



The development of a residual soil profile from a mudstone in a temperate climate

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Abstract

In the paper, the development of an expansive residual clay soil profile weathering from a Permian mudstone is described. The characteristics considered include soil mineralogy, soil chemistry, soil texture and engineering parameters including expansive potential. The effects of weathering are shown to be most evident in the development of a series of texturally distinct soil horizons. It is shown that the chemical and mineralogical characteristics of the parent mudstone are very similar to those of its derived expansive clay soils, even though the expansive potential in the clay soil is almost twice as great as in the parent mudstone. The origins of an enhanced expansive potential in the B horizon are explored, and it is found that, for the weathering of a mudstone in a temperate climate, the effects of weathering on structure are more important than the effects of weathering on mineralogy. It is concluded that most of the smectite clays in the weathered clay soils were inherited from the parent mudstone (with little or no transformation) and that these clay components were likely to have been present in the sediments from which the mudstone formed. The enhanced expansive potential in the residual clays is attributed to the physical effects of weathering in breaking down structure and/or bonding in the parent rock, which reduces the potential expansiveness of the clays contained in the parent rock. This proposal is supported by experimental evidence.

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1. Introduction

Expansiveness is a phenomenon which has long been recognised in smectite bearing soils. In many cases, the shrinking and swelling of expansive clays in response to moisture content change can be a cause of serious damage to residential buildings (Jones and Holtz, 1973; Krohn and Slossen, 1980; Freeman et al.,

1991). An appreciation of expansive soils by the geotechnical community as a significant issue on a world-wide scale has only emerged over the past 40 years. While approaches have been developed to characterise the behaviour of expansive soils and, to engineer structures to tolerate the resulting ground movements, there is as yet no unified theory to enable the behaviour of these soils to be fully understood and predicted.

There is also a scarcity of published geotechnical research on the development and occurrence of expansive soils around the world, from which a better

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understanding might follow, and much of what exists is only available locally. There is a substantial body of scientific literature devoted to soils and soil profile analysis; however, most of this research has been undertaken by soil scientists, geologists, geographers and agricultural scientists, with little or no emphasis on the importance of expansive soil behaviour to the engineering community.

It is generally understood by most engineers that clays are produced by the ‘weathering’ of rocks. It is also accepted that deposits of clay might arise as a residual layer overlying a weathered rock, or from the deposition of clays which have been previously eroded from a residual layer, and then been transported by water, wind or gravity. However, some geotechnical engineers are relatively unaware of the inherent characteristics of clay soils that exhibit expansive potential.

The aim of this paper is to present the results of a detailed examination of the residual expansive clay profile from Maryland, Australia. It explores the role of factors such as parent rock type, climate, degree of weathering and soil structure on the expansiveness of clay soils throughout the soil profile. It achieves this in the context of soil profile genesis as understood from a review of the wider scientific literature.

2. Background

The economic design of foundations on expansive soils requires data on the expansive potential of the soil. Prediction of these movements is very complicated task for many reasons: ground movements depend on the magnitude, extent and distribution of moisture changes, and the expansiveness of clay soils at all depths within the soil profile. Moisture changes are in turn influenced by the nature of the surface cover conditions, the climate, the proximity of the water table and the fabric and texture of the soil (which affects its hydraulic conductivity). The variation in soil expansiveness within a soil profile largely depends on the origin of the soil. In a residual soil, important factors include the nature of the parent rock materials, the climate under which the soil formed, the ground water regime, biological factors and topographic effects (Righi and Meunier, 1995).

The effects of expansive clay soils are most severe on lightly loaded structures, such as residential dwellings,

as the expansion of the soil is not significantly hindered by having to do work against the relatively small weight of the structure. These are among the lowest cost of all engineering structures. Whilst the cost of rectifying damage in such structures is relatively small, it often represents a substantial proportion of the total structure cost. As the prediction of ground movements in expansive soils is such a complicated task, it is generally not economic to make rigorous engineering estimates for low cost structures, and so, recourse is usually made to the crudest and most simplistic of models.

In Australian practice (AS 2870, 1996; Walsh and Cameron, 1997), foundation designs for expansive soils are often based on an assumed deformed ground shape, derived from open ground surface movement predictions that are based on an assumed moisture change distribution and on assumed depths of seasonal moisture change and soil cracking (Walsh and Cameron, 1997). Estimates of expansive potential are often made with as little as a single physical measurement on a soil sample from the soil profile. This is obviously inadequate, particularly for a residual soil profile, where the expansiveness of the soil can vary significantly with depth. One practical benefit of the research reported here is that an improved understanding of the soil profile genesis can lead to more confident assumptions of the distribution of soil expansiveness, and the depths to which cracking and moisture change extend.

Soils can be broadly divided into two groups on the basis of their origin: residual soils, formed by the in situ weathering of a rock; and sedimentary or transported soils, formed from the accumulation of soil particles derived from the fragmentation (usually by chemical and physical weathering and subsequent erosion) of rocks and soils in areas remote from the present soil deposit.

A review of existing literature suggests that information on residual soil profile characteristics is sparsely distributed and incomplete. Blight (1997) reports that residual soils most commonly form from igneous and metamorphic parent rocks, but that residual soils formed from sedimentary rocks are also common. Most of the attention paid to residual soils has been directed at soils derived from parent rocks of igneous origin. The formation of residual soils from granites has been considered by many authors, including Lumb (1961), Baynes and Dearman (1978),

Righi and Meunier (1991) and Aoudjit et al. (1995); the formation of residual soils from basic igneous rocks has been considered by Blight (1996), Smith (1957) and Sherman and Uehara (1956).

However, sedimentary rocks are considered to be the largest source of clay in the derivation of sediment on the earth's surface (Potter et al., 1980), and so their role in producing residual soil profiles should not be understated. Indeed, most of the soils, which underlie urban development along the eastern seaboard of Australia, are derived from rocks of a sedimentary origin. In addition, Righi and Meunier (1995) report that heavy clay rocks have a wide distribution in Europe and America. Despite this importance, there has been little work carried out to characterise the residual soil profiles that are formed from sedimentary parent rocks.

It is generally accepted that both parent rock and weathering environment play important roles in soil formation. It has been suggested that the relative importance of each is a function of time (Macias and Chesworth, 1992; Righi and Meunier, 1995), with parent rock characteristics dominating in young soils, and with climate and vegetation becoming dominant as weathering time increases (although the parent rock influence is seldom entirely eliminated).

The time-dependent processes of soil formation include the formation, transformation and release of clays. Millot (1970) recognises that clay minerals may be either "allogenic" (inherited during the process of soil formation) or "authigenic" (formed within the soil), and that authigenic clays can be either transformed from inherited phyllosilicates of different mineralogy (this can result from diffusion processes in the solid particles), or formed as a precipitate from solution (so-called "neoformed").

Clays in residual soils, which are derived from crystalline rocks (igneous and metamorphic rocks and volcanogenic sediments), are likely to be predominantly authigenic, so there is no opportunity to inherit or transform pre-existing clay minerals. Clearly, sedimentary soils may contain clays from any origin, but the bulk of the clays are likely to occur through inheritance (unless the soil is very old, as solid diffusional processes are usually very slow).

It is noted here that the mineralogical characteristics of residual soils formed from sedimentary mudrocks are potentially the most difficult to assess,

as these soils have a high chance of containing clays from any or all possible origins.

3. Context of the Maryland soil profile

3.1. Parent rock

The Maryland clay soil profile is derived from the in situ weathering of an argillaceous sedimentary rock. This rock could reasonably be described as a laminated mudstone or claystone (Hawkins and Pinches, 1992), as it is predominated by large fractions of both silt-sized and clay-sized particles; mudstone is adopted here. In the context of the surrounding "coal measures", the material is commonly referred to as a "laminite", which is a name given to thinly laminated mudstones which exhibit thin to very thin (<6 mm) indistinct laminations of dark grey clay/silt and pale grey silt/fine sand, in varying proportions.

The parent rock for the Maryland clay has been identified as belonging to the upper unit of the Dempsey Formation within the middle to late Permian Tomago Coal Measures (Fityus, 1999), which is described as consisting mainly of shales, mudstones and siltstones, with subordinate sandstones, thin coal seams and tuffaceous clays (Engel, 1966). In the Maryland region, laminite is dominant, with silt/clay laminations typically representing in excess of 90% of the total rock.

The origin of the laminite at Maryland is complex. Deposition of the original sediment, derived mainly from terrestrial sources (but augmented by reworked pyroclastics), is believed to have taken place in a prodelta or delta plain environment (Herbert, 1980), in water which was likely to have had a marine (or at least brackish) composition (Diessel, 1980). The prevailing climate was likely to have been cold. Subsequently, these sediments were buried by between 1600 and 2300 m of overlying sediments (estimate deduced from Diessel, 1975). The basin subsided as a result of loading, until uplift (with simultaneous erosion from the Tertiary to the present), raised them to their present near-surface position.

On a longer timescale, the Permian sediment (deposited as part of the Dempsey formation) was derived from a Devonian/Carboniferous post-subduction fold-belt complex, composed largely of sedimentary

rocks. The sediments in turn had been derived from sediments deposited in facies ranging from terrestrial, through continental shelf, to contiguous flysch (Herbert, 1980). The Devonian and Carboniferous sedimentary source rocks were predominantly siltstones and sandstones, and again, the derived sediments were augmented with pyroclastics.

Petrological examination of the Dempsey Formation laminite reveals a dominance of clays and quartz, with some minor feldspar and some larger flakes of muscovite.

3.2. Present-day regional setting

The Maryland clay is being studied at a field site situated approximately 160 km north of Sydney, 10 km west of the city of Newcastle and some 800 m north west of the suburb of Maryland, in Australia. Maryland is open farmland comprising grass-covered fields, which are being progressively subdivided for residential development. For this reason, there was a demonstrable need to gather data to enable the various aspects of expansive clay foundation design and analysis for house foundations to be modelled and tested. The influence of the expansive Maryland clay in producing ground and foundation movements due to seasonal ground moisture changes, have been studied in some detail by the authors (e.g. Fityus et al., *in press*), over a period of some 10 years.

The research site is approximately 80 m long by 25 m wide. It was covered with open eucalypt forest up until around 140 years ago, when it was cleared and put to pasture. It is presently covered with a low-running grass (kikuyu) and some scattered large eucalyptus trees (Forest Red Gums) remain. The research site is positioned mid-slope and has a uniform surface gradient of 2.5° to the south by south-east, toward the eastern extremity of an alluvium filled flood plain some 300 m away. Drainage is predominantly by surface run-off.

3.3. Climate

The local region has a temperate, or moderate, near-coastal climate with an annual rainfall typically between 1000 and 1200 mm/year. The Köppen classification is Cfa (Linacre and Geerts, 1997) and the Thornthwaite Moisture Index is +24% (Fityus et al.,

1998; Thornthwaite, 1948). The rainfall is on average relatively well distributed, although winter and autumn are slightly wetter, with typical falls of 120 mm as steady rain in July, and 90 mm as thunder storms and showers in January. However, in 1 in every 3–7 years, a dry summer is experienced, where there is little or no rainfall for up to 3 months. This is now known to arise because the region is strongly influenced by the El Nino climatic cycles, which affect land masses abutting the southern Pacific ocean. In the drought years, the soil profile dries out to its greatest depths, although it usually does not remain dry for long. Fityus et al. (*in press*) and Fityus et al. (1998) report that, because of the generally uniform rainfall, which is in excess of the average evapotranspiration at the site, the soil profile remains relatively moist or wet for much of the time.

The near-coastal climate is humid for the hottest 3–5 months of the year and subhumid at most other times. The temperature range is from 0 to 40 °C, and the average daily temperatures are 12 °C in July and 22 °C in January.

4. Characteristics of the Maryland soil profile

4.1. Description

A description of the Maryland soil profile according to the Unified Soil Classification System (USCS) is shown in Fig. 1, together with a description of the textural characteristics of the soil profile. One important characteristic of the Maryland soil profile is that there are few distinct boundaries evident between the recognisable soil horizons. Rather, the changes are gradational, with each horizon exhibiting subtle transformations with respect to increasing depth, so that the transition between horizons is relatively indistinct.

The profile could be generally described as a “red-brown earth” (which is consistent with many East-Coast Australian soils), exhibiting sufficient distinction between the A and B horizons to be described as a “duplex” profile (White, 1997). The profile exhibits a relatively well-developed B horizon (Righi and Meunier, 1995), with a zone of changing structure at its base, transitioning between the uniformly coloured, desiccated clay in the upper part of the B horizon, and the relict structure evident in the uncracked C horizon.

	USCS Description	Soil Profile Description	Soil Horizons
0.0	(CL) sandy silty CLAY, dark brown	topsoil: dark and organic in upper 100mm; becoming pale with depth, low plasticity	A1 and A2 horizons
0.5	(CH) silty CLAY, high plasticity, pale orange-brown becoming	homogenous, residual clay, no relict rock structure, desiccated when dry. shrinkage cracks coated with silty/sandy topsoil material	B horizon
1.0	mottled pale brown/grey with some red–orange staining	some development of thin ironstone bands mats of tightly packed roots in thin cracks	
1.5	(CL-CH) silty CLAY, medium to high plasticity, pale grey–brown with some iron staining (some residual rock structure)	relict rock structure evident in undisturbed soil, but remolds readily to clay with little effort, no roots or desiccation cracks.	C horizon
2.0	SILTY CLAY/ EXTREMELY WEATHERED SILTSTONE brown grey, laminated	Extremely weathered siltstone rock; brown–grey, may still be parted along original laminations, crumbles when remoulded	weathered rock
2.5	HIGHLY WEATHERED SILTSTONE light and dark grey laminations	Highly weathered siltstone rock; original colour still evident in light and grey laminations	
3.0			

Fig. 1. The Maryland expansive soil profile.

In this transition zone, between 0.9 and 1.2 m depth, the colour of the slightly desiccated clay becomes mottled, representing the zone where rock structure is being destroyed. It is interesting to note that where crack surfaces are encountered in this zone, they are commonly packed with rootlets.

4.2. Engineering parameters

An estimate of the particle size distribution of the Maryland soil profile is shown in Fig. 2. These profiles of particle size were obtained by wet sieving dispersed samples down to 75 μm , and then sizing the minus 75 μm fraction using a Malvern laser diffraction size analyser. The results indicate that the soil profile is dominated by silt-sized and clay-sized particles at all depths, with silt in slight excess at some depths. Sands make up less than 10% of the total soil at most depths. The clay fraction is found to be:

- reduced in the topsoil horizons (10–30% between 0.0 and 0.25 m)
- greatest in the desiccated B horizon (45–53% between 0.25 and 1.2 m)

- slightly reduced in the structured soil horizon (35–38% between 1.2 and 1.7 m)
- further reduced in the weathered rock horizons.

An anomalous coarsening of particle size is indicated at a depth of 1.2 m. This coincides with red–orange staining and a visible concentration of the hydrated iron oxide limonite.

Fig. 3 presents data on the physical characteristics of the Maryland clay. These include variations in basic soil parameters such as Atterberg limits and dry density. They also include trends in soil expansiveness, estimated by both direct and indirect methods. The two direct methods employed were the linear shrinkage test and the shrink–swell test. The linear shrinkage test (AS 1289.C4.1, 1977), measures the linear shrinkage strain of the –4.25 mm fraction of soil, which has been prepared to its liquid limit.

The shrink–swell test, described in AS 1289.7.1.1 (1992) (Fityus et al., 2004b), involves measurement of the axial strain of undisturbed soil specimens between extreme moisture limits: oven dry and saturation. It yields a so-called “instability index”, I_{ss} , which

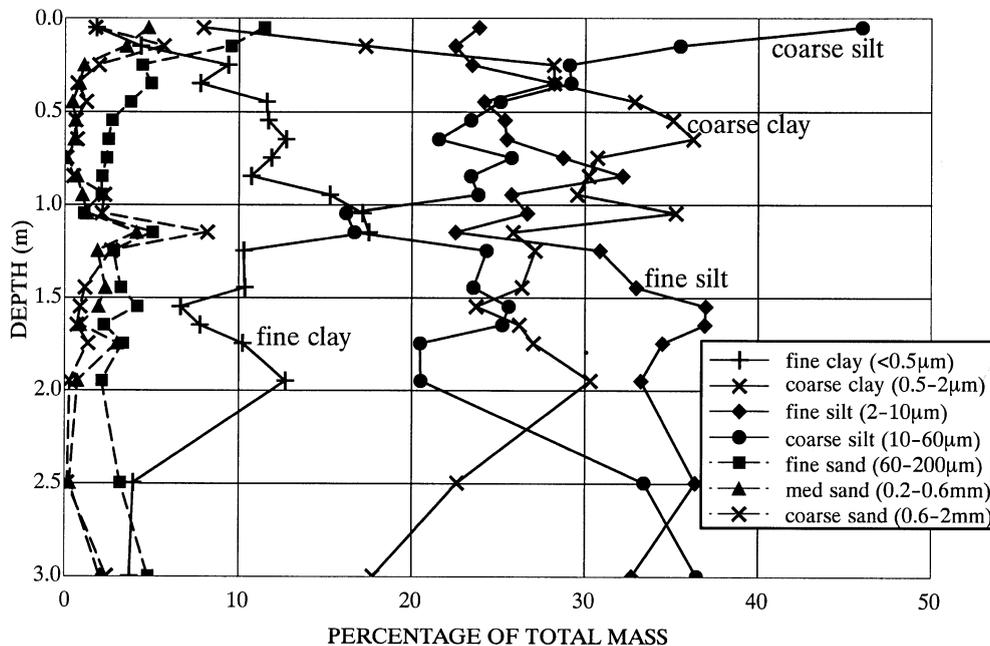


Fig. 2. Particle size percentages with depth.

describes the rate of axial strain per unit change in log suction (which is assumed to be linear throughout the zone of greatest volume change, corresponding to a suction change of 1.8 pF units; that is, over a suction change of 1.8 orders of magnitude). The test standard allows for undisturbed samples to be tested at their field moisture contents, and this is accommodated by testing a pair of samples, each involving a separate procedure: a core-shrinkage test and a one-dimensional swell test. Clearly, the strains measured in each component of the test are not directly comparable. This is accounted for in the calculation of the shrink–swell index and involves division of the swell strain component by an appropriate factor. A factor of 2.0 is typically adopted for all soils and has been shown to be an appropriate value, relatively independent of the initial sample moisture content (Fityus, 1996). The shrink–swell index has proven to be a reliable indicator of the expansive potential of a clay soil under field conditions.

Indirect assessments of soil expansiveness are based on measurements of the adsorptive potential of the clay. The expansiveness of a clay depends, to some extent, upon whether water can penetrate the

interlayer space of the clay particles, and so hydrate the clay particle surfaces and counter-ions. Accordingly, measurements reflecting the number of charged sites on the clay crystal should give an indication of the potential to adsorb water, and so an indirect indication of soil expansiveness. This approach to the estimation of clay content and clay expansiveness has been adopted by many researchers, including Fityus et al. (2000) and Cocka and Birand (1993). There are several ways in which this approach may be applied. One method uses the molecule methylene blue (an organic dye), to estimate the surface area of the clay fraction, as it is known that expansive clays tend to have larger surface areas (the methylene blue is carefully titrated into a sample of powdered clay, suspended in water, until there is excess dye present) (Fityus et al., 2000). Another indirect approach involves the measurement of the cation exchange capacity (CEC) of the soil, which gives an indication of the number of counter-ions that are adsorbed onto the clay particles. This gives an indication of the potential for clay crystal hydration and subsequent swell behaviour.

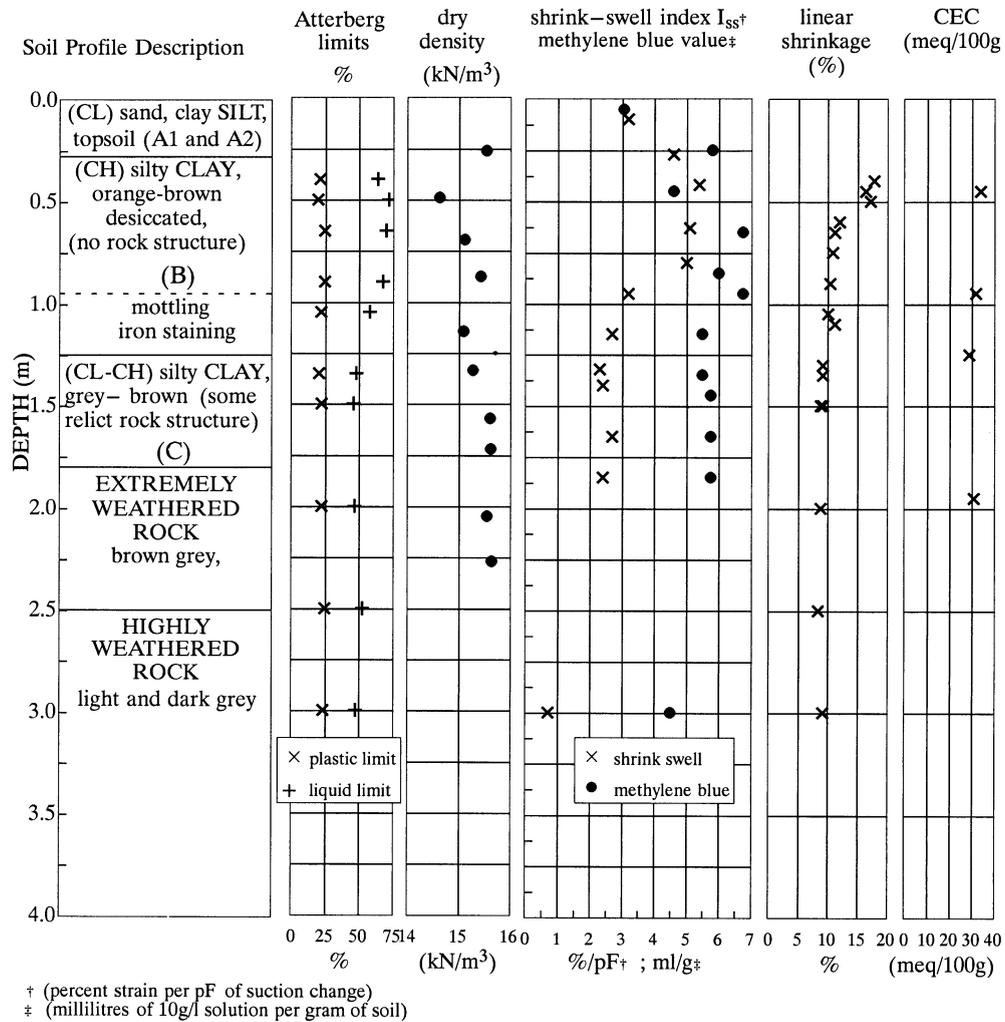


Fig. 3. Engineering parameters of the Maryland expansive soil profile.

The following trends are evident in the engineering parameters of the Maryland clay (see Fig. 3):

- The plastic limit of the soil is generally high and significantly greater in the desiccated B horizon;
- The dry density (at the time of measurement) is lower in the desiccated B horizon;
- Direct indications of volume change potential, comprising shrink–swell index (AS 1289.7.1.1, 1992) and linear shrinkage (AS 1289.C4.1, 1977), each indicate a significant reduction in the expansive potential of the clay soil from the B to the C horizon: by as much as 50%. The

expansiveness of the clay soils in the topsoil A horizons is also less;

- Indirect indications of the volume-change potential, comprising the methylene blue adsorption and cation exchange capacity measurements, suggest that the expansive potential is reduced in the topsoil layers, but is of similar magnitude in both the B and C horizons. This is discussed in a later section.

The relationship between soil suction and water content is shown by the soil water characteristic curve in Fig. 4, for the clay soil in the upper B horizon.

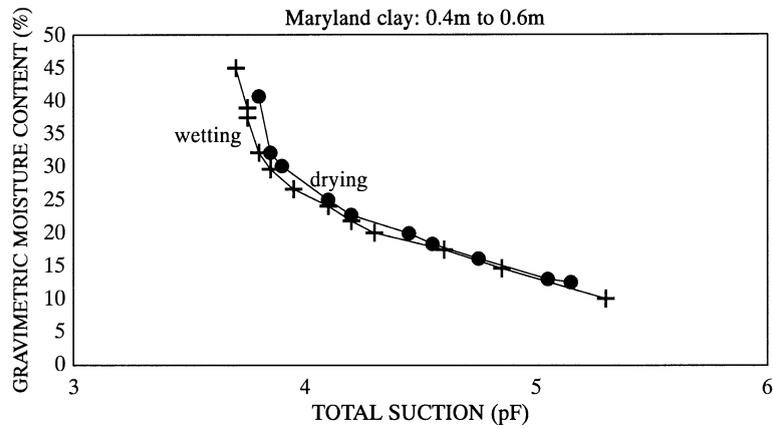


Fig. 4. Soil water characteristic curve for the upper B horizon.

Wetting and drying paths are shown, based on measurements made using a transistor psychrometer, on samples that had been conditioned to particular water

contents, either by wetting from an initially dry state, or by drying from an initially wet state. A small amount of hysteresis is evident in Fig. 4.

Table 1

Mineralogy of the Maryland clay soil profile using quantitative and semi-quantitative X-ray diffraction techniques

Depth (m)	Whole soil sample							Sub 2 micron fraction		
	Kaolinite	Other clay (not differentiated)	Quartz	Muscovite and clay micas	Feldspars (mostly plagioclase)	Haematite and goethite	Anatase	Kaolinite	Randomly interlayered smectite and illite	Smectite + minor interlayered illite
0.15	Tr	D	SD	–	Tr	Tr-A	Tr	Tr-A	D	–
0.45	12%	42%	38%	4%	<1%	<1%	<1%	16%	51% smectite + 7% illite	–
0.55	Tr-A	D	SD	–	Tr	Tr	Tr	Tr-A	D	–
0.75	Tr-A	D	SD	Tr	Tr-A	–	Tr	A	D	Tr
0.95	12%	47%	31%	5%	4%	<1%	<1%	13%	36% smectite + 21% illite	–
1.05	A	D	SD	Tr-A	Tr-A	Tr	Tr	A	D	Tr
1.25	16%	42%	29%	5%	5%	<1%	<1%	15%	36% smectite + 20% illite	–
1.55	A	D	SD	Tr-A	Tr-A	–	–	A	D	Tr-A
1.95	16%	45%	27%	6%	6%	<1%	<1%	19%	43% smectite + 14% illite	–
3.0	A	D	SD	Tr-A	Tr	–	–	A-SD	D	Tr-A
	A	D	SD	Tr-A	Tr	–	–	A-SD	D	Tr-A

The semi-quantitative abbreviations used in this table are: D=dominant, used for the component which is most abundant, regardless of its proportion; SD=subdominant, next most abundant component(s) provided proportion greater than about 20%; A=accessory, present in a proportion between about 5% and 20%; Tr=trace, present, but in a proportion less than about 5%.

4.3. Soil composition

The mineralogy of the Maryland soil profile was investigated by Fityus and Smith (2001) and is summarised in Table 1. The results are based on X-ray diffraction analyses, conducted by two commercial laboratories, both experienced in the determination of clay mineralogy.

Table 1 indicates that there is relatively little change in soil mineralogy with respect to depth. Trends are subtle and can be summarised as follows:

- There is a slight (and inconsistent) decrease (up to 4%) in kaolinite content in the upper orange–brown clay layer.
- There is a slight increase in quartz content (8–10%) in the upper part of the upper layer.
- There are slight decreases in feldspar content (4–5%) and muscovite (2%) in the upper part of the upper layer.
- The total quantity of inter-layered illite and smectite is relatively consistent throughout the soil profile, with a slight increase in inter-layering in the upper layers.

- The limited quantitative data indicates that there is an increased proportion of smectite in both shallower (B) and deeper weathered rock layers (relative to the layers at mid-depth), indicating neither an overall increasing nor decreasing trend. The increase in the B horizon is, however, more significant.

It is noted that the measured clay content based on mineralogy is greater than the measured clay content based on particle size. This suggests either that full disaggregation of particles may not have been achieved in preparing the samples for mechanical particle size analysis, or that the mechanical particle size analysis results may slightly under-predict the clay content, due to some masking of smaller particles by larger particles.

Fig. 5 shows the changes in elemental composition throughout the first 3 m of the Maryland clay profile. The results were obtained using X-ray fluorescence, ion chromatography, atomic absorption spectrophotometry and inductively coupled plasma mass spectrometry measurements on oven-dried, whole soil samples.

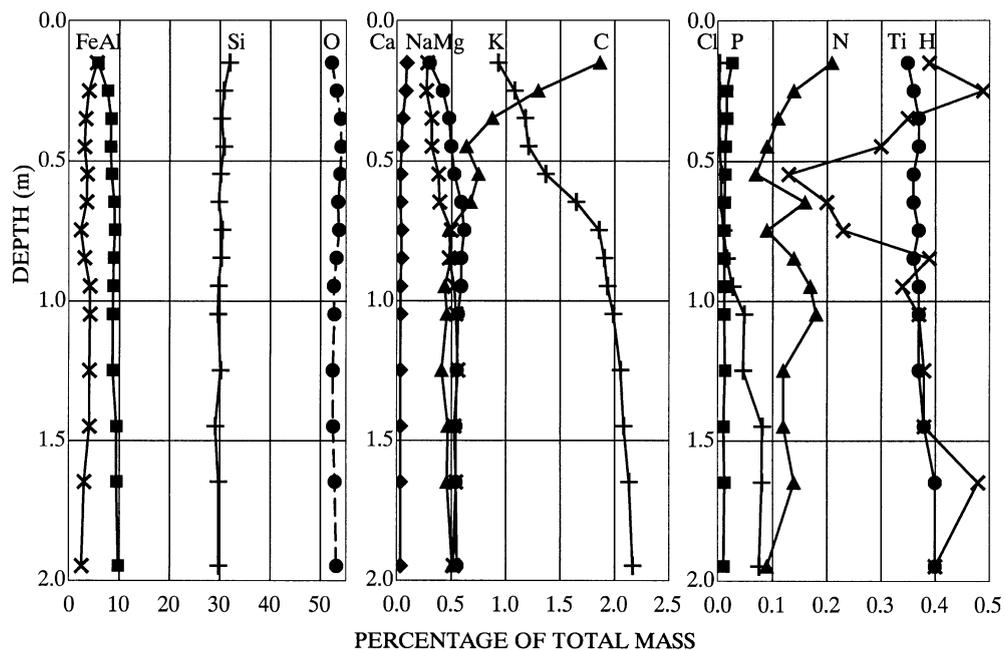


Fig. 5. Elemental percentages, by weight, with depth.

Trends in Fig. 5 include:

- The proportion of primary elements is relatively consistent, with only a slight increase in silicon and iron contents, and a slight decrease in aluminium and oxygen contents, in the topsoil A horizons.
- Of the potentially exchangeable cations, calcium is slightly elevated, while sodium and magnesium are slightly reduced, and potassium is significantly reduced in the upper 0.7 m. This represents the topsoil A horizons and upper part of the B horizon. Potassium content continues to increase slightly with depth below this level.
- Carbon is elevated in the topsoil layers and the upper part of the B horizon. The reduction with depth is rapid.
- The chlorine content is slightly reduced in the topsoil A and B horizons.
- The hydrogen content, although small in the dried soil, is erratic throughout.

5. Classification of the Maryland soil profile

From a geotechnical viewpoint, the Maryland soil profile may be simply classified as a residual clay soil profile. An attempt to create a geotechnical classification scheme for residual soils was made by the Geological Society Engineering Working Group report in 1990, but its scope was limited to tropical residual soils (*Tropical Residual Soils Working Party Report, 1990*). The scheme extends to include subtropical soils but has only limited applicability to the Maryland soil profile.

Classification in terms of other soil classification systems is difficult for two main reasons, being that:

- There is a large number of soil profile classification schemes that are commonly employed by soil scientists, which are mostly based on climatic considerations.
- Most of these are based upon experience in the Northern hemisphere, where, due to the reduced significance of the El Nino effect and generally colder conditions, the weathering patterns are different.

The prevailing soil moisture regime does not conform closely to any of the regimes described in the

United States Department of Agriculture classification scheme (*Soil Survey Staff, 1998*), but displays characteristics that are partly consistent with those of both the Udic (a soil moisture regime that is neither dry for as long as 90 cumulative days nor for as long as 60 consecutive days in the 90 days following the summer solstice at periods when the soil temperature at 50 cm below the surface is above 5 °C) and Ustic (a soil moisture regime that is intermediate between the aridic and udic regimes and common in temperate subhumid or semiarid regions, or in tropical and subtropical regions with a monsoon climate) regimes. Specifically, the Maryland soil profile has developed under conditions where the soil can be dry for up to 90 consecutive days (for one in every 3–7 years), where the climate is humid for the hottest 3–5 months of the year, and where the rainfall is well distributed for most of the year, although slightly heavier in autumn and winter.

The Tropical Residual Soils Working Party Report adopts the terminology of *Duchaufour (1982)* by defining two major soil types in northern hemisphere subtropical climates. The first, “fersialitic”, is of a Mediterranean type where the mean annual temperature is between 13 and 20 °C, the mean annual rainfall is between 0.5 and 1.0 m, and there is a dry season. Characteristics of fersialitic soils are that 2:1 structure clay minerals are dominant and cation exchange capacities exceed 25 mEq (in the context of clay chemistry, 1 mEq = 1 mmol charge/g dry clay particles). The second, “ferruginous” (including ferrisols), is prevalent where the mean annual temperature is between 20 and 25 °C, the mean annual rainfall is between 1.0 and 1.5 m, and there may or may not be a dry season. Characteristics of fersialitic soils are that kaolinite is dominant but 2:1 clay minerals are present and cation exchange capacities range from 16 to 25 mEq.

On the basis of the climatic and the soil profile characteristics, the Maryland soil profile is classified as an Ultisol according to the USDA classification scheme (*Soil Survey Staff, 1998*) or a Luvisol (*FAO-Unesco, 1988; Velde, 1995*).

6. Mineralogical evolution of the Maryland soil profile

The textural observations described in Section 4.1 record obvious, increasing weathering effects closer to

the surface. Surprisingly, however, the data of Table 1 and Fig. 5 indicate that the clay contents and compositions are very similar in both the residual soils and the weathered rock. This suggests that most of the clay in the soil was directly inherited from the parent rock, and that the weathering process did not involve significant new formation of clay minerals, or the transformation of existing phyllosilicate minerals. The soil forming processes are likely to be limited to:

- A small amount of clay translocation from the A1 and A2 horizons down into the B horizon, through leaching or illuviation (transport in a dispersed state by free water; Righi and Meunier, 1995; White, 1997), as suggested by the relative increase in silicon and quartz in the A horizons, the significant decrease in both fine and coarse clay fractions in the A horizons and their corresponding slight increase in the B horizon, and the decrease evident in both direct and indirect measures of expansiveness from the A to the B horizons.
- Minor neoformation of smectites or kaolinite through hydrolysis (bisialitisation or monosialitisation) of small amounts of feldspar (Chamley, 1989), as suggested by the reduction of feldspar in the upper part of the B horizon.
- Minor transformation of muscovite and kaolinite into illite in the B and C horizons (Chamley, 1989), as suggested by the reductions in muscovite and kaolinite in these horizons.
- Minor transformation of illite layers to smectite layers by both structural rearrangements of the crystal layers and by the leaching out of potassium counter-ions for sodium.
- Substantial breakdown of the rock fabric and structural rearrangement. This will be discussed in Section 7.

The relatively small effect of recent weathering processes on mineralogy is not entirely surprising. Robert and Tessier (1992) report that the important mineralogical alteration process of hydrolysis is relatively mild under temperate conditions, and Chamley (1989) reports that when hydrolysis does occur under warm-temperate and humid conditions, degraded (mixed-layer) smectites are formed through the negative transformation (degradation) of existing 2:1 layer clays (such as illite) rather than from neoformations.

The origin of the high smectite content in the laminite parent rocks is not immediately apparent. It could be the result of processes at various stages of the laminite formation. These processes include diagenesis at depths from 1.6 to 2.3 km, transportation and deposition in a brackish or marine environment, or even the formation of the original sediments through the weathering of yet older Carboniferous sedimentary rocks.

Significant neoformation of smectites is unlikely to have resulted from diagenesis and formation through transformation of existing clays is also unlikely. Chamley (1989) reports that dissolution or formation of clay minerals in slightly buried sediments accounts for only a very small part of the total clay content. Further, there is little mineralogical modification in clays undergoing diagenesis at depths of less than 2 km. Evans (1992) suggests that any mineral changes are likely to involve transformation of smectites into illite, chiefly through an increase in the order (decrease in randomness), and the number of illite layers, in interstratified (mixed-layer) illite-smectite clays. Velde (1995) reports that burial of less than 1 km results in few significant mineralogical changes, but that more stable non-expanding minerals (illites) begin to replace smectites at depths of up to 2 km.

Formation of the smectites at the time of the original deposition is also unlikely. Although geological evidence suggests that the Permian sediments were deposited in relatively saline waters, it has been found that the mineralogy of epiclastic sediment is neither prone to significant clay degradation nor clay formation processes as a result of such exposure (Chamley, 1989). The likely effect of deposition in saline waters would be that high concentrations of sodium and potassium are available during diagenesis. Clearly, this source of sodium and potassium cations is available to accommodate the transformations involving illite and smectite as noted above. Any neoformation of smectites is likely to have been limited to the alteration of a small component of volcanogenic sediment that may have been present (Evans, 1992).

Geological evidence suggests that the Permian laminite parent rocks were formed from predominantly epiclastic sediments, previously derived from the weathering of Devonian/Carboniferous argillaceous sedimentary rocks, which had already had ample opportunity to accumulate a large component of 2:1 clays. Examination of the outcropping remnants of

these Devonian/Carboniferous rocks, and their derived residual soils, suggests that the original Permian sediments were indeed likely to have been smectite-rich.

It is most likely that the laminite rocks contain abundant inter-layered illite-smectite, which has more or less existed since its original deposition in a cold Permian climate, where it most likely existed as a stable assemblage. This assemblage was little altered during diagenesis (perhaps there was a small increase in the illite fraction of the clay).

Weathering of the laminite has physically broken down a clay-rich rock to produce a clay soil with most of the clay inherited from the laminite. The survival of this clay mineral assemblage throughout this weathering process is likely to have occurred because it is relatively stable under the temperate climatic conditions, which prevail in the region.

7. Structural evolution of the Maryland soil profile

The Maryland residual soil profile exhibits strongly developed textural changes with increasing proximity to the ground surface (see Figs. 1 to 3). However, from the discussion in Section 6, it is concluded that these are not the result of significant mineralogical variations throughout the soil profile, as the weathering that produced the soil profile, did not cause correspondingly significant mineralogical or compositional changes (Table 1 and Fig. 5).

In the absence of a significant mineralogical variation within the soil profile, some significant inconsistencies in the data presented in Section 4 become apparent. Perhaps most striking is the apparent contradiction between the directly measured soil expansiveness, which indicated a 50% reduction in expansive potential between the B and C horizons (it is noted that these findings are consistent with the observed soil texture variations), and the indirect measurements of soil expansiveness, which suggested that both horizons should exhibit a similar expansive potential (it is noted that these findings are consistent with assessments of soil mineralogy and composition). Certainly, the small changes in clay mineralogy recorded with depth in the Maryland soil profile are insufficient to account for the 50% difference in directly measured expansiveness between the B and C horizons.

Fityus and Smith (2001) have thus concluded that the variation in expansive potential in the Maryland residual soil profile is not primarily due to the effects of weathering on soil mineralogy, but rather, it is due to the effects of weathering on soil structure. That is, the soil that exhibits the greatest expansive potential are those of the B horizon, in which all rock structure has been obliterated, while those which exhibit the reduced expansive potential are those of the C and weathered rock horizons, in which some rock structure is still evident.

Fityus and Smith (2001) noted that the processes of deposition and diagenesis of the parent laminite rock appear to have induced some significant change in the sediment structure. This change is manifested as a suppression of the expansive potential of the residual clay particles in the sediment, which persists whilst the original rock structure remains. This is consistent with some transformation of clay from montmorillonite to illite as a result of the increased pressure at depth.

The precise nature of this phenomenon remains the subject of some speculation and its treatment in the literature is less than precise. However, it is considered that there is sufficient evidence to substantiate its existence. In the context of the present discussion, two aspects of geological structure appear potentially significant; namely, particle arrangement and particle bonding.

Velde (1995) notes that, during deposition from water, clay particles form sponge-like aggregates as the result of edge-to-edge attractions and that these collapse during diagenesis to produce a more densely packed, parallel particle structure. Chamley (1989) notes that, during diagenesis, increasing depth of burial causes clayey sediments to progressively change from a randomly oriented fabric to a more or less oriented fabric, and that the physical reorganisation of particles and aggregates submitted to progressive compaction during early diagenesis is followed by a physiochemical reorganisation during late diagenesis. Whilst the diagenetic restructuring processes are poorly defined, they are reported to include a general decrease in the expansiveness of smectitic minerals and an expulsion of inter-layer water from the clay crystals. Seedsman (1987) reports that the structuring associated with the diagenesis of clay shales may involve the 'growth' of large, illite-smectite clay 'stacks' within a tightly packed, oriented fabric.

Conversely, Kodikara et al. (2002) describes the development of structure in clay soils. Kodikara uses the term soil ‘ripening’, to describe a process whereby clay soils with expansive potential undergo progressive particle rearrangement to form discrete peds, in response to repeated cycles of wetting and drying. Quirk and Murray (1991) suggest that this occurs to minimise the soil’s free energy in response to these cyclical changes. Wilding and Tessier (1988) report that this leads to a net increase in the bulk soil volume, a more dispersed structure and, ultimately, a stiffer and more stable structure in which all structural changes due to wetting and drying become reversible.

The nature of bonding in mud rocks is less well understood. Kay and Angers (2002) report that bonding can occur in clay soils due to the cementing characteristics of the sesquioxides (iron and aluminium oxides, hydroxides and aluminosilicates), while Griffiths et al. (1988) include calcium and magnesium as contributing to “bonding”. Leroueil and Vaughan (1990) include cementation by carbonates, hydroxides and organic substances, as well as by recrystallised parent minerals, modifications of the adsorbed water layers, inter-particle attractive forces (i.e. Van der Waals forces) and “cold-welding” at inter-particle contacts. Alonso and Alcoverro (2002) go as far as to include the effects of “mechanical interlock”, suggesting that, if the framework of surrounding particles prevents swelling of a clay particle, then this effectively constitutes bonding.

It is thus considered, in the case of the Maryland soil profile, that the principal effects of weathering have been to “restructure” the smectite-bearing laminites so that its expansive potential could be realised. This involved a breakdown of the “bonding” that was imparted during diagenesis, and the rearrangement of the soil fabric to give a desiccated/aggregated structure to the B horizon.

Using this model of weathering, the apparent inconsistencies in the Maryland data can be resolved. Regardless of whether bonding is present, the indirect assessments of expansive potential, using chemical sorption techniques, give results that correctly suggest that similar amounts of expansive mineral occur at all depths. However, the direct methods of assessment recorded reduced expansiveness when relict structure or bonding from the parent laminites is still present in less weathered soils.

Fityus and Smith (2001) have explored this idea further, not from the direct consideration of soil structure on a micro scale, but rather, through experiments that investigate the influence of structure on “whole-soil” expansiveness. The results are presented in Section 8.

8. Demonstration of the effects of structure

The basic premise behind the demonstration described here is that, if the suppression of expansiveness is primarily associated with rock structure, then it should be possible to unlock the suppressed expansive potential of a structured material through the physical obliteration of any relict rock structure. The ideas underlying the approach relate to the physical processes of weathering.

In order to understand how the structure and bonds are broken down during weathering, consider an element of material, at depth, in a geological profile where active weathering and erosion are occurring at the surface. On its way to becoming soil, the element will experience a series of different effects, as follows:

- At depth, the element will be composed of “fresh rock”, which is likely to be fully saturated.
- At shallower levels, the element is likely to be exposed to a relatively small vertical moisture flux, either to or from the surface depending on the prevailing climate. This moisture flux is likely to increase with increased proximity to the surface.
- At some depth, depending upon the regional climate, the element begins to experience frequent (perhaps regular) wetting and drying over a small moisture content range. This is the base of the C horizon. This may cause some anisotropic straining of the rock fabric, due to small volumetric expansions of individual clay crystals (Alonso and Alcoverro, *in press*; Seedsman, 1987).
- Nearer to the surface, these moisture changes become regular and sufficiently large to produce shrinkage strains, which are sufficient to crack the rock-structured soil. A positive feedback operates in the sense that the resulting desiccated structure facilitates more severe wetting and drying, and so volume changes become larger.

- During extremes of wetting, the swelling soil develops lateral compressive stresses, which shear and remould the softened, wet soil. This causes all relict rock structure to be lost, particles to rearrange and the formation of aggregates and peds. This is the B horizon.

Although these stages are characterised by a large number of physical and chemical processes, two physical processes would seem to play major roles in the breakdown of rock structure. They are:

- the shrinking and swelling of individual clay particles, dislodging them from the rock fabric, and
- the mechanical remoulding of the soil mass as a whole, which obliterates any sedimentary structure and causes the rotation and translation of clay particles and aggregates of particles.

With these ideas in mind, a series of shrink–swell experiments was carried out to see if soils from the more structured horizons, could have their expansive potential increased by obliteration of their relict rock structure. Samples were collected from the C horizon with relict rock structure from a depth interval of 1.3–1.8 m. From these, four undisturbed samples of soil with rock structure were tested and gave shrink–swell index values ranging between 2.3% and 2.7%. Then, after various attempts had been made to artificially simulate the physical effects of weathering (described next), the soils were reconstituted and retested. The three increasingly aggressive methods employed to accelerate the breakdown of any inherent structure resulting from the diagenetic process were

- (i) Exposure to 10 cycles of flooding with distilled, de-ionised water followed by drying at 40 °C.
- (ii) Air drying, and grinding in a dry state, to a fineness of less than 90 µm.
- (iii) Exposure to 10 cycles of flooding with distilled, de-ionised water followed by drying at 40 °C, then grinding in a slurried state in a rod mill for 2 h, until the mean particle size was less than 20 µm (as determined by laser diffraction particle sizing techniques).

In each case, the samples were reconstituted to target moisture content and density values equivalent

to those of the undisturbed parent soils. Precise details of the reconstitution process are given in Fityus and Smith (2001). The shrink–swell test then proceeded as normal.

The following points should be noted about the tests performed:

- All sample wetting was made with distilled, de-ionised water, so as not to introduce cations, which might affect the expansive potential of the clays.
- All sample drying was achieved by slow drying in a 40 °C cabinet, so as not to remove any “bound water” from the clay crystals.
- Drying was deemed to have been complete when no further reduction in mass occurred in dried samples.

The results obtained are presented in Table 2. When considering the results shown, it is necessary to note that where the shrink and swell samples do not have the same precise water content, the shrink–swell values are likely to be slightly in error:

- Where the moisture content of the shrink specimen is less than that of the swell specimen, there is a small interval of water content change not considered by the test, and so the shrink–swell index is likely to be a lower-bound value (I_{ss} values are subscripted with ‘L’)
- Where the moisture content of the shrink specimen is greater than that of the swell specimen, there is a small interval of water content change that is considered twice by the test, and so the shrink–swell index is likely to be an upper-bound value (I_{ss} values are subscripted with ‘U’).

The above results support the idea that there is a link between the potential for clay soil expansion and soil structure. Whilst the simulated mechanical breakdown of the relict rock structure of the C horizon did not fully realise I_{ss} values as high as 5–5.5%, as have been obtained for undisturbed clays in the overlying desiccated B horizon, successively greater breakdown efforts did produce an enhancement in the expansive potential from around 2.5% up to 4%. We consider these findings sufficient to validate the hypothesis that structure plays an important role in controlling expansive potential in residual soil profiles.

Table 2

Results of shrink–swell tests on mechanically broken down and reconstituted clay soils

Sample depth (m)	Treatment	Moisture contents well sample	Moisture content shrink sample	Average dry density (g/cm^3)	Swell strain ϵ_{sw} (%)	Shrinkage strain ϵ_{sh} (%)	Shrink swell index I_{ss} (%/pF)
1.32	none (undisturbed)	25.3	23.1	1.58	4.1	2.0	2.3 _L
1.48	none (undisturbed)	21.6	23.5	1.58	2.2	3.2	2.4 _U
1.66	none (undisturbed)	21.2	23.6	1.60	5.1	2.4	2.7 _U
1.84	none (undisturbed)	22.0	22.9	1.61	3.1	2.8	2.4 _U
1.32–1.84	none (undisturbed)						2.45
1.3–1.8	wet/dry (10 cycles)	19.5	17.8	1.59	3.4	2.4	2.3 _L
1.3–1.8	dry pulverised	20.4	18.4	1.59	5.1	2.8	3.0 _L
1.3–1.8	wet/dry + wet grind	21.8	19.7	1.60	7.8	2.6	4.0 _L

There are many possible reasons why the imposed physical breakdown did not result in an I_{ss} of 5.5% as in the B horizon. Whether continued efforts to unlock the expansive potential of this material would realise this I_{ss} value has not been determined. However, despite the natural weathering processes being less severe than those imposed in this experiment, they are much more persistent and likely to have a greater effect in the fullness of geological time.

Another important aspect that was not quantitatively evaluated in the above experiment is the possible effect of new soil structures that are formed from the “soil ripening” process, to effectively replace the rock structures inherited from the parent rock. Consideration of the dry densities throughout the profile show that lower densities are found in the upper desiccated B horizon. This is consistent with a breakdown of the compressed rock structure and a possible reorientation of particles from an aligned structure, relict of the sedimentary laminations, to a more random, aggregated structure, which might produce greater expansiveness in the soil mass (particularly if the aggregates do not accommodate clay particle swelling internally). Certainly, in the reconstitution process used for the test samples, there is little chance for soil ripening to occur.

It is likely, however, that the minor mineralogical variations described in Sections 4.3 and 6 are indicative of a slightly enhanced expansive potential in the B horizon arising from mineralogical factors. The slight increase in smectite layers, and the possibility of a reduction in the proportion of potassium in the exchangeable cations due to a reduction in the total potassium content, suggests that a slightly higher

expansive potential in this layer is also likely to play some role.

9. Implications for geotechnical practice

The forgoing discussions have many implications for geotechnical practice. Most obvious is the insight provided by the illustration of how structure influences expansive potential. For example, if limited experimental data on expansive potential is to be extrapolated throughout a residual soil profile, then the data presented here can be used to guide judgements on likely reductions to be applied where rock structure becomes evident. Further, the results suggest that indirect (chemical or mineralogical) assessments of expansive potential need to be interpreted carefully for residual soils showing rock structure, as this relict structure may lead to the real risk of expansiveness of the soil being over-estimated.

There is also scope to gain an understanding of other important behaviours from the structural characteristics of the full soil profile. In the assessment and design of foundations for expansive soils sites, it is often necessary to make predictions of likely ground movements. Where this is done from first principles, it is often done by integrating the soil layer volume changes over the full depth of a soil profile experiencing moisture (or suction) change. In doing so, account is usually taken of the presence of desiccation cracking, and the soil profile is treated in two parts; an upper part where the soil is cracked and soil expansion occurs in three spatial dimensions simultaneously; and a lower part where the soil is uncracked and soil volume changes are con-

strained to occur in the vertical direction only. Thus two important model parameters are required:

- the depth to which wetting and drying proceeds on a seasonal basis and
- the depth of cracking.

Observational data to guide such estimates are seldom available, with the best data coming from long-term field monitoring projects. Such monitoring is clearly impractical in routine practice, but some idea can be gained from the regional extrapolation of anecdotal experience (if available), or recourse can be made to crude prediction methods derived from climate trends (Fityus et al., 1998).

The observations of this paper give an insight into how these parameters might be estimated on the basis of soil texture observation on a given site. Most obvious is the phenomenon of soil cracking and the effects it has on the texture of a soil. Since crack-and-swell remoulding are likely to be the primary factors causing the breakdown of rock structure, it follows that the depth of significant soil cracking should be marked by the onset of rock structure in the soil profile. In the Maryland soil profile, this corresponds to a depth of between 0.9 and 1.2 m. At the Maryland site, this hypothesis is supported by the results of experiments where dye was poured into the ground. This experiment recorded the presence of interconnected macro-voids to 1.15 m under dry summer conditions. The hypothesis is also supported by the thick matings of roots that are commonly encountered in what appear to be cracks (i.e. fissures) in the soil at this depth, and the absence of roots in the rock structured soil (C horizon) below.

Less obvious, but no less plausible, is a relationship between the depth of seasonal soil moisture change, and the boundary between soil with rock structure (the C horizon) and extremely weathered rock. On the basis that weathering is accelerated by cyclic wetting and drying, it is reasonable to expect that there should be a textural demarcation at the depth at which moisture cycling ceases. In the Maryland soil profile, the depth of seasonal moisture change has been recorded at a depth of 1.6–1.7 m on the basis of a 10-year field monitoring project (Fityus et al., *in press*). This is consistent with the depth at which weathered rock is encountered.

Whilst the ideas described above have a sound basis, they have only been tested at one site. Their verification in a general sense is the subject of ongoing research by the authors.

10. Conclusions

Residual soils exhibit rapid variations in textural, structural and engineering parameters with depth. Because they are typically shallow in depth, foundations for large-scale projects are easily taken to rock, and so the engineering parameters of these soils have often received less attention than their alluvially deposited counterparts, which are often deep and soft. However, the expansive nature of some residual soils can have serious consequences for residential and other lightly loaded structures that are routinely founded in them.

Good engineering practice in such soils requires a full understanding of the relationship between their geological development and their engineering parameters. The key effects of weathering on the engineering parameters of rocks and residual soils varies according to the nature of the parent rock material, and the conditions under which the weathering takes place. In the case of crystalline rocks, any clays present in the overlying residuum must be neoformed, as they do not exist in the parent rock.

In the case of argillaceous sedimentary rocks, the origin of clays in the soil is more uncertain. The data considered in this study demonstrate that an enhanced potential for plasticity and expansivity in the heavily structured B horizon does not necessarily correspond to an increase in the proportion of expansive clay minerals due to clay formation during weathering. Rather, the engineering parameters of the residual soils formed under the prevailing temperate-humid conditions in this instance are most strongly determined by structural changes as the parent rock weathers. The net effect of these structural changes is a realisation of an enhanced expansive potential of the residual soil due to the clay minerals originally present in the rock.

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References

- Alonso, E.E., Alcoverro, J., 2002. Swelling, Degradation of Argillaceous Rocks. Keynote Address in the Proceedings of the Third Unsaturated Soils Conference, vol. 3. Recife Brazil (in press). AS 1289.C4.1, 1977. Methods for testing soils for engineering purposes: Method C4.1: Determination of the linear shrinkage of a soil. Standards Australia, Sydney.
- AS 1289.7.1.1, 1992. Methods for testing soils for engineering purposes: Method 7.1.1: Determination of the shrinkage index of a soil; Shrink swell index. Standards Australia, Sydney.
- AS 2870, 1996. Residential Slabs and Footings. Australian Standards Association of Australia, Sydney.
- Aoudjit, H., Robert, M., Elsass, F., 1995. Genesis, organisation and properties of clays formed in saprolites and soils on granites. *Clays Controlling the Environment: The 10th International Conference on Clays*. CSIRO, Adelaide, Australia, pp. 13–42.
- Baynes, F.J., Dearman, W.R., 1978. The microfabric of a chemically weathered granite. *Bulletin of the International Association of Engineering Geology* 18, 91–100.
- Blight, G.E., 1996. Properties of a soil from andesite lava. Proceedings of the 4th International Conference on Tropical Soils, Kuala Lumpur, Malaysia, pp. 575–580.
- Blight, G.E., 1997. *The Mechanics of Residual Soils*. Balkema, Rotterdam.
- Cocka, E., Birand, A., 1993. Determination of cation exchange capacity of clayey soils by the methylene blue test. *American Society for Testing and Materials-Geotechnical Testing Journal* 5, 518–524.
- Chamley, H., 1989. *Clay Sedimentology*. Springer-Verlag, Berlin.
- Diessel, C.F.K., 1975. Coalification trends in the Sydney Basin, New South Wales. In: Campbell, K.S. (Ed.), *Gondwana Geology: Papers Presented at the Third Gondwana Symposium*, Canberra, Australia, 1973. Australian National Univ. Press, Canberra, pp. 295–309.
- Diessel, C.F.K., 1980. Newcastle and Tomago coal measures. In: Herbert, C., Helby, R. (Eds.), *A Guide to the Sydney Basin*. Department of Mineral Resources, Sydney, pp. 100–115.
- Duchaufour, P., 1982. *Pedology, Pedogenesis and Classification*. Allen & Unwin, London.
- Engel, B.A., 1966. Explanatory Note Accompanying the Newcastle Geological Sheet S1 56-2 Australian National Grid. Dept. Mines NSW, Sydney.
- Evans, L.J., 1992. Alteration products at the Earth's surface—the clay minerals. In: Martini, I.P., Chesworth, W. (Eds.), *Weathering, Soils and Paleosoils*. Elsevier, Amsterdam, pp. 107–125.
- FAO-Unesco, 1988. *Soil map of the world (and revised legend)*. World Resources Report, vol. 60. Food and Agriculture Organisation of the United Nations, Rome.
- Fityus, S.G., 1996. The effect of initial moisture content and remoulding on the shrink–swell index, I_{ss} . Proceedings of the 7th, ANZ Conference in Geomechanics. Institution of Engineers, Canberra, Australia, pp. 388–393.
- Fityus, S.G., 1999. Transport processes in unsaturated soils. PhD thesis (unpublished), University of Newcastle, Australia.
- Fityus, S.G., Smith, D.W., 2001. The development of expansive potential in a clay soil of residual origin. *Chemo-Mechanical Coupling in Clays*, Balkema, 189–200.
- Fityus, S.G., Walsh, P.F., Kleeman, P.W., 1998. The influence of climate as expressed by the Thornthwaite Index on the design depth of moisture change of clay soils in the Hunter Valley. Conference on Geotechnical Engineering and Engineering Geology in the Hunter Valley. Conference Publications, Springwood, Australia, pp. 251–265.
- Fityus, S.G., Smith, D.W., Jennar, A.M., 2000. Surface area using methylene blue adsorption as a measure of soil expansivity. Proceedings of GEOENG 2000; The Millennium Conference of the 3 International Societies (ISSMGE, IAEG and ISRM), Melbourne, 2000.
- Fityus, S.G., Smith, D.W., Allman, M.A., 2004a. An expansive soil test site near Newcastle. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* (in press).
- Fityus, S.G., Walsh, P.F., Cameron, D.A., 2004b. The shrink swell test. *ASTM Geotechnical Testing Journal* (submitted for publication).
- Freeman, T.J., Burford, D., Crilly, M.S., 1991. Seasonal foundation movements in London clay. *Proc. 4th Int. Conf. Ground Movements and Structures*, Cardiff.
- Griffiths, F.J., Joshi, R.C., Nagaraj, T.S., 1988. Removal of cementation bonds in stressed overconsolidated clays. *ASTM Geotechnical Testing Journal* 11, 227–232.
- Hawkins, A.B., Pinches, G.M., 1992. Engineering description of mudrocks. *Quarterly Journal of Engineering Geology* 25, 17–30.
- Herbert, C., 1980. Depositional development of the Sydney Basin. In: Herbert, C., Helby, R. (Eds.), *A Guide to the Sydney Basin*. Department of Mineral Resources, Sydney, pp. 100–115.
- Jones, D.E., Holtz, W.G., 1973. Expansive soils—the hidden disaster. *ASCE Journal of Soil Mechanics and Foundation Division* 43 (8), 49–51.
- Kay, B.D., Angers, D.A., 2002. Soil structure. In: Warrick, A.W. (Ed.), *Soil Physics Companion*. CRC Press, Florida, USA, pp. 249–295.
- Kodikara, J., Barbour, S.L., Fredlund, D.G., 2002. Soil structure development in surficial heavy clay soils—a synthesis of mechanisms. *Australian Geomechanics* 37, 25–40.
- Krohn, I.D., Slossen, J.E., 1980. Assessment of expansive soil in the United States. *Proc. 4th International Conference on Expansive Soils*. American Society of Civil Engineers, New York, pp. 596–608. Denver.
- Leroueil, S., Vaughan, P.R., 1990. The general congruent effects of structure in natural soils and weak rocks. *Geotechnique* 40, 467–488.
- Linacre, E., Geerts, B., 1997. *Climates and Weather Explained*. Routledge, London.

- Lumb, P., 1961. The properties of decomposed granite. *Geotechnique* 3, 226–242.
- Macias, F., Chesworth, W., 1992. Weathering in humid regions. In: Martini, I.P., Chesworth, W. (Eds.), *Weathering, Soils and Paleosoils*. Elsevier, Amsterdam, pp. 283–306.
- Millot, G., 1970. *The Geology of Clays*. Masson, Paris.
- Potter, P.E., Maynard, J.B., Pryor, W.A., 1980. *Sedimentology of Shale: Study Guide and Reference Source*. Springer, New York.
- Quirk, J.P., Murray, R.S., 1991. Towards a model for soil structure behaviour. *Australian Journal of Soil Research* 29, 829–867.
- Robert, M., Tessier, D., 1992. Incipient weathering: some new concepts on weathering, clay formation and organisation. In: Martini, I.P., Chesworth, W. (Eds.), *Weathering, Soils and Paleosoils*. Elsevier, Amsterdam, pp. 71–99.
- Righi, D., Meunier, A., 1991. Characterisation and genetic interpretation of clays in an acid brown soil (dystrochrept) developed in a granite saprolite. *Clays and Clay Minerals* 39, 519–530.
- Righi, D., Meunier, A., 1995. Origin of clays by rock weathering and soil formation. In: Velde, B. (Ed.), *Origin and Mineralogy of Clays*. Springer, Berlin, pp. 43–157.
- Seedsman, R.W., 1987. Strength implications of the crystalline and osmotic swelling of clays in shales (Technical Note). *International Journal of Rock Mechanics and Mineral Science & Geomechanics Abstracts* 24, 357–363.
- Sherman, G.D., Uehara, G., 1956. The weathering of olivine basalt in Hawaii and its pedogenic significance. *Proceedings-Soil Science Society of America* 20, 337–340.
- Smith, J., 1957. A mineralogical study of weathering basalt. *Journal of Soil Science* 8, 225–239.
- Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. *Geographical Review* 38 (1), 54–94.
- Tropical Residual Soils Working Party Report, 1990. Geological society engineering group working party report: tropical residual soils. *Quarterly Journal of Engineering Geology* 23 (1), 1–93.
- Soil Survey Staff (USDA), 1998. *Keys to Soil Taxonomy*, Eighth Edition. United States Department of Agriculture, Washington.
- Walsh, P.F., Cameron, D.A., 1997. *The Design of Residential Slabs and Footings*. Standards Australia. SAA HB28-1997.
- White, R.E., 1997. *Principles and Practice of Soil Science*, 3rd edition. Blackwell, Oxford.
- Wilding, L., Tessier, D., 1988. Genesis of vertisols: shrink swell phenomena. In: Wilding, L.P., Puentes, R. (Eds.), *Vertisols: Their Distribution, Properties Classification and Management*. Texas A & M Printing Centre, Texas, USA, pp. 55–81.
- Velde, B., 1995. *Origin and Mineralogy of Clays*. Springer, Berlin.