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Implications of weathering on the engineering properties of the Fuller's Earth formation

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The Fuller's Earth formation is an overconsolidated, jointed, randomly fissured, calcareous mudstone with some thin to medium, jointed argillaceous limestone bands. South of Bath, the formation contains the commercial (montmorillonite rich) Fuller's Earth bed. This Paper reviews the effect of the proportion of calcite present on the moisture content, Atterberg limits, particle size, and residual shear strength. Attention is drawn to the importance of appreciating that the calcite percentage and the clay mineralogy are both likely to change with time as a result of weathering processes. This will affect the stability of natural slopes and man-made cuttings, excavations, etc.

KEYWORDS: calcite; clays; index properties; montmorillonite; mudstones; weathering

La formation de terre à foulon est un limon compact calcaire surconsolidé jointé et fissuré au hasard qui contient des bandes de chaux argillacée jointées d'épaisseur faible ou modérée. Au sud de Bath la formation comprend la couche de terre à foulon commerciale qui est riche en montmorillonite. L'article examine l'influence de la proportion de calcite présente sur la teneur en eau, les limites d'Atterberg, la grandeur des particules et la résistance au cisaillement résiduelle. On attire L'attention sur la nécessité de comprendre qu'il est probable que le pourcentage de calcite et la minéralogie argilleuse changeront au cours du temps ce qui entraine un processus d'effritement cela influencera la stabilité des pentes naturelles, des déblais, des excavations, etc.

It is now well established practice to correlate various engineering parameters with intrinsic soil or index classification properties, primarily particle size and Atterberg limits. The Casagrande plasticity index provides a valuable indicator of the likely engineering behaviour for most clays and silts, mainly because the index properties are related to the soil mineralogy.

Analysis of the correlations, including the bulk material properties such as particle mineralogy and bulk soil chemistry, has highlighted those geological factors which exert the greatest influence not only on the index test results, but also on the measured engineering properties of the overconsolidated, fissured, calcareous mudstones which form the dominant lithology of the Fuller's Earth formation in the south Cotswolds.

Research has confirmed a number of mineralogical changes that occur within the weathering profile. In addition, it has been shown that the variable proportion of calcite present has a profound effect on both the index and other geotechnical properties. The calcium carbonate content in any mudstone sequence varies both as a result of the natural lithological controls (the accumulated sedimentary material and diagenetic cements) and as a result of the inherent solubility of calcite. With time, ground water level fluctuations in natural slopes and alterations of the ground water regime as a result of engineering cuttings create significant changes in the proportion and nature of the calcite. This has consequential effects on the engineering properties of the strata.

This Paper reviews the effect of the proportion of calcite present on the moisture content, Atterberg limits, particle size and residual shear strength in the Fuller's Earth formation of the Bath area of the south Cotswolds (*see* Fig. 1.). Emphasis is placed on the importance of determining the percentage of calcite present and appreciating the likelihood that this may alter with time. The stratigraphy of the Fuller's Earth formation is described and the difficulty of distinguishing calcareous mudstones from argillaceous limestones, particularly in moist samples, is emphasized. The mineralogical variations of the sub-divisions are considered. Attention is drawn to the change in clay mineralogy and effects of decalcification which occur as a result of weathering, and how these will affect the commonly measured engineering parameters of a calcareous mudstone.

Discussion on this Paper closes on 1 April 1989. For further details, see p. ii.

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STRATIGRAPHY

The Fuller's Earth formation of Middle Jurassic age consists mainly of calcareous mudstones/clays, with the oolitic limestones of the Inferior Oolite below and those of the Great Oolite above (*see* Fig. 2). The full stratigraphic sequence in the Bath area according to the work of Kellaway & Welch (1948) and Arkell & Donovan (1952) is

Upper Fuller's Earth (c. 25 m)
Claystone with argillaceous, shelly and oolitic limestone bands

Fuller's Earth bed (c. 2–3 m)
Claystone rich in montmorillonite occurs about 7 m from top of sequence

Fuller's Earth rock (c. 4 m)
Rubbly, argillaceous, shelly and oolitic limestone

Lower Fuller's Earth (c. 10 m)
Silty claystones with argillaceous and oolitic limestone bands

Various authors have shown that this general succession is applicable over an area extending from the Mendips to just north of Bath, although the Fuller's Earth bed is of only limited areal extent. North of Bath the formation becomes increasingly calcareous and several of the argillaceous limestone bands seen in the Bath area coalesce to develop thick, individually named units.

SAMPLING

Samples have been collected from boreholes, mine workings and trial pits at the locations shown in Fig. 1. In view of the extensive landslipping to the west of Soper's Wood, in an area where the Fuller's Earth bed was not known, a specially drilled, cored, borehole was sunk at ST 746677 in order to obtain samples through the complete Fuller's Earth formation. Although the succession includes argillaceous limestone bands, (Fig. 2) there was nothing resembling the Fuller's Earth bed which is present in the Combe Hay area south of Bath. Visual examination of the cores indicated the Upper Fuller's Earth clays to be weathered and significantly discoloured to a depth of 4–5 m. Below this they were grey in colour and effectively fresh in weathering grade.

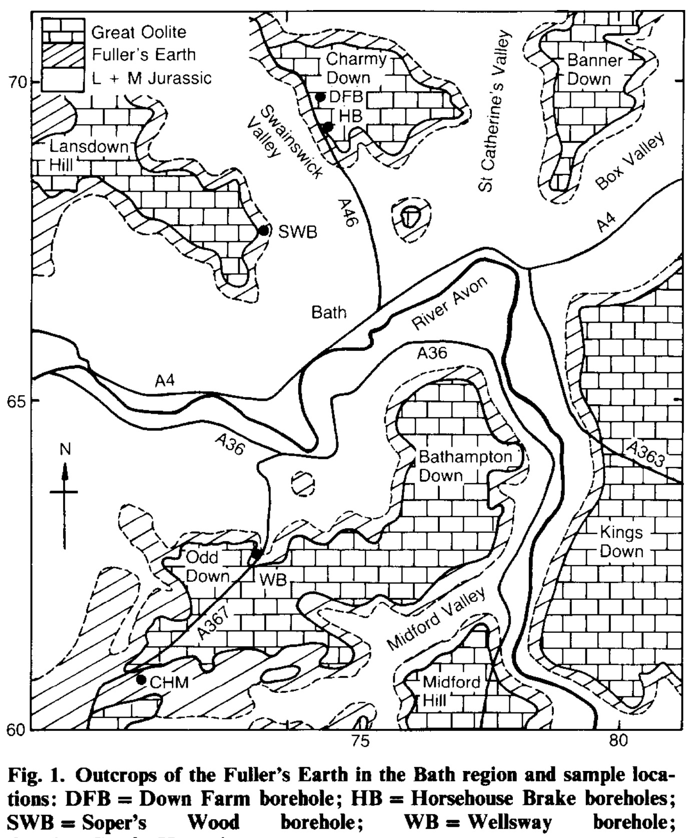

Fig. 1. Outcrops of the Fuller's Earth in the Bath region and sample locations: DFB = Down Farm borehole; HB = Horsehouse Brake boreholes; SWB = Soper's Wood borehole; WB = Wellsway borehole; CHM = Combe Hay mine

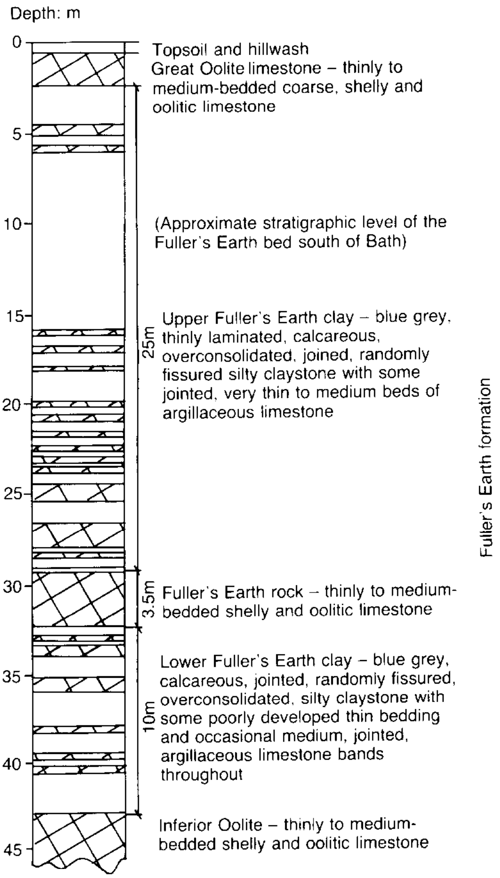

Fig. 2. Litho/stratigraphic log of the Soper's Wood borehole

Additional fresh material from the area south of Bath was sampled from the cores of a site investigation borehole undertaken immediately west of the Wellsway Road (ST 742625). This borehole penetrated the Upper Fuller's Earth but again did not encounter the commercial Fuller's Earth bed. Samples of this bed were obtained from the face of the working Fuller's Earth mine at Combe Hay (ST 730612) before it ceased active production in 1980.

Samples of weathered Fuller's Earth clay were obtained from hillslope sites within the Swainswick Valley. At Down Farm (ST 755695) a borehole located on the line of the A46 realignment (Privett, 1980) was drilled to obtain continuous U100 samples. Across the valley, adjacent to Soper's Wood, slips reactivated between 1980 and 1984 involving the weathered Upper Fuller's Earth have been examined by Lawrence (1985), who tested samples taken from shallow trial excavations.

MINERALOGY

Samples of the Fuller's Earth formation from the Soper's Wood and Wellsway borehole cores were taken at 1 m intervals, and those from the face of the mine within the Fuller's Earth bed at 200 mm intervals. Ten samples were also taken from the Down Farm borehole, at levels permitted by the U100 sampling. Additional samples at selected depths were obtained from a series of trial pits to the south of Soper's Wood.

The mineralogy of the Fuller's Earth formation was described recently by the Authors (Hawkins, Lawrence & Privett, 1986) and some general comments were made by Robertson (1986). Analysis by X-ray diffractometry (XRD) shows clearly that, throughout the succession, illite is the dominant mineral present, with kaolinite as a common subordinate constituent. Generally the glycolated XRD samples show only a very weak to weak expanded montmorillonite peak, except in the Soper's Wood borehole where, within the top 4–5 m of the Upper Fuller's Earth, reasonably strong diffraction peaks are evident. It is likely that this increased montmorillonite content is related to weathering rather than initial lithological variation in the clay mineralogy. The weathering process envisaged is that postulated by MacEwan (1949) shown in Fig. 3. In this, illite is transformed to a mixed layer, interstratified, illite-smectite (montmorillonite) assemblage by the release of potassium and the subsequent hydration and adsorption of calcium or sodium into the preferentially weathered planes of the interlayer spacings (*see* Jackson, Hseung, Corey, Evans & Vanden Heuvel, 1952).

Mineralogical and chemical determinations on samples from the Down Farm borehole and Soper's Wood trial pits suggest a change in the clay–mineral assemblage in the more weathered near surface zones, possibly exacerbated by post-glacial acid weathering transforming some of the illite to a mixed layer clay in the near surface zones. The expandable smectite component of this mixed layer mineral has been measured at 23–39% (Lawrence, 1985; Hawkins *et al.*, 1986). At none of the localities reported, however, has the montmorillonite content approached that observed in the unweathered Fuller's Earth bed.

At Combe Hay, the Fuller's Earth bed is about 2·4 m thick and contains high proportions of the smectite mineral Ca-montmorillonite (Jeans, Merriman & Mitchell, 1977). In the Top Seam (Fig. 4) large calcareous concretions and a significant fossil content contribute to a calcite percentage between 33–52%. This reduces the proportion of Ca-montmorillonite present, and thus the commercial value of this part of the bed. In the Whole Seam, however, the calcite content has been measured as less than 15% for seven of the nine

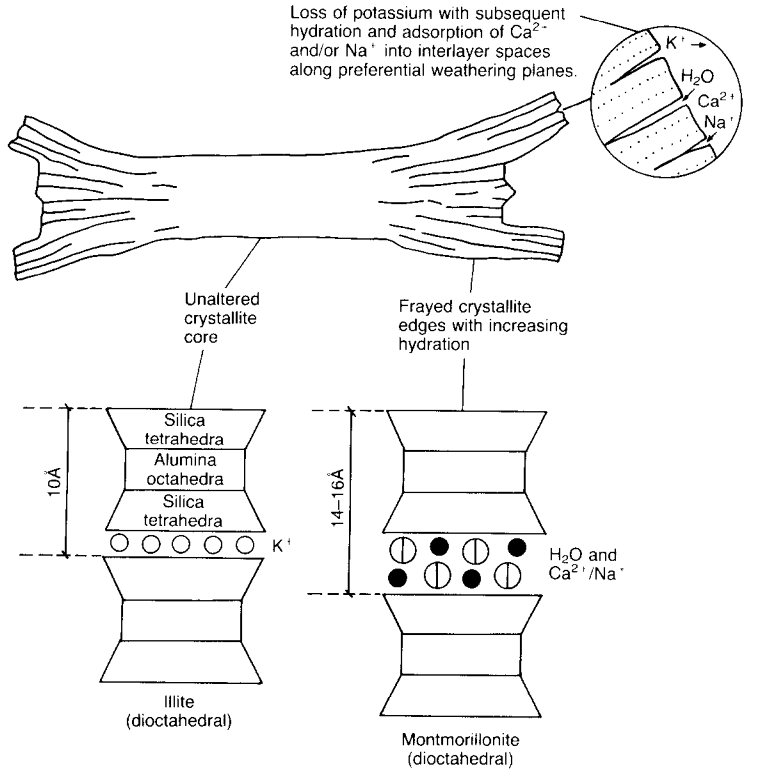

Fig. 3. Representation of the weathering of illite to montmorillonite

samples. The high clay–mineral assemblage of the whole seam is dominated by interstratified illite-smectite containing between 92% and 100% smectite. According to Penn, Merriman & Wyatt (1979) this is equivalent to a bulk Ca-montmorillonite content of 60–80%.

Visual field observations and X-ray diffractogram analysis also confirmed the presence of gypsum within the weathered and landslipped horizons at the Soper's Wood site. The trial pits indicated gypsum growths notably between 1·0 and 2·5 m below ground level within the weathering zones III and IV, a depth similar to that described by Chandler (1972) for the Lias clay. After about ten years of storage, during which the fresh Fuller's Earth clays were allowed to oxidize and desiccate, the Soper's Wood cores showed a prolific growth of gypsum on the exposed core surfaces. Such gypsum growth was also evident on Westbury Beds bag samples after only a few months (*see* Hawkins & Pinches, 1986; 1987a; 1987b).

Mineralogical analysis has indicated a trace presence of quartz, feldspar (of variable composition) and pyrite. For a more detailed, comprehensive, resistate mineral analysis for the Fuller's Earth, reference should be made to Hallam & Sellwood (1968) and Jeans *et al.* (1977).

GEOTECHNICAL PROPERTIES

To date, the only published information on the index properties of the Fuller's Earth formation in the Bath area is that presented by Chandler, Kellaway, Skempton & Wyatt (1976). They indicated a range of liquid limit values for samples from the Swainswick Valley, varying from 35 to 55% (mean 44%) for the clays of the Lower Fuller's Earth and from 40 to 65% (mean 51%) for the Upper Fuller's Earth. The average plastic limit for the material in the first 10 m below the surface is reported as between 17% for the Lower and 20% for the Upper Fuller's Earth. With mean plasticity indices of 27% and 31%, the results suggest there is no significant difference between the classification test results for the Lower and Upper Fuller's Earth at this locality.

Moisture content and Atterberg limit profiles

Moisture contents and Atterberg limits were obtained on samples at 1 m intervals on the core of the Soper's Wood borehole (Fig. 5); on

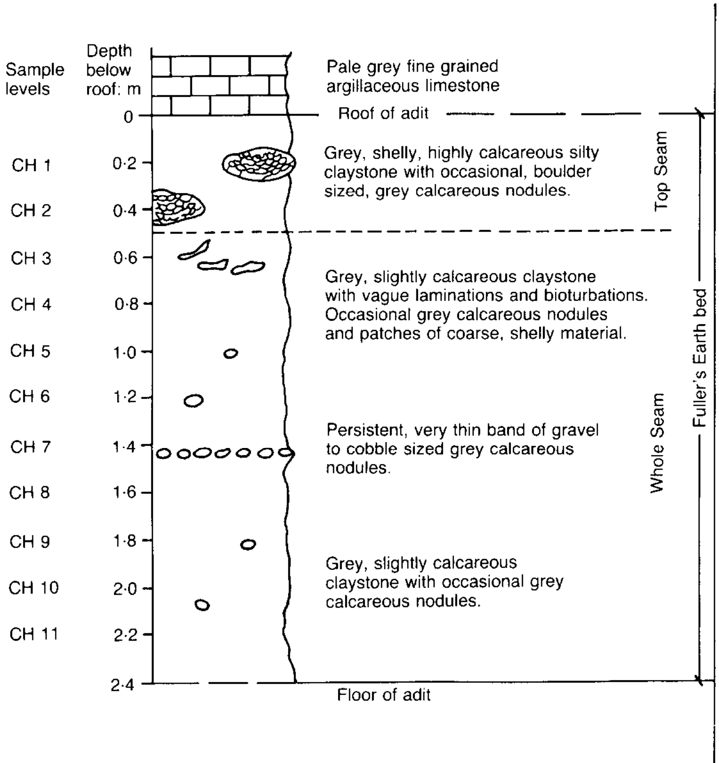

Fig. 4. Lithological sequence and sampling levels in the Fuller's Earth bed at Combe Hay mine, Bath (modified from Jeans *et al.*, 1977)

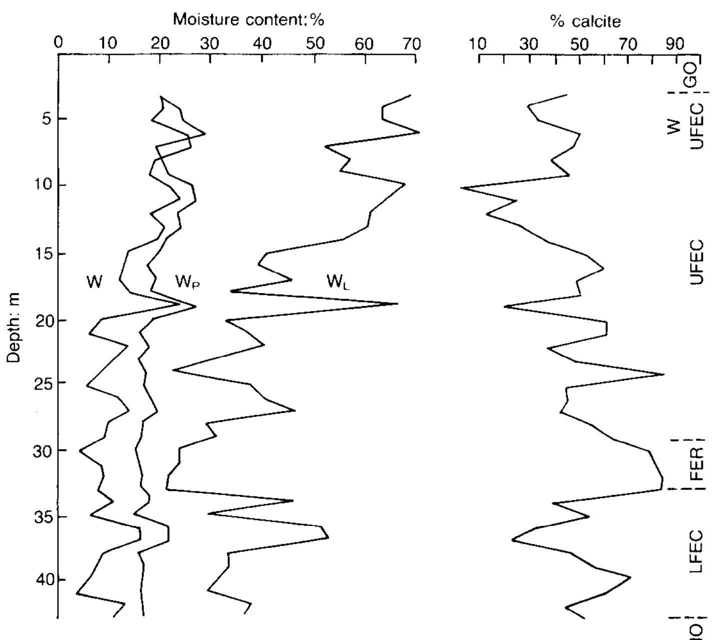

Fig. 5. Natural moisture content, Atterberg limits and calcite variation through the Fuller's Earth formation at Soper's Wood, Bath (see Fig. 2 for terminology)

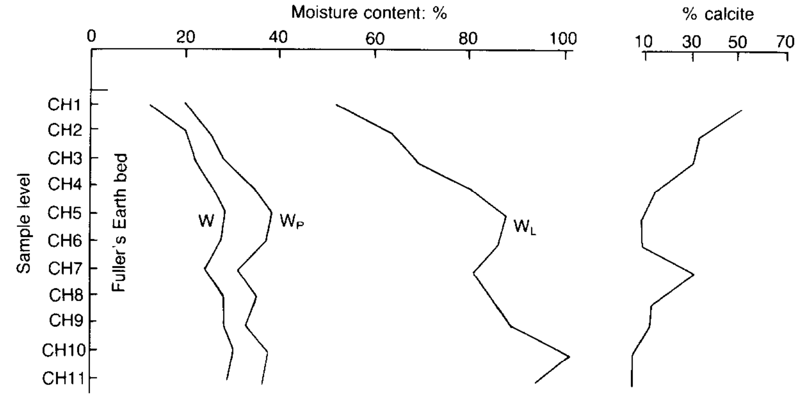

Fig. 6. Natural moisture content, Atterberg limit and calcite variation for the Fuller's Earth bed from the Combe Hay mine, Bath

material from the Fuller's Earth mine at 200 mm intervals (Fig. 6) and from U100 samples from the Down Farm borehole (Fig. 7). Although Chandler *et al.* (1976) suggest 'the natural moisture contents are, as usual in weathered overconsolidated clays, approximately equal to the plastic limit', the evidence indicates they are generally below the plastic limit in the less weathered/unweathered material but above it in the more weathered samples.

In the unweathered Fuller's Earth bed, the moisture content profile is parallel to that of the plastic limit (Fig. 6) but consistently 5–10% lower. The data from the typical succession at Soper's Wood (Fig. 5) show that, in unweathered Fuller's Earth, the moisture content approaches the plastic limit upwards through the sequence. The two profiles cross near the top of the borehole at the same level where weathering has penetrated sufficiently to increase the montmorillonite content. The effect of weathering on the moisture content–plastic limit change-over is also evident for the samples from Down Farm (Fig. 7) which afford a more detailed profile of the weathered portion of the sequence. It can be seen that, in the upper part of zone I and in the more weathered material above, the moisture content increases progressively, relative to the plastic limit. A similar trend is indicated by the test data from the Horsehouse Brake Cutting on the A46 realignment (MRM Partnership, 1985) although in this case the colluvial nature of the near surface soils produced values in the upper 2 m which are not indicative of in situ Fuller's Earth clay.

Table 1 summarizes data from the Soper's Wood area and indicates a clear, progressive

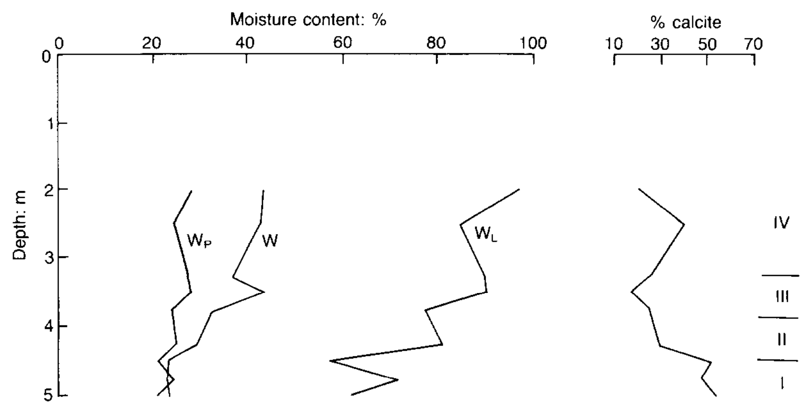

Fig. 7. Natural moisture content, Atterberg limit and calcite variation for the Fuller's Earth from Down Farm borehole, Bath: I–IV represent weathering zones

Table 1. Moisture and index values from trial pit samples at Soper's Wood (SWTP) for weathering zones II and IV of the Upper Fuller's Earth clays and for zone I from borehole samples (SWBH).

Weathering zone	w: %	w_L: %	w_p: %	I_p: %
IV (SWTP)	39–46	80–90	31–36	48–55
II (SWTP)	29–30	64–69	26–29	38–40
I (SWBH)	6–24	21–67	16–28	16–39

increase in moisture content and Atterberg limits in the more weathered material.

Index properties and calcite content

X-ray diffraction demonstrated the presence of calcite, the percentage of which was determined by acid digestion. The results are shown in Figs 5–7. In Fig. 5 the steady, upward increase of the moisture content and plastic limit and the more sensitive increase in liquid limit, is accompanied by an overall decreasing trend in the percentage of calcite. A similar trend is observed when comparing the moisture content and Atterberg limits with the calcite percentages from the more weathered samples of the Down Farm borehole (Fig. 7).

There is an observable general trend in the calcite content, although in detail the profiles are highly irregular, reflecting the lithological variations within the Fuller's Earth clays. The Atterberg limits also have very irregular profiles, yet a comparison of the liquid limit and calcite percentage indicates a strong inverse correlation which confirms both the general trend and the variation due to lithology. A similar inverse relationship is indicated for the Fuller's Earth bed (Fig. 6) although the trend is in the opposite direction. In this case the values are influenced by the high calcite percentages associated with the impure nature of the Top Seam (Fig. 4) concurrent with a clear lithological gradation into the overlying 'roof-bed' limestones.

Comparison of the weathered Fuller's Earth sequence at Down Farm (Fig. 7) and the unweathered material from the Soper's Wood borehole (Fig. 5) indicates the liquid limit values of the former (60–100%) to be considerably higher than those of the latter (21–67%). In addition, trial pit samples from the Soper's Wood site gave higher liquid and plastic limits for the zone II and IV material, compared with results from the fresh borehole samples at the same altitude, and hence probably the same stratigraphic level (Table 1). It is of note that although there is little difference in the upper values in the ranges between the zone I and II material, there is quite a marked increase between these and the upper values for the zone IV material. It is suggested that the different values reflect the change in clay mineralogy and calcite content as weathering progresses in the illite-rich calcareous mudrock.

The index limits of the unweathered Fuller's Earth bed are similar to those of the zone IV Fuller's Earth clay, suggesting that the high limits in the former reflect the greater proportion of Ca-montmorillonite in the clay mineralogy of the Fuller's Earth bed.

WEATHERING OF THE FULLER'S EARTH

The boreholes show a weathering profile in the Fuller's Earth clays, typically within 4–5 m of the ground surface (note about 6 m depth in the Soper's Wood borehole, below the 2·4 m of Great Oolite.) With the data from a large number of trial pits on the Soper's Wood site and information from the Down Farm borehole, a visual weathering classification scheme has been established (*see* Table 2, after Lawrence, 1985). The progressive alteration in material fabric and the state of oxidation forms the basis of the classification. The zonal scheme has been adapted from that presented by Chandler (1969 and 1972); EGGSWP (1972); and BSI (1981).

The main trends in index properties which can be associated with weathering of the Fuller's Earth clay have been represented in a series of bar graphs (Fig. 8). The figure includes all the available moisture contents and Atterberg limits data plotted for each of the weathering zones, and demonstrates clear trends of increasing moisture content and Atterberg limits with weathering. As would be anticipated, the most obvious trend is displayed by the variation in liquid limit; the two zone V/IV results came from disturbed material. The results from the Fuller's Earth bed are included below the weathering zones for comparison.

The bar graph plot for measured calcite content (Fig. 9) indicates a general decreasing trend with weathering grade. The very wide spread of plots, especially for the zone I material, is clearly related to lithological variations; it being very difficult to separate visually the highly calcareous mudstones from the argillaceous limestones. This decrease in calcite with weathering is more obvious than is indicated by the limited data reported by Chandler & Apted (1988).

CALCITE CONTENT AND ITS CONTROL ON GEOTECHNICAL PROPERTIES

In order to examine the inverse relationship between the calcite content and the index properties, the information has been plotted in graphical form in Figs 10–14. In these figures, the test data

Table 2. Weathering scheme for the Upper Fuller's Earth clay based on the scheme for Soper's Wood (Lawrence, 1985)

Residual soil (hillwash/solifluction)	VI	Soft to firm	In the superficial material, claystone is weathered to a soil in which the original rock fabric is completely destroyed. Mottled yellow-brown oxidation above the ground water level is extensive to complete. Some gleying occurs at shallow depths. Frequently contains many gravel and cobble fragments of weathered Great Oolite limestone derived from higher slopes. Seasonal desiccation features are common.
Completely weathered	V	Soft to firm	Claystone is discoloured and oxidized and completely weathered to a yellow-brown clay soil. Occasional small corestones may preserve relic laminations. Frequent gleyed fissures and root channels. Calcite content variable.
Highly weathered	IV	Firm to stiff	Fissured clay with extensive oxidation discoloration. Fissures are open and may be gleyed on surfaces. Oxidation alteration penetrates deeply from fissures. Lithorelicts (10–40%) indicate some remaining structure. Calcite content variable. Some gypsum crystals on discontinuity surfaces. Many minor striated shear surfaces.
Moderately weathered	III	Firm to stiff	Claystone is partially oxidized and altered to clay. Open fissures and discontinuities are discoloured orange-brown on surfaces. Alteration penetrates into soil mass, becoming yellow and grey-brown along 15 mm wide zones parallel to fissures. Lithorelicts comprise 40–70% of bulk soil. Original soil structure very evident. Calcite content variable. Many large gypsum crystals along fissure and bedding surfaces. Minor shear surfaces present with small displacements, resulting from overburden stress release and swelling.
Slightly weathered	II	Stiff to very stiff	Slightly discoloured claystone, confined to narrow oxidation zones adjacent to discontinuities which may be open and dark brown. Intact unweathered lithorelicts predominate (70–95%) and original structure is largely unaltered. Fissures are very closely to closely spaced. Calcite content variable. Some large selenite crystals, often along major discontinuities.
Fresh	I	Weak to very weak	Parent blue-grey silty claystone showing no oxidation discoloration or any other weathering effects apart from closed stress release fissuring. Occasional open and extensive joints are iron stained. Occasional iron-rich fossil nodules with local brown discoloration zones. Calcite content variable.

are presented in full to illustrate the range and variation of typical results from the Fuller's Earth. Such plots are clearer than data in table form, and allow the information to be more easily assimilated, particularly the relationship between the three groups of samples representing weathered Fuller's Earth clay, unweathered Fuller's Earth clay and the unweathered, but montmorillonite rich, Fuller's Earth bed. With some parameters, e.g. liquid limit, the effect of weathering is similar to that produced by an increase in the authigenic expanding lattice clay mineral content. Other parameters, such as the liquidity index and residual shear strength, show a dissimilar behaviour. These relationships will be examined in more detail in the following sections.

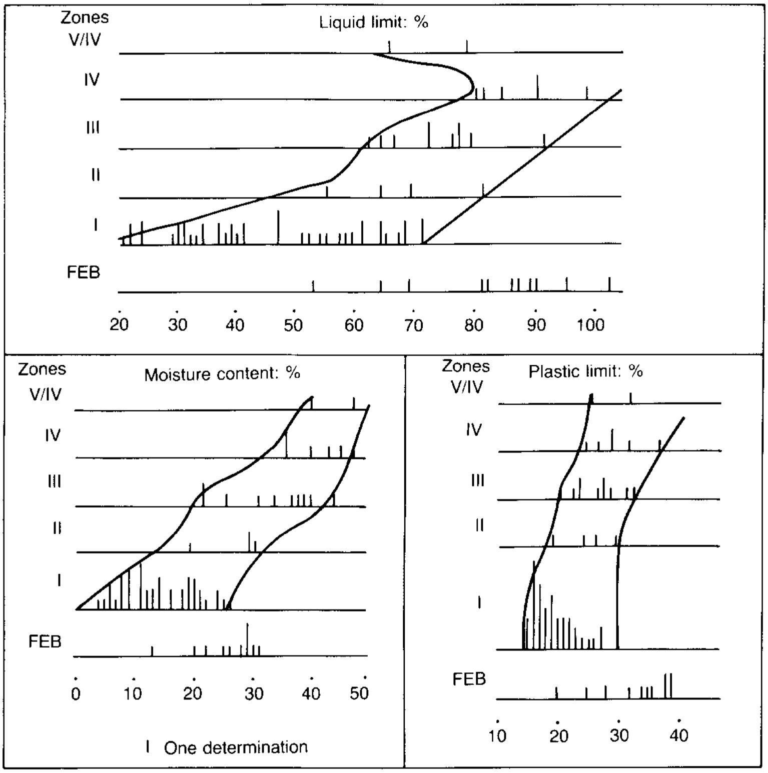

Fig. 8. Variation of natural moisture content and Atterberg limit with weathering grade for the Fuller's Earth. Fresh Fuller's Earth bed (FEB) samples are included for comparison

Index properties and calcite content

A distinct relationship between the calcite content, the moisture content and the Atterberg limits can be seen. In Fig. 10 the less weathered material is shown to possess moisture contents below 30%, with some of the more calcite-rich weathered samples (technically argillaceous limestones) having low moisture contents. Although the moisture contents separate into two

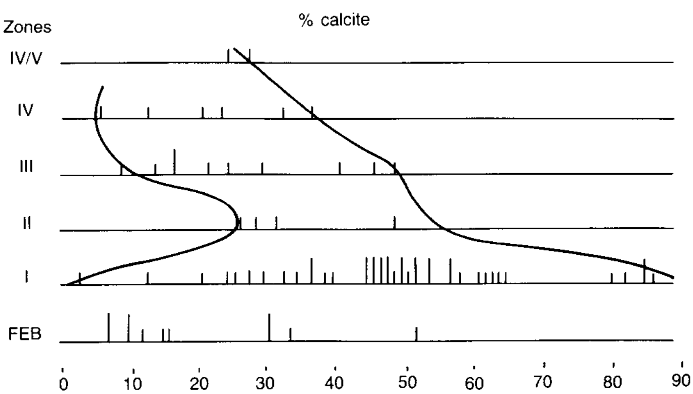

Fig. 9. Variation of calcite with weathering grade for the Fuller's Earth clay; fresh Fuller's Earth bed (FEB) samples are included for comparison

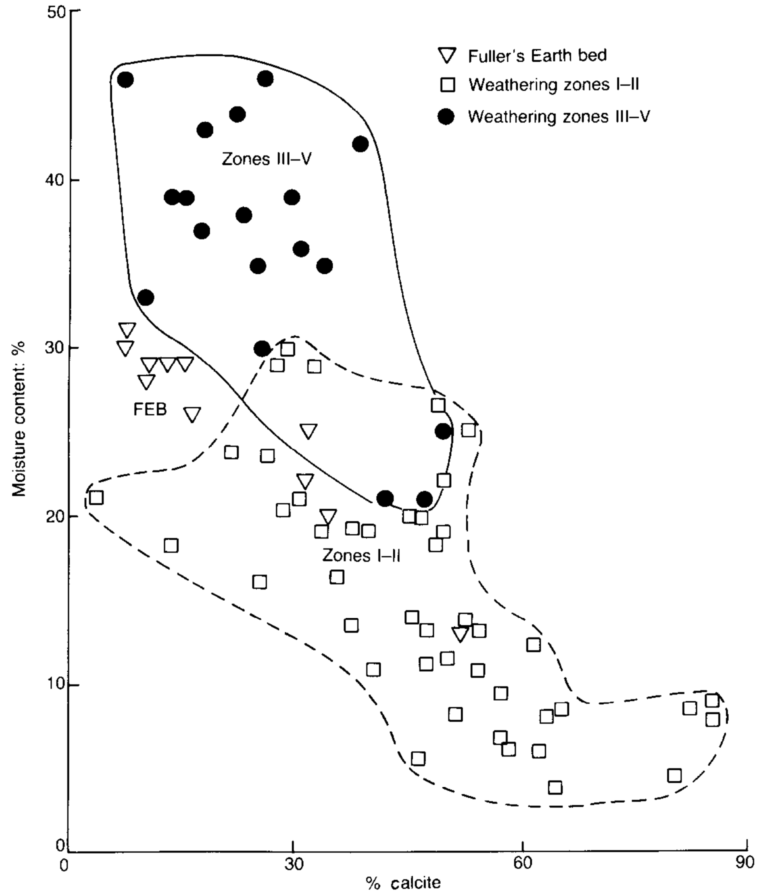

Fig. 10. Relationship between calcite and moisture content for the two groups of weathering zones and the Fuller's Earth bed

distinct groupings with only limited overlap, the data indicate no pronounced correlation. The clearly aligned data points for the Fuller's Earth bed demonstrate a very strong negative correlation of moisture content with calcite content. These results from unweathered material obtained from a limited stratigraphic horizon show less scatter than the others.

The negative correlation is slightly more evident when comparing the calcite content to the plastic limit (Fig. 11). The Fuller's Earth bed is characterized by generally high plastic limits (nearly 40%) where the calcite contents are low, and again a near straight-line relationship is exhibited. There is considerable overlap between the results from the weathered and unweathered samples. The broader zone indicates a lower degree of correlation than for the Fuller's Earth bed. The weathered samples generally plot slightly below those of the Fuller's Earth bed, in contrast to the moisture content results seen in Fig. 10. The relationship flattens at low plasticities, such that samples with plastic limits of between 15–20% have calcite contents varying from 40% to nearly 90% (i.e. technically argillaceous limestones).

The results for the weathered material and the Fuller's Earth bed lie in the same zone when the liquid limit is plotted against calcite content (Fig. 12). The scatter is greater than for the plastic limit, and samples with a difference in liquid limits of only 5% can have a calcite content varying by up to 50%; note the reduced vertical scale of Fig. 12 compared with Figs 10 and 11.

A clearer distinction between weathered and unweathered Fuller's Earth is evident when the plasticity and liquidity indices are plotted against calcite content, than when the actual individual Atterberg limits are plotted (compare Figs 13 and 14 with Figs 10–12.

There is a clear division between the weathered and unweathered material at a plasticity index of

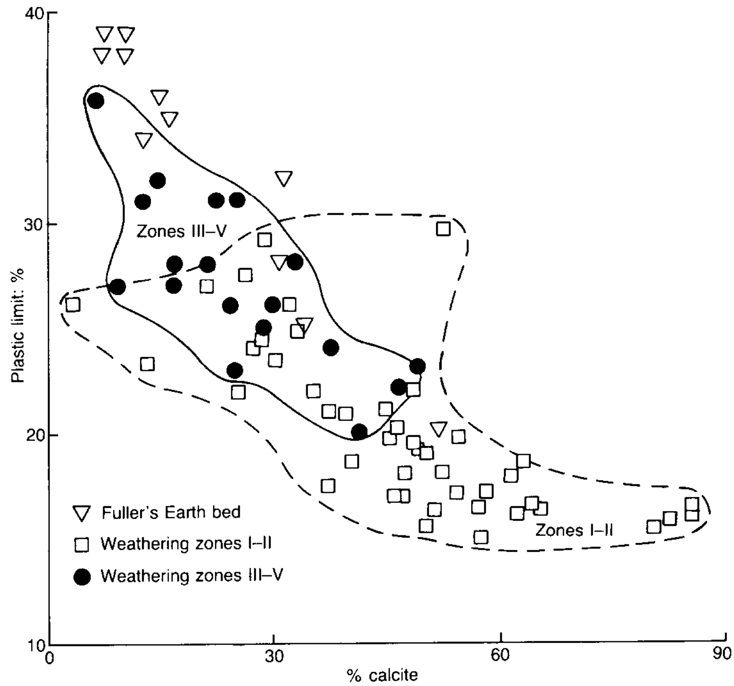

Fig. 11. Relationship between calcite and plastic limit for the two groups of weathering zones and the Fuller's Earth bed

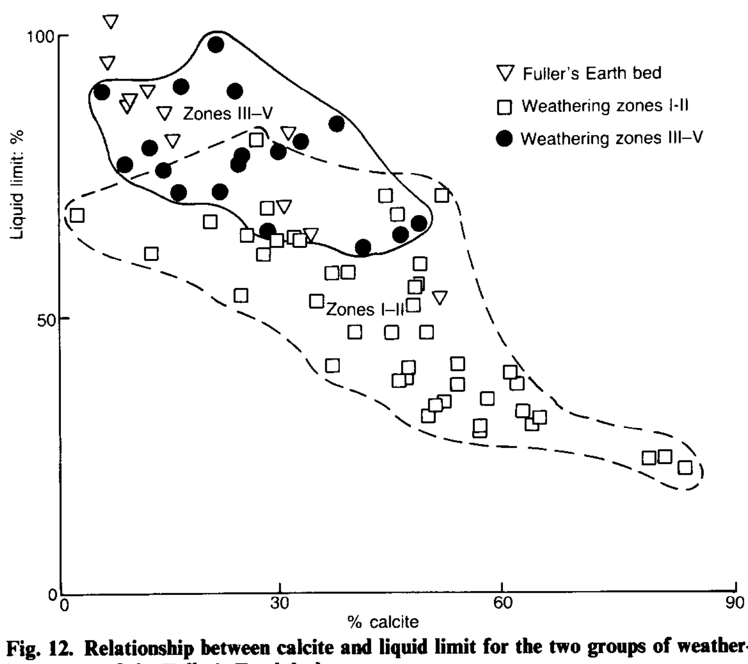

Fig. 12. Relationship between calcite and liquid limit for the two groups of weathering zones and the Fuller's Earth bed

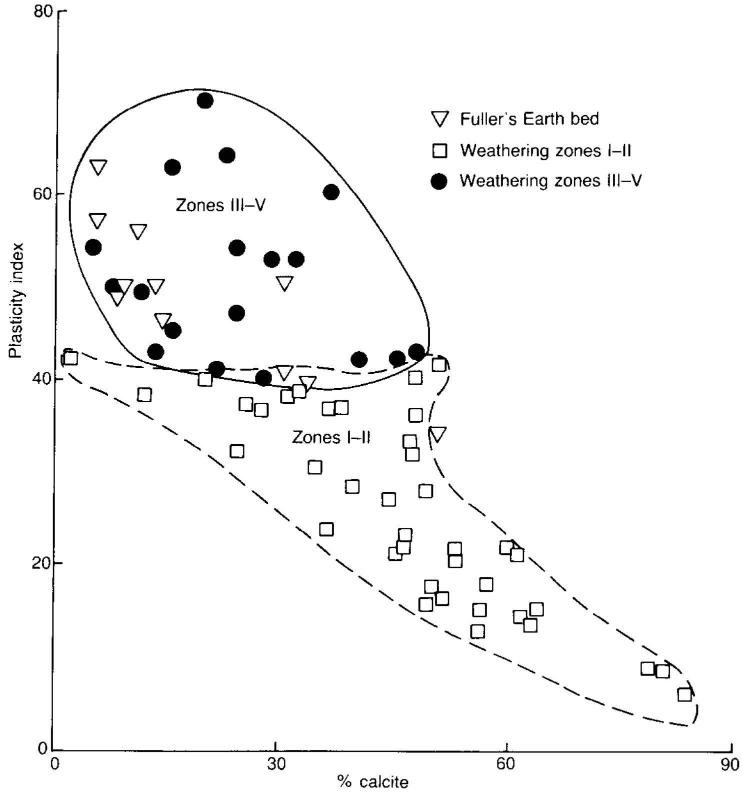

Fig. 13. Relationship between calcite and plasticity index for the two groups of weathering zones and the Fuller's Earth bed

approximately 42%, and there is more scatter in the data from the weathered than from the unweathered. As with the plastic limit and liquid limit, the Fuller's Earth bed results fall in the area of the weathered material.

The plots of calcite content against liquidity index (Fig. 14) indicate a marked separation between the two weathering groups. The weathered Fuller's Earth clay (zones III–V) is characterized by positive liquidity indices and the unweathered clays by negative liquidities, which become even more negative with higher calcite content. The Fuller's Earth bed samples fall in a narrow range between −0·1 and −0·25, i.e. within that of the less weathered clays. Around the zero liquidity index (±0·25) the plot flattens out, representing calcite contents of approximately 50% and below.

Summarizing the relationships between the various plasticity parameters and their negative correlations with calcite content for the weathered and unweathered Fuller's Earth clay and the unweathered, montmorillonite-rich Fuller's Earth bed, the following points emerge

(*a*) weathered Fuller's Earth is characterized by positive I_L, I_p greater than 40% and w generally above 30%

(*b*) unweathered Fuller's Earth is characterized by negative I_L, I_p less than 42% and w below 30%

(*c*) high calcite contents produce low I_p and large negative values of I_L because of low w%, w_L and w_p

(*d*) the Fuller's Earth bed has slightly higher w_p, similar w_L, similar I_p, but lower w, than the weathered Fuller's Earth. The lower I_L is similar to the low calcite unweathered Fuller's Earth clay.

Particle size and calcite content

Comparison of the particle size distribution data with the calcite content reveals two trends, one for the fraction finer than 2 μm (clay grade) and the other for the fraction coarser than 20 μm (coarse silt and above). In the case of the Fuller's Earth bed, the calcite content correlates well with both particle size fractions, but the relationship

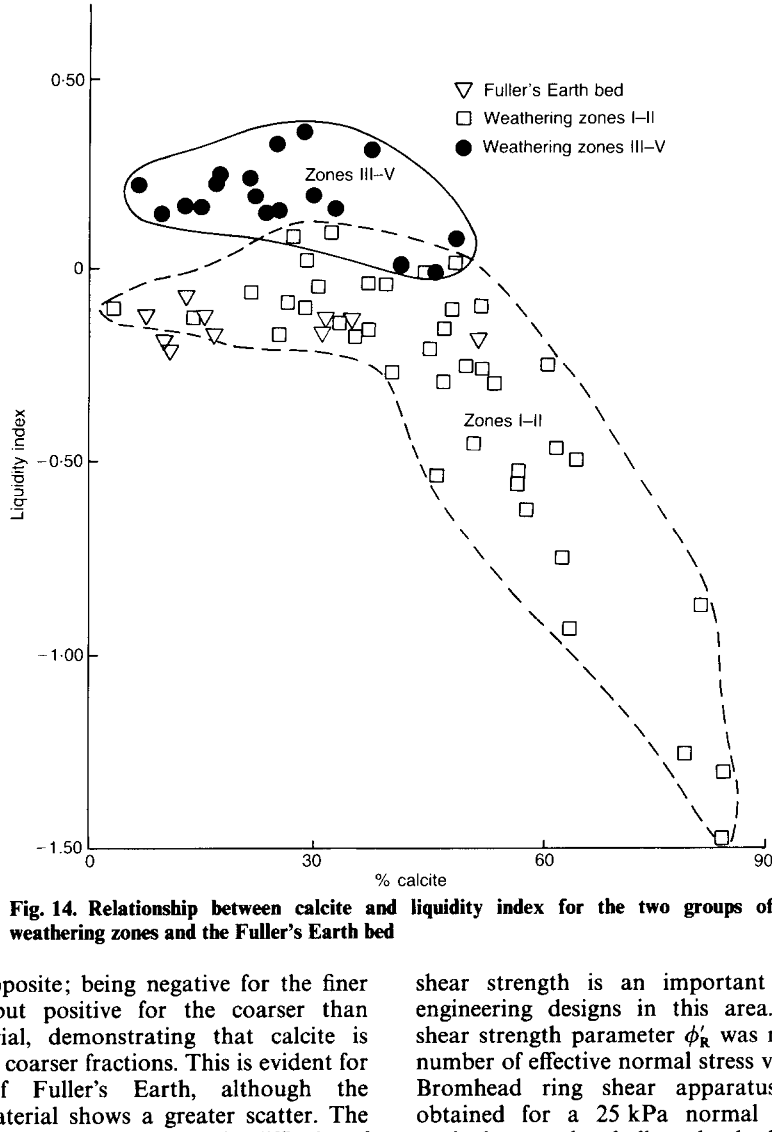

Fig. 14. Relationship between calcite and liquidity index for the two groups of weathering zones and the Fuller's Earth bed

trends are opposite; being negative for the finer than 2 μm but positive for the coarser than 20 μm material, demonstrating that calcite is present in the coarser fractions. This is evident for all types of Fuller's Earth, although the weathered material shows a greater scatter. The scatter represents, to some degree, the difficulty of disaggregating calcareous clays/mudstones for particle size determination.

It is observed that when sample CH1 (see Fig. 4) was decalcified under laboratory conditions, there was an increase of almost 40% in the relative proportion of the clay fraction. The effect of decalcification on the coarser fraction is represented by a marked reduction, from 33% to 5%.

Residual strength and calcite content

Many of the hill slopes in the south Cotswolds have suffered from both deep seated and near surface slope movements and hence the residual shear strength is an important parameter in engineering designs in this area. The residual shear strength parameter ϕ'_R was measured for a number of effective normal stress values using the Bromhead ring shear apparatus. The values obtained for a 25 kPa normal effective load, equivalent to the shallow depth slide, have been plotted against the calcite content in Fig. 15.

Although the data shows two clear zones for the weathering groups of the Fuller's Earth clays, there is no pronounced linear trend for either of these. It can be seen that, at an effective normal stress of 25 kPa, the more weathered material has a ϕ'_R of 11–16°; although this is only 5–8° for plots at 400 kPa. A similar decrease is noted for the samples from the Fuller's Earth bed, the natural samples having a ϕ'_R of 13–27° at 25 kPa and 7–21° at 400 kPa. In both cases the totally decalcified sample gives a slightly lower figure. The difference between the ϕ'_R of weathered samples and the Fuller's Earth bed at the same calcite content may be explained by the mode of

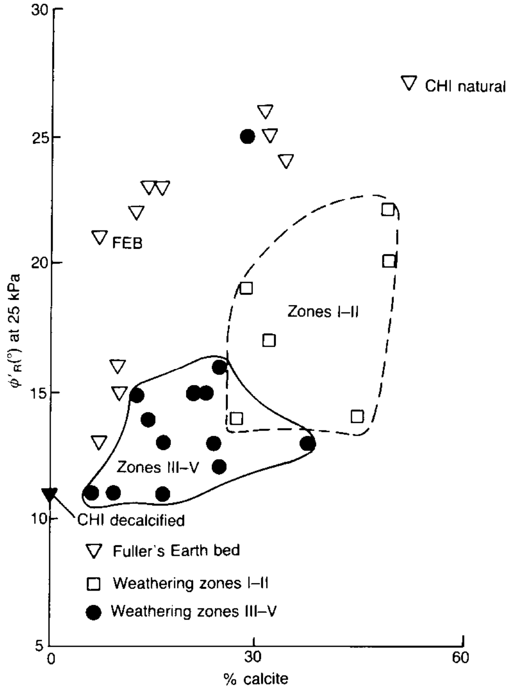

Fig. 15. Relationship between calcite and residual shear strength parameter ϕ_R at 25 kPa for two weathering groups and the Fuller's Earth bed

occurrence of the calcite; the larger grains in the fresher Fuller's Earth bed resulting in a turbulent (rolling) mode of failure compared with the smaller effect of the partially dissolved finer grains in the weathered material. It is important to appreciate this, as it is contrary to what would be expected from the presence of smectite (montmorillonite) in the Fuller's Earth bed and demonstrates the significance of the calcite.

Figure 16 shows the residual strength envelopes for samples from the 2·4 m-thick Fuller's Earth bed. The figure demonstrates the curvature of the residual failure envelopes (*see* Hawkins & Privett, 1985) which fall into three groups, depending on calcite content. Samples with greater than 30% calcite have steeper envelopes (and hence higher ϕ'_R) than the others; CH1 is the steepest (52% calcite). The steeper envelopes are also those with the less pronounced curvature at low normal stresses, i.e. the lower the calcite content, the greater the difference in ϕ'_R between high and low normal stress conditions. In order to confirm the influence of calcite on residual shear strength, sample CH1 (52% calcite) was decalcified in the laboratory by acetic acid digestion. A dramatic reduction in ϕ'_R occurred with decalcification, from 27° to 11° at 25 kPa and from 21° to 6° at 400 kPa.

CONCLUSIONS

Visual observations of the weathering profile within the Fuller's Earth clays confirm the physical changes typically associated with oxidation and softening. A general colour change from grey

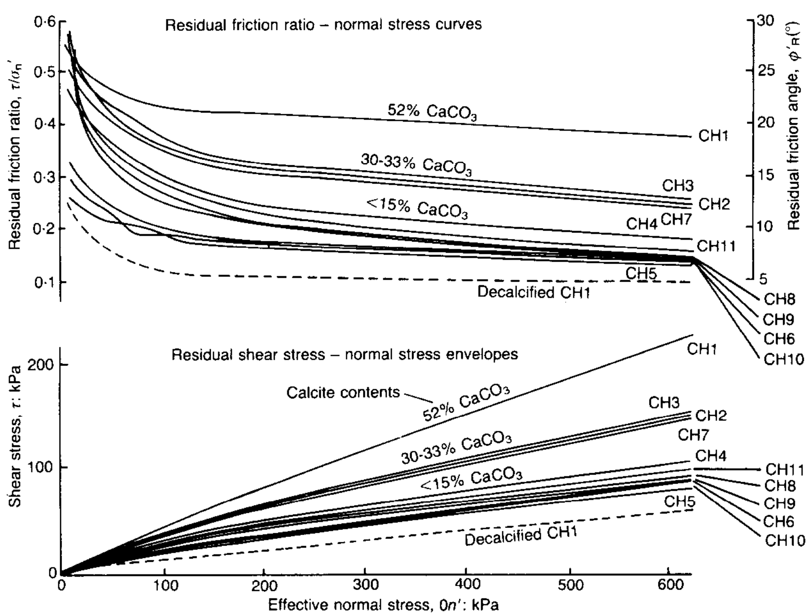

Fig. 16. Residual strength envelopes and residual friction ratio curves for the Combe Hay Fuller's Earth bed

to brown is commonly noted at the levels where stress release fissuring becomes prominent, with the consequent loss of inherent strength and the progressive degradation from an overconsolidated claystone towards a firm, structureless clay.

X-ray diffractometry analyses on samples from the Fuller's Earth formation indicate the mineralogical composition to be dominated by illite with subordinate kaolinite. The Fuller's Earth bed is exceptional, however, being composed mainly of Ca-montmorillonite. Whilst the formation is calcareous throughout, it is the lithological variations due to authigenic cements, fossil content and calcite crystals that give rise to the significant differences in the proportions of calcite content.

Analysis of fresh material from borehole cores and of samples taken from the trial sections through the surface weathered layers has been undertaken. This revealed a chemical weathering sequence involving the following processes.

(*a*) Stress relief allows the development of open fissures, facilitating the percolation of surface water into an otherwise relatively impermeable mudstone/clay mass.
(*b*) Decalcification by weak acids, including the carbonic acids in rainwater and humic acids from the vegetation layers.
(*c*) Decomposition of pyrite by oxygenated water, with the production of an acidic ground water (sulphuric acid).
(*d*) Subsequent sulphuric acid attack on calcite (calcium carbonate) liberating calcium which facilitates the formation of gypsum (calcium sulphate), *see* Hawkins & Pinches (1986, 1987a and 1987b).
(*e*) Ferrous ions converted to the ferric state produce limonite and haematite, thereby effecting the colour change from blue-grey to yellow-brown.
(*f*) Acidic ground water reacts with the clay minerals, depotassification and hydration transforming illite to interstratified illite–smectite (montmorillonite).

Within a sequence of calcareous mudstones, calcite generally comprises the coarser, more angular particles, such as secondary concretions, fossil shell fragments, broken calcitic veins, euhedral grains, and cementitious material. Although X-ray diffractometry on the separated 'less than 2 μm' clay smears suggests the persistance of calcite to at least fine silt grades, this mineral (in addition to quartz, pyrite and feldspars) comprises the bulk of the coarse silt and sand fractions.

Calcite is characterized by a relatively small surface area to particle volume ratio which, together with very low sorptive properties, accounts for the negative correlations between calcite content and the Atterberg limits. However, the predominance of clay minerals throughout the formation also explains the positive correlations of clay grade material with the index properties. Within the Fuller's Earth bed and the near-surface weathered horizons, the presence of expanding Ca-montmorillonite, with its superior sorptive properties and higher surface area to particle volume ratios, can be seen to correspond to the increased moisture content and plasticity values.

It has been demonstrated that, within a calcareous mudstone sequence such as the Fuller's Earth of the Cotswolds, weathering modifies the engineering behaviour in two major transformations.

(*a*) A decrease in calcite content and the removal of coarser particles leads to a relative increase in clay grade minerals. The reduction in a non-sorptive mineral content leads to increased plasticity.
(*b*) The transition of illite to interstratified illite–smectite (montmorillonite) increases the expanding lattice clay mineral proportion of the soil and Atterberg limit values increase accordingly.

Laboratory results suggest that for the Fuller's Earth formation, calcite content is correlated to the residual shear strength parameter ϕ'_R. This is probably because calcite occurs predominantly as equigranular, often euhedral, coarse particles (along with other common primary sedimentary minerals, such as quartz, feldspar, etc.). Such grains contribute to a 'rolling' frictional shear resistance (Lupini, Skinner & Vaughan, 1981). If decalcification is the prevalent weathering process in a calcareous mudstone under the typical United Kingdom climate, then an effective reduction in the calcite grain content will produce a relative increase in clay mineral platelets, hence promoting the weaker 'sliding' frictional shear resistance. It is suggested that this process is operative within the Fuller's Earth sampled from the Bath area.

The implications of this decalcification process and the associated potential reduction in shear strength must be considered when assessing the long term stability of natural hill slopes, and in the design of civil engineering cutting and embankment slopes. Decalcification by the initial removal of the authigenic cements results in a progressive reduction in the peak strength values (which are not discussed in this Paper). For most weathered calcareous mudstones, softening will already have begun to reduce the shear strength. In slopes in which landslipping has occurred, and hence appropriate residual shear strengths are operative, continued decalcification will accelerate this decrease. The implications of clay mineral transformation along the relatively permeable shear surfaces must also be considered, as it will have an important influence on the long term stability of such slopes.

A study of selected Fuller's Earth clay localities in the Cotswolds has demonstrated that, in a weathering profile through a calcareous mudstone sequence, decalcification and depotassification results in significant changes in fundamental engineering properties. Preliminary laboratory tests and analyses have confirmed a relationship between the calcite content and the shear strength values. Further work is required on the process of decalcification within the time-scale of particular man-made slopes and designed earth structures, as well as the long term behaviour of natural slope morphologies. The evaluation of the changes in shear strength with progressive reduction in the calcite content, and the likely long-term effect on man-made slopes, is continuing.

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