ENGINEERING GEOLOGY
OF TROPICAL RED CLAY SOILS

SUMMARY FINDINGS AND
THEIR APPLICATION FOR
ENGINEERING PURPOSES

(ODA/BGS R&D Project 91/18)

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Preface

This report is the fifth of a series of five main project reports describing the results of a study into the engineering geological characteristics of tropical 'red' clay soils. The study was funded by the Overseas Development Administration (ODA) under its programme of 'Research and Development', part of the British Government's provision of aid and technical assistance to developing countries (Project 91/18, Engineering Geology of Tropical Red Clay Soils). The main objectives of the study were to:

i) investigate the geotechnical properties of a variety of red clay soils by means of standard, specialised and/or new test procedures on both disturbed and undisturbed samples.

ii) relate the geotechnical properties of the soils to their geological provenance, position in the weathering profile and climatic and topographic conditions so that a practical classification scheme could be developed for engineering use.

The project work was conducted, primarily, on samples obtained from selected study sites in Kenya and Indonesia. In both countries, an extensive programme of field sampling was carried out to obtain a wide variety of red clay soils from contrasting climatic, topographic and geological terrains, at various depths within the weathering profiles. Fundamental material and geotechnical properties of the collected soil samples were determined from comprehensive laboratory testing programmes conducted at the British Geological Survey (BGS) laboratories (Keyworth, Nottingham, UK) and by project counterparts in Kenya (the Ministry of Public Works, Materials Testing and Research Department, Nairobi) and Indonesia (the Institute of Road Engineering, Bandung).

To complement the investigations undertaken on the Kenya and Indonesian soils, additional samples of tropical red clays were also collected (through BGS geologists and other contacts) from Fiji and Dominica, and returned to the UK for analysis and testing in the BGS laboratories. The field and laboratory test data determined for all the soil samples is stored in a PC compatible database at BGS, Keyworth.

Overseas field and laboratory investigations could not have been effectively carried out without the collaboration of project counterparts in Kenya and Indonesia.

In Kenya, the main project counterparts were the Ministry of Public Works, Materials Testing and Research Department (MT&RD), Foundations and Drilling Section, Nairobi. The Department has a keen interest in red soil research and their collaboration, support and assistance in all aspects of work undertaken in Kenya is gratefully acknowledged.

In Indonesia, the project counterparts were the Institute of Road Engineering (IRE), Bandung, who's valuable collaboration in site selection, sampling, and laboratory testing is also gratefully acknowledged.

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1 Introduction

NATURE OF TROPICAL SOILS

In the engineering literature, tropical soils (as a group of soils distinct from those formed in areas subject to temperate climates) are sometimes described as falling into two broad categories, tropical black soils and tropical red soils. The former category, which includes those soils termed ‘black cotton soils’ or ‘black swelling clays’, comprises a relatively distinct group of soils, rich in smectite clay minerals, whose engineering behaviour is dominated by volume changes (that is, shrinking and swelling) when they are subjected to changes in natural moisture content. However, there is some confusion as to what materials comprise the so-called tropical ‘red’ soils and the terms used to describe them.

Red clay soils are very common throughout the tropical and sub-tropical regions of the world (Figure 1). However, it is a misconception to consider them as forming a distinct, clearly defined soil type as they encompass a wide variety of soils whose material and engineering properties vary considerably. This variation has been reflected in the ever increasing literature on tropical soils since the 1960’s, which has seen red and reddish brown soils described as ‘laterites’, ‘laterite soils’, ‘lateritic soils’, ‘non-lateritic tropically weathered soils’, ‘latosols’ and ‘tropical red clays’.

Under certain conditions, hardened horizons, often referred to as ‘laterite’, may be associated with the soil profiles. These form as a result of the accumulation of iron which, in some areas, may develop into a continuous sheet of indurated ferricrete (‘laterite’) forming a surface or near-surface duricrust. However, not all red clay soils harden on exposure to form laterite (as defined by the original description of Buchanan, 1807) and it is unfortunate that the terms ‘lateritic clays’ and even ‘laterite’ are still used by some engineers to describe any reddish tropical soil. Due to this confusion in terminology, the soils described in this study are broadly referred to as tropical ‘red’ clays, despite the fact that they are not all red.

The tropical ‘red’ clay soils considered in this study are residual soils, that is they are formed in situ by the intense weathering of parent material, both primary and sedimentary, in tropical and sub-tropical climatic environments. This weathering process primarily involves the progressive chemical alteration of primary minerals, the release of iron and aluminium sesquioxides, increasing loss of silica and the increasing dominance of new clay minerals (such as smectites, allophane, halloysite and, as weathering progresses, kaolinite) formed from dissolved materials. Continued depletion of silica under prolonged weathering in hot humid climatic zones may eventually cause alteration of kaolinite to the aluminium oxide, gibbsite, as free alumina is formed in the soil profile. At any particular site, mineral composition and microstructure will depend on numerous factors such as the nature of the parent material, the age of the land surface (time for soil formation), climate, topography and drainage conditions (Duchaufour, 1982). Only a small proportion of sesquioxides will impart a red colouration, and because of the progressive nature of the tropical weathering process and the numerous inter-related factors controlling soil development at any particular locality, the division between red and ‘non-red’ soils are not clear cut. For example, iron oxide occurs in the form of
haematite when the soil is seasonally desiccated, giving the characteristic red colour, and as goethite in a constantly humid environment, giving the soil a brown or ochreous colour. Also, particularly in mountainous areas, soils developed over the same parent rock may grade imperceptibly from red to brown or yellowish brown soils as altitude and topographic relief vary. For example, andosols are typically brown or yellowish brown soils. They develop on recent volcanic ashes and, characteristically, contain the hydrated amorphous clay mineral, allophane. Detailed mineralogical investigations in this study have also recognised other amorphous aluminium silicate 'gels' present in ferrisols and some ferrallitic soils. Their occurrence is restricted primarily to constantly humid (but well-drained) regions and in many areas they are found only at higher elevations, where high rainfalls and lower temperatures are apparently required for these soils to develop and retain their hydrated condition (Morin, 1982). Where drainage is impeded, smectite-rich black swelling clays tend to be formed rather than andosols. With a change in climate (particularly the appearance of a marked dry season), which can occur at decreasing elevations, andosols sensu stricto give way to transitional ('andic') soils which, with increasing kaolinisation and crystallisation of hydroxides (gibbsite, goethite and haematite), can eventually grade into truly 'red' ferrallitic soils, developed over similar geological bedrock. This sequence of soil development has been described by Martini (1976), Duchaufour (1982) and Morin (1982) and others, and was clearly seen by the present authors in the mountainous regions of Kenya and Indonesia.

Viewed in carefully prepared thin sections under the optical microscope, the fabric of these soils was seen to comprise a porous, open structure of clay clusters (or 'peds'), roughly silt- to sand-sized, which are generally disseminated throughout with very finely-divided iron oxides. Optical and electron microscope studies showed that the 'clay clusters' are usually not "cemented" by iron oxide coatings (as has often been reported). Rather, the clusters appear to be weakly "bonded", possibly by a variety of mechanisms within each type of soil. In some cases, such as many of the Kenyan nitisols (ferrisols), the clay clusters are at least partly bonded by amorphous gel, which sometimes coats entire peds or develops as isolated areas at the ped contacts. In other parts of the same soil, individual peds are in direct contact, which, in the absence of amorphous gel or iron oxide cement, are apparently joined by some form of 'clay-like' bond.

Prior to this study, no generally accepted methods had been established by which tropical residual soils can be adequately classified in terms of their engineering behaviour by means of simple 'index' tests. In addition, no methods exist whereby their undisturbed (or mechanical) properties can be related to geological descriptions or to index tests, as is the case for sedimentary soils of temperate regions (Vaughan et al., 1988). In part, this is probably due to the very diverse nature of residual soils, found even within the tropical red clays of this study. However, much of the difficulty would also appear to stem from the inapplicability of 'conventional' soil mechanics concepts, developed almost exclusively from work on temperate soils, when applied directly to certain soils from tropical zones. This inability to adequately classify tropical clay soils using conventional soil engineering methods has led many workers to regard them as 'problem' soils (for example, Morin and Todor, 1975) and particularly troublesome when encountered in engineering works.
Because the geotechnical properties of tropical residual soils appear to be largely
controlled by their composition (mineralogy) and microstructure, it would seem logical
that the first level of any classification system should take account of the factors giving
rise to their development. This entails the identification of the environmental factors
(climate, parent rock, drainage conditions, etc) and the geological/pedological processes
that lead to the formation of particular soil types. At the same time, the geotechnical
properties of the soils, based on tests appropriate to the soils themselves, and the
engineering use to which the soils are put, must be determined. Such a ‘genetic’
classification, based on soil-forming processes, soil composition and microstructure in
addition to geotechnical properties, is likely to be complex, and may be unfamiliar to the
geotechnical engineer. However, only when all these inter-related elements are more
fully understood and documented will a workable classification system be derived.

The study of tropical soils has gone some way down this road, and progress continues as
engineers and engineering geologists take greater interest in these materials and more
information based on a better understanding of these soils becomes available (see, for
example, the Proceedings of the 1st, 2nd and 3rd Conferences on Geomechanics in
Tropical Soils, held in Brasilia, Singapore and Maseru in 1984, 1988 and 1992
respectively).

In late 1985, a Working Party convened by the Engineering Group of the Geological
Society was charged with the overall task of providing “a workable and practical
classification of residual soils which was scientifically based and suitable for engineering
use”. The report of this Working Party was published in 1990 (Anon., 1990). A revision
of this report is likely to be published in the near future.

The work undertaken in this study has concentrated on the identification, description
and engineering characteristics of tropical red clay soils. Significant effort was directed
to establishing the fundamental material composition (mineralogy and structure) and
‘typical’ engineering properties (on ‘undisturbed’ and disturbed bulk samples) of red clay
soils obtained from a variety of geological and topographical terrains and climatic zones.
This was deemed essential to confirm the sometimes confusing or contradictory
descriptions and data found in the published literature, and to verify or
develop suggested new methods of test to more accurately determine meaningful
geotechnical parameters. The results of the study were applied towards advancing the
work hitherto directed (by the Working Party and others) towards deriving a practical
engineering classification.

PROJECT AIMS AND OBJECTIVES

The main aims of the study were:

1. To investigate the natural development and distribution of various types of red
clay soils in relation to geology, climate, topography and elevation.

2. To investigate the fundamental soil mineralogy and structure.
3. To investigate the geotechnical properties of a variety of red clay soils by means of standard, specialised and/or new test procedures on both disturbed and undisturbed samples.

4. To relate the geotechnical properties of the soils to their geological provenance, position in the weathering profile and climatic and topographic conditions in order that a practical classification scheme can be developed for engineering use.

WORK CARRIED OUT AND REPORTING

The project investigations were undertaken primarily in Kenya and Indonesia in collaboration with the Materials Testing and Research Department (MT&RD) of the Ministry of Public Works, Nairobi, and the Institute of Road engineering (IRE), Bandung, West Java. The work was carried out in two phases.

Phase 1

This was undertaken between 1986 and 1989 and, after initial desk studies, involved the selection of study areas followed by an extensive programme of field sampling to obtain a wide variety of red clay soils from contrasting climatic, topographic and geological terrains. This was complemented by a comprehensive laboratory testing programme, carried out at the BGS laboratories in Keyworth and by the project collaborators in Kenya and Indonesia, to establish fundamental material and geotechnical properties of the collected soil samples.

Phase 2

Phase 2 of the study was undertaken between 1989 and 1991 and involved the sampling of selected deep red soil weathering profiles and further laboratory testing to investigate the variation of soil characteristics and geotechnical properties with depth. In order to investigate as wide a spectrum of red soil types as was practically possible, additional samples of tropical red clays were also obtained, through BGS geologists and other contacts, from sites in Fiji and Dominica and returned to the UK for analysis and testing at the BGS laboratories. All field and laboratory results were entered into an PC-compatible database prior to undertaking data analysis and interpretation. The extensive project data set is held at BGS, Keyworth.

The results of the project investigations are presented in five main reports: this volume and four preceding BGS Technical Reports:

WN/93/11  Project background, study areas and sampling sites, by K J Northmore, M G Culshaw and P R N Hobbs.

WN/93/12  Geotechnical characterisation: index properties and testing procedures, by K J Northmore, D C Entwisle, P R N Hobbs, M G Culshaw and L D Jones.


The results of the complimentary ODA/BGS R&D project 91/19 are presented in report:


These reports are augmented by a series of supplementary 'factual' reports detailing results of field visits and geotechnical laboratory testing.

The results of the mineralogical and soil fabric analyses (including optical and scanning electron microscope studies) and presented in further reports:


WG/89/14  *Mineralogy of further kaolinitic soils from Kenya and Indonesia*, by S J Kemp.

WG/91/7  *Mineralogical analysis of tropical red clay soils*, by S J Kemp.

WG/92/31  *Petrographical examination of some tropical red soils from Kenya and Indonesia*, by A E Milodowski.
2 Project study areas and sampling sites

SELECTION OF STUDY AREAS

The main project investigations were centred in Kenya and Indonesia (West Java). Initial desk studies, including an extensive literature review, showed that these two regions, both individually and in combination, were characterised by markedly contrasting topographic and climatic zones resulting in a wide spectrum of tropical red clay soils developed over a variety of predominantly igneous (both volcanic and intrusive) rocks. As such, these areas effectively enabled a considerable variety of red clay soils to be investigated within the time, staffing and cost limits of the study. In addition, further tropical red clay samples were obtained through contacts in Fiji (Viti Levu) and Dominica to supplement the investigations of the soils from the main Kenyan and Indonesian study areas.

The choice of Kenya and Indonesia as principal study areas was also influenced by logistical considerations. Resident BGS geologists, engaged primarily on regional geological, resource and geochemical mapping projects in both countries, provided valuable assistance in the project planning stages and facilitated contact with potential collaborating organisations. Effective project collaboration with the Materials Testing and Research Department (MT&RD) of the Ministry of Public Works & Housing in Kenya, and the Institute of Road Engineering (IRE) in Indonesia was readily established and maintained throughout and beyond the project study.

SELECTION OF SAMPLING SITES

The initial selection of regional sampling sites within the Kenya and West Java study areas was largely based on the soil classifications and distributions presented on pedological maps. Also taken into account were suggestions for sampling areas put forward by the project collaborators and engineering consultants who, with their local knowledge and experience, were able to highlight areas where current engineering works provided exposures, cuttings or excavations to facilitate sample collection, and/or areas where particular types of red clay soils had proved 'problematical' or 'difficult' during recent construction projects. However, a wide-ranging regional approach to site selection and sampling was necessarily moderated to allow time for an extensive laboratory testing programme and careful on-site sampling of selected deep soil profiles.

Kenya

In Kenya, the selection of sample sites characterised by well-developed red soil profiles was undertaken by reference to the 'Exploratory Soil Map of Kenya' (Kenya Soil Survey, 1982). This map adopts the FAO-UNESCO system for the purposes of classifying and correlating soils. Despite the generalisations inherent in presenting the soil distribution for the whole of Kenya at a scale of 1: 1 million, the map and accompanying report/key was an extremely useful information source. The map attempts to present, in general terms, the complex relationship between landforms, geology and soils using a methodology developed by the Kenya Soil Survey from 1972 onwards. Thus, the map legend provides information not only with respect to the soil mapping units, but also to related landforms and bedrock geology. Accompanying the Exploratory Soil Map is an Agro-Climatic Zone Map at the same 1: 1 million scale which, with the soil map, is
intended primarily as a tool for assessing areas climatically suitable for crop cultivation. This map provided additional information on the distribution of climatic zones (humid, semi-humid, arid, etc.) and variations in rainfall and temperature with altitude.

On the basis of the information provided by these maps, two main areas, in central and western Kenya (east and west of the Rift Valley, respectively), were identified as being most suitable for the regional sampling programme. Both areas comprise large tracts of fertile land which support relatively high population densities, and are favoured for present and future infrastructural development (roads, transmission lines, etc.). Important existing and planned construction projects concerned with water supply (dams, water pipelines, etc.) to feed the expanding needs of Nairobi were much in evidence in the highlands of the central Kenya sampling area.

Sample collection was undertaken to obtain ‘disturbed’ and ‘undisturbed’ samples from exposures, pits and/or boreholes to enable determination of geotechnical properties in the laboratory, assessment of the variation of soil properties with depth and descriptions of the weathering profiles. The first phase of sample collection involved obtaining ‘disturbed’ soil samples from 45 regional sites across the two sampling areas, the samples being carefully sealed in polythene bags to retain their natural moisture contents. This was followed by the collection of ‘undisturbed’ and further ‘disturbed’ samples from seven trial pits (five in the central sampling area, and two in the western sampling area). The trial pits were hand-excavated to a depth of c. 2 m, with an average of four undisturbed samples taken from each pit. A further eight ‘undisturbed’ samples were also made available to the project study from four deep trial pits excavated to depths ranging from 2 to 6 m in the western sampling area to assess potential source material for the Chemususu dam. The third phase of the Kenyan sample collection involved the recovery of ‘undisturbed’ core samples from borehole sites in order that complete soil profiles from surface to weathered bedrock could be investigated. Because the recovery of high quality ‘undisturbed’ samples, required for analysis of the in situ soil fabric and geotechnical laboratory testing, was critical to the project investigation, the borehole sampling programme was not as extensive as first envisaged, mainly due to the difficulties encountered in recovering samples with minimal disturbance.

During the course of the pit sampling, it was found that despite their generally high clay contents, almost all of the red soils tended to resemble relatively weak friable loams (a result of their characteristic open-textured and ‘weakly-bonded’ ped-like structure). Excess stress applied to this soil fabric when sampling resulted in severe compressional disturbance. Therefore, great care was needed to obtain high quality samples with minimal disturbance, particularly when sampling from boreholes. Because the problem of sample disturbance was fundamentally important it was decided to select an easily accessible site with a ‘characteristic’ deep, mature red soil profile to investigate various sampling techniques in order to achieve the optimum method of core recovery. This test site was located in the grounds of the Jacaranda Coffee Research Station near Ruiru, located in the volcanic footridges on the south-east facing slopes of the Aberdare Highlands approximately 25 km north-east of Nairobi. A total of ten boreholes were drilled at four locations. Of these, six boreholes were used to test and assess the effectiveness of various ‘push-sampling’ and rotary coring techniques. Continuously sampled profiles of sufficient quality (that is, with little compressional disturbance) for geotechnical testing were obtained from three of the boreholes. ‘Undisturbed’ samples
were also taken from a trial pit excavated close to the boreholes, in order to compare the
effects of any disturbance between the pit and borehole samples (over a depth range from
ground surface to 2 m). Following these borehole sampling trials, it was found that most
standard borehole sampling techniques routinely employed in temperate clay soils, many
of which have been reported as being suitable for various tropical residual soils, are not
adequate for the recovery of high-quality 'undisturbed' cores in the tropical red clays
investigated in this study. Further work was clearly required to ascertain the optimum
borehole sampling procedures for tropical red clay soil profiles. This resulted in a
separate ODA-funded R&D project (91/19), during which field trials were undertaken
at three locations in central Kenya in contrasting deep red soil profiles, developed on
Pleistocene and Tertiary volcanic rocks at elevations ranging from c. 1650 m to 2250 m.
Results of the investigations into sampling, from both pits and boreholes, are summarised
in Section 3 of this volume.

Indonesia

In Indonesia, the criteria used for the selection of regional sampling sites were similar to
those for Kenya, but with reference being made to the 1:250 000 scale Soil Map of West
Java (1966) for initial identification and distribution of residual red clay soils. The
pedological classification used for this map follows the Indonesian Classification System
of Dudal and Soepraptohardjo (1957) which describes 'red' clay soils of interest to this
study in terms of two main groups: latosols and andosols. These soils are further divided
mainly on the basis of the colour of the B horizon, thus in the map legend, a distinction
is made between Red, Yellowish Red, Reddish Brown and Brown Latosols and Brown
and Yellowish Brown Andosols. These soil divisions could not be easily correlated with
the FAO-UNESCO soil units shown on the Kenya soils map but still served as a useful
guide in selecting sampling sites of well-developed 'red' soil profiles established on
various, dominantly volcanic, rocks in contrasting topographic and climatic zones.

Nineteen sites were sampled, encompassing a variety of 'red' clay soils in West Java. As
in Kenya, the regional sampling programme concentrated on the collection of bulk
(disturbed) bag samples taken from road cuttings or 'borrow area' excavations connected
with recent or current construction works. This was followed by the collection of
'undisturbed' and further 'disturbed' samples from nine trial pits (again, each hand-dug
by local labour to a depth of about 2 m) sited at selected locations to enable 'typical' soil
profiles to be described and sampled for geotechnical laboratory testing and analysis.

At the time of the Indonesian pitting programmes, it was not logistically feasible to carry
out borehole sampling operations. Therefore, to achieve the recovery of 'undisturbed'
samples and description of soil profiles at greater depths, deeper pits had to be dug. A
fieldwork programme was undertaken in 1990 for this purpose, during which three trial
pits were hand-excavated to depths of c. 5 m. The Indonesian soil profiles revealed
during the excavation of these deep pits were found to have a much more layered
sequence than the almost uniform, structureless soil profiles encountered in the Kenyan
boreholes. Layering was observed in all the deep pit profiles and could be related to
differential weathering of the parent volcanic bedrock. In one particular pit, excavated
in an andosol soil developed on Younger Quaternary volcanic bedrock, the layered profile
was related to sequential weathering of successive layers of volcanic tuff.
Fiji (Viti Levu)

From Fiji, bulk ('disturbed') samples of reddish brown tropical residual soil were obtained from five sites in hilly terrain close to the Suva-Nadi highway, running along the southern coast of the island of Viti Levu. The samples were collected by BGS and Fiji Mineral Resources Department personnel, sealed in plastic bags to retain their field moisture contents and freighted back to the UK for laboratory testing and analysis. All the sites were involved in recent landsliding, thus some of the residual soils collected from landslide debris were to some degree transported soils. Pedological identification of these soils, was based on reference to the FAO-UNESCO Soil Map of the World (Sheet X: Australasia, 1976).

Dominica (West Indies)

From Dominica, bulk ('disturbed') samples of reddish brown tropical residual soil were obtained from five road cutting sites located in the northern, north-central and eastern parts of the island. According to the pedological classification of Dominican soils by Lang (1967), these samples comprised dark brown 'allophane latosolic' and reddish brown 'kandoid latosolic' soils. Two additional sites were also sampled near Good Hope and Castle Bruce on the eastern side of the island by staff from the Ministry of Communications and Works, Roseau. Although precise locational details of these latter sites are not known, they are apparently in landslide debris comprising reddish brown 'kandoid latosolic' and possibly 'allophane latosolic' soils, incorporating many highly weathered, gravel-sized volcanic rock fragments. The Dominican soil samples were, again, sealed in plastic bags and freighted back to the UK for laboratory testing and analysis.

TYPES OF SOILS INVESTIGATED

From the regional and trial pit sampling surveys undertaken in Kenya and West Java, 93 'undisturbed' and 126 'disturbed' (bag) samples were collected from 84 sites for laboratory description, testing and analysis. Thirteen 'disturbed' samples were obtained from the five Fiji sites and the seven sites in Dominica. From the Kenya borehole sampling programme, approximately 24 m of good-quality samples (three, virtually complete, weathered soil profiles) were obtained from three sites at the Jacaranda Coffee Research Station. Pedologically, the sampled soils included fersiallitic andosols, ferruginous (ferrisol) and ferrallitic soils of the genetically-based French classification system of Duchaufour (1982), adopted as a basis for engineering classification by the Geological Society Engineering Group Working Party Report on Tropical Residual Soils (Anon, 1990). Direct correlation between the various pedological soil classification schemes is difficult, but approximate equivalent soil classes according to the Duchaufour and widely-used FAO-UNESCO classification schemes for the soils obtained from Kenya, Indonesia, Fiji and Dominica are shown in Table 1. Also given are summary terrain and climatic details associated with the occurrence of each soil type and the parental bedrock from which they were derived.

Detailed descriptions of all the project sampling sites, including trial pit and borehole logs for all the Kenya and Indonesia subsurface investigations, are presented in project report WN/93/11.
3 Sampling

Tropical red clay soils are geotechnically unusual in that, despite having clay contents usually well in excess of 50%, they are friable and comprise an open, weakly-bonded structure of silt-sized clusters of clay particles (termed 'peds'). This structure gives a high voids ratio and a low dry density. The soils are usually only partially saturated. Because of this weak structure, these soils are liable to deform, break-up or crack if subjected to relatively minor normal and/or lateral stresses during excavation or sampling.

'Undisturbed' samples for geotechnical testing are obtained usually from tubes or split tubes pushed or hammered into the ground, from rotary coring, or from hand-cut block samples. Using the conventional techniques, all these methods can produce a significant degree of disturbance in tropical red clay soils.

INVESTIGATION AND DEVELOPMENT OF SAMPLING TECHNIQUES

Techniques for obtaining samples of these soils with minimal disturbance, from both trial pits and boreholes, have been developed progressively during four phases of project work:

i) manual sampling in plain plastic tubes.

ii) borehole sampling trials with a wide range of conventional methods.

iii) manual sampling with a new sampler incorporating a cutting shoe and axial guidance.

iv) development of a new borehole sampler and field trials to establish the optimum method of use.

The first three of these phases were carried out as part of the main research project (91/18) and the fourth as a separate specific project (91/19). For both manual and borehole sampling, the common objective has been to obtain samples of approximately 100 mm diameter in a standard plastic tubing, with minimal disturbance. With manual sampling, as carried out at surface exposures or in trial pits, the sampler length is sufficient for 200 mm long specimens to be prepared for triaxial strength testing. The borehole sampler can be configured to provide longer samples, usually of 0.5 m, or up to 1.5 m when required.

Design of the samplers is based on the use of standard plastic pipe with an OD of 110 mm and a wall thickness of approximately 3 mm. For high quality results it is important that the inner surface should be as smooth and regular as possible. This material is preferred to metal tubing, which can corrode and be dented with reuse and mishandling. The tropical clay soils are particularly subject to disturbance during extrusion from a sampling tube. With plastic tubing the need for this procedure can be obviated. On reaching the laboratory, the sample is removed by making a series of axial cuts in the tube and then carefully removing the longitudinal tube segments.

The manual sampling method, for use in trial pits and other excavations, involves the gradual insertion of the sampler into a prepared, *in situ*, truncated cone of soil. It involves first digging a pit to a level about 0.2 m above the required sampling depth
and then deepening part of the pit to about 0.2 m below the sampling depth to leave a 'step' at one end. In an approximately 1 m wide pit, two tube samples can be taken side by side. One half of the 'step' is gradually carved into an approximately 300 mm diameter cuboid pillar; the top of the pillar is trimmed flat and the sampler is placed vertically near the centre of the pillar. The pillar is trimmed to a truncated cone and the sampler gradually pushed down into the soil cone while trimming away the excess soil. When the sampler is slightly over-full, it is carefully removed by undercutting, the excess soil is trimmed away flush with the ends of the sample tube and tight-fitting end caps, preferably of plastic, are taped to each end to prevent moisture loss.

The method was used extensively in pit sites in Kenya and Indonesia. During the first phase, the sampler comprised simply a thick-wall plastic tube with a chamfered cutting edge machined at one end. It was found that sample compression could be much reduced by greasing the inner surface of the tube. For the second phase of manual sampling, the method was modified to reduce operator error in the application of the driving force (hand pressure) and to further reduce internal side friction along the tube wall as the sample slides inside. The application of the driving force was improved by using a modified photographer's tripod which serves as a guide to a pushrod for driving the sample (Figure 2). Internal side-wall friction is reduced by using a steel cutting shoe, with a slightly smaller internal diameter, on the end of the plastic tube. As a result of these modifications, only very small loads (applied by gentle hand pressure) are used to ease the sampler into the soil cone, thus reducing the chance of disturbance to the soil structure, the tripod ensuring that the load is applied parallel to the tube axis (see project report WN/93/14).

For the first phase of borehole sampling, a heavy truck-mounted long-stroke hydraulic rotary drill rig was equipped for drilling and sampling in soil and weathered bedrock to a depth of about 15 metres. Sampling equipment comprised a standard British U100 sampler, a double tube core barrel with split inner tube and a retractor type triple tube core barrel. The boreholes could be advanced by continuous flight rotary augers or full hole drilling with air, foam, water or mud as the flushing medium.

During four weeks at a site near Ruiru, to the northeast of Nairobi, all the available sampling techniques were attempted, but with only modest success. The results of the drilling and sampling techniques used are summarised in Table 2 (see also Section 2). It was found that the partially saturated soil, with clay peds bonded to form open porous structure, readily deforms and compresses under stress to a more dense and de-structured state.

Two major problems were encountered with rotary flush coring. When in situ and undisturbed, the soil has a remarkable permeability: to water, air, at least some muds and possibly even foam. When remoulded during drilling, it transforms from a friable to a highly plastic consistency and stubbornly adheres to metal, thus blocking the flush return. Results with pushing drive samplers were erratic, but rather better. There was clearly a benefit in lubricating the inner surface of a sampling tube.

The design and development of a sampler specifically for tropical red clay soils started from the drive sampling approach that had achieved the best results during the drilling
programme near Ruiru. This had utilised the inner barrel from the triple tube corebarrel, fitted with a high quality plastic liner and a very sharp cutting shoe.

It was anticipated that the main problem in demonstrating the effectiveness of a sampler would be in measuring the sample recovery (as the primary indicator of sample quality or disturbance) with sufficient accuracy. Usual practice is to measure the overall length of sample recovered after dismantling the sampler, and comparing this to length of sample drive. However, in such weak and friable soils it is rarely possible to clean the borehole completely before sampling, or to define the physical ends of a sample with much accuracy. At best, such measurements can provide only an indirect assessment of any change in the length of the material sampled during the sampler drive.

The problem could be overcome if the level of the sample top could be monitored before and after the sample drive. If this remains unchanged, the in situ sample recovery (as an indicator of disturbance) must be 100%. Furthermore, by monitoring the level throughout the sample drive, variations in the rate of sample recovery could be investigated and possibly be related to other relevant parameters. In pursuing this approach, the emphasis of the sampling project (91/19) was amended, from the mere development of a sampler, to the study of the performance and effectiveness of the sampler. For this study three parameters were monitored continuously during the sampler drive: the vertical movement of the sampler, the drive force applied to the sampler and level of the sample top.

The sampler designed at BGS specifically for use in tropical red clay soils (Figure 3) comprises five components: outer tube, liner tube, cutting shoe, sampler tube coupling and sampler head. The four steel components were designed and dimensioned to suit a standard PVC/CPE plastic liner tube, of 110 mm OD and 2.7 mm wall thickness, with a very smooth bore. The sampler was manufactured for nominal sample lengths of either 1.5 or 0.75 metres, with a sample diameter of approximately 104 mm.

A schematic drawing of the test instrumentation is presented in Figure 4. Movement of the soil sampler and of the sample top are measured, via outer and inner tubular assemblies, by the ‘drive’ and ‘compression’ transducers respectively. A load cell at the upper end of the outer assembly monitors the applied load. The three analogue data signals are converted to digital format and recorded on a laptop computer by simple icon-driven acquisition software.

A test programme to study the effectiveness of the sampler and investigate the significance of operating technique was carried out at three sites to the north of Nairobi. These sites varied in elevation from 1650 m to 2250 m, and thus provided a range of soil types as a result of the different climatic zones (see Section 2). The greater part of the programme was conducted at the first site (Mchana, 1650 m), to study the significance of different sampler configurations and operating techniques, and thus derive an optimal sampling procedure. The effectiveness of this procedure (sample compression of 1 % or less) was then confirmed by shorter sampling programmes at the second and third sites.

The raw digital field data recorded during each test comprised 1000 values each for drive distance, sample compression and drive force, together with the times at which each value had been measured. These data had first to be adjusted for calibration, zero and other corrections.
The following output parameters were then computed, with drive distance rather than test time as the primary parameter:

**Drive (D).** Penetration or vertical movement of the sampler (mm).

**Compression (C)** Downward movement of the inner rod assembly, representing sample compression (mm).

**Drive force (L)** Load applied to the sampler (kN).

**Drive Rate (DR)** Incremental rate of sampler movement (mm/s)

**Specific Recovery (SR)** Incremental sample recovery: $(\delta D - \delta C)/\delta D$ (%)

The last parameter, Specific Recovery (Hvorslev, 1949), is a particularly sensitive measure of the sample recovery/compression at any incremental point during the sample drive. This parameter, and to a less extent others such as Drive Rate, is very noisy when computed directly from the corrected digital data. Sophisticated smoothing routines were applied to the derived data, so as to reduce noise as far as practicable, whilst retaining as much of the finer detail as possible. These parameters have been presented graphically for the 36 tests where digital data were recorded (see report WN/93/27 which details the investigations undertaken into borehole sampling during both research projects).

**SUMMARY OF TEST RESULTS**

The testing programme, carried out at three distinct sites in tropical red clay soil, demonstrated the dependence of compressional sampling disturbance on the following factors:

**Sampler design**

**Cutting shoe profile.** The cutting shoes for the BGS sampler were designed and manufactured with a very shallow taper profile and sharp edges, such that care is needed in their handling, to avoid injury to the personnel or damage to the shoes. They proved to be capable of taking samples with virtually no detectable compression. Some shoes had additionally been machined with fluted serrations, as a possible means of further reducing penetration resistance or friction. This refinement gave no discernable benefit. In contrast, the blunter and less tapered shoe of the standard U100 sampler caused severely sheared annular disturbance with any operational technique.

**Internal clearance.** This clearance is achieved by machining the internal diameter of the cutting shoe to a slightly smaller size than the bore of the sample tube. Ideally this clearance, which is expressed as a percentage of the sample diameter, should relieve much of the friction between the sample and the tube, but without the sample becoming loose within the tube. (Relief of such friction also depends on having a smooth bore in the liner tube). The BGS sampler could be assembled to give internal clearances of approximately 0.25, 0.50 or 0.75%. The largest of these was found to be too great, the sample clearly being loose in the liner. There is little evidence from which to choose between the two smaller clearances and an intermediate value of 0.3% to 0.4% is suggested for future work.
Operational technique

Lubrication. The benefit of greasing the inner surface of the liner, anticipated from the earlier sampling programmes, was evident from the results of several tests run without lubrication, where the onset of severe compression (Specific Recoveries of only 50% or less) occurred quite abruptly. In one test it occurred after little more than 300 mm of sample drive (test 18, Figure 5).

Drive rate. The drive, or penetration, rate of the sampler may vary from virtually zero to the maximum feed rate of the rig in use. Before this testing programme the drive rate had not been considered a major factor. Extensive research had apparently established (at least for saturated soils) that the drive rate should invariably be as fast as possible (Hvorslev, 1949). Whilst not always clear and consistent, the test data indicate that sample compression is generally minimised with a drive rate of less than 15 mm/s. Figure 6 shows an inverse relationship between Specific Recovery and drive rate in test MCH 14. With high drive rates (Figure 6, tests 6, 7 and 12) the Specific Recovery can drop to 80% or less. To allow some margin, rates of 10 mm/s or less would be advisable (c. 1 minute for a 0.5 m drive length).

Drive Length. Although a sample length of c. 0.5 m is generally adequate for geotechnical laboratory testing, lengths of c. 1.5 m are much more economic if there is a requirement for core sampling of the complete sequence, as may be the case in engineering geological studies. The longer 1.5 m sampler was generally used, in order to investigate the dependence of sample quality on drive length, at least to an indicative level for engineering geological applications, but with much greater certainty for geotechnical sampling. The majority of the tests demonstrate that drive length is a factor of major significance, as most of the other factors are cumulatively dependent on this length. Most have only a minimal effect within the initial 500 mm of a sample drive, but may need to be closely controlled to achieve a satisfactory sample of 1500 mm length. In most instances the length of the sampler to be used will be determined by external considerations, such as the purpose and economics of the sampling project.

Drive force. Like drive rate, this factor is not directly controlled during sampling, but results from the interaction between the resistance to sampler penetration and the characteristics of the drilling rigs hydraulic system. In this test programme, the monitoring of drive force was a relatively minor consideration. It was carried out to establish the general force levels required, with the possibility that it might reveal some unsuspected features of interest. The majority of the tests show that the drive force for the new sampler, after the initial 200–300 mm of penetration, was in the range 15–25 kN (1.5–2.5 tonnes). In those tests where the force rose significantly above this range, it generally indicated the onset of significant sample compression.

The influence of soil type was most evident as a factor. In the more allophanic soils found at the higher elevations of Kibubuti (1960 m), and Mabroukie (2250 m), sample compression never exceeded 10 mm for a 1.5 m sample drive. Although the majority of tests were conducted with the optimal technique, the specific use of an un-greased liner or a high drive rate had little deleterious effect. These types of soil are evidently more tolerant of sampling technique.
RECOMMENDATIONS FOR GOOD SAMPLING PRACTICE

To sample tropical red clay soils with minimal disturbance, either in a pit or a borehole, the following factors should be observed:

- the essential components of a sampler are a plastic sample tube and a steel cutting shoe.
- the sample tube should have a smooth bore and a minimal variation in wall thickness. A wall thickness of 2.5–3.0 mm is recommended.
- the internal surface of the sample tube should be lubricated, preferably with a thin coating of silicone grease.
- the cutting shoe should have a sharp edge and the shallowest practicable taper.
- the internal diameter of the shoe (and thus the diameter of the sample) should be approximately 0.3–0.4 % less than that of the sample tube. It should have a very close or interference fit on the outer diameter of the sample tube, to ensure that the bores of the two components are as near coaxial as possible.
- the sampler should be pushed into the soil with an even force, such that the penetration rate is less than 10 mm per second.

For manual sampling, in shallow pits, the sampler should be driven by a push-rod, laterally supported in a simple framework, such as a lightweight tripod, to ensure that the axis of the sampler remains constant. It is recommended that the potential sample is initially prepared as a tapered pedestal within the pit. This pedestal is then progressively trimmed away as the sampler is pushed downwards into it.

For borehole sampling, with a drilling rig, further factors should be observed:

- the borehole should be drilled, reamed and cleaned by mechanical techniques, such as rotary augering, that minimise any disturbance, by percussion or flushing media, of the material to be sampled.
- the sampler should be push-driven in a single pass, adjusting the drive force so as to achieve a reasonably steady rate of penetration. The drive should be terminated if there is a rapid increase in this force.
- for longer samples, of up to 1.5 m length, it is essential that the detailed design criteria and operating technique are strictly observed.

For more critical applications, where it is desirable to quantify any sample disturbance, a simple lightweight inner rod assembly should be incorporated to monitor any movement in level of the sample top. This technique has been used successfully during this project for quantifying disturbance during borehole sampling, and should be equally applicable to the manual sampling technique.
4 Index properties and testing procedures

Following conventional engineering practice developed for temperate sedimentary soils, it is generally sufficient for the purposes of engineering classification to consider their simple index properties, which can be assessed easily, such as their particle size distribution, consistency (plasticity) limits or density. Test procedures for the determination of these index tests are defined in British and ASTM standards.

Conventional index tests are carried out on samples of disturbed, remoulded soil and are thus independent of the state of the soil in situ. However, for sedimentary soils, they not only give a good guide to how the disturbed soil will behave when used as a construction material under various conditions of moisture content but also give an indication of the in situ mechanical properties of the soil. In effect, standard engineering practice, by regarding the particle size and consistency limits as the basis of soil classification, is asserting that the influence of mineralogy, chemistry and origin of a soil on its mechanical behaviour is adequately measured by these simple index tests (Schofield and Wroth, 1968). This is not the case for tropical residual red clay soils. The mineralogical composition and microstructure has a pronounced influence on the engineering behaviour and measurement of the index properties of tropical red clays, which is generally much more complex and important than with sedimentary soils.

The usefulness of conventional index tests for characterising tropical residual soils in general, and tropical red clays in particular, has been questioned many times in the published literature. There have been two major concerns. Firstly, the problem of obtaining meaningful and repeatable index property measurements by following procedures laid down by current testing Standards (eg. BS1377 and ASTM). Secondly, the concern that, unlike the great majority of temperate soils, the in situ character of tropical red clay soils is so destroyed by the test procedures that the index parameters cannot give an indication of the ‘mechanical’ properties of the undisturbed soil. Problems in achieving repeatability of meaningful index test measurements relate largely to ‘standard’ sample preparation requirements prior to testing and in measuring the moisture state of the soil as part of the test requirements. For example, because of the mineralogical composition of tropical red clays, even partial air-drying at ambient laboratory temperatures may change the structure and physical properties of these soils. Some of these changes are not reversed when the soil is re-mixed with water. These structural changes are reflected in sometimes drastic changes in the index properties derived from plasticity, shrinkage and particle size tests, or, sometimes, in particle density (specific gravity).

It has become increasingly clear that conventional index testing procedures, such as those defined in the British and ASTM standards, are not necessarily applicable to tropical residual soils without some modification or change in emphasis. In recent years, various modifications to these tests procedures have been attempted, usually based on local soil engineering experience, and new indexing procedures have been put forward (for example, Vargas 1988; Vaughan, 1988; Vaughan et al., 1988). However, many engineering manuals in current use in developing countries continue to be based on
current British or ASTM standard testing procedures with little or no modifications tailored to account for the particular characteristics of residual soils in the tropics. Particle size and consistency limit test data continue to be reported widely in the published literature, much of which has been utilised by many workers as a basis to formulate classification schemes intended for local and more universal usage. It is to be regretted that much of this reported index data is not accompanied by detailed descriptions of sample preparation and test procedures employed in their determination. This has led to confusion when attempting to correlate apparently similar test data between soil types and to erroneous comparison of various soil classification schemes.

Investigation of the index properties of a wide spectrum of tropical red clay soils were conducted to:

- assess the applicability of conventional, modified and new sample preparation and index testing procedures and to evaluate these procedures in achieving more accurate and repeatable results, and
- assess the implications of these results for classifying tropical red clays in engineering terms and their applicability in indexing the mechanical behaviour of these soils.

The study findings with respect to sample preparation and test procedures to obtain repeatability of test results are summarised below. The implications of index test parameters for the engineering classification of tropical red clays are summarised in Section 6.

PLASTICITY TESTS (liquid limit; plastic limit)

The study results have shown that consistent and repeatable plasticity-related index test measurements can be obtained on a spectrum of red clay soils provided care is taken in their preparation, or pre-treatment, prior to testing. Drying of the soil in any way prior to testing will effect the test results by 'hardening' the clustered clay structure, making it generally more difficult to break down and leading to non-homogeneity of remoulded soil mixes and inconsistency in measured results. Pre-drying the soil may also drive off water held within the clay minerals and amorphous gels characteristically found in these soils (particularly hydrated halloysite and allophane). This can change the structures of these minerals and, in effect, cause the test sample to be totally unrepresentative of the natural soil. Sensitivity to pre-drying is variable for different soil types. Allophanic andosols ('young' soils) are by far the most sensitive and the most 'mature', dominantly kaolinitic, soils the least sensitive. Between the two 'extremes', soils will have a variety of clay mineral compositions and correspondingly variable drying sensitivities. These soils can comprise mainly ferrisols and ferrallitic soils, but also some andosols with weak allophanic properties. Therefore, it is recommended that no pre-drying of any tropical red soil is undertaken, and plasticity tests are carried out on soils prepared from their natural (or as received) water contents.

All of the soils investigated in this study were, to a greater or lesser extent, sensitive to the degree of manipulation of the soil-water mix. Repeatable results can only be attained if the red clay soils are completely remoulded prior to testing. This can be achieved by
thorough hand-mixing or by a simple mechanical mixing device such as the 'greaseworker'. A comparison of the plasticity characteristics (shown by means of conventional 'plasticity', or 'A-line' charts) for a variety of red clay soils prepared by standard hand-mixing and 'non-standard' greaseworker-mixing is shown in Figure 7 (a & b). The results are for soils tested from their natural state (with no pre-drying) and with hand-mixing being undertaken for at least 60 minutes until it was considered that a smooth, homogeneous paste was achieved (as required by BS1377 testing standards). The results clearly show that mixing in the greaseworker enables more thorough remoulding ('ultimate' mixing) than can normally be achieved by standard hand mixing. This is reflected in the data points for nearly all the red soil types being shifted closer to and higher up the A-line (that is, becoming more clay-like/less silt-like and more plastic). Data points for the andosol soils are the exception to this general trend and remain clustered well below the A-line in manner characteristic of high plasticity silts, whether mixed by hand or by the greaseworker. The general shift of the data points for these soils farther away from the A-line following greaseworker mixing reflects the decrease in measured liquid limit with increased remoulding, and was found to be unique for the andosols soils.

Comparative tests on subsamples are advisable to check the thoroughness of the remoulding. However, when hand-mixing is employed it is recommended that the soils are initially mixed for at least 60 minutes and that comparative tests are done by more than one operator. In this study, completely remoulded soil mixes were obtained after 500 'pumps' of the greaseworker mixing handle. This device allows more controlled and rapid mixing of the soils than conventional hand-mixing of the soil-water paste using spatulas and a glass plate. The use of this, or a similar, mixing device is recommended wherever possible. However, caution must be used when dealing with allophanic andosols. Provided these soils are not dried prior to preparation, thorough remoulding can be achieved quite effectively by hand mixing. Additional working in the greaseworker was often found to result in a decrease in the liquid limit of these andosols, although values still fell within the bounds of 'extremely plastic silts' on the A-line chart (Figure 7). For these soils it is suggested that thorough hand-mixing alone is sufficient for meaningful results. A comparison of the liquid limits determined from increasing degrees of hand-mixing or between hand and greaseworker (or similar) mixes may be a useful guide to identify the presence of allophanic soils, as no other soils investigated in this study recorded a decrease in liquid limit with increasing manipulation.

Both hand and greaseworker mixing was made easier when the soil was mixed up in its wettest state (above the liquid limit) and carefully dried back during testing to obtain the required points on the 'moisture content versus log cone penetration plot'. This 'drying-back' technique gave identical results to the conventional 'wetting-up' technique.

Prolonged remoulding to achieve destructuring of the soil in the laboratory will generally not be achieved in the field. Because of this it has been suggested by some workers that only a minimum amount of soil remoulding should be undertaken prior to testing, in an effort to avoid complete breakdown of individual aggregations of soil particles. However, the study results have shown that partial breakdown of the soil structure by incomplete remoulding will give inconsistent plasticity data. Partial breakdown (or destructuring) of these soils in a 'controlled' and repeatable manner is extremely difficult, if not
impossible, to achieve in the laboratory and cannot hope to duplicate field conditions with any accuracy.

With regard to testing procedures, some difficulty was encountered in determining accurate plastic limits using the conventional thread-rolling technique, as most of the soils tended to start crumbling before the required 3 mm thread diameter. When this occurred, and provided the thread remains intact, consistency of measurement was best achieved by continued rolling to the required diameter, and the plastic limit moisture content determined accordingly. It is recommended that this technique is adopted when undertaking conventional plastic limit tests on these soils, and that the procedure followed is described along with the test result. Slightly increased consistency was obtained by adopting a method described by Harison (1988) for using the cone penetrometer to determine the plastic limit, which tended to give slightly lower values than the conventional method. However, practical difficulties with this method remain, as does the uncertainty as to how plastic limits determined by the cone penetrometer relate to those determined by the present standard test. More detailed studies and probably equipment re-design or modification (for example, a heavier cone) are required before this test can be recommended as a standard alternative to the current testing procedure.

The plasticity chart shown in Figure 7b presents the most consistent and repeatable plasticity data obtained in the study and is derived from thoroughly remoulded greaseworkeend soil mixes which were not subject to drying prior to sample preparation and testing. The most striking aspect of this plot is the distinct clustering of the data points in terms of their bedrock pedogenesis. The most intensively weathered (dominantly kaolinitic) soils plot at the lower end of the A-line whilst soils which have undergone progressively less intensive weathering plot parallel to and higher up the A-line. The least intensively weathered soils are andosols formed over Younger Quaternary volcanics which form a distinct cluster well below the A-line. The figure clearly shows the influence of soil genesis, and how far the soils have progressed along the tropical weathering path, on the engineering properties of these soils.

**MOISTURE CONTENT**

Despite the presence of hydrated halloysite and amorphous allophane in many of the red soils investigated, no significant differences in natural moisture content determinations were found between samples oven dried at 50°C or 105°C. The lower temperature is that recommended by Anon. (1990) to prevent water of crystallisation being driven from the clay mineral structure. When compared to four temperate soils (with no water of crystallisation to drive off), the red clay soils showed the same percentage difference in moisture content measurements for samples dried at 40, 50 and 60°C, with respect to moisture contents for the same soils dried at 105°C. Unless there is irrefutable evidence that significant 'structural' water is driven off from comparative tests on samples dried at 50 and 105°C, drying at the latter conventional temperature is advised. This applies to all determinations of moisture content, including those related to other tests such plasticity, shrinkage and density tests.
SHRINKAGE TESTS (shrinkage limit; linear shrinkage)

The shrinkage limit (volumetric shrinkage) is the water content at which a soil ceases to shrink when gradually dried. Tests were conducted according to the ASTM standard method (BS1377 subsidiary method) on eleven remoulded Indonesian 'red and brown latosols' and one 'brown andosol' by project collaborators in that country. The soils were not pre-dried prior to remoulding and placing in the shrinkage limit apparatus. Shrinkage limits for the latosol soils were very consistent with values ranging from 23 to 32%. Equivalent plasticity indices for these soils ranged from 33 to 48%. No appreciable change in shrinkage limit was noted between test samples remoulded following a minimum hand-mixing of 10 minutes or after thorough hand-mixing of 60 minutes. All of these soils were developed over 'Older Quaternary volcanics' and are probably equivalent to ferrisols and/or ferrisol-ferrallitic soil associations in the pedological soil classification of Duchaufour (1982). These data follow closely those determined by Dumbleton and Newill (1962) who quote shrinkage limits ranging from 23 to 30%, with equivalent plasticity indices of between 34 to 46%, for. The shrinkage limits of the Indonesian latosols agreed very well with the range quoted by Dumbleton and Newill (1962) for halloysitic 'laterite clays' from Kenya ($w_s = 27$ to 30%).

The Indonesian andosol soil contained an appreciable amount of amorphous allophane. The shrinkage limit measured for this soil was 82.7%, much higher than those obtained for the latosol soils. Equivalent liquid limit and plasticity index values of the soil were 201% and 149%, respectively. As with the latosol soils, the degree of remoulding (10 minutes versus 60 minutes of hand-mixing) had no appreciable change on the shrinkage limit. The shrinkage limit value agrees well with the 50 to 100% range quoted by Maeda et al. (1977) for 'typical' allophane soils. However, lower values may be expected for some andosol soils with 'low' allophanic properties (that is, in soils where, due to increased weathering, the proportion of amorphous allophane decreases with respect to the presence of crystalline halloysitic and/or kaolinitic clay minerals). Maeda et al. (1977) also found that remoulding does not change the value of the shrinkage limit.

Linear shrinkage (or one-dimensional shrinkage) tests give an indication of the amount of shrinkage by determining the change in length of a semi-cylindrical bar sample of soil when it dries out, following remoulding at a water content near the liquid limit. Because the majority of the red clays obtained during the current study were found to contain 'moisture sensitive' halloysite and/or allophane clay minerals, linear shrinkage tests were conducted by drying the test specimens at both 40°C and the standard drying temperature of 105-110°C. However, for all red soil types, no significant difference in linear shrinkage was observed between samples tested at the two drying temperatures.

The effect of remoulding on linear shrinkage values was examined by testing soils remoulded to a smooth 'homogeneous' paste by thorough hand-mixing and by more controlled extended mixing using the greaseworker apparatus. As was found with the liquid and plastic limit tests, increased remoulding resulted in a corresponding increase in linear shrinkage for the great majority of tropical red clays. Linear shrinkage values for three UK soils (Gault Clay, London Clay and Mercia Mudstone) showed no difference with increased remoulding.
The greaseworker allowed more controlled and thorough remoulding of the soil-water mixes and, hence, more consistent linear shrinkage data. For the 'younger' soils developed over the Quaternary volcanics measured linear shrinkage values fell within the higher range (23 to 30%), whereas the 'older' soils developed over Precambrian Basement rocks fell within a lower range (5 to 15%). Values for soils developed over Tertiary volcanics tended to distribute relatively evenly between, and overlap with, these two end ranges.

Despite the large amount of shrinkage on drying indicated by the linear shrinkage values for those soils developed over the Quaternary volcanic soils and many soils developed over the Tertiary volcanics, one would expect little visible cracking for these soils in their 'undisturbed' natural state in the field. Because of the high voids ratios associated with these soils due to their aggregated soil fabric comprising 'clay clusters' (or 'peds') with variable amounts of finely divided iron oxides, it is likely that the shrinkage would be taken up in the small inter-cluster spaces. Maeda et al. (1977) stated that this is particularly true for allophane soils (andosols) which generally have a low natural cohesion which decreases on drying. However, it should be pointed out that shrinkage cracking may occur in reworked and compacted red clay soils.

In addition to indicating the amount of shrinkage, the linear shrinkage test can provide an approximate estimate of the plasticity index \(I_p\) for soils where the liquid and plastic limits are difficult to determine (Head, 1992). Therefore, this may be useful for those tropical red clay soils from which it is sometimes difficult to obtain reproducible results. Despite some scatter, the following approximately linear relationship between plasticity index \(I_p\) and Linear shrinkage \(L_s\) was obtained for a wide spectrum of soils:

\[
I_p = 2.5 L_s - 15.2
\]

This relationship is very similar to other (but not all) correlations between linear shrinkage and plasticity index determined for other 'typical' red tropical clays in Ghana (Gidigasu, 1976; Newill, 1961a). In most cases the scatter of points is probably too large to justify the use of a single 'universal' formula which converts the linear shrinkage to the plasticity index. However, when doubt exists over the reliability of the plasticity index obtained by normal testing methods, an appropriate local correlation of \(I_p\) with \(L_s\), developed for the particular soils under investigation, may usefully be used to check results. Linear shrinkage and plasticity are greatly influenced by the degree to which the soils are remoulded during testing and on whether the soil is pre-dried or tested from its natural state. Therefore, care is needed to ensure that meaningful and reproducible plasticity index data are acquired before developing any correlations with linear shrinkage for a particular red soil type.

Because accurate measurement of the plastic limit (needed for calculation of the plasticity index) can be difficult to determine for some red clay soils, correlation of linear shrinkage values \(L_s\) with liquid limits \(w_l\) were also examined. The results showed a reasonably good linear relationship between all soil types, but with the andosol soils clearly forming a clear 'grouping' distinct from the more mature ferrisol and ferrallitic soils. For all the red clays except the andosols the overall relationship between linear shrinkage and liquid limit was:

\[
w_l = 3.9 L_s + 6.3
\]
When the soils were considered in terms of their development over different parental bedrock the following relationships were established:

<table>
<thead>
<tr>
<th>Timescale and intensity of weathering increasing</th>
<th>Soils developed on:</th>
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<tr>
<td></td>
<td>Younger Quaternary volcanics (andosols) $w_L = 6.6 \text{ LS}$</td>
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<tr>
<td></td>
<td>Older Quaternary volcanics (ferrisols &amp; ferrallitic soils) $w_L = 2.9 \text{ LS} + 39.8$</td>
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<tr>
<td></td>
<td>Tertiary volcanics (ferrisols &amp; ferrallitic soils) $w_L = 2.7 \text{ LS} + 29.8$</td>
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<td></td>
<td>Pre-Cambrian Basement complex [mainly granites] (ferrallitic soils) $w_L = 2.2 \text{ LS} + 24.5$</td>
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Similar correlations have been obtained between linear shrinkage and such properties as clay content, liquid and plastic limits, optimum moisture content, field moisture equivalent and volumetric shrinkage for soils developed mainly over phyllites and granites from Ghana (Gidigasu, 1976). These, and the derived relationships found in this study, clearly indicate the influence of soil genesis on their engineering properties.

Experiments undertaken on nine soil samples to examine which soils shrink irreversibly on drying showed that only andosols with significant allophane content showed virtually no additional shrinkage when re-wetted and re-dried. Dominantly kaolinitic ferrallitic soils showed almost completely reversible shrinkage characteristics. Between these two extremes, soils with a mixed allophanic, halloysitic and kaolinitic clay showed variable reversibility on re-wetting and re-drying, with linear shrinkage values ranging from 30 to 60% of the original test value.

**PARTICLE SIZE DETERMINATIONS**

With the exception of the allophanic andosol soils, no difficulty was encountered in undertaking meaningful particle size analyses, even for pre-dried samples. Dispersion of the soils was effectively achieved using 'standard' sodium hexametaphosphate dispersant, provided the dispersant-soil suspension was shaken for at least 12 hours, or overnight. Comparative tests using the same dispersant but mixing in a high-speed mechanical stirrer for 15 minutes (as specified in the ASTM and 1967 British Standard) showed that the latter did not enable full dispersion of the soil particles and is not recommended. Although, pre-drying did not significantly affect the results for these soils, it is recommended that pre-test preparation and testing are performed on soils at their natural state (not pre-dried). Pre-drying significantly effected the particle size distributions of the andosol soils, and in practice a testing programme may be undertaken without realising allophanic andosols may be involved. Testing the soil without pre-drying also maintains consistency with the recommended preparation procedures for other index tests.

With respect to the allophanic andosol soils, the problem was not in dispersing the soils, but in preventing them re-flocculating (a condition also reported by Wesley, 1973). Maeda et al. (1977) stated that different allophane soils react differently to different
dispersion treatments. If this is the case, it is suggested that grain-size analysis has a limited usefulness in characterising these soils for engineering purposes, as continuous experimentation will be necessary to obtain maximum dispersion. However, not all andosols have pronounced allophanic properties and, in the first instance, it is recommended that particle size distributions are carried out following the procedures adopted for other red clay soils using 'standard' dispersant. Wherever possible, the grain size analysis should be done on field-moist samples.

Typical particle size distributions for a variety of tropical red clay soils from Kenya and Indonesia, developed over various types of parent volcanic bedrock, are shown in Figure 8.

**PARTICLE DENSITY (specific gravity)**

Particle densities varied widely for all the red soil types investigated (2.66–2.95). Results for samples which were tested from their natural moisture content (no pre-drying) generally gave higher measured particle densities than those subjected to oven pre-drying (at the standard 105–110°C). The reason for this possibly lies in the loss of water of crystallisation (or intra-particle or inter-layer water) from the clay minerals on oven-drying, and hence a reduction in the density of the solid matter. No clear distinction was found between pedological groups which either do, or do not, show a reduction in measured particle density on drying. However, the Kenyan ferrisols and ferrallitic soils developed on Tertiary volcanics and Precambrian Basement Complex rocks (mainly granites) are probably the least susceptible as a whole. The Indonesian ferrisol/ferrallitic soils ('latosols') developed over Older Quaternary volcanics appear to be most susceptible to reduction in particle density with drying, and andosols possibly less so. This does not agree with the findings of Wesley (1973) for similar tests on Indonesian 'latosols' and andosols. However, experimental error may be considerable, resulting in scatter unrelated to pedology.

No clear correlation could be established, in this study, between the reduction in particle density on pre-drying and the percentage of hydrated halloysite present in the soil, as was described by Newill (1961b) for a halloysitic red clay from Kenya. In this respect, the results agree with Wesley's findings for Indonesian red clays which showed little or no reduction in particle density with pre-drying. Mineralogical analysis on similar Indonesian red clays investigated in this study showed that many of these soils contained appreciable amounts of hydrated halloysite.

Errors in the determination of particle density, or incorrect assumptions of particle density, result in incorrect determinations of clay content, voids ratio, porosity, and hence consolidation parameters. It is recommended that particle densities are carried out at natural, or 'as received' moisture contents, rather than on pre-dried samples. The moisture content at which the test is carried out should be measured and quoted. Discrepancies reported for pre-dried results may originate from differences in the degree of ped breakdown of the dried sample prior to the test, rather than to the loss of crystallisation, or intra-particle, water *per se.*
RECOMMENDATIONS FOR GOOD TESTING PRACTICE

General
- For all index tests on tropical red clay soils, it is vitally important to report the sample preparation and test procedures undertaken to obtain the measured result. Without this information, comparison with test results on similar soils from other sites are suspect and can lead to erroneous assumptions regarding classification of the soil for engineering purposes.

Preparation of disturbed samples
- It should be assumed that all tropical red clay soils will be affected in some way by drying. Care should be taken to preserve the natural (as sampled) moisture contents by ensuring adequate sealing of field samples to prevent moisture loss. On return to the laboratory the samples should be kept sealed, and stored in a cool environment, until required for testing. Classification tests should then be carried out on the soil with no additional drying prior to testing.

- The majority of residual red clay soils have a friable texture which generally allows samples to be disaggregated, or broken down, sufficiently by light finger pressure to allow sub-division by accepted riffling or quartering procedures to obtain representative samples for testing.

- Recommendations for preparation procedures for individual test requirements are given below. The method of preparation should always be reported.

Moisture content
- It is recommended that moisture content determinations are carried out at the ‘conventional’ oven-drying temperature of 105–110°C.

Plasticity tests
- The standard fall cone apparatus (cone penetrometer) should be used in preference to the Casagrande apparatus for the liquid limit test.

- The soil should be mixed by adding water to the soil in its natural (or as received state) and worked as necessary for the liquid and plastic limit tests. Drying of the soil prior to mixing should be avoided.

- Easier and more efficient mixing is achieved by mixing the soil at a moisture content above the liquid limit (that is, in its wettest state), followed by gradual drying back to achieve the required data points on the moisture content versus cone penetration plot. At least five points should be determined.

- **Repeatable results can only be attained if the red clay soils are completely remoulded prior to testing.** The amount of manipulation to which the soil is subjected determines the extent to which the soil is broken down and has a significant effect on the measured test results. The sensitivity of the soil to remoulding should be verified using a range of mixing times prior to testing. It is
recommended that conventional hand-mixing should be undertaken initially for at least 60 minutes and, if necessary, additional mixing carried out to ensure thorough remoulding of the soil-water paste. A simple mechanical mixing device such as the ‘greaseworker’ provides the most thorough and efficient means of mixing the soil, and is independent of variations in strength/energy of the operator. It is highly recommended that such a device is used.

- The one-point liquid limit test is not advised for use with these soils.
- Difficulty may be encountered in determining accurate plastic limits using the conventional thread-rolling technique, as some red soils tend to start crumbling before the required 3 mm thread diameter. When this occurs, and provided the thread remains intact, consistency of measurement can best be achieved by continued rolling to the required diameter, and the plastic limit moisture content determined accordingly (the procedure should be reported along with the test result). Where an intact soil thread of c. 3 mm cannot be achieved by continued rolling of the soil, the soil should be recorded as ‘non-plastic’.

Shrinkage tests

- Linear shrinkage test on remoulded red soils are affected by the degree of remoulding. Procedures for the thorough mixing of the sample prior to testing should follow those described for the liquid limit test.
- The linear shrinkage should be determined at the conventional drying temperature of 105–110°C.
- It is important to distinguish between those soils which shrink irreversibly on drying and those which do not. This may be achieved by re-wetting and remoulding the samples used in the linear shrinkage test. Repeat testing of the same samples enables calculation of the percentage of additional shrinkage, if any.

Particle size distribution

- Pre-drying of the soil should be avoided. The initial sample should be weighed and a subsample taken for moisture determination, so that the initial dry mass can be calculated.
- Disaggregation of the soil sample prior to sieving and sedimentation analysis should be done using ‘standard’ sodium hexametaphosphate dispersant. The soil-dispersant solution should be placed in a sealed flask and gently agitated for at least 8 hours (or overnight) in a flask shaker, to ensure proper disaggregation.
- Following disaggregation, the soil (plus dispersant) should be washed through a 63 μm sieve and collected. Gentle agitation by light finger pressure may be used to facilitate washing through of the fine particles. The material remaining on the 63 μm sieve should be wet sieved through the normal range of sieves. Additional material passing the 63 μm sieve should be added to that collected from the initial wet sieving.
- Sedimentation analysis of the fine fraction should be undertaken according to standard procedures.

- Consistent and meaningful particle size distributions are difficult to obtain for allophanic andosol soils. Continuous experimentation is necessary to obtain maximum and permanent dispersion. However, not all andosols have pronounced allophanic properties and, in the first instance, it is recommended that particle size distributions are carried out following the procedures adopted for other red clay soils using 'standard' dispersant.

**Particle density (specific gravity)**

- Particle densities should be carried out on soils at natural, or 'as received' moisture contents, rather than on pre-dried samples. The moisture content at which the test is carried out should be measured and quoted.

- After testing the soil may be oven-dried at the 'standard' temperature of 105–110°C to determine its dry mass for use in the equation for calculating particle density.
5 Mechanical properties and testing procedures

Mechanical properties ones dependent on applied stresses or conditions. They are distinguished from index properties, which may be considered as characteristic of the soil solids rather than of the solid/void structure, and are usually derived from tests carried out on disturbed or deliberately reworked samples. In addition, compaction properties and residual strength tests are briefly considered. These tests were carried out on disturbed samples.

Mechanical properties, unlike the index properties, are capable of taking into account the natural soil fabric or structure (including voids), and stress conditions, and tend to be more complex and time consuming, with difficulties often experienced in specimen preparation. The main part of the mechanical properties test programme dealt with triaxial and oedometer tests, which, despite the use of computer control and datalogging, was designed to follow standard procedures recognised worldwide. Determinations of strength, deformation, saturation, permeability and consolidation properties were made as part of the triaxial test procedure. All triaxial tests were of isotropically consolidated, undrained compression (CIU or ICU) type, and were carried out on specimens saturated (by raising of back pressure) as part of the preliminary test procedure. With the exception of four tests on Kenyan specimens, triaxial tests were multi-stage (multi-CIU), that is, all test stages were carried out on the same specimen. In addition, two sets of samples, one from Kenya and one from Indonesia, were prepared in both destructured (that is, slurred and re-sedimented) and compacted (standard Proctor) forms for triaxial testing in order to allow comparison with the undisturbed condition. The results of a limited number of compaction and ring shear tests are also considered. The test results are summarised in Table 3.

Tests to determine mechanical properties have been selected in order to reflect standard practice worldwide, or to extend or modify that practice in areas where the need for improvement is perceived. Whilst modern apparatus has been used, particularly in the case of the triaxial tests with computerised datalogging and control, the fundamental nature of the tests is reproducible in most soils testing laboratories. No attempt has been made to carry out unsaturated tests for, without special equipment for measuring air and water phases separately, the test is unreliable (Fredlund and Rahardjo, 1993). However, problems have been experienced in the saturation process.

For the determination of index properties, the inadequacy of applying standard practice to tropical red clay soils has been discussed in Section 4. This also applies, but to a lesser extent, to the measurement of mechanical properties. Multi-stage isotropically consolidated, undrained (multi-CIU) triaxial strength and multi-specimen one-dimensional oedometer consolidation tests have been successfully carried out on these soils. Procedures described in Head (1986) were followed with minor exceptions. A total of 26 triaxial and 100 oedometer tests were carried out. In the main, 100 mm diameter × 200 mm long triaxial specimens and 50 or 75 mm diameter × 20 mm thick oedometer specimens have been used. A small number of conventional triplicated 50 mm × 100 mm (CIU) triaxial specimens were tested, but these proved less successful.
In most cases, 'mechanical' samples have matching 'index' samples so that correlations can be made between them. Such relationships have been described in the literature and are here investigated and examples given. Unusual consolidation results are described from some triaxial tests. These appear to relate to the saturation regime in the triaxial test, affecting the normal test procedure. The phenomenon of collapse, that is sudden densification on flooding under a constant applied stress, has been investigated in the oedometer. The effects on mechanical properties of total destructuring of the soil followed by resedimentation, and of standard compaction have also been investigated by special triaxial preparation techniques and SEM study. These have led to conclusions about the nature of bonding within the soil structure.

SPECIMEN PREPARATION

Difficulties have been experienced in the preparation of test specimens from 'undisturbed' samples of tropical red clay soils of both allophanic and halloysitic types. These stem from their high clay content and stickiness at natural moisture content and yet, at the same time, their friable and relatively weakly bonded ped structure and low density. Any form of trimming of specimens at natural moisture content, be it by cutting, turning, scraping, either by hand or machine, tends to be extremely difficult. The use of normal trimming tools tends to 'pluck out' or 'peel' large sand-sized clusters or aggregations of clay. This is particularly the case for the halloysite-rich types. The use of push-driven tube samples, taken from either pits or boreholes at the same diameter as the triaxial specimens (see Section 3), greatly facilitated preparation, as trimming was then confined to the specimen ends. It was found that for the wetter and stickier soils a small scalpel was best suited for trimming, whereas a hacksaw blade could be used for drier or less sticky soils.

Oedometer specimens were easier to prepare, it being usually possible to obtain four or five specimens per tube sample. Nevertheless, the problem of plucking-out or peeling-off, even when using a sharp blade, was ever present. A process of careful paring, rather than a single clean cut, had to be employed. A cheese wire, typically used for cutting clay soils, was not usually successful due to the low density of the soils. In some cases, where a level end surface could not be achieved on a specimen, fine uniform quartz sand was used as a filler. Handling of the 100 mm triaxial specimens was particularly difficult. The problem of open or loosely infilled termite or root holes in triaxial test specimens was dealt with by filling with a soil paste where possible. If such holes intersecting the specimen surface were left unfilled, membrane entry into them caused volume errors and membrane failure (Bohac and Feda, 1992). A single fresh standard latex membrane was used for each test. No filter drains were used on the specimen sides. Drainage from one end of the triaxial specimen during isotropic consolidation was used, though drainage from both ends would have been beneficial. Traditional methods of estimating the duration of undrained compression stages, based on \( c_v \) values obtained from isotropic consolidation stages, were not used. This was due to the difficulty in calculating \( c_v \) using the actuators. Also, it is likely that such calculations are inappropriate for these soils; probably producing too rapid a test rate.

Various types and sizes of tube were used during the project for sampling in hand-dug trial pits. Initially, sharpened aluminium or thick-wall plastic tubes (100 to 104 mm
bore) were used. Large diameter (150 mm) cardboard tubing was also tried in order to obtain adjacent multiple 50 mm triaxial specimens, but with limited success. The design and operation of a new sampler for manual use in trial pits has been described in Section 3. This design added a sharp, reusable, cutting shoe to a plain ended plastic tube of 250 mm length and ensured straight alignment of the tube. The length was intended to provide a 2:1 triaxial specimen after end trimming. In the laboratory, the tubes were cut from the sample by hacksaw or grinding wheel. This operation required several stages to prevent sticking of the sample to the tube segments, despite the use of release agents (subsequently, a vibrating saw jig was developed, which removes plastic tubes more accurately and rapidly, causing less damage to the sample). Extrusion of samples was avoided throughout. Plastic tube samples from trial pits were not waxed, but weighed on-site and sealed with plastic end caps and vinyl tape and packed in padded boxes. Storage was in a humidity and temperature controlled room (9°C, 80% RH). Under these conditions storage periods of up to five years have resulted in moisture losses of about 5% accompanied by shrinkage away from the liner wall of about 0.5 mm.

Destructured specimens were prepared by slurrying, achieved by mixing with water in a 5 litre mixer and a grease-worker (see Section 4), and then sedimenting in plastic tubes with side-drainage filters. A period of 3 to 6 months dewatering and air drying was allowed under a small axial stress. Laboratory compacted samples were prepared by Standard Proctor method but using a plastic sampling tube, as used for undisturbed sampling, rather than a Proctor mould. This was to allow removal of the specimen without extrusion.

In the case of four Kenyan trial pits, traditional triplicate (50 × 100 mm) triaxial specimens were hand trimmed from single 150 mm diameter cardboard tube samples (see project report WN/93/13). This method had limited success due to the difficulty in using the cardboard tube, loss of moisture through the tube, and frequent disaggregation and slumping of the test specimen during the extension stage of the triaxial test. This was believed to be due to the small size of the specimen and its inability to withstand large changes in effective stress.

TRIAXIAL TESTS

Method

Single multiple-stage, 100 × 200 mm, isotropically-consolidated, undrained triaxial tests (multi-CIU) were used throughout, with the exception of four Kenyan trial pit samples for which traditional triplicate 50 × 100 mm specimens were prepared (CIU). The apparatus used for the test program was a 100 mm Bishop & Wesley type hydraulic triaxial cell (confining stresses to 1700 kPa, deviator stresses to 5200 kPa), forming part of an integrated computer-controlled stress-path testing system (for soils).

As a first stage, saturation in steps of 50 minutes by elevated back-pressure was used (Black and Lee, 1973). Saturation was monitored by checking Skempton’s pore parameter B, a saturation of between 96 and 99.9% being assumed when B = 95% (Baldi et al., 1988). Stages of isotropic consolidation (usually 24 hours) were followed by undrained compression and extension. In the case of the multi-stage tests, more consolidation stages (between three and ten) than compression stages (between three and
Mechanical properties and testing procedures

five), were usually carried out. Compression (axial loading) was stress-controlled whereas, for software-related reasons, extension (axial unloading) was strain-controlled. Permeability tests were carried out using a direct constant flow rate method (Olsen et al., 1985) at a variety of junctures in the triaxial test, but usually post saturation, at effective stresses of between 20 and 30 kPa. No filter drains were used, and drainage was to one end of the specimen only via a porous disc (drainage could have been allowed from both ends in order to speed the test). Cell and pore water volume changes were measured throughout. Triaxial parameters were calculated from standard linear Mohr-Coulomb plots.

Consolidation in the triaxial test can be problematic with these high voids ratio, heterogeneous soils, particularly where termite or root holes are present. Deformations during consolidation may be large, even at low effective stresses, and not necessarily uniform. This may result in considerable alteration of specimen shape and misalignment or tilting of the top cap and ball seating prior to the compression stage of the test (Baldi et al., 1988).

A perceived problem in the multi-stage CIU triaxial testing of sensitive soils, or those undisturbed soils where structure dominates geotechnical behaviour, is that the structure of the test specimen changes during the test (Anon, 1990). This is certainly the case with the tropical clays described here and the results reflect the changes taking place in the specimen during the test. It is less easy to infer the causes of these changes at each stage. Similar changes take place during the oedometer test.

Results

Results of triaxial tests may be displayed statistically as derived test parameters, for example cohesion, angle of internal friction, (Table 3), or graphically as saturation versus stress, Mohr-circle or stress-path plots, and isotropic consolidation. Examples are given in Figures 9, 10 and 11, respectively. Selected parameters derived from triaxial and oedometer tests have been plotted against each other or against 'index' parameters.

The progress of saturation of triaxial specimens is shown in Figure 9 as plots of Skempton's B value versus back pressure for Kenyan and Indonesian samples. It will be noted that starting B values vary widely, the Kenyan sample plots are less scattered than the Indonesian ones, and some specimens required in excess of 500 kPa to achieve a B of 0.9. Some Kenyan specimens show an initial reduction in B at low stresses.

The results of several extended time period isotropic consolidation stages at low effective confining stresses suggest that a two-phase process is taking place in some specimens whereby a 'swelling' process either is contemporaneous with, or closely follows, a normal secondary consolidation process. Similar behaviour has been observed with a partially saturated Gault clay specimen from the UK using the same apparatus and method. However, the tropical clay results show that, whilst the volume of the specimen continues to reduce as part of the normal consolidation process, the specimen also begins to take in pore water at a steady rate for many days or weeks. Examples are given in Figure 11. The latter process starts, or is detectable, at between six and ten hours after the start of consolidation, and is particularly marked in the case of Kenyan specimens. On current evidence it seems likely that this 'swelling' process is the result of incomplete saturation
of the microstructural peds at low effective confining stresses (< 100 kPa), so that whilst the macrostructure is consolidating the microstructure is swelling; the volume changes involved in the latter become more significant as normal consolidation diminishes with time.

Study of specimens in the scanning electron microscope (SEM) taken before and after the consolidation stage described above show a denser, more fissured soil fabric after consolidation, compared with before. Soil peds consisting of partially decomposed, porous, rock fabric were observed surrounded by a thin, but continuous layer of gelified clay. This was bounded by fissures. It is conceivable that such peds could be ‘prised open’ by the stresses associated with consolidation, thus freeing new void space for saturation from the adjacent macro voids. In this way water intake (or ‘swelling’) could take place while the consolidation process, involving the closing of macro voids, was still underway.

Experiments were conducted which appeared to rule out procedural factors, such as membrane leakage, in this ‘swelling’ process. Estimates of long-term membrane leakage (Lerouil et al., 1988) suggest volume changes an order of magnitude smaller than those measured, for the same time period. Swelling was not observable, that is as a separate process contemporaneous with consolidation, in any conventional oedometer tests due to the fact that strains due to swelling and consolidation cannot be distinguished from one another.

A problem experienced with the type of stepper-motor actuator used on the back pressure line during the early consolidation stages was that the actuator could not keep pace with the very rapid rate of consolidation of the average red clay soil. Thus, the initial part (typically the first minute) of the deformation versus time plot was incorrect. This problem is magnified by the use of large test specimens. A solution to this problem would be to use a larger actuator or a different form of volume measurement for the consolidation stages of the triaxial test, for example, the more traditional constant pressure, oil-water or compressed air systems combined with an in-line, passive volume measuring device. Alternatively, the measurement of volume could be separated from the control of pressure. Typically, a 100 x 200 mm specimen of allophane-rich clay expelled a total of 300 ml of pore water, i.e. approximately 20% of its original bulk volume, during the consolidation stages of a triaxial test; most of this amount being expelled within the first minute of each stage. This resulted, in extreme cases, in a considerable alteration of the specimen shape, from a right cylinder to an ‘apple-core’ shape. In contrast, field and laboratory compacted specimens gave small pore water volume changes of only 2 to 4%.

Permeability results show an exponential reduction in permeability with time, up to 8 hours, beyond which a state of equilibrium is established. Results for saturated, undisturbed specimens show high permeabilities of $5.6 \times 10^{-8}$ to $1.1 \times 10^{-5}$ m/s for Kenyan and $2.2 \times 10^{-8}$ to $5.6 \times 10^{-6}$ m/s for Indonesian samples. These values are comparable with those of silt or very fine sand. Constant flow rate permeability test stages, carried out during triaxial tests, revealed a 100 to 200 fold decrease in post-saturation (water) permeability with destructuring, but only a two to three fold decrease with laboratory compaction, compared with the undisturbed state. The test is particularly sensitive to fluctuations in environmental temperature. Permeabilities may be
significantly increased by bioturbation (Blight, 1991). Comparison between field and laboratory permeability data depend on their relative states of saturation.

Values of effective cohesion, c', are very variable ranging from 0 to 97 kPa, but are generally high. Values of effective angle of internal friction, $\phi'$, range from 11 to 41° (Figure 12). Again, these values are high when compared with temperate soils of similar plasticity or clay fraction, and are more typical of silts and fine sands. This generally agrees with the findings of Wesley (1977) who also tested soils from Java. The effective friction angle, $\phi'$, is typically about double the total friction angle, $\phi_{cu}$. However, the effective cohesion, c', is either similar to the total cohesion, $c_{cu}$ or slightly lower. Interestingly, the Indonesian total cohesion results appear to consist of two populations, one from 10 to 20 kPa and the other from 30 to 50 kPa. Wesley (1977) noted that allophane-rich soils gave higher strengths than halloysite-rich soils. This is not borne out by the data presented here. Values of effective friction angle within the Chemususu group of samples are very similar. Axial strain at the yield point ranged from 1.5 to 3.0%, with the exceptions of the allophane-rich Indonesian samples (Pits 7, 9, and 11) and K89/3F Kenyan samples, which had strains of around 5 to 6%.

The two sets of undisturbed / destructured / compacted samples (Indonesia Pit 11, 4 m and Kenya K89/3F/1B, 0.8 m) revealed surprisingly similar stress-path and strength behaviour despite large structural differences. They showed that the estimated effective shear strengths of undisturbed and compacted specimens for the Indonesian set (an allophane-rich soil) are similar, with the destructured lower. In the Kenyan case (a halloysite-rich soil) the compacted shear strength is much higher than the destructured, which is itself higher than the undisturbed. However, if effective friction angles alone are compared, the Indonesian destructured specimen has the highest of the set while the Kenyan compacted specimen has the highest; the undisturbed specimen having the lowest in both cases. These trends are matched by the dry densities. If these results reflect the overall situation it suggests that reworked material, for example fill, should be capable of greater slope stability than undisturbed material. However, this does not take into account the large permeability and self-weight differences between the states which mitigate against stability. A typical engineered fill is probably in a state part way between the laboratory compacted and destructured states. In addition, some earthwork fills placed using a sheepfoot roller have revealed a partially sheared or remoulded fabric.

A familiar problem in conducting multi-stage triaxial tests is in determining the correct axial stress at which each stage of compression should be terminated (Head, 1986). This is particularly difficult for the first stage where no pattern of behaviour has been established. With structural changes taking place during the consolidation and compression stages of the test a pattern may not be established. On-line test plots of stress-ratio and pore pressure are useful here. The choice of whether to use multi-stage or multi-specimen tests is influenced by structural alteration, lithological and structural variability, and specimen size.

Transitions from below to above bonding yield, with each stage of increasing effective confining stress, can be seen in the shape of some triaxial compression stress-paths, for example Kenya Chemususu Pit 3, 5.7 m and Indonesia Pit 11, 4.0 m (Figure 10). These are analogous to 'over-consolidated' and 'normally-consolidated' behaviour in
sedimentary soils, that is, a transition from ‘dry’ to ‘wet’ of critical with increasing effective stress. The transition occurs at stresses of between 50 and 150 kPa. This may also represent the gradual transition from an open, bonded structural state to one more typical of a temperate clay soil. The effect of bonding as described by Vargas (1973), can also be seen in a plot of triaxial maximum shear stress versus effective average stress (Figure 13). Here a ‘bonding’ or ‘apparent overconsolidation’ effect is seen as a flattening of the plot line below a yield stress or bond strength. This is most clearly seen in the Kenyan undisturbed (halloysite-rich) specimen below $t' = 150$ kPa. It is not seen in the Indonesian undisturbed (allophane-rich) specimen which has a straight plot line.

Failure modes during the compression stages were typically a combination of barrelling and shearing, developing contemporaneously. Shearing often consisted of either one pair of conjugate shears or one major and one minor pair. In some cases shearing was not clearly defined but rather a kind of ‘stratified’ densification and spreading occurred. In other cases complex shear zones and some tensile ‘columnar’ failure elements were seen. It was frequently observed that shearing was accompanied by tilting of the upper part of the specimen. This is not uncommon for tests using a ball-jointed top cap. Few specimens developed a classic single shear plane by the end of final compression (Indonesia Pit 1, 2.0 m and Pit 4, 2.0 m are ones that did). More often, multiple shallow-angled shears, or an absence of discrete shears, were noted. The allophane-rich specimens, in particular Indonesia Pit 11, 4.0 m, showed drastic volume reduction resulting in an apple-core shape, followed by barrelling and multiple shears. The two laboratory compacted specimens did not exhibit shears or significant barrelling, but appeared to compact further during the compression stage of the test.

Oedometer Tests

Method

Multiple oedometer consolidation tests were carried out on push-driven tube samples. The samples from trial pits matched those taken for triaxial tests in most cases. Conventional front-loading, dead-weight, lever-arm type apparatus were used, capable of applying axial compressive stresses of up to 2000 kPa to the specimens mounted in open, fixed-ring cells, with drainage at both ends, and with computer-controlled logging of deformation. Two high capacity tests were carried out in a converted lever-arm type tensile testing machine capable of applying up to 32 MPa axial compressive stress on a 75 mm diameter specimen.

The use of multiple tests on specimens taken from the same ‘undisturbed’ sample enabled an examination of collapse behaviour, and the effects of pre-drying the specimen. Each set of tests included at least one where flooding of the test cell took place at the start of the test (that is, the British Standard method). For ‘collapse’ tests the specimen was flooded at stresses of between 100 and 200 kPa as a separate test stage inserted into the normal 24 hour loading cycle. Oedometer tests were also carried out at the MT&RD, Nairobi, Kenya. These used shorter time increments than 24 hours, and mostly dealt with shallow samples (~1.0 m depth) not matching those used at the BGS.
Results

An example of the progress of settlement with time in the consolidation test is shown in Figure 14. This shows a plot of settlement versus (log) time for all the loading stages for Kenya Pit 1, 2.0 m (C). It will be noted that at low stresses primary consolidation is almost instantaneous. At moderate stresses it is very quick, and at high stresses it resembles that of a conventional temperate soil plot, that is, the plot has a recognisable parabolic primary phase followed by a secondary phase, the two separated by a point of inflection. The transition appears to have taken place between 800 and 1000 kPa.

The voids ratio versus (log) normal stress plots ('e - log P') are shown in Figure 15. Many samples showed the tendency to exhibit true collapse to a greater or lesser extent, in particular the shallow samples (1.0 m depth) tested at MT&RD and a shallow road embankment sample (field compacted). Perhaps surprisingly, the samples with highest voids ratio did not show collapse. Many other samples showed a marked deviation from the smooth voids ratio versus log stress curve, at an axial stress (typically between 100 and 200 kPa), apparently unrelated to the stress at which flooding took place.

Initial undisturbed voids ratios were highly variable, from 1.14 to 5.36 for Indonesia and from 0.92 to 3.47 for Kenya, allophane-rich soils tending to have the highest values in both cases. These high voids ratios (and low densities) are accompanied by high natural moisture contents (greater than 150% in one case). Variation in initial undisturbed voids ratio between specimens taken from the same tube sample, but for different purposes, was between 1 and 18%, but typically around 5%. For both Kenyan and Indonesian samples it is the allophane-rich soils which showed the most variability, probably the result of lithological variability and sample disturbance. In three Indonesian trial pits (9, 10, and 11) the voids ratio was found to increase with depth, rather than decrease. The reverse was the case for those Kenyan samples taken from the same borehole.

The coefficient of consolidation, \( c_v \), was impossible to calculate in most cases, at low effective stresses, because of the very rapid primary consolidation. In fact, up to half of the total consolidation settlement took place typically within the first few seconds of the test. An alternative indicator of consolidation rate has been used, that is percentage consolidation within the first minute. Allophane-rich samples tend to have a marked reduction in consolidation rate (\( c_v \)) with increasing stress, whereas halloysite-rich samples tend to maintain a high rate, at least up to 1000 kPa. However, in general at high effective stresses the settlement versus time plots begin to resemble those of a temperate clay, that is, having a measurable parabolic primary portion to the curve and a smooth transition to the secondary stage. Where a sequence of samples with varying depth was available, it was seen that primary consolidation rate tended to decrease with depth for a given applied stress.

Compressibility, \( m_V \), is found to range from 'high' to 'very low'. There tends to be an overall decrease in compressibility with increasing applied stress. It is notable that above applied stresses of about 500 kPa the \( m_V \) versus log stress curves tend to coalesce in the case of specimens taken from the same sample, irrespective of voids ratio, whereas they do not, with one exception, for specimens taken from different depths at the same location. The Compression Index, \( C_C \), is generally 'moderate' to 'high' (between 0.20 and 2.08), and highest for Indonesian samples and allophane-rich samples. Swelling
index, CE, which measures the extent of recovery on unloading, ranges from 0.02 to 0.14, and may be considered 'low' to 'very low' compared with temperate clay soils. This is probably due to non-recoverable strain associated with major densification of the macro-pores in a ped-type soil structure. It is notable that the high-pressure oedometer tests, (Indonesian Pits 1, 2.0 m and 5, 2.0 m) which take the soil to much lower voids ratios than normal tests, give higher CE values than the matching low pressure tests, indicating a degree of elastic recovery.

Vaughan (1988) defined ‘relative voids ratio’, $e_R$, as follows:

$$e_R = \frac{e - e_{opt}}{e_L - e_{opt}}$$

where: $e$ = natural voids ratio
$e_{opt}$ = voids ratio at optimum compaction
$e_L$ = voids ratio at liquid limit

A reasonable positive correlation has been obtained between Compression Index, CC, and relative voids ratio, $e_R$; the more plastic soils have both higher compressibility and higher relative voids ratio (Figure 16). The problem of finding the ‘correct’ liquid limit with which to derive $e_R$ is discussed in project report WN/93/12.

The consolidation process may be usefully divided into ‘primary’ and ‘secondary’ stages, the primary representing the expulsion of water from macro-pores and rapid, large-scale densification due to compression of those voids, and the secondary representing visco-elastic creep of the solid phase. The coefficient of secondary consolidation, $C_s$, ranges (at a confining pressure of 200 kPa) from 0.004 to 0.052 for Indonesian, and 0.003 to 0.134 for Kenyan samples. Values of $C_s$ tend to rise and become more diverse between about 100 and 200 kPa. Allophane-rich samples’ $C_s$ values rise particularly sharply (Indonesia Pit 7, 2.0 m and Pit 9, 2.0 m). This rise appears to be related to the yield point seen on the voids ratio versus log stress plots. There does not appear to be a clear correlation between $C_s$ and depth, or between $C_s$ and pre-drying.

A small number of ‘pre-drying’ experiments were carried out as part of the multiple oedometer tests. Here, one of the five test specimens from an individual sample was pre-dried in air prior to testing, resulting in reductions in saturation of between 11 and 53%. Some of these specimens collapsed and others swelled, with no clear pattern emerging.

The geotechnical implications of bonding in soils are described by Vaughan (1988) and Lerouil and Vaughan (1990). The relationship of an undisturbed, bonded oedometer soil specimen to its ‘destructured’ state line is shown applied to a test plot example (Indonesia Pit 10, 5 m) in Figure 17. Such behaviour is seen in over consolidated clays, cemented soils, weak rocks, and dense sands, and was noted in the oedometer test results, particularly in the following cases: pre-dried Kenyan specimens, high-pressure test (Indonesia Pit 5, 2.0 m) in which a clear decrease in compressibility is seen at about 800 kPa, and normal tests (Indonesian Pits 10, 5.0 m and 11, 4.0 m). In some cases the bonded part of the $e$ - log $P$ curve may be obscured by collapse. Two yield points have been observed in some triaxial (first stage) test stress-strain curves.
Scanning electron microscopy (SEM) has revealed something of the nature of bonds, and their ability to sustain a sizeable void network up to effective stresses in the range 50 to 200 kPa. Both the fundamental mineralogy and the structure of these soils are complex. The minerals halloysite and allophane exist together, and the former in more than one form (see report WG/92/31). These may be tubular, platy, spheroidal, or block. Peds may consist of agglomerations of clay particles or of partially decomposed parent rock particles with a coating of gel-like clay. Peds may be connected by ‘bridges’ of clay. Abundant pores in the narrow size range of 0.005 to 0.015 μm have been found in helicities with small particles (< c. 0.08 μm in width) but not in helicities with larger particles (0.1 μm in width). Individually, tubular particles have the combined properties of high voids, high surface area, and high strength. In abundance these may impart the same properties to the soil mass. The accessibility of tubular particles to water is also of interest. Is such water ‘bound water’ or ‘free water’?

Results of destructuring experiments suggest that the destructuring process is not simply one of densification and loss of bonding. It is possible that fresh bonds, perhaps of a different nature, may be established within a destructured clay soil. The precise nature of the undisturbed bonding, and the effect on it of applied stress, may have an important influence on mass permeability and saturation. The effect of compaction also has profound influence on the soil structure, possibly in a detrimental way in some applications. For example, ‘reconstituted’ oedometer test specimens (from Kenya Pit 5, Indonesia Pits 10 & 12) have higher initial voids ratios than the equivalent undisturbed specimens. A normalising parameter, the voids index, Iv, was suggested by Burland (1990) to relate the different fundamental states of a soil to its structure. This is a similar concept to that of Vaughan (1988) but applies to consolidation rather than compaction and liquid limit. The voids index is defined as follows:

\[ Iv = \frac{(e - e_{100})}{Cc} \]

where:
- \( Cc \) is the compression index (= \( e_{100} - e_{1000} \))
- \( e \) is the initial voids ratio,
- \( e_n \) is the voids ratio at a consolidation stress of \( n \) kPa

The voids index ranges from 0.03 to 0.60 and tends to decrease with depth. The investigation into the phenomenon of collapse has been notable for the significantly larger collapses (as measured by the collapse index, CI, in the oedometer consolidation test) obtained by MT&RD compared with BGS. This is probably due to MT&RD testing shallower samples (~1.0 m depth) having lower initial degrees of saturation. BGS sample K89/3F/1 (0.6 m), for example, collapsed in a similar manner to the MT&RD samples. Kenya Pit 4, 2.0 m and some pre-dried specimens showed negative CI values; that is, they swelled. It is likely that the net biological disturbance (e.g. shrub rootlets, fungi, termites) is more significant at shallow depths. Collapse measured in the oedometer test appeared generally to be independent of flooding but more dependent on stress. A small number of field collapse tests were carried out in Indonesian pits 10, 11, & 12. Significant collapse was noted (on flooding at 100 kPa) at a depth of 3 m in Pit 11.

The coefficient of secondary consolidation, \( C_{sa} \), characterises the long term consolidation behaviour of a soil. A notable rise in the value of \( C_{sa} \) is typically found beyond stresses of between 100 to 200 kPa, particularly for allophane-rich soils (for example, Kenya Pit 3,
Indonesia Pits 7 & 9). These stresses match those measured for yield point, which again lie typically between 100 and 200 kPa.

Throughout the project every attempt has been made to minimise sample disturbance, recognised as a particular problem with weakly bonded soils (Vaughan, 1988) and soils with high voids ratios. However, whilst it is impossible to eliminate this problem, neither has it been possible to quantify sample disturbance in the manner used for temperate soils (Schmertmann, 1953). The absence of bonding inferred from an oedometer test may indicate either that the bonding has been destroyed by sample disturbance or that there was no bonding. Every indication is that bonding does exist in these soils, and that sample disturbance is minimal. De-stressing due to exhumation cannot readily be mitigated. However, both the trial pitting and drilling procedures have been carefully considered, executed, and monitored (see Section 3).

**COMPACTION TESTS**

Compaction tests were carried out on Kenyan and Indonesian samples using both the Proctor and the Dietert apparatus (Institute of Road Engineering, 1987; Wachira, 1988). Compared with typical temperate clay soils, values of Maximum Dry Density (MDD) were low, and values of Optimum Moisture Content (OMC) high. On a plot of moisture content versus dry density (Figure 18) the Kenyan Pits 5 and 7 data are closely grouped with OMC’s of 44 to 48% and MDD’s around 1.2 Mg/m³, whereas samples ES4, 2.0 m, Pit 3, 1.0 m, and Pit 3, 2.0 m were widely scattered, albeit on a common curve. The sample with the highest MDD/lowest OMC was ES4, 2.0 m (Tertiary volcanic origin). Indonesian data were similar to the Kenyan but without the very high and very low values. All Indonesian compaction data were from samples of ‘Older Quaternary Volcanic’ origin. Unfortunately, there were no representatives of ‘Younger Quaternary Volcanics’ soils. For Indonesian samples values of OMC were found to be between 0 and 10% lower than natural moisture content (NMC) measured in the field, whereas for Kenyan samples they were between 5% higher and 5% lower. Voids ratio values after compaction were used to calculate ‘relative voids ratio’ (Vaughan, 1988).

Problems are frequently experienced in reaching target MDD’s on road construction projects in Kenya. Considerable shrinkage problems are also experienced if soils are compacted near their natural moisture content. Longitudinal cracks were frequently observed parallel with embankment flanks. These were generally absent on adjacent sections of road in the same soil type in cut. In some cases (for example, the Eldama Ravine–Nyaru road) drying to below optimum had to be carried out to preclude shrinkage. A variation of the linear shrinkage test, using a compacted specimen, could usefully be run in parallel with the compaction test. Typically, OMC’s are between 80 and 105% of the NMC’s. In Indonesia, experience of compaction with red clay soil fills has generally been good, compared with the other soils available. The red soils tend to be compacted slightly wet of OMC despite relatively low MDD’s, and some longitudinal cracking of embankments has been observed, as in Kenya. It would appear that whilst reworking of soils in excavation will lead to a reduction in shear strength (Belloni et al., 1988), this is not as severe as the reduction produced by embankment construction where reductions in undrained strength of up to ten times are reported (Anon, 1992).
Successful compaction using light compactive effort is reported by Knight et al. (1982) and Rouse et al. (1986).

Cutting slopes and embankment slopes are often constructed in tropical clay soils at angles of 30 to 40°, that is, much steeper than an equivalent temperate clay slope. This means that commonly used stability charts do not apply (Wesley, 1977). In the case of the cutting slopes the strength is achieved by virtue of the natural bonded structure which imparts a significant effective cohesion (Vaughan, 1988). This strength may be unaffected by transient saturation, at least within the normal climatic regime, bearing in mind that the undisturbed soil is highly permeable and will allow effective drainage of the most severe tropical storm flows. Wesley (1977) suggested that allophane-rich soils are fundamentally stronger than halloysite-rich soils, despite their higher moisture content and plasticity. He attributed this to their fundamentally less-developed weathering state. The embankment (fill) case is different in that the soil is no longer undisturbed, and has a new, denser structure possibly containing discontinuities induced by construction plant. This new structure may be as strong as the undisturbed structure (this is suggested by the special triaxial test data) but less as the result of bonding. This will be a function of the extent to which excavation and placement have destroyed the original structure. The compactive effort and method are key factors. The destruction may be only on a macro scale. However, the new structure will certainly be denser and less permeable. It will probably also be more prone to swelling and shrinkage, and dilatant behaviour when subject to shear.

RING SHEAR TESTS

A small number of Bromhead ring-shear tests were carried out on Kenyan soils in order to measure the residual strength of a remoulded sample (Njaibu, 1988). This is a useful parameter where large-scale strains along a particular slip plane or zone of movement, take place, either within an initially undisturbed soil profile or within an embankment or other reworked soil fill material. The tests were carried out on soil pastes prepared from disturbed samples, both at natural moisture content, and pre-(air)dried. Values of effective residual friction angle, \( \phi_R' \), and effective residual cohesion, \( c_R' \), ranged from 20.1 to 31.2° and 0 to 11.0 kPa, respectively. The effect of pre-drying was to increase slightly \( \phi_R' \) and decrease \( c_R' \), with the sole exception of Pit 7, 2.0 m. Compared with temperate soils of similar plasticity these values are particularly high. The \( \phi_R' \) versus PI relationship does appear to correspond with data given by Boyce (1985). Lupini et al. (1981) described the influence on residual strength of clay mineral morphology. Smectites and kaolinite are dominantly plate minerals and provide low resistance to shear at high values of strain. On the other hand, halloysite and allophane are not characteristically plate and provide a greater resistance to shear at large strains (Anon, 1990). This is suggested by the results of the tests (Figure 19) when compared with envelopes for typical temperate clays.
DISCUSSION

The voids and structure of the tropical red clay soils are key to their undisturbed mechanical behaviour. This structure, in contrast to that of sedimentary soils, is dependent on the parent rock and the weathering processes to which it has been subjected. Voids ratios are generally high and may decrease or increase with depth. Voids in these residual soils are produced as a result of mineral dissolution, alteration, and biological disturbance. The effects of high voids ratios are seen as high consolidation rates and amounts, high permeabilities, and some of the properties of a silt. This permits free drainage and high effective strength above the water table. The coefficient of consolidation is difficult to determine at low and moderate stresses. The effects of geological provenance are also seen in some aspects of mechanical stresses.

Scanning and transmitting electron microscope investigations (SEM & TEM) have shown both tubular and plate halloysite structures, bonding of peds largely by clay bridges, and a ‘flowing’ geliferous clay structure (allophane?). Little influence due to iron compounds has been found. Mineralogical quantification of halloysite and allophane content has proved elusive. Collapse has been observed in some oedometer test specimens, particularly in shallow specimens. Collapse appears to be depth (and possibly method) related, and may in turn, be related to bio-disturbance. Pre-drying oedometer experiments have proved inconclusive; most specimens having swelled on flooding. Primary consolidation in the triaxial and oedometer tests is extremely rapid. The effects of bonding have been observed in some triaxial and oedometer tests. Unusual consolidation behaviour, for apparently saturated specimens, has been noted at low effective confining stresses in the triaxial test. This appears to involve rapid primary consolidation, followed by slow swelling accompanied by continuing secondary consolidation. This appears to be due to incomplete saturation, and reflects the bi-modal macro- and micro- structure, respectively.

The effect of destructuring and compaction have been investigated and compared with the undisturbed state for two triaxial specimens. The results are surprising inasmuch as the destructuring process, whilst reducing voids ratio dramatically has not changed the strength significantly. Further laboratory testing of this kind is required. There does not appear to be a clear distinction between allophane-rich and halloysite-rich soils in terms of strength. Residual strength was high compared with temperate soils of similar plasticity.
SUMMARY OF RESULTS

- Tropical red clay soils have a high voids ratio / low dry density / high mass permeability; the highest voids ratios are for allophane-rich soils.

- Tropical red clay soils exhibit a two-phase structure giving clay-like behaviour on the micro-scale and silt-like behaviour at the macro-scale.

- Destructuring and resedimentation results in a large decrease in voids ratio but no significant strength increase. The effect of bond breakage counters the densification effect.

Strength

- Tropical red clay soils are bonded and have yield points typically at stresses between 100 and 200 kPa.

- Stress paths may be interpreted in terms of yield.

- Large volume changes should be anticipated in consolidated, undrained tests.

- The two-phase structure of tropical red clay soils results in incomplete saturation of micro-pores using conventional Skempton B saturation criteria.

- Apparent contemporaneous swelling and consolidation is observed during the low effective stress consolidation stages of the triaxial test.

- Effective strength behaviour is relatively 'brittle' with peak strength achieved at around 2% strain.

- Residual shear strength is higher than for temperate clays of similar plasticity. This may be due to the mainly non-platy clay mineral morphologies of halloysite.

Consolidation

- Consolidation rate is extremely high at low stresses. Most primary oedometer consolidation is completed within 30 seconds. Primary and secondary consolidation are more easily distinguished at high stresses.

- Many tropical red clay soils do not exhibit true collapse, but do exhibit large volume changes, particularly post-yield with allophane-rich soil. Yield appears to be independent of collapse.

- A reasonable positive correlation is found between relative voids ratio and compression index in the oedometer test. More data are required to more fully determine the relationship.

Compaction

- Compaction data show very low maximum dry densities and high optimum moisture contents, particularly for allophane-rich soils.
RECOMMENDATIONS FOR GOOD TESTING PRACTICE

- High quality push-driven sampling, combined with suitable preparation techniques, should be used for triaxial and oedometer test specimens. The use of extrusion should be avoided. The need for trimming should be minimised.

Strength testing
- Large specimens should be used for all triaxial tests.
- Multi-stage triaxial tests can be used successfully.

Consolidation testing
- Multiple oedometer tests may be useful to evaluate the effects of pre-drying and collapse.
- A high-speed data logger is required at low stresses.

Compaction testing
- Separate sub-samples must be used for each stage of the compaction test. This means that large samples (c. 25 kg) must be collected. Excessive pre-drying should be avoided.

To reduce the need for large samples, non-standard methods (for example, the Dietert test) may be useful.
6 Identification and classification of tropical red clay soils

The main objective of a good classification scheme is to enable identification, description and grouping of soils with similar characteristics to be easily undertaken in a systematic manner, and without recourse to complicated and costly test procedures. Traditional geotechnical classification schemes have been developed for temperate soils, which are often little altered sedimentary or transported deposits. For tropical residual soils, the nature and properties of the soils are directly related to the weathering of rock masses in situ and are intimately associated with the mineralogy of the parent materials, the nature of the tropical climate and on drainage conditions. Unlike most temperate soils, the products of tropical weathering can, under certain conditions, contain minerals with unusual properties and possess a highly porous structure comprising clusters or 'peds' of clay minerals disseminated throughout with finely divided iron oxides. The clusters tend to be weakly 'bonded' and have a significant role in controlling engineering behaviour and in the preparation of samples for geotechnical index testing.

The influence of soil pedogenesis on the engineering properties of tropical soils is critical. As such, it is logical that it should form the basis of any systematic engineering classification scheme for these soils. As stated by the Geological Society Working Party Report on Tropical Residual Soils (Anon., 1990), the importance of recognising the interaction of the soil-forming factors for engineering classification is that the groups of secondary minerals which form the basis of the pedogenetic classifications are all characteristic of distinct geotechnical behaviour. Anon. (1990) proposed a systematic engineering soil classification scheme based on the pedogenetic system of Duchaufour (1982). The classification includes both 'black' and 'red' tropical soils and also concretionary weathering products or duricrusts (for example, ferricrete, alucrete, gypcrete, silcrete). The 'black' soils are those formed from a variety of parent materials under conditions of impeded drainage and termed 'vertisols' in the major pedological soil classifications and known locally by such names as 'black cotton soils'. 'Black' soils and 'cretes' were not investigated in this study and are not referred to further. However, it should be recognised that such soils can be intimately associated with tropical red soils under appropriate local topographic and drainage conditions. Based on Duchaufour's scheme, the classification of Anon. (1990) consider tropical red clays to comprise those contained within ferruginous, ferrisol and ferrallitic profiles. In the present study, andosols were considered as forming a distinct type of so called 'red' tropical soil. This was because soils designated as andosols in Kenya (Kenya Soil Survey, 1982), were distinctly reddish in colour over large areas of that country, grading transitionally into the more characteristic brown andosol soils at higher elevations.

The classification of Anon. (1990) requires recognition of geological, climatic, topographic and soil forming factors, and the role and limitations of geotechnical index tests for the geotechnical evaluation of tropical residual soils. The comments given below are directed to the use of geological and pedological maps as sources of 'environmental' information and the role of geotechnical index properties for the engineering classification of tropical red clay soils. The comments are made with the aim of
amplifying the classification scheme of Anon. (1990) with respect to tropical red clays developed from the weathering of igneous rocks under well-drained conditions.

**GEOLOGICAL MAPS**

Residual red clay soils in the tropics and sub-tropics can occur over all types of bedrock. However, the unique properties of the soil at any particular location will have developed in response not only to the underlying geological parent material, but also to the combined effects of other environmental factors such as climate (especially rainfall and temperature regimes), water movement (drainage conditions), topography, vegetation and age of the land surface (how long the soil has been forming). When interpreted with respect to these other factors, geological maps can provide information very useful to the preliminary engineering assessment of the residual soils developed over the mapped parent materials.

For example, geological information can give an initial indication of the general type and form of the weathered soil profile which may develop over different types of bedrock under tropical weathering conditions. Townsend (1985) and Wesley (1988) both commented on the different weathering profiles which can form over acid igneous and metamorphic rocks (granite, gneiss and phyllites) and over basic igneous rocks (basalts, pyroclastics). In the former case, the rocks are composed dominantly of quartz and feldspars. The quartz is very resistant to weathering and has an important role in influencing the texture of the secondary products by remaining as quartz particles. The zone of alteration in these quartz-rich rocks is usually quite thick, forming a sequence of successively altered weathering zones ranging from completely weathered residual soil through to successively less altered rock with depth in the profile (Figure 20, a & b). In basic igneous rocks, the rock minerals (olivines, pyroxenes and calcic plagioclases) weather rapidly into soils which often provide an abrupt contact with the parent rock, with only a very thin zone of transition material (Figure 20c). In layered or interbedded sequences of both igneous and sedimentary rocks (such as multiple basic lava, tuff, pyroclastic flows or quartz-rich sandstones interbedded with clays) the soil profiles are likely to be more complicated, reflecting both the weathering sequence and the differences in the parent rock (Figure 20d). The presence of faults, also identified from geological maps, indicate areas where tectonic movements have displaced adjacent blocks of strata. These are zones of weakened, disturbed or broken rock which enable deep penetration of downward percolating waters and enhance weathering and alteration of the rock mass. Therefore, fault zones are likely to be characterised by thicker weathering profiles than adjacent strata.

With regard to the type of residual red soil formed over various types of parent rock under well-drained conditions, the sesquioxides of iron and aluminium can occur due to the weathering of practically all igneous rocks and kaolinite clays are the eventual end product, with clay minerals of the smectite group being a precursor in the weathering of basic rocks. Pyroclastic and other extrusive volcanic rocks can also produce allophanes, helicities and metahalloysites in addition to kaolinite, particularly under cooler climatic conditions encountered at higher altitudes. The type and proportions of these various minerals at any location (which impart to the soil its particular engineering characteristics) will depend on a number of environmental factors. For this reason the
information from geological maps should be supplemented by an assessment of the environmental influences on the weathering process, such as site elevation, slope angles, morphological history and drainage conditions (for a given site with similar bedrock and climatic conditions, impeded drainage will tend to result in the formation of smectitic clays, such as 'black cotton soils', whereas free draining conditions result in 'red clay soils').

PEDOLOGICAL MAPS

Pedological, or soil, maps are a very useful means by which tropical soils of different types can be differentiated. However, because different classification schemes are used in different countries, care is needed in comparing like soils identified under different schemes. In addition, the quality and detail shown on pedological maps varies greatly. However, once understood, they can provide the geotechnical engineer with a sound basis by which different types of residual soils can be distinguished in broad terms and provide an initial indication of soil types likely to show similar engineering properties.

Three of the most widely used pedological classifications systems are the French (Duchaufour, 1982), the American Soil Taxonomy (Soil Survey Staff, 1975) and the FAO-UNESCO (1969, 1988) schemes. The FAO-UNESCO system is used as the basis for the Soil Map of the World, and, as such, is the most universal of the major classifications. However, it is a system developed to overcome gaps in national classification systems in order to accommodate world soils, and although internationally accepted, it is to some extent a compromise. Many of the diagnostic concepts of the FAO-UNESCO system have been derived from the U S 'Soil Taxonomy' system, but each rely on subtle changes in the soil profile to distinguish soil groups and, to the lay person, employ complex terminology. The French system of Duchaufour, based on phases of the weathering process and the resulting mineral composition of the soil, is perhaps most readily understood by the engineering geologist or geotechnical engineer. It is for this reason that the Geological Society Working Party (Anon., 1990) in preparing a guide to the classification and behaviour of tropical residual soils, based its approach on the Duchaufour scheme. The use of this scheme also helps to clarify the complex terminology applied to tropical residual soils, which has arisen by the unsystematic use of soil science names applied to particular soil groups by engineers and other non-soil scientists. In particular, there is considerable confusion in the engineering literature over the use of terms for 'red tropical soils'. Only a small proportion of sesquioxides will impart a red colouration, but the findings of this study have shown that variable amounts of these iron and aluminium oxides and different associations of clay minerals, will result in a wide variation of geotechnical properties. Therefore it is important to distinguish between different types of red soils. In the Duchaufour scheme 'red tropical soils' are identified as those contained within the ferruginous, ferrisol and ferrallitic profiles. However, 'andosol' soils, although generally brown, can also have a red colouration and are often closely associated with other red clays in field situations (for example, in Kenya). For this reason, andosols, were considered as part of the spectrum of 'tropical red clays' investigated in the present study. In the Duchaufour system, these comprise those soils termed 'fersiallitic andosols'. The 'red soil' terminology adopted by Anon (1990) is recommended but, as in this study, may be sensibly expanded in countries such
as Kenya, on the basis of soil colour, to include *fersiallitic andosols*. Summary characteristics of the fersiallitic andosol soils, ferruginous, ferrisol and ferrallitic red soil types, which represent increasingly intensive phases of the tropical weathering cycle, are as follows:

**Fersiallitic soils.** Fersiallitic soils (*sensu stricto*) are formed mainly in sub-tropical or Mediterranean-type climates with mean temperatures of 13 to 20° C, rainfall 500 to 1000 mm, and a hot dry season; tropical sub-types are also known. 2:1 clays are dominant and the main new clay mineral formed is smectite, especially where drainage is impeded, but kaolinite may form on older well-drained land surfaces and silica-poor parent materials, such as basalt. On recent volcanic rocks, particularly ashes, tuffs and pyroclastic material *fersiallitic andosols* are formed under perennially wet and cooler climatic conditions found at higher altitudes. These immature soils are generally brown (but may be reddish brown or brownish red) in colour, highly porous and of low bulk density, and contain amorphous, or imperfectly crystallized, clay minerals (allophanes) produced by the rapid weathering of volcanic glass. As silica is lost during the development of andosols, allophanes are replaced by disordered fibrous clay minerals (imogolites) and eventually by the 1:1 clay mineral, halloysite and possibly kaolinite (Mohr et al., 1972). Andosols may have a high content of organic matter due to the formation of allophane-humus complexes. They have enormous water-holding capacity which can be reduced by prolonged desiccation, often irreversibly. They have high cation exchange capacity, are very clay and iron rich and indurate on drying. Quantin (1985) described andosols from Vanuatu which have developed in less than 5000 years, whilst Yamada (1977) reported that these soils can be developed in between 500 and 1500 years, depending on site conditions.

**Ferruginous soils.** These soils are formed in climatic zones which are either more humid (humid sub-tropical, without a dry season) or slightly hotter (tropical with dry season) than the Mediterranean-type areas. They are more strongly weathered than fersiallitic soils, but orthoclase and muscovite typically remain incompletely altered. Kaolinite is the dominant 1:1 clay mineral formed and gibbsite is usually absent; 2:1 clay minerals (for example, smectites) are subordinate and tend to occur in clay-rich horizons due to preferential lessivage. On older land surfaces and more permeable base-rich parent rocks, soils transitional between ferruginous and ferrallitic soils, known as *ferrisols*, may be formed. These are more deeply weathered and tend to have thicker profiles (often greater than 3 m) than typical ferruginous soils but the weathering of primary minerals is not complete. In very humid zones with ferrallitisation dominant, they tend to occur at higher altitudes (mountain slopes) where lower temperatures slow down ferrallitisation, or where erosion on steep slopes rejuvenates the soil profiles and prevents their complete (ferrallitic) development.

**Ferrallitic soils.** These soils are formed in the hot humid tropics where annual rainfalls exceed 1500 mm and mean temperatures are above 25° C, with little or no dry season. They represent the final phase of soil development in a hot, humid climate and the soil profiles may be several metres thick. All primary minerals except quartz are altered by hydrolysis in near-neutral or slightly acid conditions, and much of the silica and bases are removed in solution. Remaining silica combines with alumina to form kaolinite, but with insufficient silica, excess alumina results in the formation of gibbsite. Most ferrallitic soils
probably take 10,000 or more years to form, with development being more rapid on silica-poor rocks such as basalt than on silica-rich rocks like granite or gneiss. Increased silica content of the parent rock is usually reflected by kaolinite formation in the subsoil. This zone of kaolinite formation is often poorly drained and mottled with white, red and ochreous patches (plinthite) and can harden irreversibly on exposure; it may be overlain by a 'lateritic' horizon enriched with iron mobilised from acidic near-surface (and upslope) horizons or by fluctuations in the water table. The formation of kaolinite is encouraged by the poor drainage, whereas free drainage removes dissolved silica and favours the development of gibbsite. The iron-enriched horizon may be moderately or strongly indurated (hardened), pisolithic from the welding of concretions or vesicular from precipitation of iron in a polyhedral network of fissures and subsequent removal of softer interstitial material. On silica-poor basic rocks on well-drained slopes, these soils are generally less deep with little or 'slowed down' neoformation of kaolinite. However, this clay is stable and tends not to be degraded, as it is bound within aggregates 'cemented or 'bonded' by iron oxides. This results in the formation of a friable, aggregate soil structure of high porosity, which does not harden irreversibly on exposure. Concretions are usually absent but when present are usually soft.

From the foregoing, it is clear that soil maps, when available, can provide a guide to the occurrence and distribution of tropical soils of use to the engineer, provided the general process of weathering leading to soil composition and fabric in the tropics is appreciated, and the basis of the soil classifications employed on the various maps is readily understood. However, the limitations of such maps must also be recognised. For example, Buurman (1980) stated that, especially on volcanic rocks, there is considerable doubt about soil classification because of textural differences arising from stratification of the parent material. The divisions between different soil types as shown on pedological maps are rarely, if ever, sharply defined in field situations. Local variations of weathering grade and soil type, both areally and with depth, are not possible to present at regional mapping scales, and may make preliminary interpretations for engineering use somewhat tentative. Soil maps do, however, provide a valuable indication of the general occurrence of broad soil types. For example, in this study, the pedological soil maps available in Kenya and Indonesia enabled rapid identification of those areas where fersiallitic andosol and ferrallitic soil development dominated. In the scheme of Duchaufour (1982), these soil types represent the 'end members' of sesquioxide-rich (red) soil development in hot tropical and sub-tropical climates, the ferrallitic soils developing from long periods of intense weathering, and the andosol soils under less intensive weathering conditions which have inhibited completion of the ferrallitisation process. The marked differences in the mineralogy and structure of these soil types are reflected in their engineering index properties. Ferruginous soils represent an intermediate stage of soil development between that of fersiallitic andosols and ferrallitic soils, and as such may be expected to show a transition in mineralogy and index properties between these soil types, that is:

\[
\text{fersiallitic andosols} \rightarrow \text{ferruginous soils (ferrisols)} \rightarrow \text{ferrallitic soils}
\]

Because of the important effect of climatic control (rainfall and temperature), the general relationship between the broad development of these different soil types with decreasing elevation in Kenya and Indonesia was fairly clear. However, the boundaries between the main soil types were not clear cut in the field, and the gradual transition of one into the
other was not clearly represented on the soil maps. Local topographic, climatic, and erosional effects also give rise to different stages of soil development within each of the broad soil zones. These local and broad transitional variations in soil types make it difficult to accurately predict engineering properties at the site specific level. However, they can provide a useful initial means of assessing the broad distributions of soils likely to show distinct or similar engineering properties (for example the presence of allophanic andosol soils).

Not all pedological classification schemes follow that of Duchaufour (1982) and correlation between them and the French system can be difficult. Approximate correlations between the Duchaufour scheme and the FAO-UNESCO and American Soil Taxonomy systems are shown in Table 4. Approximate correlations between the FAO-UNESCO and French (Duchaufour) schemes for soils obtained and investigated in this study from sample sites in Kenya, Indonesia, Fiji and Dominica are given in Table 1, along with related terrain and climatic details.

ENGINEERING INDEX PROPERTIES

The usefulness of conventional index tests such as plasticity limits and particle size for the identification and engineering classification of tropical residual soils has been questioned on a number of occasions. This is primarily because of the dependence of such tests on sample preparation (which has led to inconsistent test results) and the destruction of the natural soil structure which occurs during preparation (with the implication that index tests give no indication of the properties of the undisturbed soil *in situ*). The results from this study have shown that, with simple modifications to preparation and test procedures, meaningful and repeatable index property measurements can be achieved. As also found by Wesley (1988), the study has shown that index properties are very useful for identifying and ‘grouping’ tropical soils likely to possess distinctive or similar engineering properties. For example, the position which a soil occupies on the conventional plasticity (or A-line) chart was found to be particularly useful in distinguishing different types of red clay soils (Figure 7b). However, problems can arise when attempts are made to directly relate other engineering properties to index test measurements for these soils in different structural states.

A primary purpose of an engineering classification system based on simple index tests is to rapidly identify and group soils into ‘classes’ with similar index properties. It can then be reasonably inferred that, under similar conditions, the engineering behaviour of the soils in each class will be similar. In effect, once meaningful and repeatable liquid and plastic limit data are obtained, the position of the soils on the plasticity chart identify the ‘footprint’ of those soils likely to show similar behaviour in similar undisturbed or ‘destructured’ states under similar conditions of moisture content.

The grouping of soils on the plasticity chart reflect the soil mineralogies which, in turn, are dependent on the degree of soil pedogenesis. Therefore, the plasticity chart can be used to classify the pedological soil divisions of Duchaufour in more quantitative engineering terms. This is illustrated in Figure 21, which shows the position of the fersiallitic andosol, ferrisol and ferrallitic soils investigated in this study when plotted on the plasticity chart. The soils are also distinguished in terms of their development over
different types of bedrock. Vargas (1985) showed that classification of tropical clays by means of the A-line plasticity chart can sometimes be enhanced by incorporating a plot of ‘activity’. Activity (defined as the ratio of plasticity index to percentage clay fraction, % < 2μm) can further indicate the nature of the dominant type of clay minerals present in the soil. For example, smectites are ‘high activity’ clays (activity > 1.25) whilst kaolinite-type clay minerals are ‘low activity’ clays (activity < 0.75). This combined plot (also shown in Figure 21) would appear to be quite useful for distinguishing red clays from other tropical soils (for example, smectite-rich vertisols or ‘black cotton soils’, and a variety of saprolitic soils), but is perhaps of more limited use in distinguishing between different types of red clay soils, particularly those developed over igneous rocks (virtually all of which, in this study, possessed activities < 0.75). Of the very few data points plotting in the range of ‘high activity’ clays (>1.25), all are andosol soils. However, because of the difficulty in obtaining meaningful clay contents of these soils from particle size distribution tests, the activity values for these soils are unreliable.

The significant influence of parent igneous rock on the red soil groupings is clearly shown in Figures 7b and 21. Similar relationships between soil engineering properties and parent rock type have been reported elsewhere (by Gidigasu (1976) for red soils developed over phyllites and granites in Ghana, and by Tuncer and Lohnes (1977) for red soils from Hawaii and Puerto Rico). This has led to a number of descriptive or classification methods being developed for local use in particular formations. However, as noted earlier, particular types of red soils develop not only in response to parental bedrock, but also to other environmental factors. Because of this, locally developed classifications may not be applicable to soils developed in other terrains and under different intensities of weathering.

Soils formed from similar parental rock under similar conditions of weathering can be expected to have similar index properties, and this study has shown that the plasticity chart is an effective means by which these similar groups of soils can be distinguished. Comparison of soils on the basis of index data obtained for the complex spectrum of tropical clay soils worldwide, developed over a variety of rock types under different climatic conditions, can only be achieved if consistent standardised procedures of sample preparation, such as those recommended elsewhere in this report. In practice, the plasticity chart should provide an effective means for identifying the ‘footprint’ of soils likely to show similar behaviour for local use during engineering projects. It could also be effective in distinguishing tropical red clay soils developed in a variety of terrains at a country-specific level.

INDEXING THE MECHANICAL BEHAVIOUR OF TROPICAL RED CLAY SOILS

Having established the ‘footprints’ of similar red soil groups from the plasticity chart, the question remains as to how this data can be used to assess their in situ mechanical behaviour. For the tropical red clay soils considered in this study, in situ behaviour will be controlled by both their mineralogy and structure (that is, the aggregated ped-like soil fabric) and the ‘bond’ strength between aggregated peds. The mineralogy can be indicated by plasticity data. Therefore, when grouped or classed together on the plasticity chart, it is reasonable to expect that soils with the same in situ structural state will behave
as other soils within each particular group. Soil structure can be indicated by in situ densities, or voids ratios, which will vary according to how much the soil is destructured.

Vaughan et al. (1988) proposed that the in situ mechanical behaviour of residual soils can be usefully assessed empirically by indexing the in situ voids ratio (e) of the soil in relation to the voids ratio of the soil at two 'standard' de-structured states, in a manner similar to the indexing of sands by relative density or of sedimentary clays by liquidity index. It is suggested that the voids ratio at the liquid limit (eL) is used as the higher of the two standard voids ratios and the standard lower voids ratio is measured at the optimum dry density (eopt), as determined from the proctor compaction test. The plastic limit, as currently measured, is not suitable for establishing the second lower standard voids ratio. Vaughan et al. (1988) defined the relationship between these voids ratios at the in situ and 'standard' destructured soil states as the relative voids ratio (eR), equivalent to the liquidity index for sedimentary soils, as follows:

\[ e_R = \frac{e - e_{opt}}{e_L - e_{opt}} \]

The use of this index requires trial in the field to determine fully its practical applications. Too few compaction tests (to determine eopt) were undertaken in this study to allow detailed conclusions of the effectiveness of the above relationship to 'index' the mechanical properties of undisturbed red soils investigated here. However, for the limited results obtained (albeit using the small-scale Dietert apparatus and not the standard Proctor compaction method specified by Vaughan, et al.), there appeared to be a good relationship between eR and 'compression index' determined from oedometer consolidation tests. The 'relative voids ratio' appears to be a promising method for engineering correlation of tropical residual soils in their undisturbed state. Moreover, its basis is not related to stress history which is irrelevant to residual soil behaviour. It also provides a link between easily determined index properties and undisturbed soil behaviour.
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Map Sheet III: Mexico and Central America: 1972
Map Sheet IV: South America (2 sheets): 1971
Map Sheet VI: Africa (3sheets): 1973
Map Sheet VII: South Asia (2 sheets): 1974
Map Sheet VIII: North and Central Asia (3 sheets): 1977
Map Sheet IX: Southeast Asia: 1976
Map Sheet X: Australasia (2 sheets): 1976


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Figures
Figure 1. Map showing simplified world distribution of residual tropical 'red' clay soils (based on the FAO Soil Map of the World; Sheets II-X).

[The distribution of these soils extends beyond the tropics into humid sub-tropical and Mediterranean-type climatic zones and continental coastal areas in mid latitudes where topographical, geological and climatic factors favour their development, and/or into areas where they are inherited from past climatic conditions.]
Figure 2. Schematic representation of the tripod sampler
Figure 3. Sampler for tropical red clay soil - 0.5 m capacity (shown 1/3 scale)
Figure 4. Schematic drawing of the sampler test instrumentation
Figure 5. Compression profiles for sampler tests at Mchana, Kenya (highlighting the greatest compressions)
Figure 6. Composite graph of processed parameters for sampler test MCH14
Figure 7a. A-line plot for soils remoulded by thorough hand-mixing.

Figure 7b. A-line plot for soils remoulded by mixing in the 'greaseworker'.
Figure 8 (a-d). Triangular particle size classification charts for tropical red clays developed over various types of parental bedrock.
Figure 9. Progress of saturation of triaxial specimens
Figure 10a. Triaxial compression stress paths, INDONESIA, Pits 1 - 9

Figure 10b. Triaxial compression stress paths, INDONESIA, Pit 11, 3.8-4.0m
Figure 10c. Triaxial compression stress paths, KENYA, Pits 1 - 7

Figure 10d. Triaxial compression stress paths, KENYA, Chemususu Dam
Figure 10e. Triaxial compression stress paths, KENYA, K89/3F

Figure 10f. Triaxial compression stress paths, KENYA, K89/3F, 0.8-1.0m
Figure 11. Triaxial consolidation 'swell' effect
Figure 12. Histograms of effective cohesion and angle of friction.

- Effective cohesion KENYA
- Effective friction angle, $\phi'$, KENYA

- Effective cohesion INDONESIA
- Effective friction angle, $\phi'$, INDONESIA

Counts

C' (kPa)

0 10 20 30 40 50 60 70 80 90 100

Counts

$\phi'$ (degrees)

0 10 20 30 40 50
Figure 13. Shear stresses showing a 'bonding' effect
Figure 14. Stress dependance of oedometer consolidation settlement.
Figure 15b. Voids ratio vs. (log) stress for Kenyan oedometer samples
Compression index, $C_c$ (oedom.) vs. Relative voids ratio, $e_R$

Key: 2 = soils developed on Older Quaternary volcanics
3 = soils developed on Tertiary volcanics

Figure 16. Relationship of Compression Index, $C_c$, to relative voids ratio, $e_R$.
Figure 17. Application of Vaughan's 'bonded' soil model
Figure 18. Compaction test plots
Residual friction angle vs. Plasticity index (Kenya)

Residual friction angle vs. Clay size fraction (Kenya)

Ring shear test plots (Kenya) Normal stress vs. Shear stress

Figure 19. Results of ring-shear tests on remoulded Kenyan samples
Figure 20. Examples of tropical weathering profiles in igneous rocks.

(A & B after BS 5930:1981 and Anon, 1990)
Figure 21. Data for Kenyan and Indonesian soils plotted on a combined 'Plasticity/Activity' chart for classifying tropical clay soils (after Vargas, 1988).
<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>APPROXIMATE EQUIVALENTS OF SOIL MAP UNITS AT SAMPLE SITES</th>
<th>ELEVATION (m ASL)</th>
<th>BEDROCK GEOLOGY</th>
<th>CLIMATE</th>
<th>AVERAGE ANNUAL RAINFALL ZONES (mm)</th>
<th>SEASONALITY OF RAINFALL</th>
<th>MEAN ANNUAL TEMPERATURE RANGE (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kenya</td>
<td>Andosols (FAO Classification) Andosols (French Classification Duchaufour)</td>
<td>2200 + (E of Rift)</td>
<td>Late Tertiary (Pliocene) to Pleistocene (?) pyroclastic rocks and basalts.</td>
<td>Fairly cool, humid</td>
<td>1100 - 2700</td>
<td>Seasonal</td>
<td>14 - 16</td>
</tr>
<tr>
<td>Nitrosols with andosols</td>
<td>Ferrisols with andosols</td>
<td>1860 - 2280 (E of Rift); 1100-c.2000 (W of Rift); c.2000+</td>
<td>Tertiary (Pliocene) to Pleistocene (?) basalts.</td>
<td>Fairly cool to cool temperate, humid</td>
<td>1100 - 2700</td>
<td>Seasonal</td>
<td>14 - 18</td>
</tr>
<tr>
<td>Nitrosols</td>
<td>Ferrisols</td>
<td>1140 - 2900 (E of Rift); 1100-c.2000 (W of Rift); c.2000+</td>
<td>Mainly Tertiary (Miocene) basalts and rhyolites, Precambrian biotite gneiss in some areas W of Rift.</td>
<td>(E of Rift): Fairly cool, sub-humid to fairly warm, semi-humid</td>
<td>(W of Rift): Cool, humid to warm temperate, sub-humid</td>
<td>(E of Rift): 14 - 16 to 22 - 24</td>
<td>(W of Rift): 12 - 14 to 20 - 22</td>
</tr>
<tr>
<td>Nitrosols with acrisols and cambisols</td>
<td>Ferrisols with ferrallitic (rejuvenated?) soils</td>
<td>1610 - 1680 (E of Rift)</td>
<td>Tertiary trachytic tufts and agglomerates.</td>
<td>Warm temperate, semi-humid</td>
<td>800 - 1400</td>
<td>Seasonal</td>
<td>18 - 20</td>
</tr>
<tr>
<td>Association of acrisols (ferric, orthic, plinthic) and cambisols (ferralic)</td>
<td>Association of ferrisols and ferrallitic (rejuvenated?) soils</td>
<td>1370 - 1830 (W of Rift)</td>
<td>Precambrian? granites.</td>
<td>Warm temperate sub-humid to fairly warm/temperate, humid</td>
<td>1000 - 1500 to 1100 - 2700</td>
<td>Weakly seasonal (with little or no dry season)</td>
<td>16 - 18 to 20 - 22+</td>
</tr>
<tr>
<td>Ferrisols (sometimes with associated orthic acrisols and ironstone soils)</td>
<td>Ferrallitic soils</td>
<td>1370 - 2280 (W of Rift)</td>
<td>Tertiary phonolite lavas. Precambrian biotite gneisses, granites and undifferentiated Basement System rocks.</td>
<td>Fairly cool, semi-humid to warm/fairly warm, humid</td>
<td>800 - 1400 to 1000 - 1500</td>
<td>Weakly seasonal (with little or no dry season)</td>
<td>14 - 16 to 22 - 24+</td>
</tr>
<tr>
<td>Indonesia (West Java)</td>
<td>Andosols</td>
<td>1190 - 1580</td>
<td>Quaternary volcanics (breccia, lahars and tuff).</td>
<td>Warm temperate, humid</td>
<td>2000 - 4000+</td>
<td>Weakly seasonal to seasonal</td>
<td>24 - 25</td>
</tr>
<tr>
<td>Nitrosols</td>
<td>Ferrisols in association with ferrallitic soils</td>
<td>125 - 1170</td>
<td>Quaternary volcanics (andesitic/basaltic lava, breccia and tuff).</td>
<td>Warm temperate, humid to hot, humid</td>
<td>1500 - 2000 to 3500</td>
<td>Seasonal</td>
<td>25 - 32</td>
</tr>
<tr>
<td>Ferrisols</td>
<td>Ferrallitic soils</td>
<td>70 - 130</td>
<td>Quaternary volcanics, tuffaceous sandstones and alluvial fan deposits derived from volcanic rocks.</td>
<td>Hot, humid</td>
<td>2000 - 3500</td>
<td>Seasonal</td>
<td>21 - 34</td>
</tr>
</tbody>
</table>

Table 1. Approximate FAO-UNESCO and French (Duchaufour) equivalents of soil map units at project sample sites in Kenya, Indonesia, Fiji and Dominica in relation to general terrain and climatic details.
<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>APPROXIMATE EQUIVALENTS OF SOIL MAP UNITS AT SAMPLE SITES</th>
<th>ELEVATION</th>
<th>BEDROCK GEOLOGY</th>
<th>CLIMATE</th>
<th>AVERAGE ANNUAL RAINFALL ZONES (mm)</th>
<th>SEASONALITY OF RAINFALL</th>
<th>MEAN ANNUAL TEMPERATURE RANGE (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiji</td>
<td>Cambisols (chromic and dystric) and associated ferralsols</td>
<td>10 - 100</td>
<td>Tertiary (Miocene) volcanic and sedimentary rocks (andesitic breccia, volcanic conglomerate and sandstones).</td>
<td>Warm, humid</td>
<td>3000 - 3500 +</td>
<td>Seasonal</td>
<td>c. 24 - 25</td>
</tr>
<tr>
<td>Dominica</td>
<td>Andosols</td>
<td>250 - 300</td>
<td>Mainly Pleistocene volcanics (agglomeratic ashes and tuffs, and andesitic / dacitic lavas).</td>
<td>Warm to fairly hot, humid</td>
<td>3750 - 6000 +</td>
<td>Perennially wet</td>
<td>21 - 32</td>
</tr>
<tr>
<td></td>
<td>Nitosols, cambisols and associated luvisols (chromic)</td>
<td>30 - 225</td>
<td>Tertiary and Pleistocene volcanics (agglomeratic ashes and tuffs, basalt and andesite).</td>
<td>Warm to fairly hot, humid</td>
<td>2100 - 3750</td>
<td>Weakly seasonal</td>
<td>21 - 32</td>
</tr>
</tbody>
</table>

Table 1.-- cont'd Approximate FAO-UNESCO and French (Duchaufour) equivalents of soil map units at project sample sites in Kenya, Indonesia, Fiji and Dominica in relation to general terrain and climatic details.
<table>
<thead>
<tr>
<th>Site</th>
<th>Bh</th>
<th>Depth</th>
<th>Runs</th>
<th>Drilling Method</th>
<th>Sampling Method</th>
<th>Flush</th>
<th>Problems Encountered</th>
<th>Sample Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3.8</td>
<td>-</td>
<td>continuous flight rotary</td>
<td></td>
<td></td>
<td>shallow soil profile</td>
<td>bulk samples only</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3.9</td>
<td>-</td>
<td>continuous flight rotary</td>
<td></td>
<td></td>
<td>high penetration resistance in 'murram'</td>
<td>&gt;95% with grease; 60-80% without; disturbed</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>9.9</td>
<td>-</td>
<td>augering</td>
<td>U100; some liners greased</td>
<td></td>
<td>remoulded clay adhering to barrel and blocking flush return</td>
<td>formation and sample contaminated by flush</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>7.4</td>
<td>8</td>
<td>triple-tube rotary coring</td>
<td>water + 'Claystab'</td>
<td></td>
<td>82-94%; severely disturbed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.6</td>
<td>2</td>
<td>triple-tube rotary coring</td>
<td>air/foam</td>
<td></td>
<td>82-94%; severely disturbed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>triple-tube rotary coring</td>
<td>bentonite + 'Claystab'</td>
<td></td>
<td>82-94%; severely disturbed</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>n r</td>
<td>n r</td>
<td></td>
<td>continuous flight rotary</td>
<td>1.5 m inner barrel; liners greased</td>
<td></td>
<td>none</td>
<td>95% to &gt;98%; 'undisturbed'</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>5.6</td>
<td>4</td>
<td>continuous flight rotary</td>
<td>1.5 m inner barrel; liners greased</td>
<td></td>
<td>none</td>
<td>95% to &gt;98%; 'undisturbed'</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>2.9</td>
<td>2</td>
<td>augering</td>
<td>U100</td>
<td></td>
<td>samples compressed &amp; sheared</td>
<td>disturbed</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>5.8</td>
<td>2</td>
<td>augering</td>
<td>U100</td>
<td></td>
<td>samples compressed &amp; sheared</td>
<td>disturbed</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>7.3</td>
<td>1</td>
<td>augering</td>
<td>0.75 m inner barrel</td>
<td></td>
<td>samples compressed &amp; sheared</td>
<td>disturbed</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8.0</td>
<td>2</td>
<td>triple-tube rotary coring</td>
<td>bentonite + detergent</td>
<td></td>
<td>remoulded clay adhering to barrel and blocking flush return</td>
<td>formation and sample contaminated by flush</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8.0</td>
<td>2</td>
<td>triple-tube rotary coring</td>
<td>bentonite + detergent</td>
<td></td>
<td>remoulded clay adhering to barrel and blocking flush return</td>
<td>formation and sample contaminated by flush</td>
</tr>
</tbody>
</table>

**Table 2.** Summary of drilling and sampling investigations at Ruiru, Kenya, 1989
<table>
<thead>
<tr>
<th>KENYA</th>
<th>INDONESIA</th>
<th>Latosol &amp; nitisol</th>
<th>Andosol</th>
<th>RING SHEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TRIAXIAL</strong></td>
<td><strong>OEDOMETER</strong></td>
<td><strong>COMPACITION</strong></td>
<td><strong>RING SHEAR</strong></td>
<td></td>
</tr>
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<td>$c'$ (kPa)</td>
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| KEY: | $c'$ effective cohesion | $s'$ effective shear strength | $c_{tu}$ undrained cohesion | $c_{tu}$ undrained friction angle | $c'$ yield point | $C_c$ compression index | $C_e$ recompression index | $M_v$ coeff. volume compressibility | $C_l$ collapse index | OMC optimum moisture content | MDD maximum dry density | CBR California bearing ratio | $e_R$ relative voids ratio | $c'_r$ effve. residual cohesion | $s'_r$ effve. residual friction |

Table 3. Summary of mechanical properties
Table 4. Approximate correlation between the major classes of tropical residual soils in the FAO-UNESCO, French (Duchaufour), and American soil classification systems [based on Duchaufour, 1982; Uehara, 1982; Morin & Todor, 1975; Anon, 1990].

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