

# THE INFLUENCE OF PRE-DRYING ON TROPICAL SOIL TESTING

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## ABSTRACT

Large parts of Western and Central Africa fall within the tropics, a humid, temperate region known for rapid and intense weathering of rock. These tropical soils develop due to a complex weathering process, mainly as the result of chemical breakdown. Accordingly tropical soils exhibit different engineering properties and a clear understanding of these properties are required in the design of road pavements. Standard testing used to characterize soils in Southern Africa, in particular the determination of Atterberg limits and the grain size distribution of particles less than 0.075mm, influence bonded and structural water present in and around a soil particle through drying, mixing and dispersion with the use of flocculants.

This paper discusses some of the basic concepts of tropical soil testing and presents laboratory test results used to establish and characterize the properties of the soils encountered during project investigations in West and Central Africa. Testing findings are supplemented by visual examination of soil particles under high magnification as well as XRD and XRF analysis. Standard drying methods affect clays and clayey materials the most, and the drying temperature should be kept as low as possible. Both Atterberg limits and hydrometer results are affected by drying temperature. Manipulation prior to testing needs to be carefully controlled as it leads to breakdown of the soil structure resulting in varying Atterberg limit test results.

## 1 BACKGROUND

### 1.1 Introduction

Soil is a 3-dimensional body with properties that reflect the impact of mankind, climate, vegetation, fauna and relief on the soil's parent material over a variable time span. The nature and relative importance of each of these 'soil forming factors' vary in time and in space (Deckers et al., 2001). As far back as the eighteenth century, geologists identified that in warm, moist, temperate and tropical climates, water percolating through rock has a strong weathering action (Russel, 1889). Chemical reactions increase with an increase in rainfall and temperature, and accordingly soils from the tropics exhibit different engineering properties (Millard, 1993). Other factors add to the complex weathering process in tropical environments, such as the structure and texture of the parent rock, but annual precipitation and particularly the seasonal distribution therefor largely determine the intensity of the weathering process.

Rainfall, the main agent for chemical weathering, is also the principal climatic control mechanism for vegetation. A number of indices have been developed to identify areas with potentially high weathering action, the most common being the Weinert N-value (Weinert, 1968). A Weinert N-value below 5 (0.7 in the study area) indicates that sufficient water is available for weathering. At values below 1, deep weathering with mainly decomposition occurs where montmorillonite and kaolinite change to sesquioxides (Weinert, 1980).

In an effort to better understand the reaction of tropical soils to standard soil testing techniques, the origin of these soils has been researched. Gidigas (1976) summarized the three stages of tropical weathering as follows:

- Decomposition and disintegration (or the physio-chemical breakdown) of primary minerals and release of constituent minerals. Chemical weathering processes includes; solution, ion exchange, hydration, hydrolysis, carbonation, oxidation and reduction while physical weathering takes place by means of unloading, frost action, salt growth, action of organisms etc.
- Laterization or leaching of combined silica and bases and enrichment from outside sources of oxides and hydroxides (sesquioxides) ( $Al_2O_3$ ,  $Fe_2O_3$ ,  $TiO_2$ ).
- Dehydration or loss of water, concentration and crystallization of amorphous iron colloids into dense crystalline iron minerals.

Numerous studies have indicated difficulties when testing tropical soils. Particle size distribution of weathered volcanic ash, for instance, showed anomalous results when slightly altered by heat or working (Millard, 1993). Gidigas (1976) reported two basic factors that underlie the inconsistency of particle size distribution results of tropical soils; vulnerability to degradation and the cementing effect of sesquioxides that binds the natural clay and silt size fractions. Disaggregation of the sesquioxide-bound structure is required and achieved through the use of dispersing agents. Different dispersing agents have been used. The TMH 1 (1986) Method A6 specifies Sodium silicate and Sodium Oxalate. Sodium Hexametaphosphate, however, has been reported to be the most effective dispersing agent when testing tropical laterites (Gidigas, 1976; Netterberg, 1978; Bell, 2000).

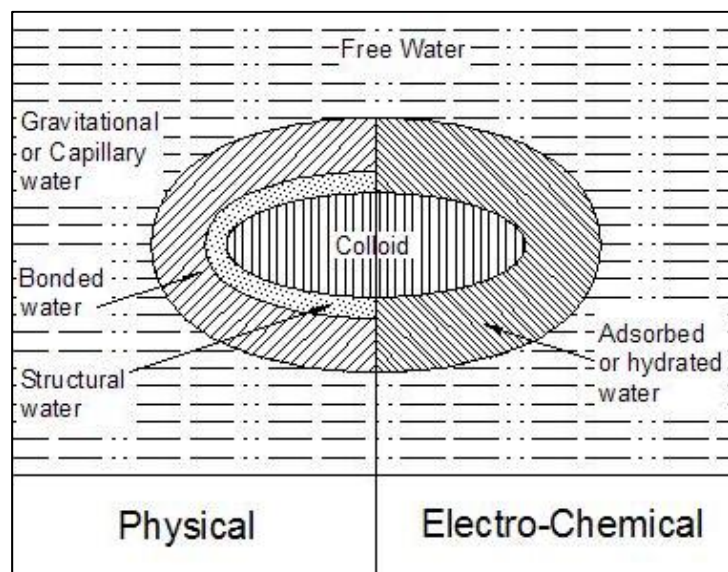
As a result of pre-drying, material changes can be contributed to the tendency to form aggregation on drying, the loss of water in hydrated minerals and possible mineralogical movement. Standard TMH1(1986) test methods require that field soil and gravel samples are weighed and then oven-dried to a constant mass at 105 to 110°C, usually overnight. Method A1 (b) does provide for dry sieving, 'where the boiling and heating of the fines may influence the results'. Northmore et al (1992) recommended that no pre-drying should be carried out on any tropical residual clay soils. A recent and more general approach in the local industry suggests that the soil and gravel samples are oven-dried to a constant mass at 80°C.

The objective of the study was to determine pre-drying sensitivity of some West African tropical soils and clays. The synopsis was:

- To understand the behavior of water, clay and tropical residual soils.
- To evaluate standard TMH1 methods with adjusted pre-drying regimes.
- Mineralogical analysis of the materials.
- Visual examination of the tropical soils by means of Scanning Electron Microscopy (SEM) and petrographic microscopy.
- Conclusions and recommendations.

## 1.2 Water, clay and plasticity

Philip et al (1984) stated that a colloidal state is somewhere between a solution and a suspension. A colloid is simply a fluid filled with a large quantity of very small solid particles. Three types or phases of water exists within soils (Hogentogler, 1937; Gidigas, 1976) as shown in Figure 1; 'loose', 'normal' or 'free' pore water, not bonded but merely attracted to the soil particle; a viscous water film that is typically 'bonded' strongly to the particle; and 'structural' water that is crystalized within the mineral structure of the soil particle. Conventionally the definition of the moisture content is based on the loss of weight when the soil is dried to constant mass between 105 °C to 110 °C. Structural water should not be considered part of 'free' water in the usual engineering sense (Fookes, 1997).



**Figure 1: Types of soil moisture (Hogentogler, 1937)**

A clay particle's behaviour is controlled by surface-derived or electrical forces. Clay can therefore be described as a colloid. Montmorillonite, the smaller and most water sensitive clay particles, and kaolinite, the larger and less water sensitive clay particles have specific surface areas of 800 m<sup>2</sup>/g and 10-20 m<sup>2</sup>/g respectively. The clay particle's water-retention capacity is generally proportional to its surface area, where the water is held in pores, structural channels or in interlayer positions (Lambe and Whitman, 1969).

The water adsorbed between layers or in structural channels may further be divided into zeolitic and bound waters (Nagata et al, 1973). The latter is bound to exchangeable cations or directly to the clay mineral surfaces. Both forms of water may be removed by heating to temperatures in the order of 100 to 200°C and in most cases, except for hydrated halloysite, are regained readily at ordinary temperatures.

## 1.3 West and Central African tropical soils and clay

The U.S. Soil Taxonomy (Soil Survey Staff, 1999) lists twelve soil orders. Typical West and Central African tropical soils featuring on the list include:

- Laterites, laterization and red clays;
- Andosols and halloysitic soils (oxisols and ultisols); and
- Black clays and vertisols.

Vertisols contain swelling smectite-type clay minerals and have a pH greater than 7. Oxisols however, contain kaolin-group clay minerals and metal oxides and the presence of ferromagnesian parent materials are thought to be essential during their formation. Ultisols, found in geologically old landscape settings, are characterized by a humus-rich surface horizon (the uppermost layer). These well-developed, extensively leached soil horizons are enriched in kaolin-group clay minerals and in metal oxides and appear as red or bleached layers.

Kaolinite appears as six-sided flakes, regularly elongated in one direction and expressed as  $2\text{SiO}_2 \cdot \text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$ . Halloysite, although similar in structure to kaolinite, appears more tubular by nature and has a hydrated form with a composition of  $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \cdot 2\text{H}_2\text{O}$  (Fookes, 1997). This hydrated form irreversibly changes to a dehydrated variety at relatively low temperatures ( $60^\circ\text{C}$ ) or low relative humidity when the water between halloysite layers is lost during dehydration. Smectite's structure can be derived from pyrophyllite ( $4\text{SiO}_2 \cdot \text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ) and talc ( $4\text{SiO}_2 \cdot 3\text{MgO} \cdot \text{H}_2\text{O}$ ). The distinguishing feature of the smectite structure is that water and other polar molecules (in the form of certain organic substances) can cause the structure to expand.

#### 1.4 Organic matter and cation exchange capacity

Deeply weathered soils, typical to the tropics, characteristically show depletion of major elements such as Si, Ca, Mg, K and Na and the relative accumulation of Fe and Al oxides and hydroxides. Cation exchange capacity and pH values are generally low, as is the content of soil organic matter. Smectite clays have a high cation exchange capacity, while kaolinitic, gibbsitic, and halloysitic soil mineralogy classes have a low cation exchange capacity and a low base saturation (acidic soil) (Baillie, 2006).

Smectite and other expansive clay minerals can accommodate relatively large, inorganic cations within their structural layers. These interlayering materials are predominantly thermally stable and hold as pillars to allow a porous structure. Certain organic molecules, coating the surface of a clay mineral, change the surface from hydrophilic to hydrophobic, thereby losing its tendency to bind water so that it can react with additional organic molecules (Frost, 1996).

## 2 TEST METHODS AND INVESTIGATIVE TESTING

The colloid-water interaction appears to be an important aspect to control during characterization testing. The plasticity of clay soils is attributed to the attracted and held water because of its dipole structure (McCarthy, 1982). When drying a soil sample, the normal pore water will evaporate quickly, but the bonded water may remain for the duration of the drying regime and even beyond. When bonded and structural water are no longer present, the clay minerals in particular show significant changes in their properties and structure. Conventional oven drying has a substantial effect on soil properties, but drying at lower temperatures can also produce significant changes (Fookes, 1997). When heated at temperatures beyond dehydroxylation, the clay mineral structure may be destroyed or simply modified, depending on the composition and structure of the substance. In the presence of fluxes, such as iron or potassium, fusion may rapidly follow dehydroxylation. In the absence of such components, particularly for aluminous dioctahedral minerals, a succession of new phases may be formed at increasing temperatures prior to fusion (Frost, 1996).

The reproducible determination of Atterberg limits for tropical soils has also been a contentious topic. According to Bell (2000) the drying of the sample is primarily influenced by temperature with the time of drying being secondary. Clay and tropical soils often become more silt-or sand-like with increased temperatures, with a lower plasticity, although in some instances the opposite may occur. The literature accordingly recommends that classification testing for soils should be performed with as little drying as possible or at least until such time that it can be established from comparative testing that drying has no significant effect on the test results (Northmore et al, 1992; Fookes, 1997). The degree and method of drying should also be researched for a particular study area (Bell, 2000).

Tropical soils and clays originating from West and Central Africa were used to perform a series of laboratory tests, including grain size distribution, Atterberg limits and pH values. A description of the samples analyzed in the current study is provided in Table 1.

**Table 1: Description of the samples tested during the current investigation**

Sample number	Depth	% Passing 0.425mm	GM	PI	LS	Materials description
1318	1 – 2 m	95	0.23	18	9	Moist, orange brown, clayey silt.
1324	2 – 3 m	94	0.16	16	8.5	Moist, light brown, clayey silt. Colluvium.
1329	2 – 3 m	96	0.13	20	9.5	Moist, brown, clayey silt. Iron rich layer colluvium.
1331	8 – 9 m	44	1.67	23	9.5	Moist, reddish khaki, silty clay. Residual shale.
1334	8 – 9 m	49	1.5	22	12.5	Moist, reddish khaki, silty clay, Residual shale/siltstone
1341	0 – 2 m	67	1.07	17	12.5	Moist, brown, clayey silt with gravel. Colluvium
1342	0 – 2 m	90	0.72	15	9	Moist, brown, sandy silt matrix with abundant rounded cemented manganese nodules. Colluvium.
1409	0 - 1 m	97	0.32	28	16.5	Moist, brown, clay. Colluvium.

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The following pre-drying methods were:

- The samples were oven-dried to a constant mass at 110°C.
- The samples were oven-dried to a constant mass at 80°C.
- The samples were oven-dried to a constant mass at 50°C.
- The samples were dried overnight on top of the 110°C oven to a constant mass.

Laboratory trial testing constituted the determination of the Atterberg limits (TMH1, 1986) and the grain size distribution of soils by means of a hydrometer (ASTM, 2007). Atterberg limits were performed after 5, 10 and 20 minutes mixing, to investigate possible influences of material handling on engineering properties. The hydrometer testing was performed with 125ml Sodium Hexametaphosphate as dispersive agent. The pH's of the soils were also determined at field and oven-dried (to a constant mass at 110°C) moisture contents to confirm the presence of organic matter to some extent.

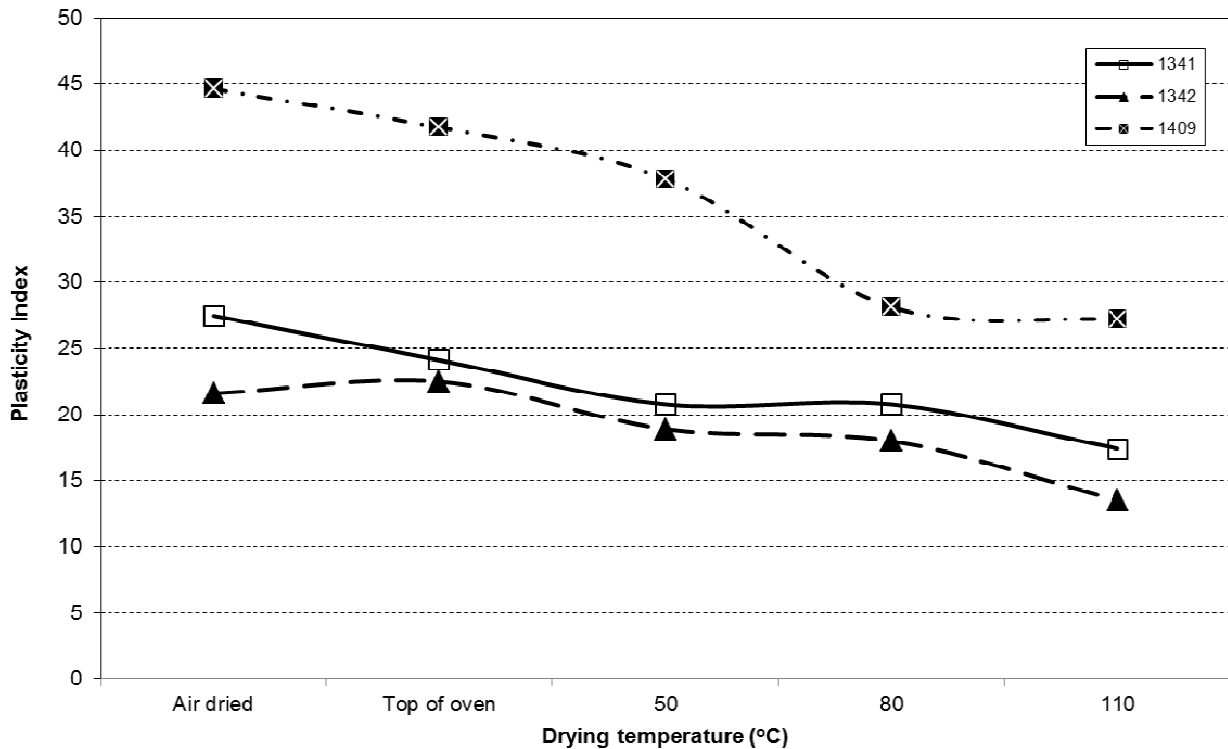
### 3 TEST RESULTS AND OBSERVATIONS

The pH tests at field and oven-dried moisture contents are summarized in Table 2. The pH test results indicate that the kaolinitic study group soils have a low cation exchange capacity and a low base saturation (acidic soil), and will generally have a low content of soil organic matter.

**Table 2: The pH values of various samples at field and oven-dried moisture contents**

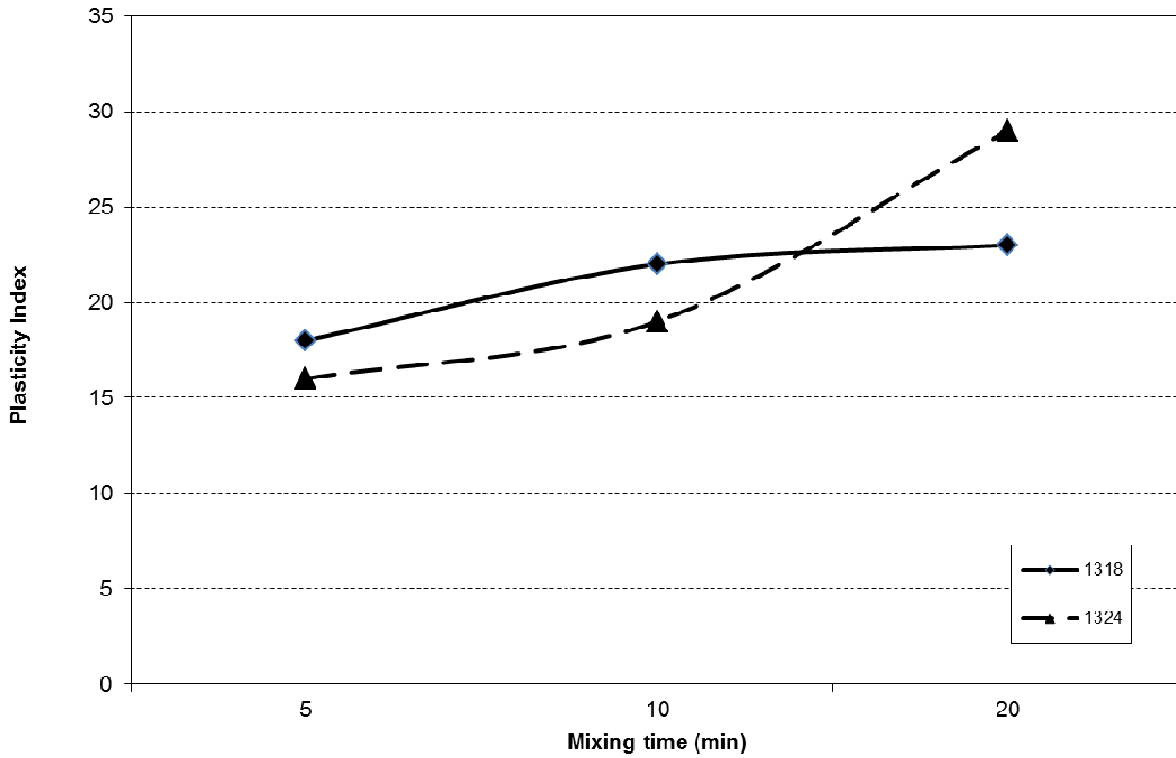
Sample number	Field moisture content pH	Oven-dried moisture content pH
1318	7.22	5.86
1324	6.09	5.75
1334	6.06	5.91

The test results of Atterberg limit tests performed during the investigation revealed that samples that were not completely dry prior to testing have increased plasticity (cohesion strength) as shown in Figure 2. The degree to which the cohesion is affected by the various drying methods is evident, with the less plastic materials having smaller standard deviations.



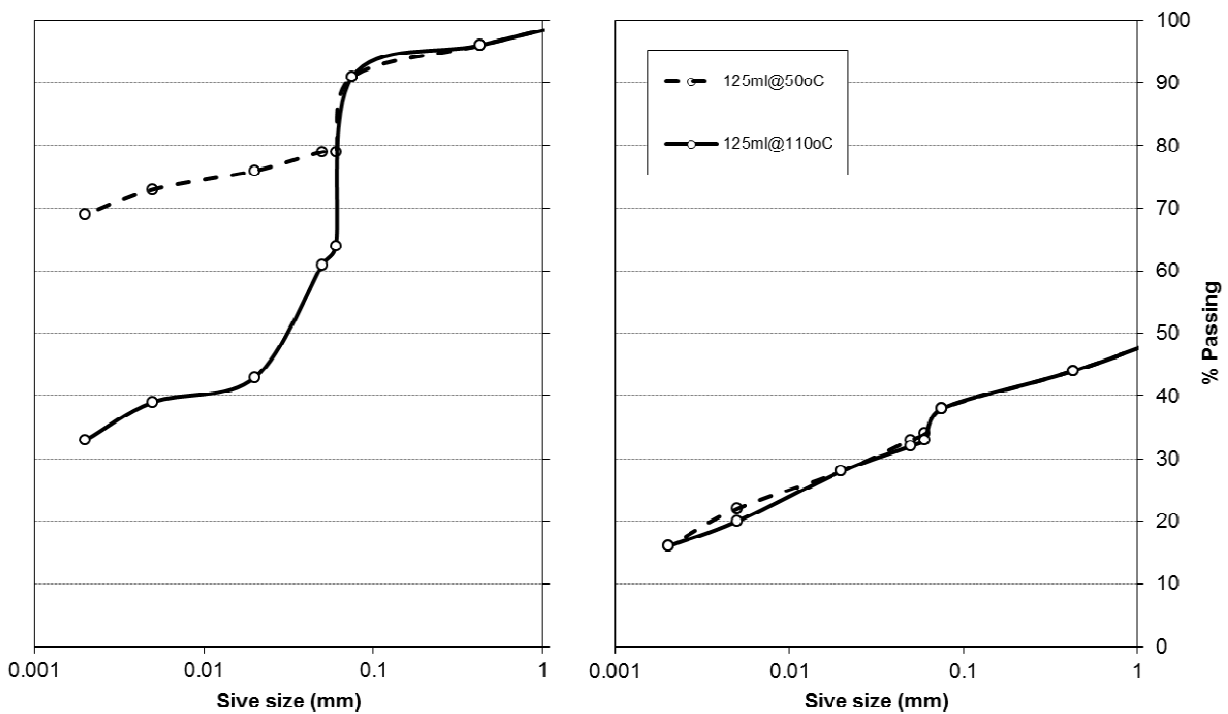
**Figure 2: Influence of drying temperature on the weighted PI of a sample**

Figure 3 depicts the test results from the 110°C-samples for samples 1318 and 1324. It is evident that the plasticity of the materials increased with manipulation from 5 to 10 to 20 minutes. This confirms an earlier finding that excessive manipulation prior to testing leads to breakdown of the soil structure resulting in higher liquid limit values (Terzaghi, 1958, Sherwood, 1967 and Townsend et al, 1969).



**Figure 3: Influence of mixing time on Plasticity Index**

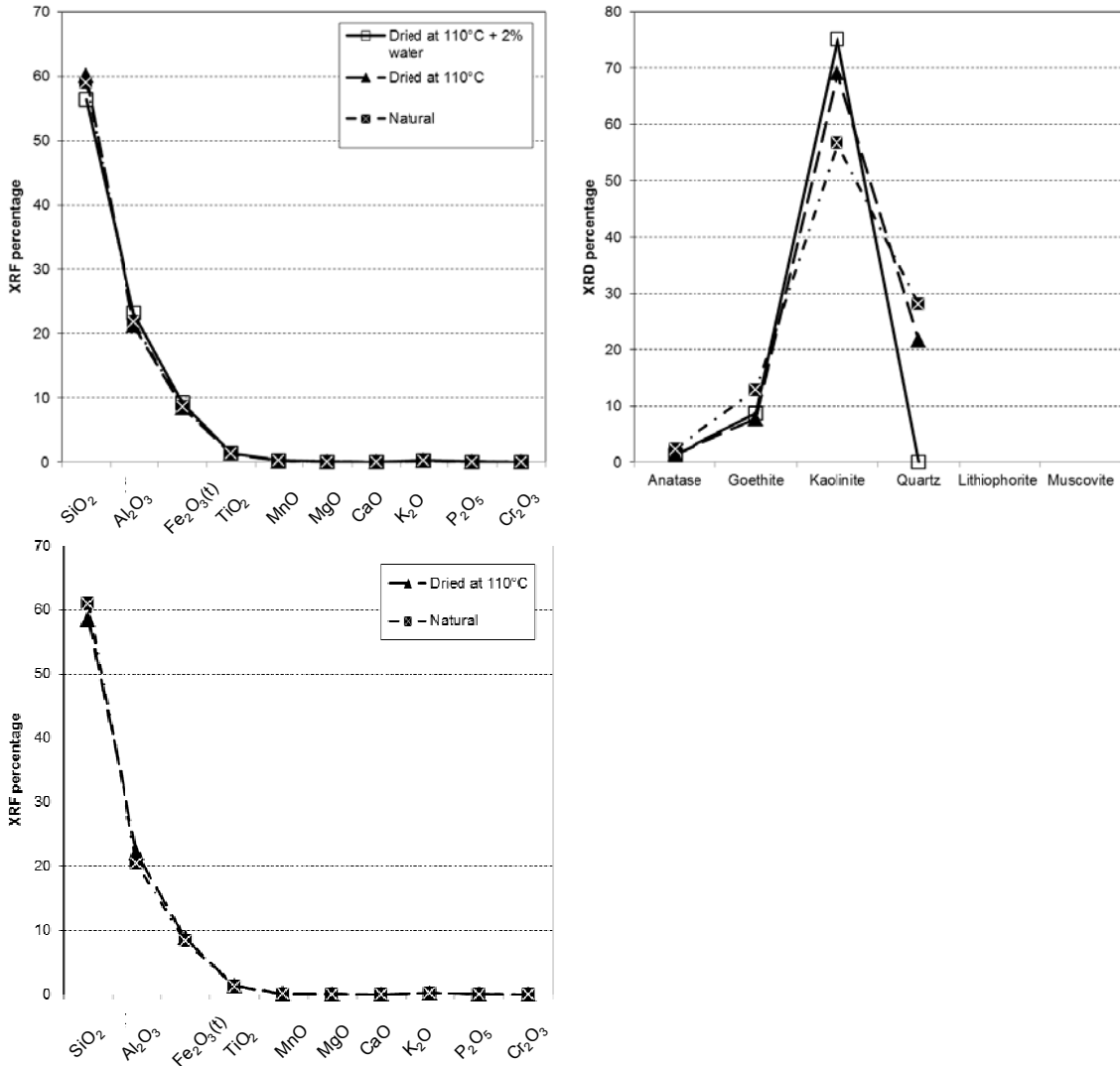
The effect of various pre-drying methods on particle size distribution test results is shown in Figure 4. The sample with higher clay content (sample 1331) seems to be more sensitive to drying at 110°C. At a temperature of 110°C it appears that the particles start to aggregate, forming a strong bond which makes dispersion of the particles difficult. This resulted in the material appearing less clayey than it should be, as confirmed by Northmore et al (1992).



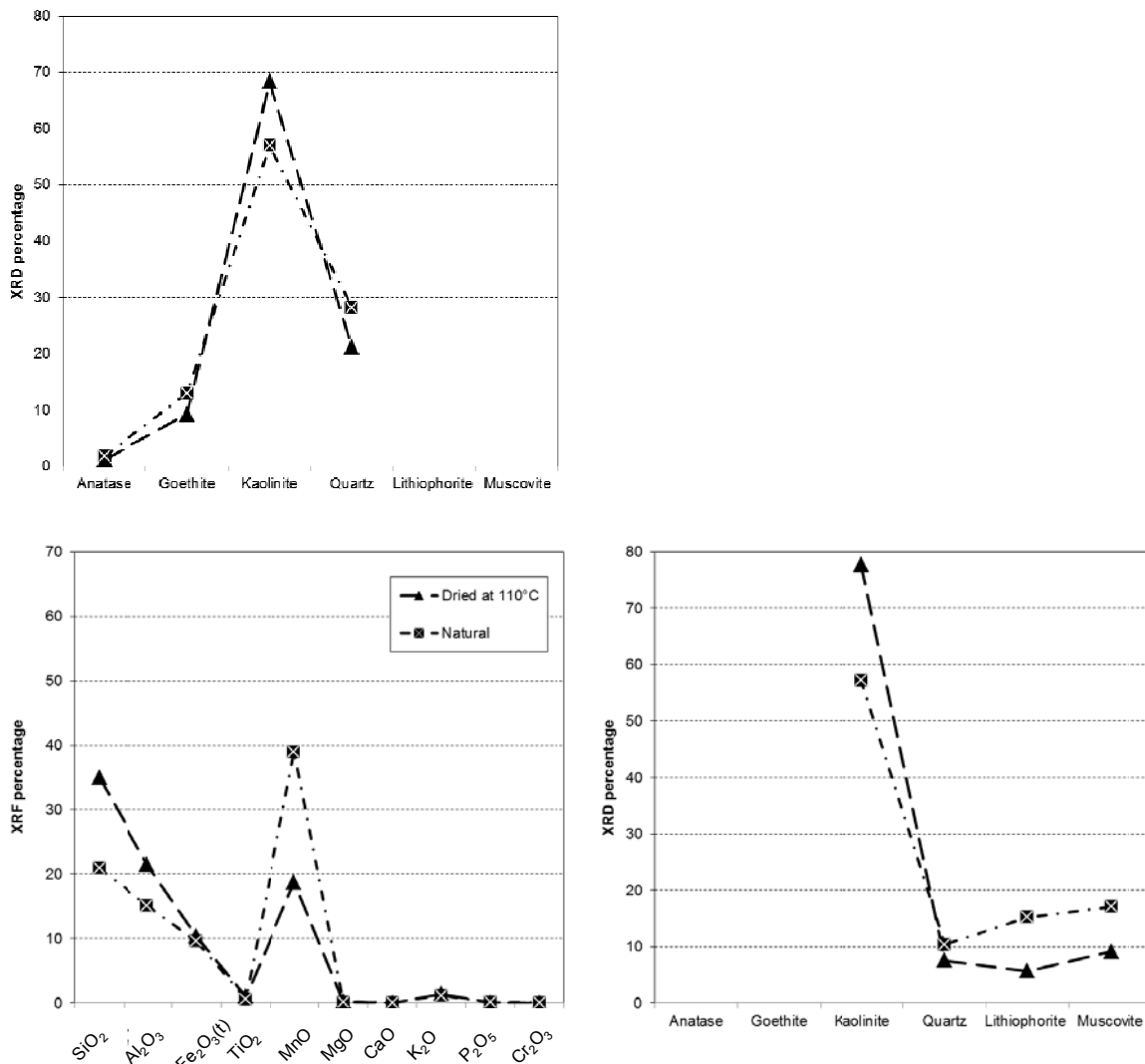
**Figure 4: The effect of pre-drying on hydrometer analyses (sample 1329 left and sample 1331 right).**

#### 4 MINERALOGICAL ANALYSIS

To get a better understanding of the tropical soil's mineral composition, a series of X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD) tests were performed on a selected number of samples. The mineralogical composition of the samples from the XRD and XRF analysis are shown in Figure 5.





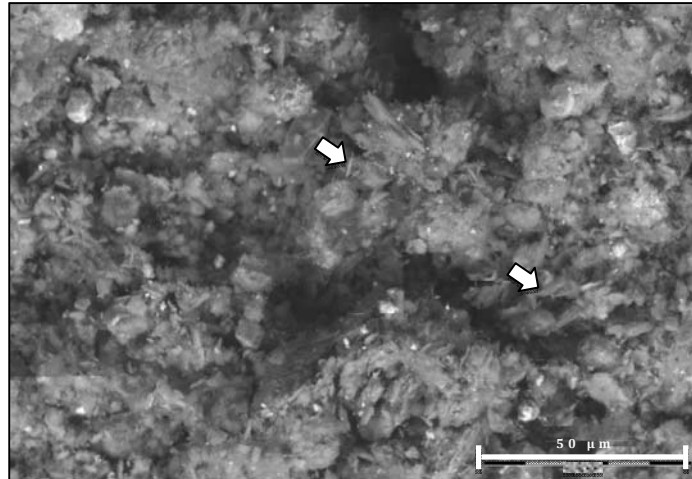


**Figure 5: XRF and XRD results.**

It appears that kaolinite is present in all the samples. No anatase or goethite is present in sample 1334. Sample 1334 contains Mn-minerals causing large peak to background ratios in the scans, therefore the quantification may not be precise. A low carbon content for all the samples also confirmed earlier assumptions on the pH results regarding the presence of organic matter.

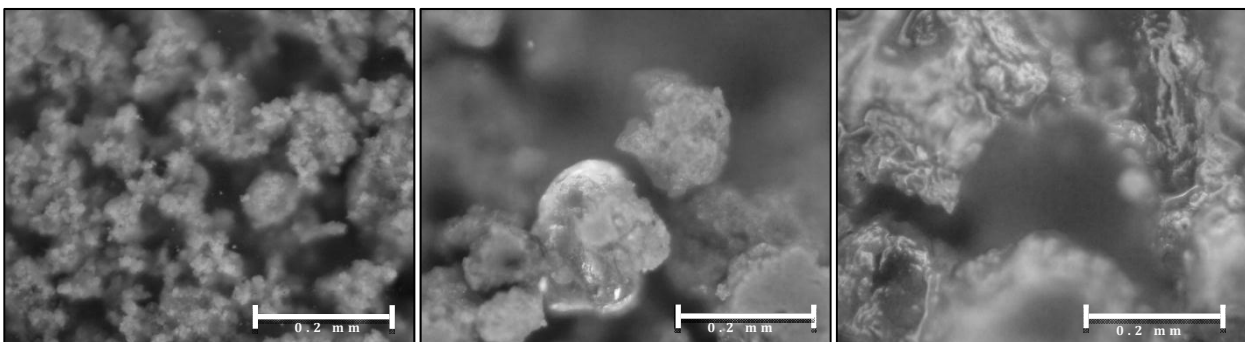
## 5 VISUAL EXAMINATION

To supplement the laboratory trial testing for the study, the samples were visually examined under high magnification in an effort to elucidate the soil-water interaction. For this purpose both high magnification using SEM and petrographic microscopy using up to 400x magnification were utilized. Figure 6 shows a SEM slide of a gravelly clay (sample 1331) at a magnification of 3,000x. From this magnification clay platelets can be seen as flat discs. SEM sample preparation requires the sample to be moisture free and the examination of the soil-water interaction could thus not be done directly.



**Figure 6: SEM photograph of a gravelly clay (1331) at 3,000x (clay platelets indicated with the white arrows).**

Figure 7 shows sample 1318 air-dried, at natural moisture content and wetted at x400 magnification. At increasing moisture content the smaller particles are bonded together and the particle shapes appear more rounded.



**Figure 7: 400x magnification of sample 1318 air dried (left), at natural moisture content (middle) and wetted (right).**

## 6 CONCLUSIONS AND RECOMMENDATIONS

Characterizing tropical soils by means of standard test methods can provide misleading test results. The Atterberg limit samples that were air-dried provided higher PI results than the samples that were dried in the oven at 110°C. It is clear that the standard drying method affects clays and clayey materials in tropical soils the most. Excessive manipulation prior to testing leads to breakdown of the soil structure resulting into higher liquid limit values.

Additional recommendations relating to Atterberg limits and grain size distribution testing are:

- Drying of samples during preparation: Granular materials of at least TRH 14 (1985) G7 quality and cohesionless materials; oven-dry to a constant mass at 110°C. Fine clayey gravels and clays; air dry to a constant mass, but should local conditions including high humidity levels prolong the drying time, oven-drying at maximum 50°C can be considered.

- Atterberg limits: If no particles are retained on the 0.425 mm sieve, water can be added directly to the natural materials. Larger than 0.425 mm weathered fractions should be broken down by soaking the soil in potable water and washing it through the 0.425 mm sieve. The paste/slurry should be air-dried and then used for testing. Grinding and conventional drying should not be allowed. For the Atterberg limits sample preparation a fixed ten minutes mixing time must be adhered to.
- It should be noted that the standard PI and linear shrinkage test result ratio may not be applicable, where the LS value is normally considered to be approximately 50% of the PI value. Local correlations should be established.
- For Hydrometer testing, the passing 0.425 mm fraction should be used for testing. The quantity dispersing agent solution (sodium hexametaphosphate) should be increased to 125 ml per sample. The solution is 36 gram per liter distilled water. No additional water should be added to the dispersive agent and sample mixture during the 2 hour standing period. Pre-drying temperature should be kept as low as possible.
- Any deviations from standard test methods must be clearly noted on the sample test result forms.

'Bonded' and structural water should possibly be considered to be part of the clay particle, since it provides the natural material with its inherent properties. 'Loose', 'normal' or 'free' pore water, not bonded but merely attracted to the soil particle, should be considered to be the water content (contained) in the material. Accordingly fine clayey gravels and clays should have a moisture content of 1- 2% prior to testing.

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