24	27.1	29.4	33

Compaction, OMC (%) — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*6*	13				**17.5**				27

Compaction, OMC (%) — AREA 9

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*8*	12				**15.5**				19

Compaction, MDD (Mg/m^3) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*30*	1.41	1.44	1.54	1.62	**1.71**	1.80	1.88	1.99	2.03

Compaction, MDD (Mg/m^3) — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*6*	1.51				**1.72**				1.93

Compaction, MDD (Mg/m^3) — AREA 9

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*8*	1.65				**1.82**				1.94

COMPACTION TESTS — California bearing ratio (CBR)

California bearing ratio, CBR (%) — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*10*	1			6.75	**10.5**	11.88			19.5

California bearing ratio, CBR (%) — AREA 8

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*29*	0	0	0.4	2.5	**6.5**	21	26.8	58.6	73

California bearing ratio, CBR (%) — AREA 9

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*6*	2				**8.5**				17

COMPACTION TESTS — Moisture condition value (MCV)

Moisture condition value, MCV — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*13*	6.2			8.6	**10.1**	12.5			14.4

Moisture condition value, MCV — AREA 8

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*11*	9.6			13.8	**14.4**	15.2			17

FIELD TESTS — Standard penetration test (SPT)

Standard penetration test, SPT (N) — AREA 1

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*323*	9	27	42	62	**94**	160	260	750	9999
LKM 3a	*5*	116				**200**				600
LKM 3b	*15*	27			65	**96**	181			428
LKM 3b/4	*6*	42				**163**				750
LKM 4	*28*	9		41	74	**123**	182	250		300
LKSB 3a	*5*	58				**62**				100
LKSB 3b	*18*	48			69	**93**	125			300
LKSB 3b/4	*7*	71				**103**				200
LKSB 4	*20*	27			61	**72**	129			9999
MKM 2/3a	*7*	21				**65**				93
MKM 3a	*22*	44			61	**89**	156			200
MKM 3b	*15*	32			58	**72**	147			9999
MKM 3b/4	*38*	23		60	69	**106**	195	346		9999
MKM 4	*104*	26	29	38	48	**77**	130	194	385	9999

LKM Lower Keuper Marl   LKSB Lower Keuper Saliferous Beds   MKM Middle Keuper Marl

Standard penetration test, SPT (N) — AREA 2

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*1338*	3	18	37	65	**122**	161	229	420	9999
1/2	*6*	112				**178**				262
2	*133*	39	81	122	140	**160**	228	300	500	750
2/3	*257*	15	69	99	122	**146**	176	281	420	9999
3/4a	*132*	8	24	38	67	**117**	148	183	286	9999

Rw Reworked

Standard penetration test, SPT (N) — AREA 3

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*747*	7	16	35	67	**112**	170	220	300	1000
ElM 1	*6*	200				**219**				1000
ElM 1/2	*23*	111			163	**169**	195			250
ElM 2	*62*	43		61	101	**145**	208	235		1000
ElM 3a	*16*	23			33	**58**	84			156
ElM 3b					58	**84**				156
TwM	*8*	19				**31**				44
TwM 1	*6*	178				**300**				394
TwM 1/2	*19*	150			178	**191**	240			428
TwM 2	*455*	18	49	67	93	**132**	174	227	304	789
TwM 2/3a	*12*	18			26	**48**	65			116
TwM 3a	*75*	10	18	28	44	**58**	79	96	116	168
TwM 3b	*43*	7		11	17	**25**	34	41		61
TwM 4	*5*	7				**16**				19
TwM Rw	*5*	15				**22**				41

ElM Eldersfield Mudstone Formation TwM Twyning Mudstone Formation Rw Reworked

Standard penetration test, SPT (N) — AREA 4

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*118*	7	12	22	40	**104**	149	214	306	750
2	*7*	56				**150**				214
2/3	*5*	29				**175**				184
3	*41*	16		20	33	**73**	124	214		375
3/4	*5*	147				**214**				300
3/4a	*15*	9			41	**105**	132			300
4a	*16*	7			24	**80**	123			300
4b	*15*	9			42	**61**	128			177

Standard penetration test, SPT (N) — AREA 5

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*87*	3		20	30	**50**	83	107		170
2	*27*	16		26	47	**72**	84	104		170
2/3	*5*	65				**86**				113
3	*45*	3		23	30	**45**	78	108		134
	8	8				**22**				35

Standard penetration test, SPT (N) — AREA 6

	No.	Min.	2.5	10	25	**50**	75	90	97.5	Max.
Stratig. &/or weath. zone										
All data	*152*	6	13	21	38	**64**	124	176	242	300
1	*7*	107				**131**				282
2	*37*	36		67	94	**144**	176	213		300
3	*11*	32			39	**59**	74			250
3b	*26*	12		23	29	**40**	50	56		64
4	*8*	12				**17**				35

Standard penetration test, SPT (N) — AREA 7

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*65*	13		25	38	**63**	88	184		255
2/3	*5*	56				**65**				230
3	*30*	13		27	38	**66**	86	159		255
3/4a	*19*	26			44	**65**	86			173

Standard penetration test, SPT (N) — AREA 8

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*521*	4	12	22	38	**74**	164	250	500	9999
CBp 2	*19*	38			74	**186**	228			9999
CBp 3	*52*	8		19	28	**57**	120	395		9999
CBp 4a	*15*	16			33	**46**	82			164
CBp 4b	*18*	7			34	**43**	58			164
Edw 2	*8*	65				**155**				300
Edw 3	*7*	16				**36**				214
Edw 3/4b	*5*	59				**68**				77
Edw 4a	*15*	13			50	**69**	107			161
Edw 4b	*18*	21			52	**87**	128			230
Gun 2	*29*	15		49	74	**144**	182	340		750
Gun 2/3	*13*	66			114	**120**	244			454
Gun 3	*100*	10	19	28	57	**113**	200	300	500	600
Gun 3/4a	*65*	12		19	29	**49**	109	212		517
Gun 4a	*27*	4		8	14	**43**	91	199		483
Gun 4b	*10*	14			34	**120**	187			500
Hly 4	*5*	8				**18**				36
Rdc 3/4a	*6*	38				**189**				375
Rdc 4a	*5*	16				**32**				517
Snt 2	*6*	50				**172**				216
Snt 3	*11*	45			55	**118**	160			375
Snt 3/4a	*13*	15			32	**35**	133			200
Snt 4a	*13*	26			35	**41**	62			129

CBp	Cropwell Bishop Formation	Edw	Edwalton Formation	Gun	Gunthorpe Formation
Hly	Hollygate Sandstone	Rdc	Radcliffe Formation	Snt	Sneinton Formation

Standard penetration test, SPT (N) — AREA 9

Stratig. &/or weath. zone	*No.*	Min.	2.5	10	25	**50**	75	90	97.5	Max.
All data	*11*	17			57	**83**	104			200
3b	*6*	17				**57**				89

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