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**SPECTROSCOPY AND SWELLING SOILS**  
**An Integrated Approach**

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P.C Kariuki

# **SPECTROSCOPY AND SWELLING SOILS**

## **An Integrated Approach**

### **PROEFSCHRIFT**

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## SUMMARY

The fact that expansive soils are a major engineering problem makes their study an important research aspect due to the accruing cost involved in terms of economic loss when construction is undertaken without due consideration to the probability of their presence. Though there are several methods that have been used to recognise their presence a need of a fast and relatively cheaper methods continues to be a necessary undertaking. In this thesis new methods are explored where the various aspects of swelling soil properties are investigated consisting of engineering, geophysical, reflectance spectroscopy and remote sensing where data from two study areas one in central Kenya and the other in southern Spain were used.

The study relied on the establishment of indicator spectral parameters as to the presence of three clay minerals commonly used in soil classification to swelling potential classes namely; smectites, illites and kaolinites. This was through several reflectance spectra analysis techniques among which are; absorption feature mapping, derivative analysis, optical density and band normalised with centre. This was followed by the establishment of correlations between these parameters and the commonly used physicochemical indices of Atterberg limits, Cation Exchange Capacity (CEC), Saturated Paste (SP), and Coefficient of Linear Extensibility (COLE) tests. In this, their widely accepted thresholds within which soils are assigned to a swelling potential class and provisionally to a dominant clay mineral were used.

This was followed by analysis of airborne hyperspectral data, in the Spain case and Landsat Thematic Mapper (TM) image data for the Kenyan study area to establish similar compositional differences. In both cases the lower spectral information content was taken into consideration where not only the spectral characteristics were used but also the surface expression of the soil compositional differences in the Kenyan area in the form of gilgai microrelief. This information was integrated with field based data consisting of topography, drainage and vegetation differences and correlations with field based soil classification maps to establish the potential of remote sensing in the mapping of swelling potential. Finally a prove of concept as to the potential discrimination of swelling soils under buried non-swelling soils was also explored where two geophysical methods consisting of Induced Polarisation (IP) and Nuclear Magnetic Resonance (NMR) known to give indication as to the CEC, moisture and clay mineralogy differences

were used at a laboratory scale with the aim of identifying the problems to be overcome for such methods to be applicable in a field setting where they would provide faster ways of establishing the swelling potential characteristics based on the fact that these soil properties are the key to their swelling behaviour.

From the engineering methods, three of the indices were established to best represent the potential volume change and consisted of those directly related to the clay mineralogy type i.e. CEC and the Atterberg limits of liquid limit and plastic index. This was interpreted to show them as most suited from an engineering perspective in the identification of swelling soils and as best suited at the exploration as to other methods capability at identifying these soils.

The absorption feature mapping technique established several feature parameters to be diagnostic as to the dominance of these minerals in soils where significant presence of kaolinite enhanced the hydroxyl features whereas substantial amounts of smectite enhanced molecular water features. Manipulations of the spectral curves in the form of first and second derivatives were also observed to give similar information whereas other manipulations such as the optical density and the band normalised with centre were not as promising. The potential of spectral data to discriminate the soils based on the clay mineralogy differences was thus concluded to show spectroscopy to have a potential at mapping swelling soils an assumption that was finally confirmed through correlations between the spectral parameters and the established swelling potential indices. This was also confirmed based on spectral information from the hyperspectral image data where derivatives established several wavelength positions to give strong indications of such a potential.

Landsat image data on the other hand added a new dimension to the potential identification and mapping of swelling soils other than the spectral differences in the form of recognition of gilgai topography pattern exclusively present in these soils. This provides a possibility of carrying out more detailed analysis of the potential differences among the swelling soils where spatial analysis of the gilgai patterns in the form of parameters such as homogeneity index can be used to relate soils in different regions based on the similarity of such indices and their association to environmental factors. This when coupled with spectral differences in the form of such indices as the soil brightness index were established capable in assigning soils in the Kenyan study area to swell potential categories upon integration with other field based information such as topography and drainage patterns coupled with land cover differences. The geophysical methods (IP and NMR) though laboratory based were also established as potentially useful in the study of these soils and could be useful in their recognition in places where they

could be buried based on good correlations obtained between the normalized IP and the CEC on the one hand and moisture and grain size distributions and the NMR parameters on the other. However, for the two methods to become operational there are some factors that require to be addressed one of which is the influence of salinity on the obtained IP and a proper calibration of the NMR to measure the various properties on which it has a potential to give information on.

Reflectance spectroscopy was therefore concluded to have a potential application in swelling soil identification and to offer a fast non-destructive method based on diagnostic spectral features. Low spectral but high spatial resolution images were found useful in the recognition of these soils and to offer a potentially important tool for the comparison of the soils over wide areas through the established gilgai pattern analysis based on their expression of underlying forces resulting from differential swelling. Geophysical methods of NMR and IP were also established to have a potential to non-intrusive identification of these soils if some influencing factors could be overcome. Conclusions were therefore drawn that though soil swelling is a complex phenomenon involving several underlying factors i.e. compositional differences, structure and moisture regime etc, clay mineralogy plays a central role in determining it and thus has an overall controlling influence to most of the soil properties making their use in its estimation possible. The research however established that there are still more handles to be overcome as to the full operation of these new techniques.

# CHAPTER 1

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## GENERAL INTRODUCTION

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*"We may be willing to tell a story twice, but are never willing to hear it more than once." – William Hazlitt, English writer*

*though*

*"Very few wise men are wise by the counsel of their own teaching. For he that was only taught by himself had a fool for his master." – Ben Johnson, English dramatist.*

Swelling soils contain clay minerals that change volume with water content changes that result in major geological hazards and extensive damage worldwide. The swelling is caused by the chemical attraction of water where water molecules are incorporated in the clay structure in between the clay plates separating and destabilizing the mineral structure. Of significance is the type and amount of clay present, cation exchange capacity, clay particle size, soil density, soil moisture content, soil structure and organic matter content among other minor contributing factors. The clay minerals related to this process have been grouped into three main categories of smectite, illite and kaolinite, in decreasing order of potential volume change and methods of engineering classification of soils into swelling potential classes have been to a large extent based on recognizing the presence of these minerals through their physical/chemical properties. The methods are time consuming and expensive because of extensive laboratory measurements needed and there is therefore the need to continue exploring new methods that would bring about identifying swelling soils rapidly and at low costs. Spectroscopy (laboratory, field or imaging), together with some geophysical methods could provide such methods where recognition and quantification of these minerals based on their influence on physicochemical properties could be measured in faster and less expensive ways.

Work on high spectral resolution radiometry has shown that earth surface minerals can be identified using spectral information from scanner data (Goetz *et al*, 1981) and spectral resolution of such instruments has developed quite rapidly over the years since the first imaging spectrometer, the Airborne Imaging Spectrometer (AIS) was developed. Recently spaceborne imaging spectrometers have been put in place among them the Hyperion (Pearlman *et al*, 2001) making the study of the potential of such systems in mitigating against environmental factors such as soil swelling even the more important. The increased spectral resolution has gone hand in hand with improved spatial resolution of remote sensing sensors that also offers another significant tool that could be of use in the study of surface expression of these soils that has in the past been established to show significant differences with other soils. By integrating such a study with well-established physical chemical methods such as the Atterberg limits, cation exchange capacity (CEC) and coefficient of linear extensibility (COLE), a better understanding of these soils could be achieved. Incorporation of geophysical methods for use in depth study of these soils could also be of significance in establishing their volumetric extent from the surface. There having been little research with regard to such an integrated approach, it is against this background that the current research was undertaken with the following set of objectives:

1. To establish better understanding of relationships between soil properties and soil swelling potential
2. To establish spectroscopic parameters diagnostic of the swelling indicator clay minerals and on this basis their potential in differentiating among soils in which the minerals dominate
3. To study relationships between these diagnostic spectral parameters and the physicochemical properties of soils currently used as swelling potential indicators and from this establish empirical relationships to predict soil swelling from spectral information
4. To establish the role of high spatial / spectral resolution remote sensing in such applications.
5. To investigate the potential of geophysical methods in swelling soil mapping based on their potential to recognize the presence of these minerals remotely

### **Study Areas Selection**

Two study areas were selected for the study, one in central Kenya and the other in southern Spain from both of which there is a wide information database on the soils. Selection of the areas was based on the fact that the environment in which soils develop has been sited to influence the physicochemical properties and the mineralogical assemblage of soils. The two areas represent a tropical and an intermediate temperate Mediterranean climate in which there are different mineralogical assemblages dominant in the soil matrix. The area in Spain is rich in 2:1 type of clay minerals with illite dominant and inter-layer illite/smectite being the other major assemblage. The selected area in Kenya is rich in both the 1:1 and 2:1 type of clay minerals, which is largely dependent on the topographic position. The soil of the low-lying plains to the centre of the area (see figure 1.1) consist of smectite as the dominant clay mineral type whereas those from the upper grounds surrounding these plains consist of the kaolinite family as the dominant clay mineral.

The soil information reveals the occurrences of swell/shrink soils in the selected area in Kenya to be more spatially widespread and these type of soils in overall terms in the country have been described to occupy approximately 28% of the country's total surface area (Muchena and Gachene, 1988). The soils are more limited in Spain and in the selected area in particular. Table 1.1 gives a summary of the two areas in terms

of parent material, dominant clay mineralogy, and the total number of collected samples. Table 1.2 provides a summary of the available sources of data among them the resolutions of spectral data where there was availability of higher spectral resolution in Spain relative to Kenya. Though it had been the intention to obtain higher spectral resolution for the two areas especially in terms of satellite imagery, availability at the time even in terms of ASTER was not forthcoming in the Kenyan case where imagery was unavailable since the bypass over the study area was in most cases at night. The only daytime image availability was late in the month of July 2003 when the writing of the dissertation was complete. Landsat image acquired during the time of the fieldwork was used instead.

**Table 1.1.** General information on soils parent material, dominant mineralogy and swell potential

Site	Parent material	Dominant clay mineralogy	Average Swell	No. of samples
Spain	Sedimentary rocks Marls, dolomites, conglomerates & sandstones	Illites & illites/smectites interlayer	Moderate/low	44
Kenya	Volcanics & basement rocks	Kaolinite & smectites	High/low	97

**Table 1.2** Used data for the Kenya and Spain study areas

Sensor details	Aerial Photo Interpretation	Hyperspectral (DAIS)	Multi spectral
Spatial resolution	1:25.000	5 m	20-30m
Spain	+	+	-
Kenya	-	-	+
Soil information	Semi-detailed (1:50 000)	Reconnaissance 1:150.000	
Spain	+	-	
Kenya	+	+	



### **Kenya Study Area-Nairobi**

The study area (Figure 1.1) is bounded by  $1^{\circ} 00'$  to  $1^{\circ} 30'$  S latitudes and  $36^{\circ} 30'$  to  $37^{\circ} 30'$  E longitudes. The climate is pleasant with temperatures ranging between  $14^{\circ}$  and  $28^{\circ}$  C while rainfall is moderate and fairly uniform throughout the year increasing as one moves from the east to the highlands in the northwest of the area. This pattern is reflected in the soil development coupled with the influence of the parent material (country rock).

The soils to the northwest are products of weathering of the mainly volcanic rocks under relatively high temperature and rainfall coupled with good drainage. They consist of strong brown to yellow-red friable clay and red friable clays with high humus layer overlying clay, having developed from lava, volcanic tuff and ash in humid conditions with a rainfall of more than 1000mm per year. This gives way southeastwards to red friable clays developed on similar rock types in areas where annual rainfall is slightly lower 762-1000mm (Saggerson, 1991). These conditions have resulted in soils rich in both kaolinite and iron oxide, which have been attributed to the leaching of soluble bases and silica leaving aluminium in the form of the kandite clay minerals and the iron oxides (Dumbleton, 1967; Sherwood, 1967). The leached components accumulate in the plains in the middle of the area and stretching southwards, which coupled with poor drainage due to impermeable underlying rocks, has resulted in development of black to dark grey soils comprising of *vertisols* with calcareous and non- calcareous variants and dominated by smectite as the clay mineral. To the east are soils that are products of the basement system of rocks subjected to low rainfall and good drainage resulting in kaolinite as the major clay mineral.

The soils range in depths from a few centimeters to several meters dependent on the physiographic position in the landscape. The red soils in the highlands are deep with well-developed profiles while those in the low-lying plains vary in depth dependent on their position within the plain i.e. the soils are more shallow on the convex buff slopes than on the flat mid plains. In some areas the concept of litho-morphic versus topomorphic characteristics could be applied as the controlling factors in these soil development. In both cases though, the neo-formation of smectites clay is important with the *Vertisols* best developed where the thickness of the solum (A&B horizons) is thicker than 90 cm. Shallow stony soils characterize the east-southeast trending valleys and have been described to derive from various soil types that have been subjected to accelerated erosion.

In terms of cover, heavy healthy vegetation characterize the higher grounds to the east and northwest comprising of the red soils where intense farming is carried out due to the soil fertility. The plains, whose main soils are the vertisols, comprise of scarce vegetation cover making it ideal for remote sensing data applications, with the main landuse being grazing. Attempts to cultivate adapted crops like millet, maize etc. often fail because of unreliable and insufficient rains in addition to the workability of these soils. They are very hard when dry and very sticky and plastic when wet. Expansion of the city of Nairobi towards the plains has caused construction problems for the foundation of structures, sewage, road construction etc, because of the swell/shrink properties of these soils and special provisions need to be taken to prevent collapse of walls, drainage channels, etc in such constructions, which make their study even the more important.

Table 1.3 provides a relative classification of the soils by Scott (1963)/ Sombroek et al. (1980) and a modified classification (Siderius and Kariuki) based on geomorphology. It shows the high swelling *vertisols* variety to form zone 2 (midsection) which is categorized as of generally flat to undulating topography, grey to black in colour with poor drainage and volcanic rocks as the main parent material. The soils flanking the plain to the northwest, consist of *Ando-humic Nitisols*, *Humic Nitisols* and *Eutric Nitisols* (zone1) and those to the east/southeast *Eutric Nitisols*, *Ferrasols*, *Ferric Acrisols*, and *Ferralic Arenosols* (zone3) which in the classification are described to comprise of highly weathered kaolinite and iron oxide rich soils with good drainage supporting strong vegetation cover. Their parent material however vary with those of zone 1 consisting of volcanic and those to the east/southeast of basement system rocks.

**Table. 1.3.** Geomorphological classification of the major soil units

Scott (1963)	Sombroek (1980)	Kariuki/Siderius (2002)
Zone 1; high ground eastern flank Rift Valley (dissected narrow, broad very broad) (Northwest of study area)	R: volcanic foot ridges (dissected lower slopes of major older volcanoes and mountains; undulating to hilly (R1, R2, R3)	Volcanic foot ridges; interfluves, valley sides and valley bottoms
Zone 2; Athi-Kapiti plains (flat to gently undulating) (Midsection)	L: plateaus and high level structural plains (flat to gently undulating; L11, L17, L15) and minor valleys	Structural and denudational plains; lava flows (buffs and mesa's); inclusive of alluvium
Zone 3; Central Hill Mass East of the Machakos District inclusive individual hills (East south east of area)	H: hills and minor scarps (H13, H15) and U: uplands on various levels (Uh15, Uu3) and plain remnants (L1, L14)	Hills and hill land (summit shoulder complex; back slope; foot slope; toe slope; associated with remnants of old peneplains (mainly basement system of rocks)

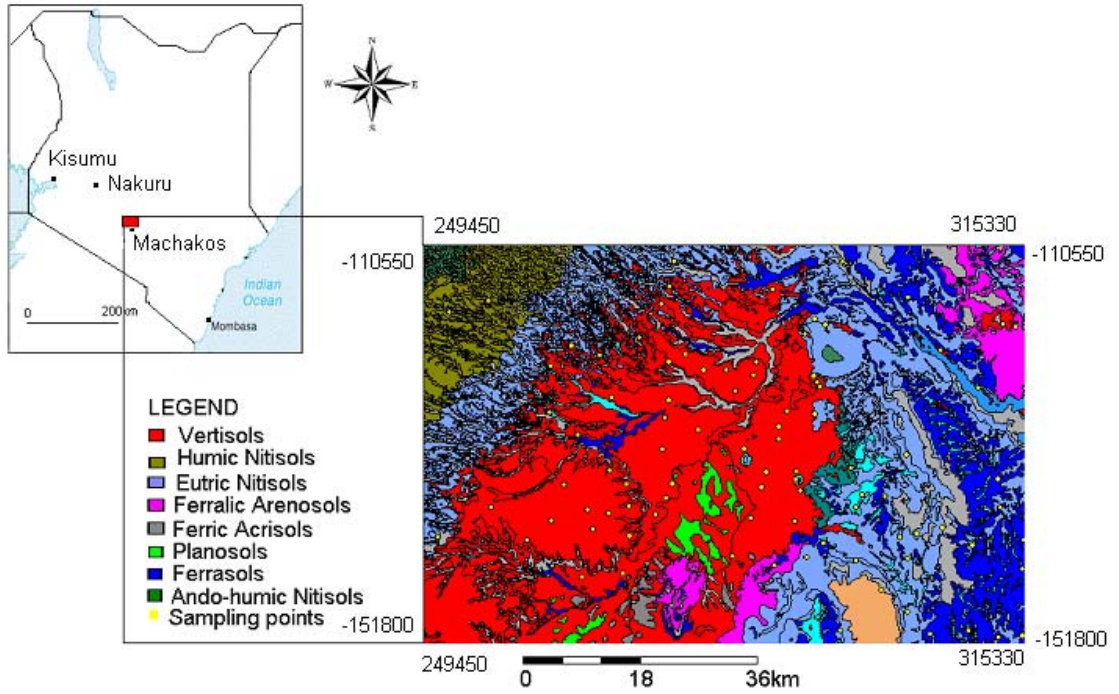


Figure 1.1. Soil map of Nairobi study area (after Scott, 1963)

## Spain Study Area-Antequera

The study area is to the south of Spain (figure 1.2) and lies between latitudes  $4^{\circ}31'10''$  E and  $4^{\circ}51'10''$ E and longitudes  $37^{\circ}00'04''$  N and  $37^{\circ}10'04''$  N. It is about 45km North of Malaga covering a strip of 3 by 21 km between the Municipalities of Antequera, and Campillos in a Northwest -Southeast direction. It falls within the continental Mediterranean type of climate and has a dry summer with an overall mean annual temperature of  $17.6^{\circ}\text{C}$  and rainfall concentrated between the months of October to April. The soils are rich in 2:1 type of clay minerals with illites dominant and interstratified illite/smectite forming the other major group. The soil formation has been greatly influenced by the geology, the main sources being multi-coloured marls, gypsum, dolomites, dolomitic limestone, dolomitic breccias, limestone, white marls, bioclastic sandstone, conglomerates and calcareous sandstone. Geomorphological processes have also played a significant role in the soil development, thus the degree of development has a high correlation with the physiographic position. Classification of the soils in the legend is made based on these landscapes (Siderius, 2002). The main landscapes are: Mountain (Mo), Ridge (Ri), Plateau (Pu), Piedmont (Pi), Hilland (Hi), Alluvial Plain (Pa), Lacustrine Plain (Pl) and the soil map code refers to these codes.

The greater part of the survey area consist of Hill land (Hi) on various parent rock. The nature (composition) of the country rock (viz. resistance to weathering) is thought largely responsible for the present topography. Four major hilllands are distinguished: the first one developed on coloured marls and gypsum, with inclusions of dolomite and dolomitic limestone (Hit), the second one dolomite, dolomitic limestone and limestone with white marls and calcareous sandstone (Hij), the third one on marls and grey calcareous sandstone (Him) and the fourth one on bioclastic sandstone and conglomerates (His). The division of the sloping areas in the hillland into: summit/shoulder, back slope, footslope, footplains and valleys facilitated the recognition of the soils encountered as related to the landscape.

The hilltops comprise of well-drained soils that are shallow appearing as pockets spread out throughout the area with a texture that range from sandy clay loam, to clay and are generally dark in colour (Hit-111 and His-111). Some are however in elongated ridge-like summits and associated shoulders (Hij-111 and Him-111) and are well drained, shallow, dark brown, strongly calcareous, gravelly silty clay. On the hillsides (Hit 112 Him-112 and His-112), old *Alfisols* occur which when subjected to erosion result in the exposure of the *Petrocalcic/Calcic* horizons and in some cases the bedrock. The soils are well drained with a texture ranging from loamy-sand to clay-loam and a variant colour ranging from dark brown to reddish brown. On the foot slopes (Hit-113, Him-113 and His-113), remnants of the *Alfisols* are still predominant and are moderately deep-to-deep, well drained, of sandy clay

loam to clay texture and a colour ranging between dark yellowish brown to yellowish brown. Soils of the foot plains (Him-231, His-231, and Hit-231) vary from well drained, very deep, strong/reddish brown to yellowish red, heavy, cracking clay to well drained, very deep to deep, (dark) reddish brown, strongly calcareous clay that may contain varying amount of coarser fragments and are mainly *Vertic Calcixerepts*). These soils are very extensive and form rather homogeneous units.

Some soils occur in the valleys with or without a drainage channel, vales (Hit 211, His-211 and Him-211) and swales (Hit-221, His-221 and Him-221) respectively whose parent material is a mixture of alluvial and colluvial materials derived from the surrounding higher ground. The two soils are similar and are well drained to moderately well drained, deep, reddish brown, strongly calcareous, silty clay to clay. The occurrence of multiple deposits in which soils have developed is not uncommon in this topographic position, although the upper soil is described and classified.

In the piedmont (pik-111,112,113 and 121) young soils, which are shallow to moderately deep, have developed over old *Alfisols* due to depositional and erosional processes. They are well drained with a sandy clay loam, to clay texture and a colour that varies from very dark brown to yellowish brown. The plains are composed of fluvial (pla) and lacustrine (plht) deposits with soils developed from the lacustrine deposits being moderately deep, well drained, strongly calcareous, sandy-clay to clay texture and dark brown to brown in colour. Along Guadalhorce river are the alluvial plains with soils that are too recent to develop argillic horizons but on the higher terrace, are deep, dark brown to brown in colour with textures ranging from silty clay to clay and possess *Vertic* properties.

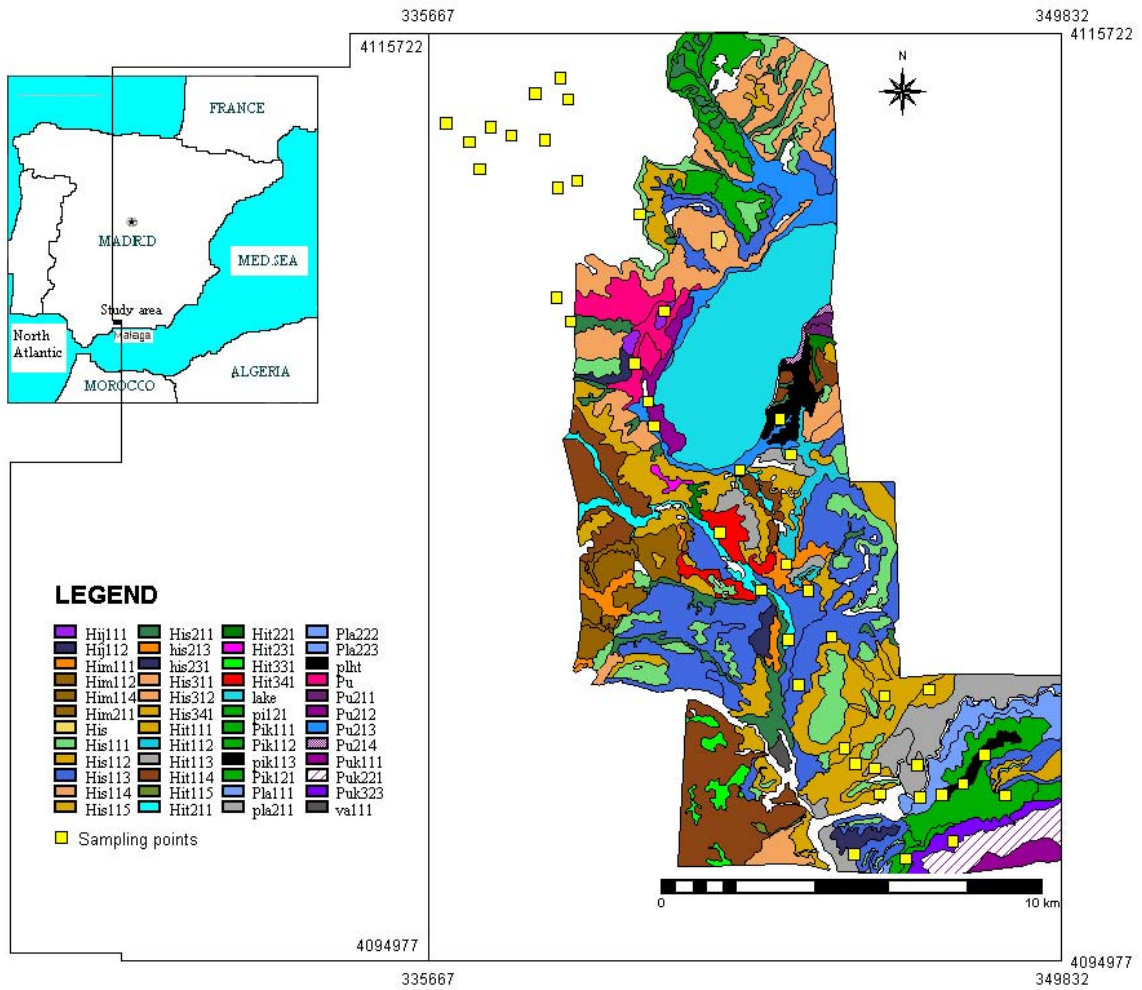


Figure 1.2. Soil map of Spain study area

## **Outline of the Thesis**

Chapter 1 is an introduction to the research that provides a background and problem definition, the objectives of the study and description of the study areas with an emphasis on the soils. In chapter 2, the theory of reflectance spectroscopy is discussed with an emphasis on its application in deriving diagnostic spectral parameters of clay minerals commonly used as swelling potential indicators. The presence of similar spectral parameters in natural soils and their potential to differentiate among the soils on the basis of these minerals are also discussed together with the influence of organic matter and moisture. The soil properties currently used to quantify swelling potential and the potential to apply them as a unified index to estimate swelling on the basis of their indication of clay mineralogy is discussed in chapter 3.

The relationships between soil activity in terms of wet chemistry and physical properties in the form of plasticity with the spectral parameters observed in chapter 2 to have a potential at soil discrimination based on clay mineralogy assignments are discussed in chapter 4. Chapter 5 addresses the issue of reducing the various swell indices to obtain a unitary swelling index that in turn was used to establish spectral assignments with a potential at estimating swelling potential considering the various influencing factors represented by this index. Chapter 6 deals with the issue of mapping of these soils with hyperspectral data, where the obtained relationships in chapter 5 are tested on the airborne spectral data and their limitations addressed. Multi-spectral data integration with ancillary information is discussed in chapter 7 where the complimentary role of high spatial resolution to low spectral resolution to map surface features related to presence of these soils are addressed. The potential application of geophysical methods of nuclear magnetic resonance (NMR) and Induced Polarisation (IP) to determine clay type, moisture content and cation exchange capacity thus deep non-intrusive mapping of these soils in the event they are buried under recent deposits is the subject of chapter 8 at a laboratory scale, as prove of concept for future studies. Chapter 9 summarizes the obtained results discusses their implications on the future mapping of swelling soils and touches on the limitations of the used methods.



## CHAPTER 2

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### **SPECTRAL PROPERTIES OF CLAYS AND CLAY SOILS**

*Based on: Kariuki, P.C., Woldai, T., and Van der Meer, F.D., 2003, Effectiveness of Spectroscopy in Identification of Swelling Indicator Clay Minerals (International Journal of Remote sensing, 24(), in press)*

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*"Fortune is not on the side of the faint-hearted." – Sophocles, Greek dramatist  
(496-407 BC)*

## **Abstract**

Smectite, illite and kaolinite are clay minerals widely used as pathfinders to hydrothermal deposits in geology and in civil engineering as swelling potential indicators. This chapter reviews the background of optical spectroscopy and its capability at qualifying and quantifying these minerals where synthetic mixtures and soils rich in the minerals are used. The physical basis behind the ability to differentiate among these minerals and their influence on the soil spectra are also discussed based on the assignment of the spectral parameters identified as giving good basis for discriminating the minerals to their related crystal structure. The most diagnostic of the features were the hydroxyl and molecular water features that result from vibrational processes in their bonds with metal cation. Organic matter and moisture, two of the most common and influencing soil constituents were established to have varying influence on the spectral diagnostic features dependent on the clay mineral type dominant in a mixture or soil. The results show a potential application in future mapping of soil differences on the basis of these minerals from spaceborne and airborne platforms if the influence from organic matter and excess moisture could be overcome.

## **2.0 Introduction**

Clay minerals and clay soils have unique physicochemical properties that have been widely used to differentiate among them (Head 1992). Of special interest in construction has and continues to be the characteristics of three clay mineral groups namely smectite, illites and kaolinite based on their water absorption tendencies and their potential to act as indicators of soil swelling properties and their identification and quantification in soils has been described as critical for any engineering project (Mitchell, 1993). Easy determination of their presence and abundance has been and continues to be a subject of research and many direct and indirect methods have been established, mainly based on their influence on the soil physicochemical properties such as plasticity, linear extensibility, particle size distribution and cation exchange capacity (CEC) among others. This has resulted in thresholds within which a soil is described as dominated by one or the other (Skempton 1953; Pearring 1963; Holt 1969; McKeen and Hamberg 1981; Hamberg 1985; Nelson and Miller 1992). Other more direct but more expensive methods include X-ray diffraction (XRD), differential thermal analysis (DTA) and scanning electron microscope (SEM), which are rarely used in small projects. The establishment of quick and non-intrusive/destructive methods of identifying these minerals and as such swelling potential of soils could offer a very significant development and spectroscopy offers such a potential based on its potential at separating soils on the basis of these mineralogical differences.

Spectroscopy's potential is based on the significant diagnostic information found in the short wave infrared (SWIR) for these minerals and has been widely used in exploration of hydrothermal deposits where the minerals act as pathfinders. Several studies have established a possibility of using this information not only to recognise the presence of these minerals but also to quantify their related soil properties among which are Goetz et al (2001) estimation of smectite and Kruse (1991) relative kaolinite fraction estimation in interlayer smectites and kaolinites. Others have reported on the potential application of spectroscopy to estimate associated properties, among which are cation exchange capacity (Chang et al 2001; Kariuki et al 2003), particle size distribution (Zhang et al 1992) and saturated moisture content (Ben Dor et al 2002). Recent studies have even established potential application of airborne spectroscopy for related studies (Muller and Decamps 2000; Chabrillat et al 2002).

Launching of spaceborne hyperspectral imaging systems, such as the Hyperion (Pearlman et al, 2001) has further necessitated a more aggressive search for applicability of spectroscopy to solve practical world problems such as the swelling potential tendencies for such would provide tools for mapping at large scales. Van der Meer, (2002) has reported on the potential of these new systems at identifying types of exposed minerals, in small, sub-pixel units. Rowan and Mars (2002) have also identified the potential identification of the Al-OH Mg-OH and Fe-OH, key components of the three minerals, based on relative band depths of 5 bands in the area of OH and H<sub>2</sub>O bending and stretching modes using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imager. With such a rich potential for the surface mapping of these minerals and their related properties, a need exists to investigate the spectral differences of their mixtures that is the norm rather than the exception in natural environments and the possibility of using linear unmixing techniques to qualify their presence. Influence of other major surface soil constituent's namely, organic matter and moisture, usually intricately mixed with the minerals in nature need some attention to enable understand the limitations to the use of such data.

## **2.1. Rational For This Study**

### *2.1.1 The Absorption Process*

Photons entering an absorbing medium are absorbed in accordance to Beer-Lambert Law, where the concentration( $c$ ) and absorption coefficients ( $k$ ) of the material determine the level of absorption (Svanberg, 2001). Absorption is therefore a function of the type and arrangement of atoms within the crystal lattice of the material and directly influence the appearance of the spectrum, more so the

intensities and shape of the absorption features. Thus for absorption spectra, the intensity of the emerging energy ( $I$ ) can be expressed in terms of the incident energy ( $I_0$ ) and in Beer Lambert law is given as:

$$\text{Log}_{10} (I_0/I) = \log_{10} (1/T) = kcl = A \quad (2.1)$$

Where  $A$  is absorbance;  $k$  proportionality constant called molecular absorption (extinction) coefficient characteristic of the absorbing media,  $c$  is the concentration of absorbing molecules and  $l$  the path length of the irradiating energy through the sample. Thus the absorbance is directly proportional to the concentration of the absorbing material and a linear relationship exists between absorbance and concentration, provided Beers law is upheld.

In spectroscopy, reflectance ( $R$ ) is analogous to transmittance and equation 2.1 can be expressed as:

$$\text{Log}_{10} (1/R) = kcl = A \quad (2.2)$$

This is more commonly expressed as

$$A = \text{Log}_{10} (1/R) \quad (2.3)$$

This has the advantage of a near linear relation between the concentration of the absorbing component and its contribution to  $\text{Log}_{10} (1/R)$  at the wavelength absorbed (Hruschka, 1987). The parameters of these absorption features namely; position, shape, depth, width and asymmetry (Figure 2.1) are controlled by the particular crystal structure in which the absorbing species is contained and by the chemical structure of the mineral. This makes identification and quantification of such minerals from these parameters possible.

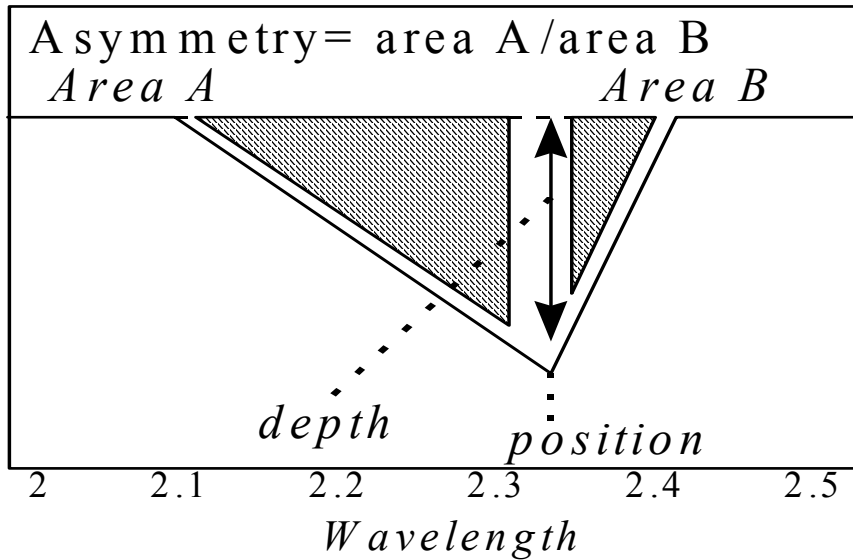


Figure 2.1. Absorption feature parameters

Where, position is the wavelength of minimum reflectance and width,  $W$ , is given by:

$$W = \frac{Area_{left} + Area_{right}}{2D} \quad (2.4)$$

$D$  is the depth of the feature relative to the hull (Green & Graig, 1985) and area is given by the summation of the  $Area_{left}$  and  $Area_{right}$  of the line through the centre of the absorption feature. Asymmetry,  $S$ , is the ratio of the  $Area_{left}$  to  $Area_{right}$  of the absorption centre,

$$S = Area_{left} / Area_{right} \quad (2.5)$$

There are three major absorption features that characterize the reflectance spectra of clay minerals in the SWIR region, which are overtones and combinations of fundamental features that occur at longer wavelengths due to vibrational processes in OH, and H<sub>2</sub>O making applications of SWIR spectroscopy in clay mineral studies ideal. Such has included the study of chemical substitution of their octahedral major cations of Al, Mg and Fe all of which have different bond lengths to the molecules of OH, and H<sub>2</sub>O, and therefore have different, predictable wavelength positions which can be used to identify the specific molecular bonds and the mineral species in which they occur (Alonzo, 2002). Crystallinity or order in the minerals can also be obtained based on its dependence on the type, size and arrangement of atoms and molecules. In cases where when bonds are consistent in length and atoms fill lattice sites, order in the crystal is promoted and is manifested in the spectral signatures by sharp, well-defined absorption feature profiles which can be quantified from the asymmetry value (Hauff, 2000). Dislocations charge imbalance or substitutions, result in disorder and the spectral signature manifests this with broad, shallow absorption features with shifting wavelength values for the minima.

Manifestation of these characteristics is key to identification of the minerals in natural materials such as rocks or soils where they commonly occur in mixtures. However, insufficient research has been done to understand more than the basic theories that govern these features making it literally impossible to accurately unmix or mix materials in percentage models without empirically determined calibration data (Hauff, 2000). This therefore necessitates studying known mixtures of these minerals for better understanding of spectral characteristic differences among soils especially based on the knowledge that such mixtures have in the past been successfully used to provide important information on soil properties (Mitchell, 1993).

Mathematical models for the analysis of reflectance spectra of mineral mixtures have been presented by many workers among which is that of Hapke (1981) that is widely accepted due to simplicity and straight forward approach. It has been applied successfully in many studies (Clark, 1983; Mustard and Pieters, 1987; van der Meer 1995) and was used as the reference in this paper where reflectance spectra of the clay mineral mixtures are studied as functions of compositional fractions as is usually the case in soils. The effects of two other common soil constituents namely, organic matter and moisture on the resulting spectra area also addressed.

First the theory is briefly discussed followed by discussion on the diagnostic differences in terms of absorption feature parameters in the said minerals. Later, results of curves calculated based on the theory are compared with those obtained from powders of two of the minerals and their mixtures thus assessing the potential of quantifying compositional differences in the minerals based on reflectance theory. Finally, the conclusions drawn from the artificial mixtures are used to interpret the reflectance spectra of soils rich in these minerals.

## 2.2 Reflectance Theory

Hapke (1981, 1986) obtained a method where diffuse reflectance,  $r$ , of a particulate medium can be related to mean single-scattering albedo,  $\omega$ , of an individual particle through the Kubelka-Munk (1948) equation i.e.

$$\sqrt{(1-w)} = (1-r)/(1+r) \quad (2.6)$$

which can be rearranged to give

$$w = 4r/(1+r)^2 \quad (2.7)$$

where  $r$  and  $w$  are functions of wavelength. For a mineral having a measured bihemispherical reflectance spectrum,  $r(\lambda)$ , the single scattering albedo spectrum can be derived directly from (2.5) and from Hapke's (1981) Eq. (17), the mean single-scattering albedo,  $w(\lambda)$ , of a multi-component particulate mineral mixture is a linear combination of the single scattering albedos of each of the components, weighted by their effective cross-sectional area. This yields

$$w(\lambda) = \frac{\sum M_i w_i(\lambda) / \{\rho_i d_i\}}{\sum M_i / \{\rho_i d_i\}} \quad (2.8)$$

where  $i$  refers to the  $i^{\text{th}}$  component in the mixture,  $M$  is the mass fraction,  $\rho$  is the particle density, and  $d$  is the effective particle diameter. This equation assumes that the particles are homogeneously distributed and that one particle does not coat another. By inverting (2.5), the bihemispherical reflectance of the resulting mixture can be obtained as

$$r(\lambda) = \frac{1 - \sqrt{(1 - w(\lambda))}}{1 + \sqrt{(1 - w(\lambda))}} \quad (2.9)$$

Further development of this model to incorporate the phase and the backscattering functions of the surface adds unknowns to the equation and has been found to only add a few percentages in the derived reflectance level (van der Meer, 1995). This makes the use of the simple model to assess quantitative mixtures adequate where a linear combination of spectral end-members can be chosen to decompose the mixed reflectance spectrum  $R_i$ , into fractions  $f_j$  of its end-members,  $Re_{ij}$ ,

$$R_i = \sum_{j=1}^n f_j Re_{ij} + \varepsilon_i \quad \text{and} \quad 0 \leq \sum_{j=1}^n f_j \leq 1 \quad (2.10)$$

where  $R_i$  is the reflectance of the mixed spectrum in wavelength  $i$ ,  $f_j$  is the fraction of each end-member  $j$  calculated wavelength by wavelength,  $Re_{ij}$ , is the reflectance of the end-member spectrum  $j$  in wavelength  $i$ ,  $j$  is each of the  $n$  end-members and  $\varepsilon_i$  is the residual error. This residual error,  $\varepsilon_i$ , is the difference between the measured and modelled signal in each wavelength and should in theory be equal to the instrument noise in case that only the selected end-members are present as was the case here.

### 2.3 Reflectance Spectra of Clay Minerals

Water molecule ( $H_2O$ ) and hydroxyl ( $OH$ ) produce diagnostic absorptions in clay minerals in the short-wave infrared (SWIR) wavelength region. The overtones of water are seen in reflectance spectra of smectites, the water-bearing mineral in the group, where the first overtone of the  $OH$  stretch occur at 1400nm and that due to



the combinations of the H-O-H bend with the OH stretch occur near 1900nm. The combination of fundamental OH stretching ( $\nu$ ) and bending ( $\delta$ ) modes occur between 2200 and 2300nm and is also diagnostic of the clay minerals (Clark, 1999). Farmer (1974) assigned them to combination of fundamental OH stretching ( $\nu$ ) and bending ( $\delta$ ) modes of OH-metal-OH bonds in octahedral positions as 2160-2170nm, 2210-2240nm and 2300nm for ( $\nu_{\text{Al-OH-Al}} + \delta_{\text{Al-OH-Al}}$ ), ( $\nu_{\text{Al-OH-Fe}} + \delta_{\text{Al-OH-Fe}}$ ) and ( $\nu_{\text{Mg-OH-Mg}} + \delta_{\text{Mg-OH-Mg}}$ ) respectively. The positions as previously discussed, vary among the minerals, depending on the details of their composition and associated atomic bonding characteristics. Crowley and Vergo (1988) observed the 2200nm OH band to occur near 2220nm in illites, closer to 2200nm in smectites and near 2199nm in kaolinite, which they attributed to ratios between the three basic metal cations of Al, Fe and Mg.

At high resolution, kaolinite shows diagnostic doublets at 2200nm and 1400nm, consisting of 1395nm and 1415nm for the 1400nm OH stretch overtones and 2163nm and 2208nm for the 2200nm Al-OH bend plus OH stretch combinations. Their strength in kaolinite has been attributed to higher fraction of octahedral (1:1 Al-OH: SiO<sub>4</sub>) to tetrahedral structure relative to (2:1 tetrahedral: octahedral) in the other clay minerals. The spectrum of smectite is typical for a water-rich mineral with strong absorption bands, near 1400nm and 1900nm and an additional weaker band near 2200nm that is usually broad due to the presence of structural water. In the absence of free water the feature at 1900nm is sharp and intense and shifts to lower wavelengths and is diagnostic (Hauff, 2000). Ben Dor et al, (1999) attributed the presence of the structural water in smectites to high specific surface areas combined with high levels of substitution resulting in excess charge thus necessitating the accommodation of the water to neutralize the charge. Illite like smectites does not show fine structure at the hydroxyl positions but diagnostically shows additional bands near 2350nm and 2450nm.

Very strong molecular water bands in dried samples are therefore indicative of bound water typical of smectites while strong hydroxyl bands are typical of kaolinite (Hunt and Salisbury, 1970) while illite shows broader and low absorption intensities for both features since the hydroxyls are more randomly distributed in the octahedral sites (Mathews et al. 1973). Table 2.1 gives a generalized description of the important absorption features in these minerals spectra and their molecular assignments, a potential interpretational tool of fractional quantities where they occur in mixtures.

**Table 2.1.** Major clay mineral related absorption feature positions (after Hauff, 2000)

Major Feature positions	Molecule	Clay mineral
1400nm	OH and H <sub>2</sub> O	Kaolinite/smectites/illites
1900nm	H <sub>2</sub> O	Smectites/illites
2170nm	Al-OH	Kaolinite
2200nm	Al-OH	Kaolinite/smectites/illites
2290nm	Fe-OH	Smectite (notronite)
2300nm	Mg-OH	Smectite (hectorite)
2340nm	Fe-OH/Mg-OH	Illite
2384nm	Fe-OH	Kaolinite

### 2.3.1 Laboratory procedures

Clay mineral powders of kaolinite and montmorillonite, (the two being the extreme end members of the soil properties under study), supplied by Ankerpoort NV mineral company Netherlands to the Engineering Geology department of Delft Technical University together with clay soils with the minerals as dominant in their clay content were used in this study for comparison with the theoretical mixtures made using the Hapke model in which the specific gravity values for the minerals given in Table 2.2 were used. The mixtures were made quantitatively at increments of 10% to between 0-100% percentages for each mineral, which were then oven dried at 30<sup>0</sup> for 24hours and cooled in a desiccator prior to spectral data acquisition.

The reflectance spectra were quickly taken using a Portable Infrared Mineral Analyzer (PIMA II) spectrometer that has an internal 10-Watt stable lamp as the light source and an automatic wavelength calibration that uses a built calibration target. The spectra are radiometrically calibrated during each spectral scan to give a spectral resolution of an average of 7nm at a spectral sampling intervals of 2nm.

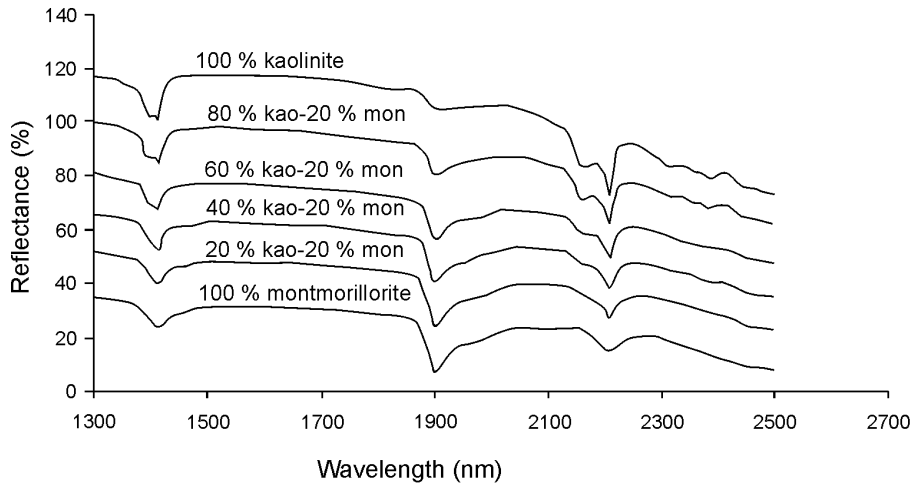
**Table 2.2.** Specific gravity/surface area of minerals used in the mixing

Mineral	Specific gravity (g/cm <sup>3</sup> )	Specific surface area (m <sup>2</sup> /g)	Formula/unit cell
Kaolinite	2.6-2.63	10-20	(OH) <sub>8</sub> Si <sub>4</sub> Al <sub>4</sub> O <sub>10</sub>
Smectite	2.35-2.7	50-120(primary) 700-840(secondary.)	(OH) <sub>4</sub> Si <sub>8</sub> Na <sub>0.33</sub> (Al <sub>3.34</sub> Mg <sub>0.66</sub> ) O <sub>20</sub> .nH <sub>2</sub> O
Illite	2.6-3.0	65-100	(K, H <sub>2</sub> O) <sub>2</sub> (Si) <sub>8</sub> (Al, Mg, Fe) <sub>4</sub> , 6O <sub>20</sub> (OH) <sub>4</sub>

The absorption feature mapping technique (Mustard and Sunshine, 1999), a physically based method that exploits the characteristic of materials to exhibit absorption bands that are diagnostic of type and composition together with the derivative analysis technique (Duckworth, 1998) were used in the analysis.

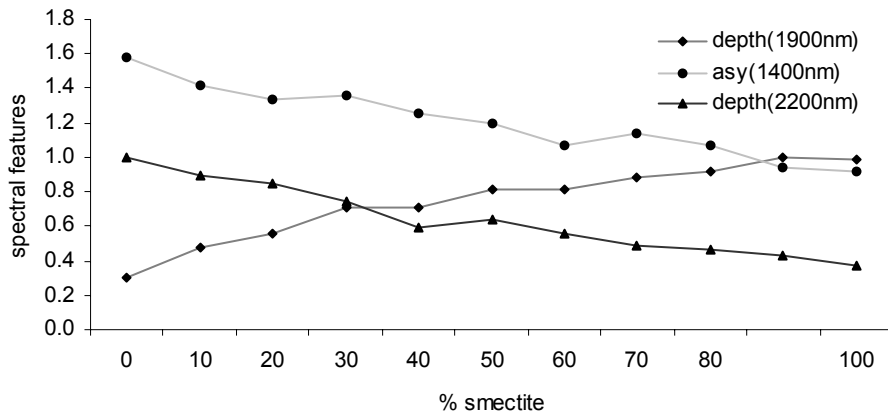
Figure 2.2 gives an illustration of the observed changes in the absorption features with changing contents of the two minerals where abundant kaolinite show three unique diagnostic features at 1395nm, 2170nm and 2384nm up to 40% percentage with the doublets appearing as strong shoulders up to 20% level. It is evident that the presence of doublets and the OH feature sharpness and intensity decrease with decreasing kaolinite. The molecular water absorption feature on the other hand is seen to increase both in depth and sharpness from the generally broad feature at 100% kaolinite, to a relatively sharp feature at 100% smectite signifying presence in a structured position. The results could be described to show the linear mixing of the minerals to provide quantitative evidence of the increasing contents of these minerals. This giving credence to Hapke (1981) theory of simple linear mixtures being provisionally adequate to qualify the abundance of these minerals and thus the applicability of the linear unmixing technique to quantify fractional abundance of the various end members in a mixture.

80 % kao-20 % mon



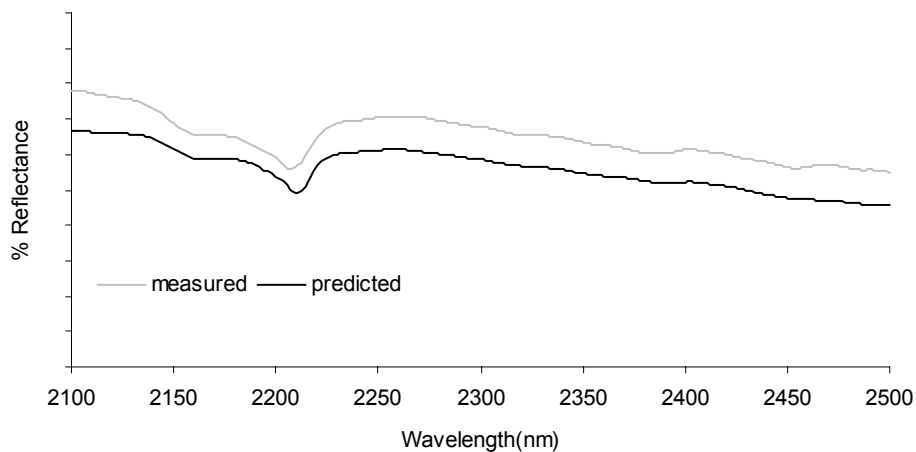
**Figure 2.2.** Calculated reflectance spectral of mineral mixtures of kaolinite and montmorillonite (20 $\mu$ m) notice changes in 2200nm shape

Figure 2.3 shows the absorption parameters as a function of weight percentage of smectite among the used physical mixtures where the general trend described in the foregoing text becomes more evident. Depth intensities at 1900nm increase and asymmetry and depth of the hydroxyl positions at 1400nm and 2200nm generally decreased though subtly with increase in smectite. It is worth noting that aluminum has been described to bring order to the clay structure, which may explain the significance of the changes in asymmetries with kaolinite ratios in which the ratio of aluminum to the other cations is generally higher. Duke (1994) found the wavelength of the Al-OH to shift from 2217 to 2199 nm, corresponding to increase in octahedral aluminum (Al) from 3.3 to 3.7 atoms per 22 oxygens relative to Fe and Mg and described this as a function of cation mass and radius. Gaffey (1984) described these two parameters as the first and second most important factors in determining the absorption feature position. Shift in position is characteristic of cation substitution at the exchangeable sites (Van der Meer, 1995). However, no significant shifts were observed for the hydroxyl feature positions.



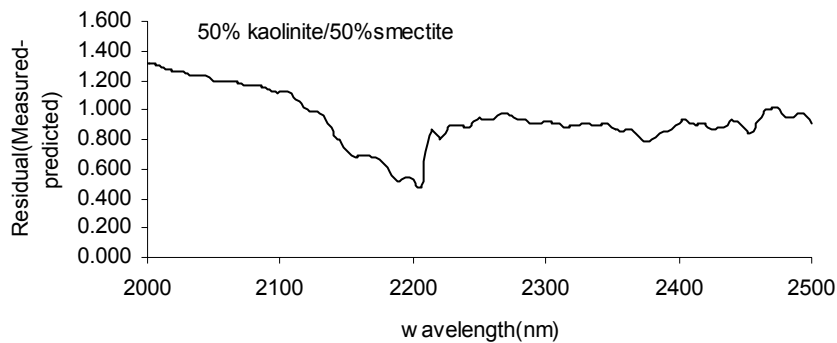
**Figure 2.3.** Changes in absorption feature parameters with smectite content

Figure 2.4 illustrates the measured and calculated spectra in the whole 2100-2500nm region for the same mixture as an illustration of the similarities in the measured and theoretically derived mixtures, which confirm the linear mixing to closely approximate the true mixtures. The spectra are similar, making the assumption that the linear mixing procedures do give an indication as to the compositional differences viable. Kruse (1991) successfully used such an approach on natural samples getting significant results.



**Figure 2.4.** Calculated & measured reflectance of 50% kaolinite/ smectite mixture

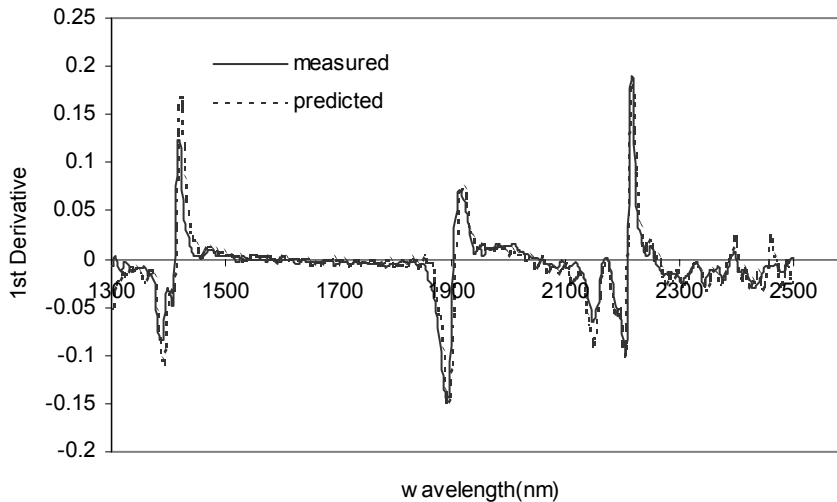
The difference between the estimated and the true measures of the spectra for the various mixtures were established to be less than 2% reflectance as is illustrated in Figure 2.5 for this particular mixture establishing the theoretical estimation to generally approximate the true reflectance of the physical mixtures.



**Figure2.5.** Difference between measured and calculated spectra of above spectra.  
The difference is less than 1.5% reflectance

Derivatives have been used in many works to resolve compositional information from spectra and are based on the presumed capability of their removing the baseline effects and thus separating subtle spectral differences particularly in overlapping features thus enabling more detailed analysis (Escadafal, 1994). The first derivative measures the slope of the spectral curve and the second the change in slope.

The two were observed to enhance the water and hydroxyl peaks to different magnitude among the mixtures dependent on the quantitative abundance of the minerals used. Absorption peaks were stronger at the molecular water absorption features in abundant smectite and for hydroxyl in abundant kaolinite. Figure 2.6 illustrates the enhanced first derivative peak intensities for both theoretical and quantitative mixtures of kaolinite and smectite of the example used above where the characteristic peak intensities are strong for both the hydroxyl and water features due to their similar compositional abundance. Note the opposite signs of the peak intensities.



**Figure 2.6.** Calculated & measured derivative peaks of 50% kaolinite/ smectite mix

It can therefore be concluded that in simple mixing several characteristics of spectra gives an indication as to the potential quantitative contents of the clay minerals for which fractional abundance can be estimated from the resulting spectra. It is however, worth noting that in natural systems the mixtures are usually intimate resulting in non-linear mixtures thus requiring calibration before such interpretations can be made. Other factors are also known to influence the spectra in the natural environment more so the albedo and absorption feature intensities. The two worth better understanding when considering soil spectral are moisture content and organic matter.

## 2.4 Effects of Moisture and Organic Matter

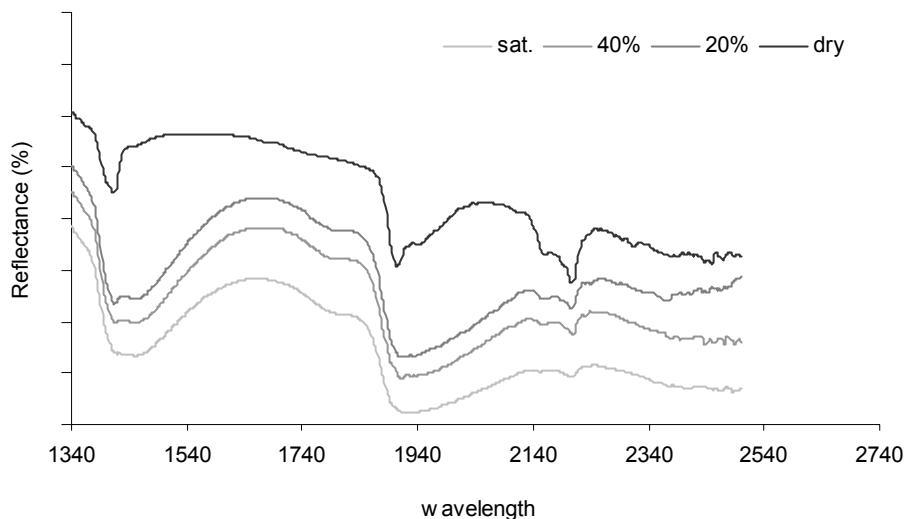
In this section the influence of moisture and organic carbon on the spectral characteristics of the used mixtures are evaluated. The two are common in soil with an effect on the overall reflectance and absorption intensities of the compositional elements of the soil (Mulders 1987).

### 2.4.1 Moisture content effects

Three forms of water as found in soils are active in the SWIR and have been classified into hydration (incorporated in the lattice), hygroscopic (adsorbed on surfaces) and free pore water (in between the particles). Each of these categories influences soil spectra differently, providing the possibility of identifying the water

condition of a sample. Bands due to water bonded to clay minerals (hydration) are narrower and occur at shorter wavelengths because of the OH modes (Van der Meer, 1995) while free and hygroscopic water reduce the overall soil reflectance (Bowers and Hanks 1965; Bedidi et al, 1991) and mask contribution from other soil constituents dependent on quantities. Presence of excess water result in the characteristic water absorption features at 1400nm and 1900nm appearing rounded in shape a characteristic that has been described to portray water in unordered positions (Hauff, 2000). Weidong et al, (2002) found the thresholds at which each of these waters influence the soil spectra to be different dependent on the dominant clay mineral type thus diagnostic and attributed this to their differences in affinity to water due to varying specific surface areas.

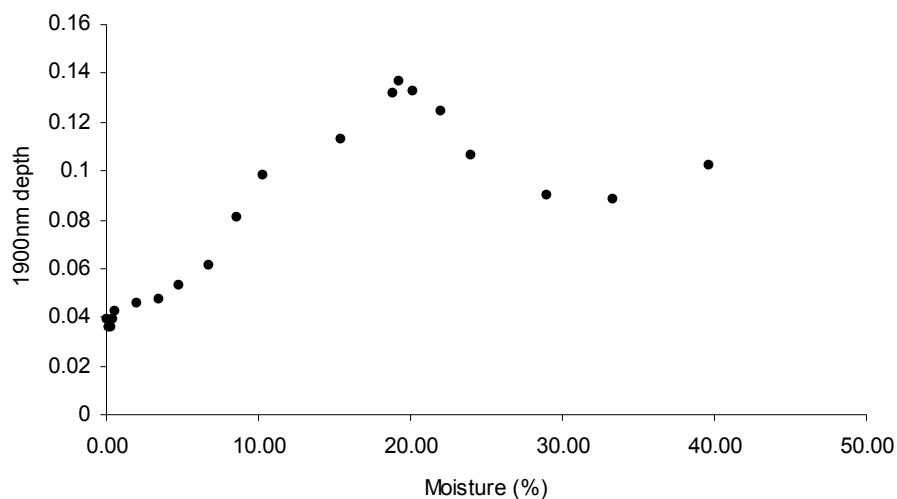
Figure 2.6 gives an illustration of spectra changes with water content for the mixtures where there is a clear shift in water absorption feature centres from longer wavelengths (1440nm and 1945nm) to shorter wavelengths with decrease in moisture and a presence of a weaker feature near 1800nm at substantial free water content that disappears at oven dry state. The feature has been reported as important for remote sensing applications. Worth noting is the little change in position for the 2200nm OH feature regardless of water content, the only notable differences having been intensity which was established to be the case even for the other different ratio mixtures.



**Figure 2.6.** Shift in position and increase in feature sharpness with decrease in % moisture for the 50% mixtures of each of kaolinite and smectite



Transition from free to hygroscopic/hydration water was evident at the two water features with the 1900nm position observed to increase in sharpness and shift to lower wavelengths of between 1914-1918nm and 1908-1910nm for abundant kaolinite and smectites respectively at oven dry state. The depth in abundant kaolinite is shallow and broad feature relative to the sharp and deep feature in abundant smectite at the oven dry state. The change in depth was linear to a threshold of about 20% in kaolinite rich samples after which there was a sharp drop to a relative constant at higher moistures that probably signifies a specular reflectance (Figure 2.7), assumed to result from most pores having been occupied by water molecules that water formed a film around the particles. It should be noted however that the feature remained intense in abundant montmorillonite and gave no pattern in change in intensity the only major difference being the changes in sharpness, this probably due to the unmasking of structural water.

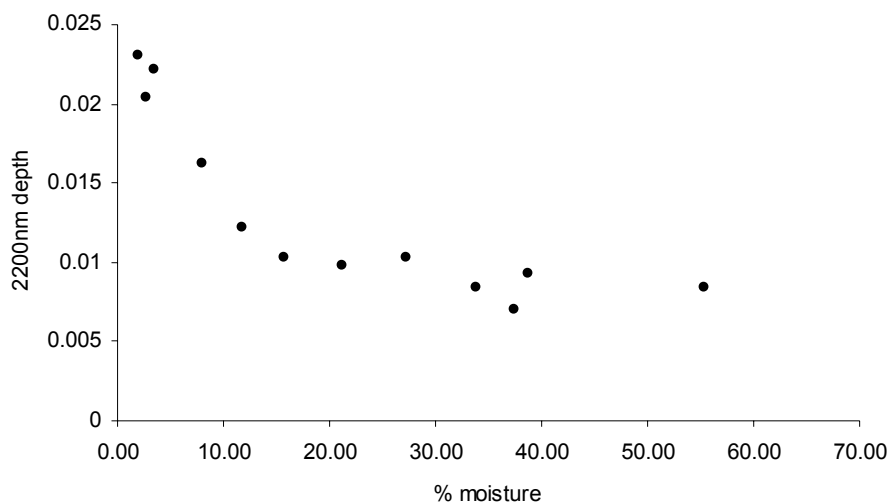


**Figure 2.7.** Changes in depth of molecular water feature with changing moisture for kaolinite rich sample

Position in the 1400nm gave no particular trend though observed show a significant spike at 1418nm at moistures below 30% in abundant kaolinite. Depth increased linearly with moisture to a relative constant at between 20% and 30% content for most samples, regardless of the quantitative contents. However, the feature increased in sharpness with decreasing moisture in all samples to acquire a characteristic reminiscent of the dominant clay type at between 10-20 % moisture but with a much

lower gradient for the smectite rich samples. The lack of difference among the mixtures in increase in depth was attributed to the complexity of the feature due to its increased intensity in both presence of moisture and unmasking of the hydroxyl influence in strong kaolinite presence with reduced free water.

Contents of 10-15% moisture masked the diagnostic kaolinite features at 2170nm and 2384nm, 2200nm was however evident even at saturation in abundant kaolinite and increased in depth with decreasing moisture to acquire the doublet shoulder at 20% and complete sharpness indicative of mineralogical differences at 10-15% moisture. The feature in smectite rich samples, was completely masked at between 20% and 30% moisture (Figure 2.8). It was therefore found safe to draw conclusions based on these mixtures, that moisture contents below 20% leaves enough information on the spectra that could be used to establish diagnostic spectral assignments to the mineralogical compositional fractions. This has good implications to the possibilities of acquiring similar information of the natural soil surfaces where at relatively normal conditions the moisture conditions are usually below the 20% threshold.



**Figure 2.8.** Decrease in depth at the 2200nm feature with increase in moisture for a smectite rich sample. Masking is complete at 20-30%

#### 2.4.2 Organic matter influence

Organic matter is abundant on surface soils and small amounts are known to substantially influence scattering by reducing the overall brightness and masking absorption features. The amount of organic matter to substantially affect the spectrum has been the subject of several studies and has been shown to vary. Baumgardner et al, (1985) gave a threshold of 2% to completely mask contribution from other soil constituents while Montgomery (1976) observed organic matter of as high as 9% not to affect contribution of other soil components. Clark (1983) established it to completely mask pure smectite features at 20% drawing conclusions that the ratio of overtone bands vary as a function of opaque content and can be used to estimate their contents. Schreier (1977) described organic matter content to affect the soil reflectance in a curvilinear exponential function and Da Costa (1979) found simulated Landsat channels of bands 4, 5 and 6 to yield reflectance readings that are significantly correlated with organic carbon content in soils. Ben Dor et al, (1997) on their part established organic matter influence on reflected spectra to be a function of age. These studies thus suggest organic matter to have a substantial influence on quantitative information on other soil constituents that requires more understanding if meaningful information content is to be established from such spectra. However it is also important to note that mineral soils consist of relatively low organic matter contents of between 0 and 4%(Ben Dor et al, 1999) that could fall well within thresholds at which the quantitative information can still be established based on the established thresholds by various workers.

Quantitative mixtures of the clay minerals and carbon established small amounts of the carbon at as low as 5% to result in the spectra changing in shape though complete masking was observed to vary with the abundant mineral type. Masking of the 2200nm feature was complete in abundant smectite at 10%-15% but at 20-25% carbon in abundant kaolinite. The opposite was the case for the 1900nm feature that was evident at as high as 30% carbon in abundant montmorillonite but complete at less than 10% in abundant kaolinite. That of 1400nm was complete at 20-25% in either abundance though that of kaolinite was slightly higher. This seems to agree with the results of Clark (1983), Crowley (1986) and Van der Meer (1995).

## 2.5 Soil Reflectance Characteristics

22 soil samples rich in the clay mineral used above were used to qualify the conclusions drawn from the mixtures after subjection to similar conditions prior to the spectral measurements.

### 2.5.1 Absorption feature parameters

The absorption feature parameters found significant in differentiating among the clay mineral mixtures were also significant among the soils (Table 2.3). Unique presence at 2160-2170nm, 2384nm diagnostic for dominant kaolinite and 2340nm for illite were observed among the soil samples and interpreted as representative. The 2160-2170nm feature was attributed to high Al-OH ratios relative to the tetrahedral as previously discussed and was concluded to be typical of kaolinite abundance in soil and together with the feature at 2384nm (attributed to Fe-OH in table 2.1), assumed to signify substantial kaolinite contents in a soil. Their uniqueness confirmed their importance in assigning soils to kaolinite dominance which probably show the soils to still possess significant information as to the differences associated with the minerals structures such as lack of widespread substitution of the Aluminum (Al) by  $Mg^{2+}$  and  $Fe^{3+}$  at the Al-OH site in kaolinite. The presence of the 2340nm feature in the illitic soils (assigned to Fe-OH/Mg-OH in table 2.1), a usually weak feature, was interpreted very significant in the assignment of soil to illite abundance.

The 2200nm feature and that at 1400nm variation in position were found to be minimal and insignificant as a source of information as to the clay mineral differences in soils just as previously established in the mixtures. The position of the water feature (1900nm), however gave characteristic differences among the soils separating them into two groups. One consisted mainly of the smectite rich samples that had the feature at an average position of 1908nm while the other had the feature as generally broad and at around 1918nm. This was attributed to probable differences in the nature of water where those of abundant smectite had the water subject to stronger electrostatic forces requiring more energy to excite, thus the shift to lower wavelengths, whereas in the other samples the force was weaker due to water being mainly held on the surfaces of the particles. The shift in position could also be explained in terms of the linear nature of the water association with the minerals.

**Table 2.3.** General groupings based on spectral parameters differences

Abundant clay mineral	Smectitic	Illitic	Kaolinitic
Wavelength			
1900nm(shift)	< 1910	>1910	>1910
1900nm(depth)	Intense	Broad and shallow	Shallow
2160-2170 nm	Largely absent	Present/Absent	Present
2340-2350 nm	Largely absent	Present	
Asymmetry (2200,1400nm)	<1	Varied	Mostly >1
2200nm(depth)	Generally broad	Broad	Sharp and intense

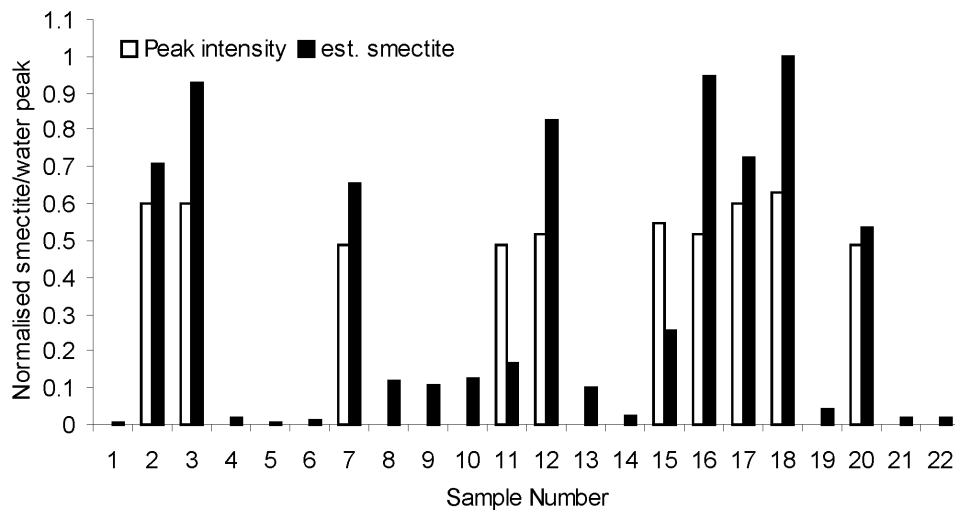
Asymmetries at 1400nm and 2200nm just like in the mixtures, were observed to give an indication of differences based on Van der Meer (1999) scheme that describe asymmetries in the range 2000-2500nm as good indicators to clay mineral differences. Kaolinitic samples generally gave higher asymmetries while those consisting of high smectites generally gave the lowest asymmetry values. Hauff, (2000) described asymmetries in general to indicate order in structural sites and asymmetry to the right at 2200nm (which would explain the smaller value of asymmetry based on the previous description) to show an increment in smectite. She further described asymmetry to the left in strong kaolinite presence as due to the characteristic doublets in kaolinite which show order, a result of multiple sites filling of inner and outer hydroxyls. Thus, it could be concluded that kaolinite rich samples gave generally higher asymmetries at the hydroxyl sites attributable to its characteristic doublets and structural order. This combined with presence of 2384nm can thus be used to assign a soil to abundant kaolinite. This can also be confirmed by the visual observation of the characteristic doublet or shoulder. The samples consisting of high illite contents were observed to give no specific trend probably due to the general broadness of the features in illite (Farmer 1974).

Only two depths were found to vary significantly with the assigned mineral types. The feature at 1900nm gave stronger intensities for samples with high smectites and that at 2200nm in kaolinitic samples, as was the case with the mixtures. In the illite rich samples these differences were not as clear. The differences in intensity

at 1900nm were again attributed to structural water differences. That at the 2200nm was attributed to what Alonso et al, (2002) described as broadening of the feature due to quantitative differences in Al, Fe and Mg as  $\text{AlFe}^{3+}$  and  $\text{AlMg}^{2+}$  increases in the illitic/smectitic soils relative to  $\text{Al}^{3+}$  with much more developed structure which was assumed higher in the kaolinitic samples. The depths thus give a semi-quantitative indication of the abundance of the causative mineral in the absence of external influence.

### 2.5.2 Derivatives

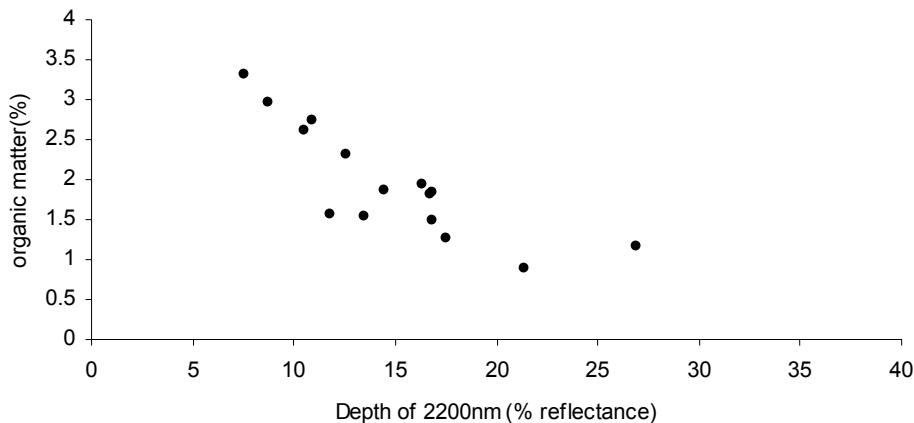
Figure 2.9 gives variation in the bound water peak relative to increase in smectite based on relative estimates among the soil samples where it is mainly those samples with high smectite contents that show significant peaks in the second derivative of the reflectance spectra. This supports observations by Goetz et al, (2001) in which they established derivative peak in the region between 1800-2000nm to give relevant information to bound interlayer water for the detection and quantification of smectite. The fact that the water absorption peaks were more pronounced in high smectite is significant, and confirms the applicability of this peak to estimate smectite abundance and related soil properties.



**Figure 2.9.** 2<sup>nd</sup> derivative water peak (around 1896-1900nm) and relative smectite content relationships

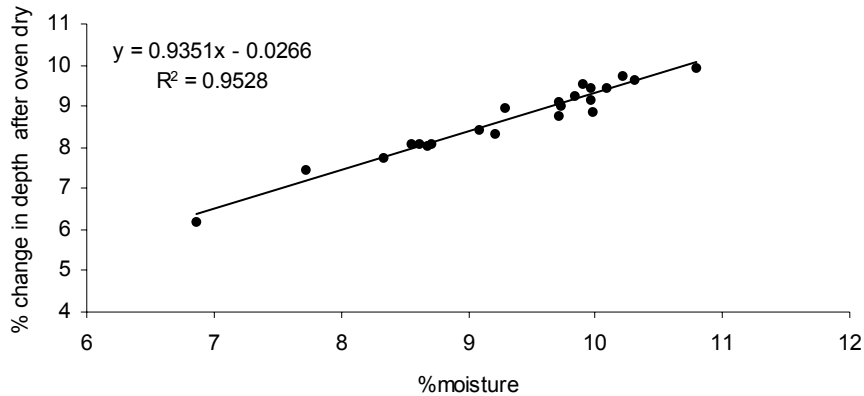
### 2.5.3 Effects of Moisture and Organic Matter on soil spectra

Illustrations of organic matter and free water effects on the intensity of absorption features among the soils are given in Figures 2.10, and 2.11. Figure 2.10 shows the relationship between the organic matter and depth intensities of the 2200nm absorption feature among similar samples that show an indication of an exponential decrease with increase in organic matter content ( $r^2=0.71$  for  $n=15$ ). The effect is more pronounced than in the mineral mixtures probably due to the complexity of the soil.



**Figure 2.10.** Decrease in depth with increasing organic matter

Figure 2.11 shows the relationship obtained between the at field moisture percentage and the difference in depth intensity between this and oven dry state which clearly show a linear ( $r^2=0.95$ ,  $n=22$ ) relationship between this moisture and the change in depth intensity among the soils. The results confirmed those of the synthetic mixtures of there being a near linear relationship between the hydroxyl feature intensity and moisture below a 20% threshold.



**Figure 2.11.** Relationship between % field moisture and differences in depth at 2200nm between oven dry and field moisture

The soils therefore confirmed the potential application of the absorption feature parameters together with the derivatives to obtain information on the compositional differences based on clay mineralogy influence on these spectral parameters.

## 2.6 Conclusions

From the results it has been shown that differences in the parameters of absorption are important in determining the abundant clay mineral type both in synthetic mixtures as well as in soils probably showing a potential of using the method to make quantitative estimates of the minerals in prepared soils based on the variation of these spectral parameters. The physical understanding of the unique nature of these features for these minerals has been shown as possible in that they can be assigned to the minerals crystal structure differences where kaolinite imprints characteristics of order in hydroxyl site while smectite imprints order in the molecular water position. Some problems still have to be overcome especially that of presence of two of the minerals in significant amounts, free water and substantial organic matter, which all tend to mask the diagnostic characteristics in the spectra. Thresholds of these masking components were however established at below 20% for moisture and 15% for organic matter. Thus the results give a strong case in the potential application of spectroscopy in the identification and quantification of these minerals and their related soil properties.



## CHAPTER 3

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### SOIL SCIENCE AND ENGINEERING METHODS FOR EXPANSIVE SOIL IDENTIFICATION

*Based on: Kariuki, P.C., and van der Meer, F.D., 2003. A Unified Swelling Potential Index For Expansive Soils. Engineering Geology, (in press)*

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*"Nothing is really work unless you would rather be doing something else." – Sir James Barrie, Scottish writer (1860-1937)*

*thus*

*"The greater the difficulty, the greater the glory." – Cicero, Roman statesman-philosopher (106 BC-43BC).*

## Abstract

In geotechnical site investigation one factor that must be identified is the expansive properties of the soil. This study was undertaken to assess the expansive nature of different soils using selected physicochemical and mineralogical soil properties and to examine relationships between them and potential volume change resulting in the classification of the soils into swelling potential classes and the establishment of a unified expansive index rating based on available measurements. The methods consisted of particle size distribution (PSD) analysis, coefficient of linear extensibility (COLE), cation exchange capacity (CEC), exchangeable cations, the Atterberg limits and saturation moisture (SP) contents tests. The COLE as the most direct indicator of quantitative potential volume change (PVC) among the indices was used as the point of reference to qualify the relative potential of each of the other indices for inclusion in the proposed index based on the Pearson's correlations between the said index and the PVC. Results indicated a wide range in swelling potential among the various soils. CEC, liquid limit (LL) and plastic index (PI) were established as the most significant for inclusion in the proposed unified index based on their strong correlations with the PVC. Two exchangeable bases namely  $Mg^{2+}$  and  $Ca^{+}$  gave moderate correlation whereas  $Na^{+}$  and  $K^{+}$  together with the various particle sizes gave poor correlations with the PVC. Normalization of the significant indices with clay content resulted in indices with relatively good correlations with the PVC and their combinations were used to establish unified swell potential ratings.

## 3.1 Introduction

Expansive soils occur the world over and pose serious problems to engineering structures more so in areas of rapid urban growth. The swelling is restricted to soils containing clay minerals, which are susceptible to penetration of their chemical structure by water molecules (Carter and Bentley, 1991). It has been attributed to osmotic pressures generated by chemical potential gradients between free water and water in diffuse double layers (DDL) forming around the clay mineral surfaces (Parker et al, 1977). The DDLs are due to electrostatic attraction by the negatively charged clay particle surfaces to positive ions in the pores resulting in concentration of the ions around them. Overlapping of the DDLs generate inter particle repulsive forces resulting in swelling (Bohn et al, 1985). Thus, fundamentally soil swelling is an intrinsic property of the clay mineralogy (Seed et al, 1963), though other factors such as the valency of the adsorbed cation play some significant role in the overall volume changes. It is on the basis of this concept that many of the soil swelling potential indices have been developed.

One setback though, has been the lack of a standard definition of swell potential (Nelson and Miller 1992) since not only do sample conditions vary in the different swell tests (i.e. disturbed or undisturbed samples), but also testing factors over a wide range of values. Thus, whereas Holtz (1959) referred to swell potential as the volume change of air dried undisturbed sample, Seed et al, (1962) defined it as change in volume of a remolded sample. It is therefore not to be unexpected that disparities occur in classifications when these indices are applied, making it difficult to use one method to conclusively state the nature of the expansiveness of a soil. Many examples abound where either of the indices have been described to best represent the swelling potential. McCormack and Wilding, (1975) described clay content to be as reliable in predicting swelling potential as the Atterberg limits in soils dominated by illite. Ross (1978) however, found it to be less certain relative to the specific surface area (SSA) and Yule and Ritchie (1980) and Gray and Allbrook (2002) reported that there being no relationship between clay percentage and soil swelling.

Gill and Reaves (1957) described CEC, saturation moisture and PI as some of the most representative properties in the estimation of swelling potential having established them as highly correlated to the SSA. Snethen et al, (1977) evaluated seventeen swelling indices and concluded that liquid limit and plastic index are the best indicators of potential swell while Parker et al, (1977) established swell index (Lambe 1960) and plasticity index as superior to other indices. Schafer and Singer (1976) on their part concluded that clay type rather than the clay content is more important and Thomas et al, (2000) described smectite content as critical in determining the swelling potential level. Karathanasis and Hajek (1985) in a study of montmorillonitic soils, found smectite content as the only consistent soil property that significantly correlated with laboratory-measured shrink–swell potential.

This has led to the general conclusion that no one method estimates swell potential accurately for all soils and there is therefore the need to use a combination of these methods for better results. Several classification schemes have taken cognition of this fact among them Pearring (1963) and Holt (1969), which combine mineralogy, engineering properties and cation exchange capacities and one by McKeen and Hamberg (1981) which is an extension of the former scheme to include COLE. Thomas et al, (2000) on their part instead established an integrated protocol based on the various indices where they use the various indices relationships with quantitative volume change to establish ratings based on their sums.

This study sought to integrate the works of Thomas et al, (2000) and Hamberg (1985) to obtain an expansive index rating based on the knowledge that the

potential volume change is to a large extent dependent on the surface properties of the clay fraction. It offers an index that emphasizes on the understanding of the various soil properties on the basis of clay type contribution to the resulting swell measure providing a normalized and universally applicable index.

## **3.2 Materials and Methods**

### **3.2.1 Sampling sites selection**

Two zones falling in the temperate Mediterranean and humid tropical type of climate were used for this study where sampling sites were carefully selected based on existing soil information so as to represent a wide variation in swelling properties. The Spain samples were of sedimentary origin where their parent materials consisted mainly of limestones, dolomites and marls whereas those from Kenya had volcanic rocks and basement system rocks as their parent material. Illite was the main clay mineral type in the Spain samples with mixed layer smectite/illite dominating in some cases and kaolinite rare. Kenyan samples on the other hand had kaolinite and smectites as the dominant clay minerals dependent on the topographic position from which a sample was obtained. This provided a data set that represented the most common of the soil variation in terms of swelling potential on the basis of clay mineralogy.

### **3.2.2 Laboratory analysis**

The samples were sieved to remove coarse fragments >2mm prior to analysis for the various indices. Table 3.1 provides a summary of the applied methods and the obtained soil properties (swelling indices). The Atterberg limits (PL, PI, LL) were measured by BS1377: Part 2:1990 method (Head 1992), PSD was through the pipette method (Reeuwijk, 1995) while CEC was through NH<sub>4</sub>OAc pH 7 mechanical extractor method (Reeuwijk, 1995) and the methylene blue absorption spot test method (Verhoef, 1992). COLE was by the clod test method (Nelson and Miller 1992) and SP was calculated as the difference in weight between saturation and oven dry state. PVC was determined on the basis of COLE through the method of Parker et al, (1977). Skempton (1953) and Pearring (1963) and Holt (1969) methods of using clay content to normalize plastic index and CEC were used to obtain Activity ( $A_c$ ) and cation exchange activity ( $CEA_c$ ) respectively. The classification charts resulting from the latter as established by McKeen and Hamberg (1981) and Hamberg (1985) were used to classify the soils into swelling potential groups and to clay mineral type relative abundance.

Table 3.1. Soil properties measured and the methods used

Soil property	Method	Reference
CEC (sum of cations)	NH <sub>4</sub> OAc pH 7 (mechanical extractor method) & methylene blue spot method	Reeuwijk 1995 & Verhoef, 1992
pH-H <sub>2</sub> O	pH measures at 1:1 soil/water suspension	Reeuwijk 1995
Particle-size distribution (PSD)	Pipette method (%)	Reeuwijk 1995
Coefficient of linear extensibility (COLE)	COLE clod procedures	Nelson and Miller, 1992
Exchangeable bases: Ca, Mg, Na, and K	Atomic absorption spectrophotometer	Reeuwijk 1995
Saturated moisture content	Saturation and oven drying at 105 <sup>0</sup> C	
LL, PI, PL,	BS1377: Part 2:1990 method	Head 1992

#### *Particle Size Distribution Analysis*

A soil consists of an assemblage of discrete particles of various shapes and sizes. For all the other engineering tests to be effective, determination of the particle sizes is important due to its strong relationship with engineering behaviour. Particle size distribution (PSD) of the obtained samples was done by use of two separate and quite different procedures, sieving and the sedimentation. Sieving was used for sand size particles determination where a series of sieves of standard aperture openings were used. For the much smaller silt and clay size particles, a sedimentation procedure was used by means of the special pipette method (see Head et al, 1992 for details).

#### *Linear Extensibility Test*

The Coefficient of Linear Extensibility (COLE), the most commonly used technique in soil science was used to determine potential volume changes for the different soil samples. In this technique, natural clods of about 10 to 25cm<sup>3</sup> (fist size) are used. The elasticity of saran resin and the fact that it permits the slow passage of water vapour enables the determination of the volume of clods at various moisture contents and thereby enabled the determination of COLE.

$$COLE = \Delta L / \Delta L_D = (\gamma_{dD} / \gamma_{dM})^{0.33} - 1 \quad (3.1)$$

Where  $\Delta L/\Delta L_D$  = linear strain relative to dry dimensions

$\gamma_{dD}$  = dry density of oven dry sample

$\gamma_{dM}$  = dry density of sample at 1/3 bar pressure.

These values have been used as both classification indices of the soils swell potential, or estimators of clay mineralogy. Such is the classification by the National soil Survey Laboratory (1981), where the ratio between the linear extensibility values and the clay content is used as estimators of clay mineralogy.

#### *Atterberg Limits*

The property of plasticity in clays is a function of the electrochemical behaviour of the clay minerals (Carter et al, 1991). Soils that possess no clay minerals do not exhibit plasticity and, as their moisture content is reduced, they pass directly from liquid to the semi-solid state. The cone penetrometer method was used where the liquid limit (LL) was taken as the water content at which a cone of weight 0.78N and an apex angle of  $30^0$  penetrated 20mm in 5seconds into a soil when dropped from a position at which the point just touched the soil surface. The plastic limit was then determined as the water content at which the strength was one hundred times that of liquid limit and was the moisture content at which the rolled threads of the soil started to crumble. The plastic index was then calculated as the difference between the liquid limit and the plastic limit and assumed to be the water content needed to bring about strength change of roughly a hundred-fold, within the plastic range of the soil.

The ratio of the plasticity index to the percentage of material finer than  $2\mu\text{m}$  gives indication of the plasticity of the purely clay sized portion of the soil and is called "activity." A high activity is associated with those minerals that can absorb large amounts of water within their mineral lattice, and is related to the chemistry of the clay particles. Thus, activity is a measure of the propensity of clay to swell in the presence of water and may be used to identify expansive clays. In a broad sense, the plasticity index reflects the ratio of clay mineral to silt and fine sand in a soil and was calculated as the ratio between the derived plastic index and the clay content.

$$\text{Activity } (A_c) = \text{Plasticity Index} / \text{clay content} \quad (3.2)$$

*Methylene Blue Adsorption (MBA) Test*

Cation exchange capacity (CEC) is the quantity of exchangeable cations needed to balance the negative charge on the surface of clay particles and is usually expressed in milli-equivalents per 100 grams (meq/100g) of dry clay. High CEC values indicate a high surface activity. In general, swell potential increases as the CEC increases and the total CEC value is the summation of the individual CEC values of each of the present clay minerals, as a fraction of the total clay content. Two methods were used in the establishment of the CEC i.e.  $\text{NH}_4\text{OAc}$  pH 7 mechanical extractor method (see Reeuwijk, 1995 for details) and the Methylene Blue Analysis (MBA) spot test method.

In the Methylene Blue Analysis (MBA) spot test, the Methylene blue adsorption value was calculated in grams MB adsorbed by 100g of a sample. Titration was done on a sample solution in distilled water until a halo formed around a blue spot on a chromatography paper the point at which the methylene blue was assumed to have completely replaced the exchangeable cations on the clay mineral surfaces. The CEC was thus calculated by;

$$\text{MBA} = (c \times p) / (A/100) \quad (3.3)$$

MBA = Methylene blue adsorption value  
 c = concentration of Methylene blue solution (g/ml)  
 p = amount of MB adsorbed (ml)  
 A = weight of soil

We then calculated the adsorption in milli-equivalents as follows

$$M_f(\text{CEC}) = (100 \times N \times p) / A \text{ [meq/100g]} \quad (3.4)$$

N = normality of the MB solution [meq/l]

$M_f$  = amount of MB adsorbed per 100g clay [meq/100g]

From the obtained MBA values,  $\text{CEA}_c$  was obtained through Pearring (1963) and Holt (1969), established clay activity ( $A_c$ ) i.e.

$$\text{CEA}_c = \text{CEC} / \text{clay content} \quad (3.5)$$

### 3.2.3 Statistical analysis

Correlation and regression are useful statistical techniques for both identifying related variables and for modelling and predicting the relationship between variables. Correlation techniques compare individual variables with one another and calculate estimates of the strength, or magnitude, of the statistical relationship. In this study, Pearson's correlations was used to obtain the relationships between the various soil properties and to obtain the most significant among them for inclusion in the unified index for the estimation of PVC after normalization with the clay content. This resulted in a unified Expansive Soil rating (ESI). The PVC was assumed to be close to field conditions thus a near ideal representation of the natural volume changes that would be expected due to the preserved structure resulting from the undisturbed nature of the clod during collection in the field and the ideal pressure under which the clods saturation with water were made.

### 3.3 Results

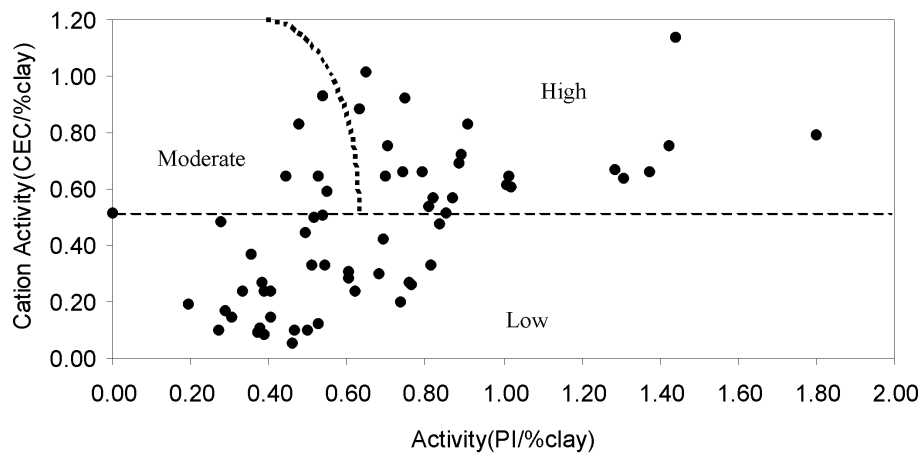
In the discussions, swell indicators are soil properties, such as clay content and type and the various physicochemical properties that directly or indirectly contribute to swelling tendencies. The term swelling potential indices is used when they are quantified and used to estimate the swell potential. Swell potential in turn refers to the definition of low, moderate, and high classes (Nelson and Miller, 1992) grouped on the basis of the established thresholds for the various indices and the typical measure, COLE, used here as the relative standard of the potential of each of these indices to measure quantitative potential volume change in a soil. Table 3.2 provides a summarized classification schemes from various works in which the thresholds are used to assign soils to a swelling category and to a dominant clay mineral type.

**Table 3.2.** Modified clay mineral type allocation (after Nelson & Miller 1992)

Activity	Cation activity	LEP	SSP	Swelling potential	Mineral assignment
>0.6	>0.5	>0.15	>1.5	High	Smectite >50%
0.4-0.6	0.4-0.5	0.05-0.15	1-1.5	Moderate	Illite > 25%
<0.4	<0.4	<0.05	<1.0	Low	Kaolinite >50%



Figure 3.1 shows the distribution of the samples into these classification charts in terms of swelling potential (Nelson and Miller 1992). The majority fell into the low and high swelling classes and thus in terms of clay mineralogy would be described to consist of kaolinite and montmorillonite though the interlayer category is also well represented based on the background on the soil sources where the dominant interlayer mineral determines the category into which a sample falls in the classification.



**Figure 3.1.** Modified (Nelson & Miller, 1992) swell potential chart

In terms of hue, soils grouping in the low swelling category were generally found to be mostly of orange, brown to reddish color, interpreted to reflect high contents of iron oxides and indicative of high levels of weathering and good drainage. High swelling samples were grey to black in color a fact attributed to significant levels of organic matter and accumulation of divalent cations. They were mainly from low lying plains with restricted drainage. Soils with inter-mediate swelling potential consisted of both varieties.

Table 3.3 gives the statistics of the various measured soil properties showing the samples to consist of a wide range of clay contents (3 and 82%) with a mean of 45%. The soil population could thus be described to be mainly of a clay texture and to belong to the family of fine in particle-size class, as defined by Soil Survey Staff (1994). The mean of the Atterberg limits (the LL, PL and PI) also show the samples to average at high plasticity levels. Liquid limit was highest in the Kenyan plain soils relative to all the others and was assumed to reflect the presence of smectite with much greater specific surface area, thus higher affinity for water required to satisfy conditions at the liquid limit, especially given that water adsorption is the same for all surfaces (Mitchell, 1993). Plasticity index followed the same trend as liquid limits giving the indication that soil with high layer charges can retain plasticity at much lower moisture contents than their counterparts with less layer charge. The saturated paste average was also significantly high showing the soils to generally possess a high affinity for water and thus collaborating the liquid limit obtained averages.

Average CEC was also significantly high and also its dynamic range (4% and 60%) probably a reflection of the range of swelling potential differences among the soils which when coupled with the range of clay content provide a representative soil population.  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  were dominant as the exchangeable bases in the samples with the  $\text{Ca}^{2+}$  average higher.  $\text{Na}^+$  and  $\text{K}^+$  averages were low with  $\text{K}^+$  being slightly higher. The pH ranged between moderately acidic (5.0) to alkaline (9), though with an average of slightly acidic whereas organic matter was generally low (0.5% in the well drained and 6% in poorly drained soils). Thus the organic matter was not significantly high as to have a great influence on the soil properties.

**Table 3.3.** Statistics (sample size, mean, and the range) of the properties in the used soil

Soil property	n	Mean	Minimum.	Maximum.	Standard deviation
CEC, meq/100g	103	36	4	60	13
COLE	103	0.089	0.014	0.195	0.05
Saturated moisture (%)	103	53	26	88	15
Liquid limit (%)	103	53	24	82	15
Plastic limit (%)	103	29	15	40	6.3
Plastic Index (%)	103	24	10	47	9.1
Activity	103	0.641	0.196	1.422	0.27
Cation Activity	103	0.405	0.052	1.141	0.25
% Volume change	103	29	16	67	14.9
pH (H <sub>2</sub> O)	103	6	5	9	0.82
Clay (%)	103	45	3	82	17.6
Silt (%)	103	20	2	48	11
Sand (%)	103	32	6	91	17.7
Exchangeable base	103				
Ca	103	13.12	0.14	39.5	12.9
Mg	103	3.712	0.118	12.69	3.4
Na	103	0.671	0.04	2.466	0.63
K	103	1.15	0.02	4.55	0.95

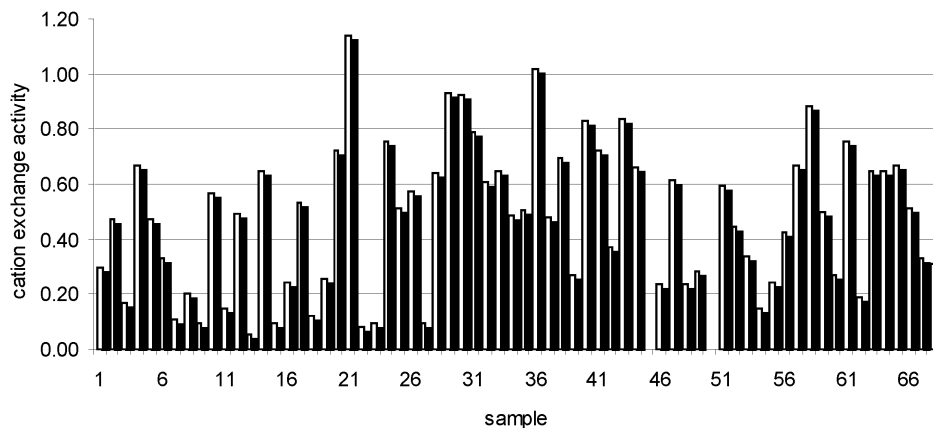
Correlations between the measured soil properties are given in Table 3.4 and show strong correlation between some, (CEC, PI, LL, SP, Mg<sup>2+</sup> and Ca<sup>2+</sup>) and poor correlations between others such as the various particle sizes, the pH and exchangeable Na<sup>+</sup> and K<sup>+</sup>. Relationships with the PVC show relatively good correlations with the former (LL, PI, SP and CEC) portraying them as better in its estimation. The divalent exchangeable cations (Ca and Mg) gave moderate correlations while the various particle sizes and pH returned poor correlations with the PVC and were thus concluded as poor in its estimation as individual variables. The poor predictive power of clay content in particular was unexpected though it probably vindicates observations by Parker et al, (1977) of the clay type rather than content to determine the PVC of a soil. It however contradicts findings by McCormack and Wilding, (1975) who described it as the most important in potential volume change estimations though this could have been due to their using soils dominated by illite a less swelling member of the clay family. The exchangeable Na has also been described as good in the estimation of swelling potential (Anderson et al, 1973) but was here found to be a poor estimator. This probably show the discrepancies in the various methods and the difficulties in universally applying one particular method, emphasizing instead the need to use a combination of methods in order to draw meaningful conclusions.

**Table 3.4** correlations between estimated percentage volume change and soil properties

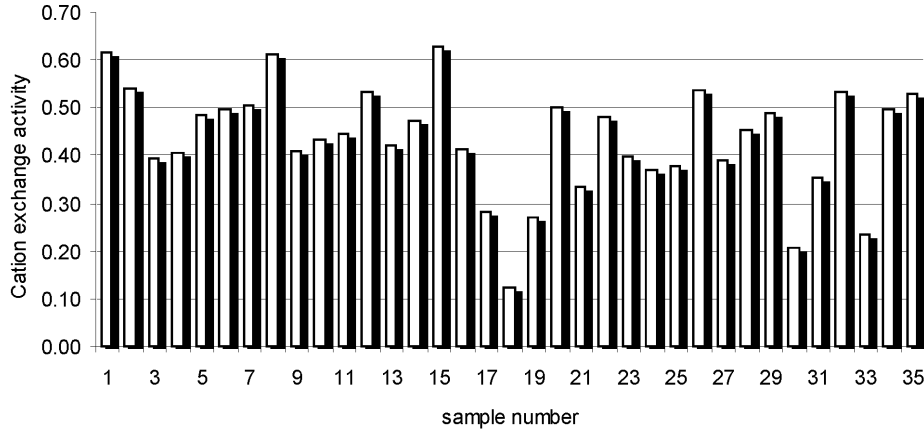
	<i>PL</i>	<i>LL</i>	<i>PI</i>	<i>CEC</i>	<i>%Sand</i>	<i>%Silt</i>	<i>%Clay</i>	<i>A<sub>c</sub></i>	<i>CEA<sub>c</sub></i>	<i>Ca+</i>	<i>Mg+</i>	<i>Na+</i>	<i>K+</i>	<i>pH</i>	<i>SP</i>
<b>PL</b>	1.00														
<b>LL</b>	0.80	1.00													
<b>PI</b>	0.60	0.87	1.00												
<b>CEC</b>	0.68	0.71	0.64	1.00											
<b>%Sand</b>	-0.43	-0.45	-0.24	-0.42	1.00										
<b>%Silt</b>	0.47	0.40	0.31	0.23	-0.17	1.00									
<b>%Clay</b>	0.12	0.32	0.28	0.45	-0.72	-0.29	1.00								
<b>A<sub>c</sub></b>	0.40	0.49	0.53	0.18	0.18	0.59	-0.50	1.00							
<b>CEA<sub>c</sub></b>	0.64	0.51	0.50	0.71	0.00	0.45	-0.20	0.57	1.00						
<b>Ca+</b>	0.60	0.77	0.72	0.88	-0.45	0.18	0.48	0.15	0.63	1.00					
<b>Mg+</b>	0.51	0.67	0.61	0.75	-0.54	0.16	0.53	0.07	0.47	0.89	1.00				
<b>Na+</b>	0.21	0.14	0.14	0.23	-0.28	0.13	0.26	-0.09	0.10	0.06	-0.08	1.00			
<b>K+</b>	0.14	0.23	0.16	0.14	-0.20	0.37	-0.04	0.24	0.20	0.31	0.35	-0.22	1.00		
<b>pH</b>	0.16	-0.07	-0.03	-0.18	0.08	0.23	-0.40	0.44	0.19	-0.21	-0.20	-0.13	-0.02	1.00	
<b>SP</b>	0.61	0.72	0.66	0.8	-0.60	0.38	0.49	0.17	0.46	0.80	0.75	0.03	0.30	-0.06	1.00
<b>%Vol.</b>	0.72	0.81	0.77	0.84	-0.40	0.47	0.30	0.8	0.72	0.77	0.69	-0.03	0.23	-0.08	0.84

The correlations were on the overall significantly low giving an indication of potential influence from other factors and were rather varied based on the differences in the status of the sample preparations and the procedures of the tests. One way of reducing the variability was the use of normalized indices by division with the clay content to provide indices based on the activity of clay content, as is the case with the various indices given in Table 3.1 providing information of the activity of the clay content thus providing tools which could enable better comparison of soils. Skempton (1953) established activity to change little in the presence of a particular clay mineral type while Pearring, (1963) and Holt, (1969) established the cation exchange activity, to be important in estimation of the dominant clay type. The two therefore provide more fundamental soil analysis tools, which are closer to a standard measure than their contributing properties. As is evident from Table 3.4 these indices gave generally good correlations with the PVC though not necessarily improving significantly the originally obtained indices. They however though have an advantage of removing influences from the sand and silt content thus probably giving a more standardized and a fundamental representation of the relative differences among the soils. This by giving an indication of the potential volume change due to what is generally described to be the driving force behind soil swelling, the clay content (Carter and Bentley, 1991).

Figures 3.3 and 3.4 show the dynamics of the two sets of data used in the study where the Kenyan samples are seen to generally have both extremes of very high and very low swelling potential characteristics relative to the Spain samples, with more of the samples falling in the moderate swell potential category. The fact that Kenyan samples were either rich in the smectite or kaolinite as opposed to those from Spain, which were mainly rich in illite and smectite/illite interlayer, could probably explain the general trend. Clear differences among the Kenyan samples are evident between the low and high swell samples whereas for the Spain samples, this does not come out clearly. This was attributed to the environment of formation (Uehara 1982) playing a significant role. The tropical climates under which the Kenyan samples developed i.e. high temperatures and yearlong rainfall favour development of the kaolinites in the well drained higher grounds due to washing out of the silica. Accumulation of this combined with poor drainage in the lower grounds result in development of smectite. A combination of low temperatures and less rainfall in the temperate Mediterranean Spain climate on the other hand has resulted in mainly illite and interlayer smectite/illite which are mostly of the moderate swell potential with exceptions in cases where the smectites ratio is higher in the interlayer or in extreme cases in the accumulation zones along the alluvial plains in the low grounds.



**Figure 3.3.** Variation in cation exchange activity among the Kenyan samples



**Figure 3.4.** Variation in cation activity among the Spain samples

Disparities that occur in singular index estimation of swelling potential levels is evident even with these standardized indices as seen in their differences in the level of correlation with the established potential volume change. This calls for the need of establishing ways of combining these indices to best represent the swelling potential thus maximizing on their information content. Combining the indices also results on better judgment based on a wider array of information resulting in more reasoned conclusions. If one of the indices is found to abnormally vary from the rest for a particular sample it could be checked to establish whether it was due to error during the measurements and could be estimated from such a unified swelling potential index.

#### *Proposed Unified Expansive Soil Index*

By using the concepts of Thomas et al, (2000), of the most significant of indices, in terms of correlation with the PVC, for inclusion in the swell potential rating and that of Hamberg (1985), of assigning the normalized swelling potential indices to certain thresholds, we could then establish expansiveness due to the clay content as a more reliable relative measure. This resulted in three swelling potential ratings based on the availability of measurements.

$$\text{ESI-1} = A_c + \text{CEA}_c + \text{SSP} + \text{LEP} \quad (3.6)$$

$$\text{ESI-2} = A_c + \text{CEA}_c + \text{SSP} \quad (3.7)$$

$$\text{ESI-3} = \text{SSP} \quad (3.8)$$

Where ESI is the established swelling potential rating and  $A_c$ ,  $\text{CEA}_c$ , SSP and LEP are the various indices given in table 3.2.

The indices refer to decreasing number of available measurements and should be used for different levels of risk estimation with the third index for example, used as a fast reconnaissance field index and the first for detailed site characterization where preliminary results show the need for a follow up. Table 3.5 gives the proposed thresholds for each rating level. Due to the lack of measurements on LEP in most cases, the alternative ESI-2 and in extreme cases ESI-3 could be used, the two having been established to be strongly correlated with ESI-1. Figure 3.5 shows the relationship between ESI-1 and ESI-2 that shows the later it to well represent the former. The indices not only show a standardized swelling potential index but also a potentially less expensive method to identify the dominating clay mineral type.

**Table 3.5.** Classification based on ESI

ESI-1	ESI-2	ESI-3	Rating	Mineralogy
<1.75	<1.70	<0.5	Low	Kaolinite
1.75-2.69	1.7-2.6	0.5-1.0	Moderate	Illite/mixed layer
>2.69	>2.6	>1.0	High	Smectites

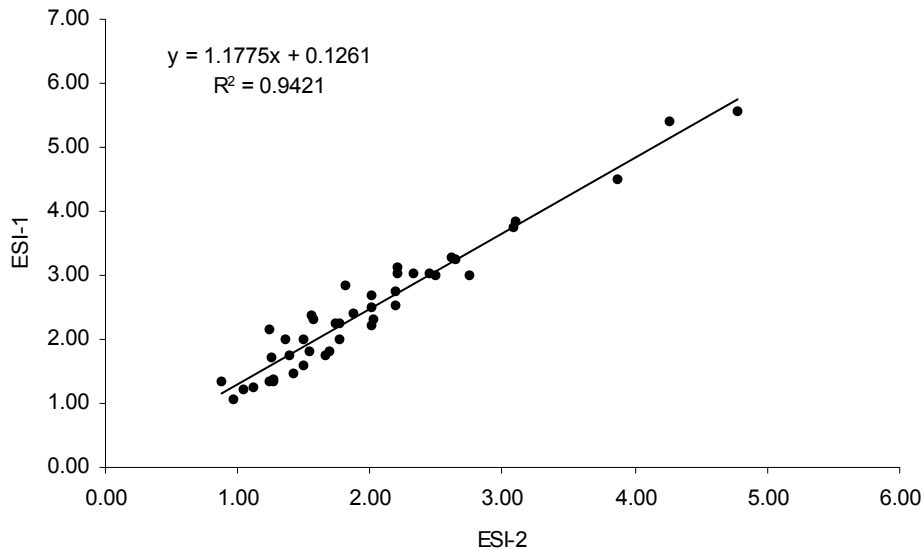


Figure 3.5. Relationship between proposed ESI of different levels

### 3.4 Discussion

The strong correlations between the PVC and a select group of the indices with strong dependence on clay mineralogy and poor correlations with others among which was the clay content could be attributed to both the central role played by the clay mineral type and the variability of the results for the various methods. This emphasising the need to use more than one method in drawing conclusions as to the swelling potential level of a soil. The fact that the most highly correlated indices (CEC, PI, SP and LL) were those closely associated with clay type and high specific surface area (SSA) of soils (Thomas et al, 2000), is an indicator of the central role played by the dominant clay type in determining the resulting potential volume change. This makes methods that measure the clay mineral differences important in the estimation of swelling potential. This could also be attributed to the affinity of water in soils which Ben Dor et al (1999) described to vary with clay type decreasing in the order smectite>illite> kaolinite due to variation in their specific surface area. The various clay type related indices have been widely studied in the context of the soil properties and found to be very representative.



Yule and Ritchie (1980) described CEC to integrate the amount and activity of clay present in a soil whereas Amer and Al-Rawas (1999) described active clays in soils to have greater influence on the swelling behaviour than any other factor describing smectites as the most active and as responsible for swelling problems. Liquid limit, represent the moisture content at which a soil changes from a plastic body to a viscous liquid and has been reported to be heavily dependent on the specific surface area (Mitchell, 1993) where the greater the specific surface area, the greater the total amount of water required to satisfy the conditions at the liquid limit. The plastic limit, on the other hand has been described as the lowest moisture content at which the physical properties of water no longer correspond to those of free water (Terzaghi, 1925) that probably explains the differences in the presence of different clay minerals based on their electrostatic forces on the soil water. The plastic index, a measure of the range at which a soil remains plastic thus an indicator of the present clay mineral electrostatic forces influence on the soil's plasticity, making soils with high PI to be highly expansive. This explains the observed high correlation between the PI and the PVC.

Relatively strong correlation with divalent exchangeable cations ( $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) and lack of it for monovalent ( $\text{Na}^+$  and  $\text{K}^+$ ) cations contradicts reported strong correlation between exchangeable sodium (Smith et al, 1985; Amer and Al-Rawas, 1999) and COLE instead confirming the observed lack of relationship between exchangeable cations and COLE by Gray and Allbrook (2002). It could however be providing an indication of environmental factors, where conditions favouring formation of smectites have been described to include the presence of more  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  relative to  $\text{Na}^+$  and  $\text{K}^+$  (Mitchell, 1993), which probably makes them dominate the exchangeable sites. The lack of strong correlation with the clay content was attributed to the relatively high contents of clay in most of the soils in the population a fact that can be described to probably further confirm the dependence of the swelling potential on the clay type rather than content. This was best illustrated by the soil set from Kenya that had high clay fractions in both the plain samples (which were dominantly of smectite composition), and the upper catchment samples of dominantly kaolinite, the two having had contrasting values on the indices directly related to the clay mineral type such as the CEC.

Though the normalized indices do not drastically improve the relationships for the various indices, they probably present more universally applicable indices based on their associated assignment to a fundamental soil property, the clay mineralogy (Franzmeier and Ross, 1968; Parker et al, 1977). Carter and Bentley (1991) described activity to change little for each clay type and further described the

activity values assigned to the various clay minerals to hold true for not only the minerals but also soils in which they form the clay fraction. Mitchell (1993) described the activity to separate the reflection of both the clay content and type. Holt (1969) established cation exchange activity to vary little for a clay type, and as a result assigned them thresholds. This probably explains significant correlation of the indices even after normalization with the clay content whose correlation with the PVC was poor as an independent index. The proposed combination is therefore not only fundamentally based but also reliable by giving indices, which could easily be compared among soils and an added advantage of deducing the probable dominant clay mineral type.

### **3.5 Conclusions**

The results show clay type rather than clay contents to be of more significance in the determination of swelling potential where currently applied indices indicative of the clay type generally gave high correlations with the established potential volume change. The normalized indices provide a more fundamental way of characterizing the soil by giving an indicator as to the dominant clay mineral type allowing for more universal application. The established ratings provide tools that could be used to classify soils on the basis of available measurements and establish soils in which further tests would be required based on the use that is envisaged for a site. The results also show some of the commonly measured soil properties, readily available in most soil science databases, such as CEC, saturation moisture content and clay content when used in combination to lead to reliable estimates of the swelling properties.

## CHAPTER 4

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### **SPECTROSCOPY TO ESTIMATE SOIL ACTIVITY INDICES**

*Based on Kariuki P.C., Van der Meer, F.D., and Verhoef, P.N.W., 2003, Cation exchange capacity (CEC) determination from spectroscopy (International Journal of Remote Sensing, 24(1), 161-167) and Kariuki, P.C., and Van der Meer, F.D., 2003, Determination of soil activity from optical spectroscopy. In: Geoinformation for European wide Integration, Edited by T. Benes (Rotterdam: Millpress), pp.587-590.*

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*"Man, unlike any other thing in the universe, grows beyond his work, walks up the stairs of his concepts and emerges ahead of his accomplishments." – John Steinbeck (US novelist)*

### **Abstract**

Soil activity is mainly due to a soil to possessing excess negative charges on its clay mineral surfaces resulting in ability to attract water molecules and exchangeable cations in the clay structure where with increased water; both the exchangeable cations and the clay surfaces are hydrated. Methods of their measurements have been developed over the years most significant of which are plasticity and cation exchange capacity, which directly relate to these electrochemical forces. By obtaining correlations between the two and soil spectra parameters, simple empirical models were established and showed the two to be closely related with parameters established in various studies to relate to clay mineralogy differences.

### **4.0 Introduction**

Soil activity is a term generally applied on the ability of a soil to take in and dispose water under changing moisture conditions and is mainly due to presence of clay minerals with a net negative charge to neutralize which, water and exchangeable cations are attracted to the mineral surface. The methodology aimed at establishing empirical relationships between spectroscopic indicators and soil activity indices known to represent a fundamental physical property of the soil, the clay mineralogy type. This in a bid to establish the commonality of their dependence on compositional differences mainly in terms of clay mineralogy previously established to have an overriding influence on the various swelling indices and the spectral properties of soils. Such relationships would allow estimating the indices from spectral data. Among these are Atterberg limits and cation exchange capacity tests, which are used to determine the soil activity and cation activity respectively and found in the foregoing chapter to be among the most important in establishing the swelling levels among the soils. These methods are time consuming and at times expensive. While this might not be a big problem in the industrialized world it is a great challenge in the developing world and at times leads to construction without proper site investigations more so if such construction is of light structures. It is therefore important that efforts be made in establishing whether spectroscopy would offer faster and cheaper methods for their estimations.

In this paper we report on the findings of an approach in which spectroscopy was used to address the swelling potential based on the two activities in a set of samples collected from Kenya with the aim of establishing the potential of this approach as a faster and probably more cost effective method. The Methylene blue absorption (MBA) and the Atterberg limits were used as the engineering indices to determine the soil cation activity and activity respectively. The outcomes of the analyses are relationships between the two swelling potential indices and their spectral indicators leading to a better understanding of the processes governing swelling.

#### **4.1 Methodology**

The data used in this section consisted of select samples from that used in the foregoing chapters where data on the two soil properties was complete. The relationship between the two indices and the spectral parameters were obtained using the simple Pearson's correlations and the regression analysis techniques. This resulted in empirical estimations based on the strongest correlations between the various spectral parameters and the two indices, providing the absorption feature parameters with a potential in providing information as to the two soil properties.

#### **4.2 Results**

Table 4.1 shows the results of the correlations between the various absorption feature parameters and the established soil activity indices and that of clay content. They show strong correlations between the two soil properties (i.e. CEC and PI and their normalised activities) established in the foregoing chapter to relate strongly to the clay mineralogy type, and the various absorption feature parameters previously also observed to relate to clay mineralogy differences and diagnostic of the dominant mineral type. Of significance are the observed positive and negative though weak correlations with the 2200nm feature position depth respectively, which adds some insight to the strength of this feature in the presence and absence of the highly active minerals in the soil. Similar results for the 2380nm feature are evident but was concluded not reliable though its presence was interpreted as diagnostic of strong kaolinite presence based on the subtle nature of the feature. The feature has been described as diagnostic for kaolinite (Hauff, 2000) and as good in discriminating clays (Crowley and Vergo 1999).

The clay content generally gave poor correlations, as was the case with the volume changes in the previous results. This was attributed to the fact that the clay content is a physical property that does not have intrinsic diagnostic in the spectra but instead a generally overall influence on the albedo irrespective of the compositional differences and. However, when used to normalise the two indices the resulting parameter gave significant correlations making the clay content useful in cases where comparisons of soils is needed based on its reduction of influence from other grain sizes.

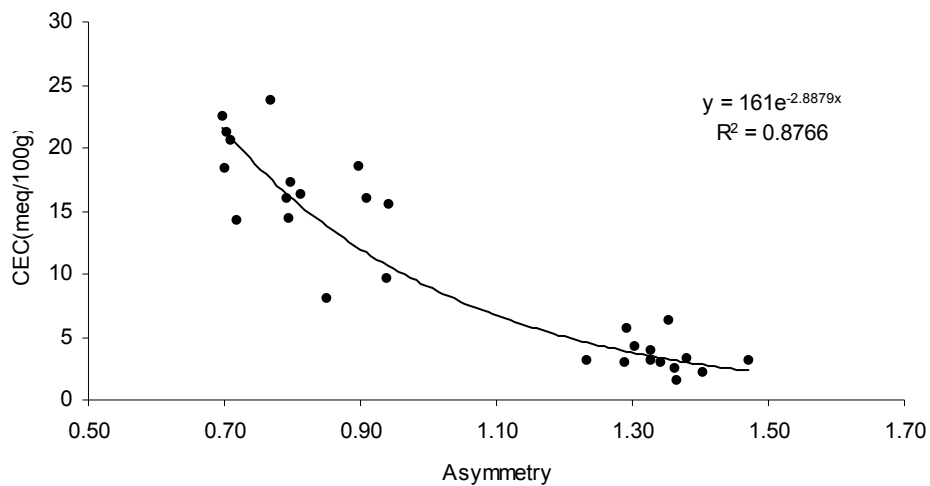
Table 4.1. Correlation between engineering indices and absorption feature parameters

1400nm	Wave	Depth	Width	Area	Asymmetry
PI	0.45	-0.25	0.65	0.04	-0.77
CEC	0.41	-0.07	0.47	0.19	-0.52
%Clay	-0.31	0.35	-0.31	0.30	0.42
Activity	0.46	-0.30	0.62	-0.04	-0.83
Cation activity	0.54	-0.28	0.57	-0.01	-0.80
1900nm	Wave	Depth	Width	Area	Asymmetry
PI	-0.70	0.71	-0.30	0.66	-0.19
CEC	-0.78	0.67	-0.43	0.59	-0.25
%Clay	0.32	-0.09	0.42	-0.05	0.46
Activity	-0.68	0.55	-0.50	0.46	-0.44
Cation activity	-0.82	0.68	-0.60	0.59	-0.47
2200nm	Wave	Depth	Width	Area	Asymmetry
PI	0.60	-0.53	0.73	-0.24	-0.85
CEC	0.35	-0.32	0.61	-0.08	-0.55
%Clay	-0.17	0.40	-0.12	0.43	0.22
Activity	0.32	-0.55	0.63	-0.35	-0.64
Caactivity	0.51	-0.57	0.75	-0.34	-0.80
2380nm	Wave	Depth	Width	Area	Asymmetry
PI	-0.25	0.07	-0.67	-0.10	-0.60
CEC	0.29	-0.60	-0.74	-0.72	-0.33
% Clay	0.36	0.24	-0.22	0.17	-0.12
Activity	-0.35	-0.01	0.20	-0.02	0.43
Caactivity	0.10	-0.65	-0.32	-0.73	0.29

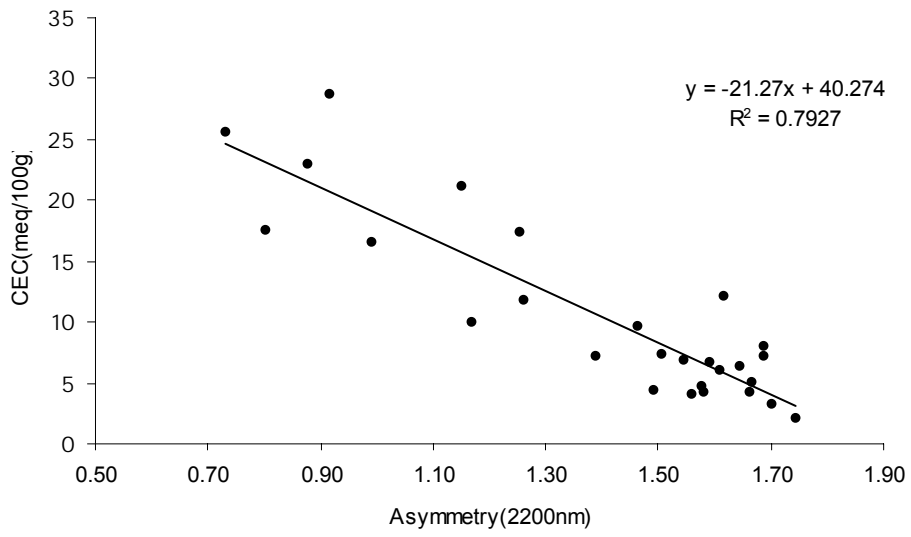
#### 4.2.1 CEC (cation activity) relationship with spectral data

The fact that obtained values of the CEC obey the law of additivity makes it ideal to use in combination with spectral data in determining the fraction of active clay. This assumption was used as the basis of the analysis where the CEC index values were observed to show negative correlation with hydroxyl feature parameters (Figures 4.1 and 4.2) previously established to be strong in the presence of abundant kaolinite. The negative relationship with the molecular water position

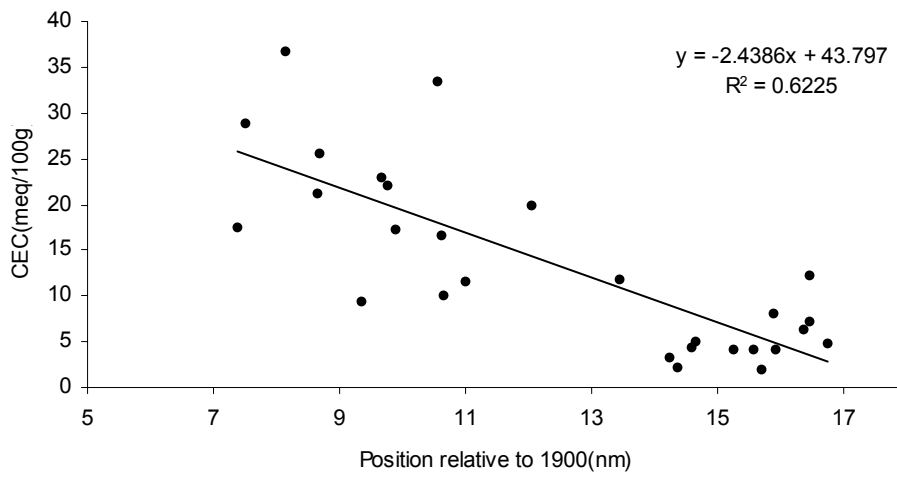
(Figure 4.3) was attributed to electrostatic attraction differences dependent on the specific surface area thus available force in each sample to be overcome for the vibration to occur. The relationship could also be attributed to the multiple phase influence where changing contents of the active minerals exerts varying degrees of influence which in turn is confirmed by its depth positive correlation with both the CEC and cation activity. (Hauff, 2000) described the depth as a semi-quantitative estimator of the smectites which when coupled with the fact that CEC is indicative of the available negative charge resulting mainly from isomorphous substitution show the results to be representative.



**Figure 4.1.** Decrease in asymmetry at 1400nm with increase in soil CEC



**Figure 4.2.** Decrease in asymmetry (2200) with increase in soil CEC

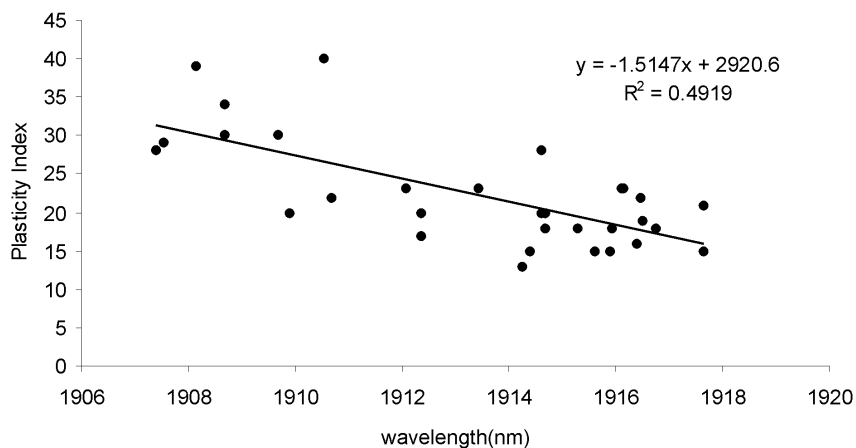


**Figure 4.3.** Shift in 1900nm wavelength position with increase in soil CEC



#### 4.2.2 Plasticity index (activity) relationship with spectral data

The results were found to give similar relationships with those of the CEC thus providing an indication as to the potential of spectroscopy to relate to similar characteristics of the soil with those established by both the CEC and PI. The correlations were however weaker relative to those of the CEC (see example Figure 4.4) a fact attributed to influence of other soil characteristics on plasticity unlike the case with CEC that is totally dependent on the active clay surface. One of this could be the relativity of the two limits used to obtain the plastic index as opposed to the CEC determinations, which have well defined estimates. The observed relationships were thus assigned to clay mineralogy differences based on previous engineering results where the two had been established to be two of the swelling indices with direct relationships to the clay mineral type. This makes the established diagnostic spectral parameters have a physical basis and ideal for the estimation of the soil activity (read clay activity) thus the swelling potential from spectral information.



**Figure 4.5.** Increase in wavelength position (1900nm) with decrease in plasticity

### 4.3 Discussion

Soil spectra in the short-wave infrared (SWIR) are largely dependent on mineralogy (Courault et al, 1988) and are similar to those of the dominant minerals pure form (Escadafal, 1994; Hunt 1979). Thus, though soil is a complex combination of four major components (clay minerals, organic matter, soil water and sesquioxides) differences in the spectral response can be used as indicators of the mineralogical differences as was the case in the observed results. Shifts in the 1900nm feature clearly confirm previous observations (see chapter 2) of clay mineralogical differences and could be explained in terms of the lattice water which where present gives it a sharp form signifying location in a structured position. The positive correlation between the two activities and the 1900nm depth intensity could thus be attributed to this considering that the activities are direct indicators of increased surface area as is usually the case with increased smectite described by Russell (1987) to have a water-bending mode at 1890nm. The shift to lower wavelengths could also be described to show increased electrostatic forces with increased surface activity and to show the nature of interaction between water and the active soil particles to be molecular in nature given the linear relationship. This supports observations by Clark (1999) in which he established linear variation in the depth intensity when working with pure minerals and increased humidity. This is also well documented by among others Bowers and Smith (1972) and makes it possible to relate the soil water diagnostic spectral parameters to the quantitative increase in adsorbed water in the soil matrix, as is the case in the various engineering indices.

The asymmetries strong negative relationships with the two activities could be attributed to kaolinite quantitative opposite nature of influence on soil activity relative to that of water bearing smectites. Some complexities in these relationships are however evident in the form of the non-linear relationship at 1400nm signifying the need to test such relationships individually before using them in detailed analysis. This particular case could probably be due to the influence of both the water and hydroxyl vibrations on this parameter. Presence of subtle features such as the 2380nm despite their poor correlations with the two activities goes further to show the capability of spectroscopy to diagnose especially clay mineralogy related soil differences and thus estimate related soil properties.

It is also worth noting that, soil activity is basically due to the electrochemical behaviour of the clay minerals and is unique to soils containing clay mineral particles (Carter et al, 1991) and that electrochemical bonds act through the water surrounding the clay particles. This could thus explain the complex inter-relationships observed

between the various spectral parameters and the soil activity. The nature of hydroxylation interlayer (Fe-OH, Al-OH, Mg-OH) has also been determined to have effects on the two activities (Mitchell, 1993). Al-OH is the principal interlayer material in acid soils, whereas Mg-OH is the principal interlayer component in alkaline soils, which respectively form the least and most active soils respectively. This could also then explain the prominence of the spectral parameters diagnostic of this bonding where strength of Al-OH the principle interlayer in acid soils and mainly associated with kaolinite dominance in terms of clay mineralogy was negatively correlated with the activities. Thus though the shifts in wavelength positions at the 2200nm were weak in their relationships with the activities, they could have indicated these cation quantitative differences.

It is clear that clay mineralogy is the key to soil activity in terms of both spectral response and engineering properties. The convergence seem to occur due to the dependence of both on the OH metal bonding where in engineering terms, the OH metal bond determine the acidity of the soil whereas in spectroscopy terms, the absorption parameters are dependent on the octahedral ligands.

## **Conclusions**

Relationships between the absorption feature parameters and the soil activity indices have shown dependence on a common soil characteristic that based on the established diagnostics was concluded to be the clay mineralogy. Careful analysis of the spectral feature parameters can therefore help determine soils dominant clay mineral and thus derive the soil properties resulting from their presence and abundance. The results show that despite the soil being a complex composition of various minerals and other compositional elements, the information content as to the active elements in the various wavelength regions of the spectrum though probably degraded is still enough to at least qualitatively establish their presence. Their associated influence on the soil physicochemical properties can also be realised, as is the case in the obtained results. Thus, it can be concluded that with proper calibration of the spectra information, soil properties without a primary response on the spectra could be measured based on the diagnostics of compositional elements with such a response.

## CHAPTER 5

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### EMPIRICAL SPECTROSCOPY FOR DESCRIBING SWELLING SOILS

*Based On: Kariuki P.C., and Van der Meer, F.D., 2003, Issues of effectiveness in empirical methods for describing swelling soils (International Journal of Earth Observation and Geoinformation, 4(3), 231-241*

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*“Always remember that your own resolution to succeed is more important than any other thing.” – Abraham Lincoln, US President (1809-1865)*

## **Abstract**

Various engineering swelling potential indices were here reduced through factor analysis to obtain a swell index that was in turn used to obtain various spectral parameters with a potential to estimate its value based on absorption feature mapping, optical density, and derivative spectral data analysis methods. The spectral parameters found to have high correlations with the swell index were then used to establish statistical empirical models to quantify soil swelling from spectral data. The physical understanding of these spectral parameters was sought and the results show a close relationship between the clay mineralogy spectral features (i.e. bound water and hydroxyl groups features) and the swelling index.

## **5.1 Introduction**

Expansive soils are a major engineering problem and their identification and mapping is an important undertaking in the building industry. The potential volume change is dependent on several physical and chemical properties, among them, clay content, clay mineral type and environmental factors such as the moisture conditions of a site. Clay mineralogy plays the most important role in controlling these properties where their size and type determine the state of packing, the manner in which the soil particles adhere to one another, and the extent to which the voids or spaces between them are filled with water. The individual clay mineral types exhibit different swelling potentials due to variations in their structures and interlayer bonding with smectites and vermiculites undergoing more volume changes on wetting and drying relative to kaolinites and illites. Thus presence of smectites leads to soils undergoing high volume changes whereas illites and kaolinite give the soils moderate and low, swelling potential respectively. Presence of these minerals even in small amounts influence the overall properties of the entire soil mass (Head, 1992) and recognizing their presence is therefore important in classifying potentially expansive soils (Mitchell, 1993).

Due to problems in performance of structures founded on expansive soils, engineers have made numerous attempts to develop reliable methods for determining the swelling properties of soils where the most successful are based on the determination of factors directly related to the clay mineral composition as previously discussed. Among these are plasticity index (PI), cation exchange capacity (CEC), colloid content and X-ray diffraction (XRD) analysis from which thresholds have been established within which soils are characterised as dominated by either of these clay minerals (USA National Soil Survey Laboratory 1981;Pearring 1963;Hamberg 1985). These indices offer parameters, which could be used to establish the potential application of other methods in the identification and

mapping of swelling soils where the clay minerals possess diagnostic characteristics.

Reflectance spectroscopy is one such method where the clay minerals give diagnostic absorption features in the short-wave infrared (SWIR) region (1.3-2.5 $\mu$ m) of the reflected spectrum, resulting from the vibrational processes of their water and hydroxyl molecules. The various parameters of these features varies among the minerals, depending on the details of the composition, structure, and associated atomic bonding characteristics which as previously discussed offers a tool that could be of significant potential in swell potential mapping by assigning soil to dominance by one or the other mineral. Strong molecular water bands at 1400nm and 1900nm due to bound water are typical of smectite whereas strong hydroxyl bands at 1400nm and 2200nm are typical of kaolinite providing a good source of information on related properties such as the swelling potential differences. Mulders, (1987) described soils to exhibit reflectance greatly derived from their clay mineralogy though affected by other constituents such as organic matter and Goetz et al, (2001) found the 2<sup>nd</sup> derivatives of the reflectance spectra as good in the estimation of smectites in soils. De Jong (1994) established clay as an important parameter in the description of soil properties from reflectance spectroscopy and in the recent past spectroscopy has been successfully used in the estimation of soil properties among them cation exchange capacity (CEC) (Chang et al, 2001; Kariuki et al, 2003), and particle size distribution (Zhang et al, 1992). Others (Chabrilat et al, 2002; Ben Dor et al, 2002) have gone further and applied airborne imaging spectroscopy in determining soil properties.

With such applications becoming possible more so the remote based, a need exists to investigate possibilities of establishing the robustness of the various diagnostic spectral parameters to qualify and quantify these minerals in soils, where they form the most important constituents (Bridges, 1997) and the spectral data potential to determine related physical/chemical properties such as the swelling potential. This paper reports on the findings in which some of the widely used and accepted swelling indices and in the foregoing chapters established to largely determine the swelling potential were used to obtain a unified swelling potential index (ESI). This index was then used as a parameter with which to establish the reliability of the various spectral parameters to establish empirical models, which could quantitatively estimate soil swelling from spectral information.

## 5.2 Materials and Methods

### 5.2.1 Soil sampling

Stratified random sampling of the soil samples used in the foregoing chapter was done where samples representing the whole range of high to low swelling types and known to consist of varying abundance of the indicator clay minerals were obtained resulting in a total of 68 soil samples.

### 5.2.2 Spectral data acquisition procedures

The samples were then placed on crucibles, their surfaces gently flattened, and oven dried at 105<sup>0</sup> C to eliminate hygroscopic moisture upon which they were cooled in a desiccator before the spectral data acquisition. A Portable Infrared Mineral Analyzer (PIMA) upgrade spectrometer that covers the spectral range between 1300nm and 2500nm with a 2nm-sampling interval and 7-10nm spectral resolutions and measuring hemispherical reflectance in 601 continuous spectral was then used to obtain spectra on each of the soil samples where the acquisition port was placed in contact with the sample to avoid atmospheric interference.

### 5.2.3 Spectral data analysis procedures

Analysis of the spectra was by use of several techniques and included the previously described absorption feature mapping (Mustard and Sunshine, 1999) and derivative analysis (Duckworth, 1998). Others include, band depth normalized with centre (BNC) as described by Curran (2001), and optical density (log 1/R) (Chang et al, 2001).

The BNC method is a detailed analysis of the absorption features by measuring the depth of the waveband of interest from the continuum line, relative to the depth of waveband at the centre of the absorption feature from the continuum line.

$$\text{BNC} = (1 - (R/R_i)) / (1 - (R_c/R_{ic})) \quad (5.1)$$

Where, R is reflectance of sample at the waveband of interest and R<sub>i</sub> that of the continuum line at this wavelength. R<sub>c</sub> and R<sub>ic</sub> are the reflectance at absorption feature centre and that of the continuum line at this centre respectively. The other methods were as described in the previous chapters.

#### 5.2.4 Statistical analysis and data reduction procedures

Factor analysis method was used to reduce the various swelling potential indices (see chapter3) into representative factors assumed to optimise the information content as to the swelling potential of each soil by weighting the resulting index on the various properties represented by each of these indices.

Factor analysis is based on principal components and common factors analysis, which though based on different mathematical models, are used on the same data. The difference of the two is that the elements on the principal diagonal are replaced by communalities in the factor analysis, which means that only the common variance of the variables (separated from unique factors) are analysed. The method is often used in exploratory data analysis to study correlations among large numbers of interrelated quantitative variables by grouping the variables into a few factors where variables in a factor are more highly correlated with one another than to those in another factor. Each factor can therefore be interpreted according to the meaning of the variables contributing to it. In this case the factor interpreted to represent the highest information content as to the swelling potential based on the contribution of the various indices was used as the expansive swelling index (ESI) based on the potential volume change (PVC) loading which as previously discussed is the most direct representative of the swelling level among the used indices.

#### 5.2.5 Quantitative estimation of ESI from spectral features

The multivariate regression analysis was used to obtain the empirical models representative of the ESI from the spectral parameters based on the Near Infrared Reflectance Analysis (NIRS) method, where it was assumed to be a function of the spectral parameters

Thus,

$$ESI = \beta_0 + \beta_1 \lambda_1 + \dots + \beta_i \lambda_j \quad (5.2)$$

Where,  $\beta_0$  = intercept

$\beta_i$  = the spectral parameters coefficient

$\lambda_j$  = the spectral parameter



NIRA method involves a calibration and validation stage and assumes a linear relationship where the calibration is used to obtain a regression model to predict the variable in question and the validation to test its applicability where samples not used in the calibration have the variable estimated from the calibration model. The standard error of calibration (SEC) and the standard error of prediction (SEP) are used to assess the predictive power of the model (Ben Dor, et al, 1991). The method is commonly used in applied spectroscopy (Duckworth, 1998) and has in the recent past been used to quantitatively estimate several soil properties (Ben Dor et al, (2002); Chang et al, 2001; Kariuki et al, 2003).

### 5.3 Results

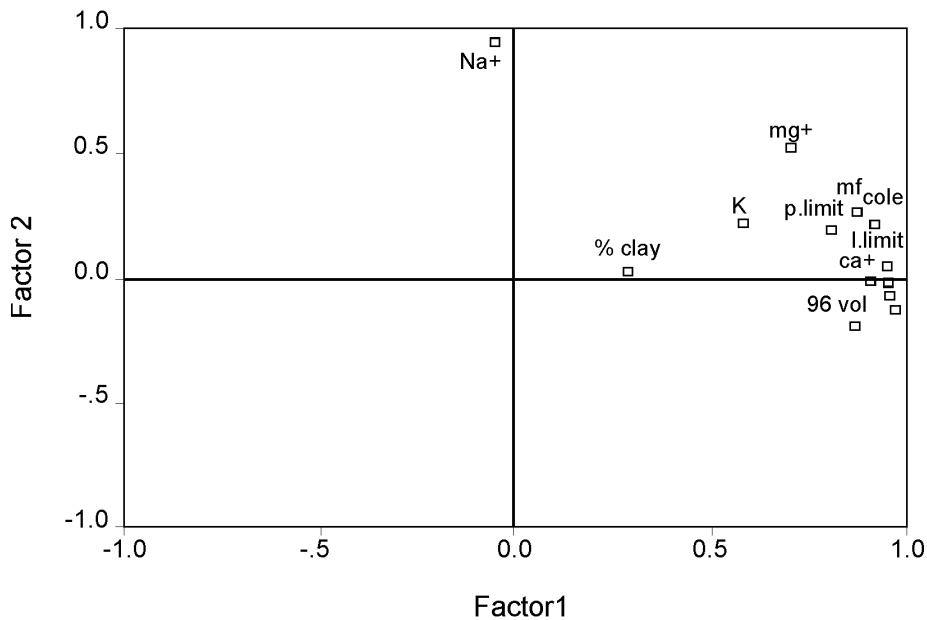
Table 5.1 gives the summary of the classes into which the soil samples used in the analysis belonged based on the various established thresholds which was found representative of the variability in the levels of swelling.

**Table 5.1.** Swelling and mineralogical classification (Hamberg (1985), Pearring (1963) and Holt (1969))

Swelling class	Mineralogy (%)	Number of samples
Low	Kaolinite > 50	28
Moderate	Illite > 25	10
High	Smectites > 50	30

#### 5.3.1 Data reduction

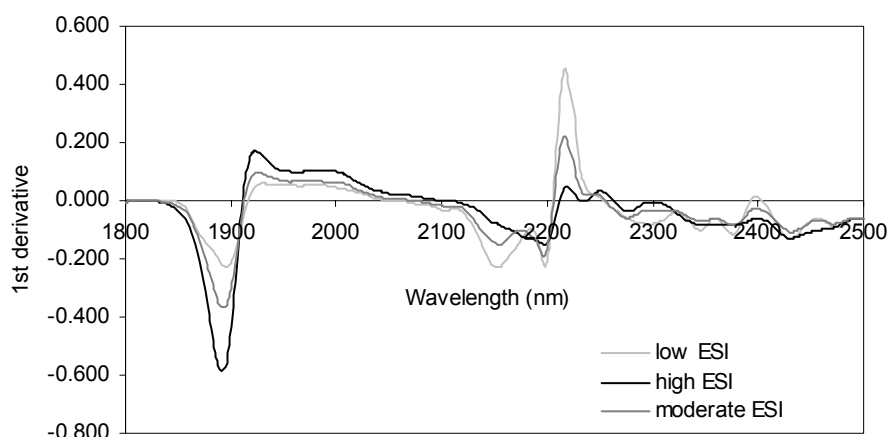
The factor analysis results from the established indices provided a weighted parameter to represent the swelling levels among the soils minimizing the uncertainty in their classification disparities. Two factors were found to adequately represent the indices variance (Figure 5.1). Factor 1 was interpreted to represent most of the information as to the swelling having had high loadings from most of the indices i.e. CEC, PI, LL, PL,  $\text{Ca}^{2+}$ , SP and COLE (the most direct measure of the potential volume change) and moderate loadings from  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$ . Exchangeable  $\text{Na}^+$  and % clay were found not to contribute significantly to this factor and were therefore assumed as not important sources of swelling potential information as independent variables for the set of soil samples used. The second factor was therefore assumed to represent the residuals resulting from errors. The obtained common factor scores of the soil samples resulting from the first factor were therefore used in the subsequent analysis as the swelling potential index (ESI).



**Figure 5.1.** Common factor scores of the engineering indices

### 5.3.3 Data Integration

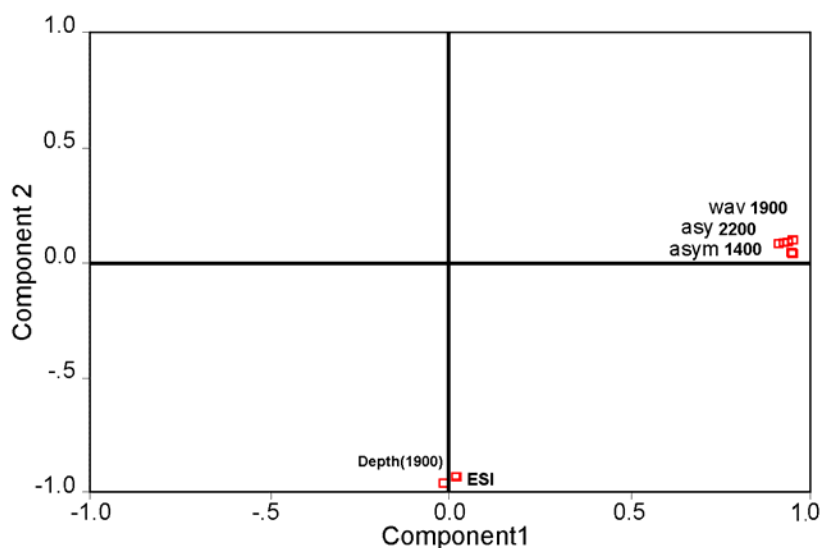
The optical density gave poor correlations with the established index throughout the spectral range whereas derivatives gave strong correlations (highest  $r = -0.8$  at 2200-2260nm interval and  $r = -0.73$  and  $0.7$  at 2100-2200nm and 1800-1900nm intervals respectively for second and first derivatives). Figure 5.2 gives an illustration of the averaged differences among the soils in the peak intensities for the first derivative where the average of soils with high ESI had the bound water peak (1800-2000nm) intense relative to those with moderate and low ESI values. The two also reflect characteristic differences where their highest peak is at the 2200-2300nm assigned to the combination of hydroxyl stretching and bending modes by Goetz et al, (2001) for the lowest ESI value soils. The moderate ESI samples give an intermediate spectrum that shows significant intensities for both of these characteristic peaks.



**Figure 5.2.** 1<sup>st</sup> derivative spectrum of representative samples of the 3 ESI classes

The BNC gave significant correlations at the 95% confidence level with ESI over small ranges in the neighbourhood of major absorption features. Those found to be of note included 1860-1880nm ( $r = 0.85$ ), 2160-2220nm ( $r = -0.76$ ), 2240-2280nm ( $r = 0.6$ ), 1420-1460nm ( $r = 0.7$ ) and 1370-1390nm ( $r = -0.73$ ) that show a positive relationship with the bound water range and the reverse for the hydroxyl spectral range.

Principal components were used to derive information from the absorption feature parameters obtained from the absorption feature mapping where the parameters were chosen in several steps with those with little contribution removed in the final analysis where width, area and reflectance intensity were found not to give significant relationships with the ESI and were therefore removed in the preceding steps. Figure 5.3 shows the principal components loadings of the two factors found to explain 95% variance of the spectral information represented by these parameters. Component 1 had high loadings from asymmetries (1400nm and 2200nm) and 1900nm wavelength position. This was assigned to order in structure positions of both the bound water and the hydroxyls based on previous results where the compositional differences in terms of clay minerals had been found to play an important role in determining the strength of these parameters. The second factor consisted of the water absorption depth and the ESI and was interpreted to show quantitative increase in bound water among the samples with increasing ESI.



**Figure 5.3** Results of principal component analysis on soil samples spectra

#### 5.3.4 Quantitative estimation of ESI

Table 5.3 gives the spectral parameters of the two most promising empirical models to estimate the ESI from the various spectral data analysis methods where it is evident that the bound water and order of hydroxyl sites parameters play a significant role on the obtained models. The prediction errors of both the calibration and the prediction are low showing the parameters as good in the prediction of the ESI. The parameters are given without coefficients since this may vary from one site to another but the fundamental parameters remain the same having been established to work for the two study sites.

**Table 5.3.** Significant spectral parameters for ESI estimation and their statistics

Spectral parameters	Correlation	Contributing parameters	SEC/ SEP
Absorption feature parameters	0.82	Log (asy1400),(pos1900),(depth1900), (asy2200)	0.62/1.96
2 <sup>nd</sup> derivative	0.84	2180,1440,1880, 2240 and 2310	0.44/3.5

The results confirm the role of the clay mineralogy specifically the three fundamental indicator groups of kaolinite, illites and smectites in determining both the engineering properties and the spectral characteristics of the soils in which they form a significant compositional content. They give an indication as to the potential application of spectral data on classifying soils into swelling potential categories based on these minerals.

#### **5.4 Discussion**

The generally strong loadings for the established ESI from indices previously established to portray information on clay type and less so for those with much less dependence on the clay type show the significant role played by clay mineralogy as the fundamental factor controlling expansive soil behaviour. Thomas et al, (2000) alluded to this fact by describing clay mineral type as the most important factor in establishing a swelling index. The low contribution of some of the individual swelling indices to the ESI however can be attributed to the differences in the conditions under which the measurements are made (Nelson and Miller, 1992) and also to the variation in how the soil properties they represent relate to swelling. Whereas some, such as the CEC and PI are direct measures of the clay type and thus associated differences in the volume change, others such as the clay content do not represent a direct measure of the clay type and marginally influences the volume change. This makes the use of indices such as clay content alone as an index of swelling a misrepresentation which however when used together with the other parameters e.g. plasticity (to obtain activity) normalizes the obtained values making them easy to compare. Thus, the data reduction established a protocol that integrates the indices and furthers the ideas of Hamberg (1985) and Thomas et al (2000). This by providing a more reliable and unbiased method of combining the indices into a swelling index that weights the contributions to the swelling by the properties they represent enabling establish a representative swelling parameter whose physical significance can be explained.

The optical density general decrease with increase in the obtained ESI was attributed to an increase in bound water and thus an enhancement of the absorption effect at the expense of the scattering effect. On the other hand, the negative relationship between the index and BNC at the various wavelengths of the absorption features could be assigned to the influence of the lattice hydroxyl (OH), described by Farmer et al, (1974) to be strong in the presence of kaolinite. The feature at 2160-2220nm (the combination and bending modes of Al-OH) has been described to increase in intensity as the fraction of the octahedral (Al-OH) to tetrahedral (SiO<sub>4</sub>) ratio increases as is the case in kaolinite rich soils which probably explains this negative correlation. Increased substitution of the Al<sup>3+</sup> by

$Mg^{2+}/Fe^{2+}$  results in broadening and thus weakening of the feature (Alonzo et al, 2002). The positive correlation at 1440-1460nm can be attributed to the shoulder of bound water (Hauff, 2000) that is to the right of the absorption minima centred at 1400nm. Russell (1987) described a water-bending mode of montmorillonite to be responsible for the feature at the 1870-1880nm that could explain the positive correlation with the ESI. The positive relationship at 2240-2260nm was attributed to increasing levels of Fe-OH at the expense of Al-OH ratio as ESI increased since 2240nm has been established to be diagnostic for Fe-OH (Farmer, 1974) and probably confirms the replacement of  $Al^{3+}$  with  $Fe^{2+}$  in the octahedral structure among the clay minerals to reflect on the soil reflectance. The differences observed in the derivatives were also attributed to these differences based on the derivatives ability to separate overlapping bands and isolate weak features (Wessman, 1994). The subtle differences in the positions and intensity of the peaks seem to show these characteristic differences where the strength of the peaks among the samples tally with the bound water (1800-2000nm) and hydroxyl (2100-2200nm) regions described by Goetz et al, (2001).

The results from the absorption parameters agree with what Kariuki et al (2003) described to be changes in surface area and influence of the minerals crystal structure. Thus, the strong loading by both the water feature depth and ESI on the second component can be interpreted to represent increase in surface area and thus mineral bearing bound water (read smectite) as ESI increased. This supports Ben Dor et al, (1999) conclusions on order of increment in surface area i.e. smectites >illite> kaolinite the important clay minerals in swelling potential estimations. This also supports Chabrillat et al, (2001) findings of the feature intensity being diagnostic in the identification of swelling soils. The negative correlation by the feature position can be said to indicate distinct differences between the soils in terms of the water structure a fact that could be attributed to what Kariuki and van der Meer (2003) described as differences in electrochemical forces on the water molecules. The asymmetries at the two hydroxyl feature positions strong loadings for the 1<sup>st</sup> component probably also reflect the Al/  $Mg^{2+}$  and  $Fe^{2+}$  ratios among the samples since strength of the 2200nm, has been established to reflect the level of substitution of the  $Al^{3+}$ . Kruse (1991) established asymmetry at 2200nm as important in the determination of kaolinite/smectites ratios in clay soils which goes far in supporting these findings.

In other studies, spectral data has been found to be a good predictor of some of the swelling indices used to obtain the ESI to very high levels. Such include field moisture ( $r^2= 0.9$  by Dalal and Henry, 1986) and CEC ( $r^2= 0.95$  Shepherd and Markus 2002) prediction where the  $r^2$  values are for measured vs. predicted values. This makes a case for the obtained results and shows that though soil is a heterogeneous mixture, compositional related properties can be estimated from

their spectra. The fact that several spectral parameters could give distinct differences among the soil groups, diagnostic of minerals, show the potential of spectroscopy in the estimation of soil properties.

## 5.5 Conclusions

It is clear from the results that clay mineralogy is a major factor in determining both the soil physical/chemical properties and their spectral characteristics. The results show dependence of both on the characteristics of the clay mineralogy in the soil where properties such as surface area are seen in the strong positive correlation between ESI and the structural water parameters. Strengthening of the hydroxyl parameters among the soils, with decreasing ESI, as seen in asymmetries and their related derivatives peaks and the strengthening of the molecular water spectral parameters with ESI can be concluded to indicate these soil mineralogical differences. This supports the conclusions of Mathews et al, (1973) of hydroxyl bands in soils being typically strong in kaolinite relative to smectites and vice versa for the molecular water bands. Thus these spectral parameters are ideal in the estimation of soil swelling properties and provides a tool from which the influence of the dominant clay mineral type on the soil can be established. It provides a new method by which future mapping of swelling soil will be done bearing in mind the increasing spectral resolution in the family of satellites with a capacity to resolve these diagnostic parameters. However, the method still requires more thought on ways of generalising the method.

## CHAPTER 6

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### **SWELLING SOIL MAPPING; LABORATORY SPECTROSCOPY AND HYSENS DAIS ANALYSIS**

*Based on: Kariuki P.C., Van der Meer, F. D., and Siderius, W., 2003, Classification Of Soils Based on Engineering Indices and Spectral Data (International Journal of Remote Sensing, 24(12), 2567-2574)*

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*"A happy life must be to a great extent a quiet life, for it is only in an atmosphere of quiet that true joy can live." – Berrand Russell, British philosopher.*

*"Money is a stupid measure of achievement but unfortunately it is the only universal measure we have." – C. P. Steinmetz (1865-1923)*



## **Abstract**

Data acquired from the hyper spectral airborne sensor Digital Airborne Imaging Spectrometer (DAIS-7915) over Antequera in southern Spain was processed to yield a quantitative soil swelling potential map based on three of the previously discussed physicochemical properties namely cation exchange capacity (CEC), coefficient of linear extensibility (COLE), and Saturated moisture content (SP). The method adopted was the use of the statistical procedures of cluster and factor analysis to obtain spectral parameters with a potential to classify the soils into classes based on existing classification thresholds where laboratory, field and image extracted pixel spectral data analysis were first used. Obtained relationships were then applied on a pixel-by-pixel basis revealing images that described spatially and qualitatively the surface distribution of these properties and thus swell potential differences among the soils in the area. The results gave an indication of the possible use of airborne spectral data for swell potential estimation.

**Keywords:** Physicochemical properties, Absorption feature mapping, Derivative analysis, Factor analysis, Clay minerals

## **6.1 Introduction**

Works based on laboratory and field soil spectral reflectance has demonstrated their potential to provide information on soil properties among which are quantitative estimation of moisture (Galvao, 2001), organic matter (Ben-Dor and Banin, 1995) and clay fraction (Escadafal, 1994). Airborne high spectral resolution sensors such as Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and Digital Airborne Imaging Spectrometer (DAIS), have also proven useful in such estimations on soil surface compositional information with Ben-Dor, et al, (2002) and Chabrillat et al, (2002) using such to obtain several soil properties. New remote sensing satellites such as HYPERION with 220 contiguous spectral bands in the 400-2500nm spectral ranges offer a new range of instruments that will in future make it possible to obtain such information from space. This will allow easier establishment of soil properties by comparing pixel spectra and laboratory spectra with known quantitative information on the soil properties, providing faster and less expensive methods of the properties determinations.

This paper reports on the results where laboratory, field and airborne spectral data were used together with physicochemical soil properties (CEC, SP, COLE) to establish spectral parameters with a potential to derive information on soil swelling where the laboratory and field spectral data was degraded to the resolution of the airborne DAIS hyperspectral data to obtain the information.

### 6.1.1 Study Area

The study area is to the south of Spain (Figure 6.1) with soils rich in 2:1 type of clay minerals, with illite dominating and in some cases interstratified illite/smectite. The soil formation has been greatly influenced by the source rocks and geomorphological processes thus the degree of development has a high correlation with the parent material and physiographic position. The main parent material being multi-coloured marls, gypsum, dolomites and dolomitic limestone. Others include dolomitic breccias, limestone, white marls, bioclastic sandstone, conglomerates and calcareous sandstone.

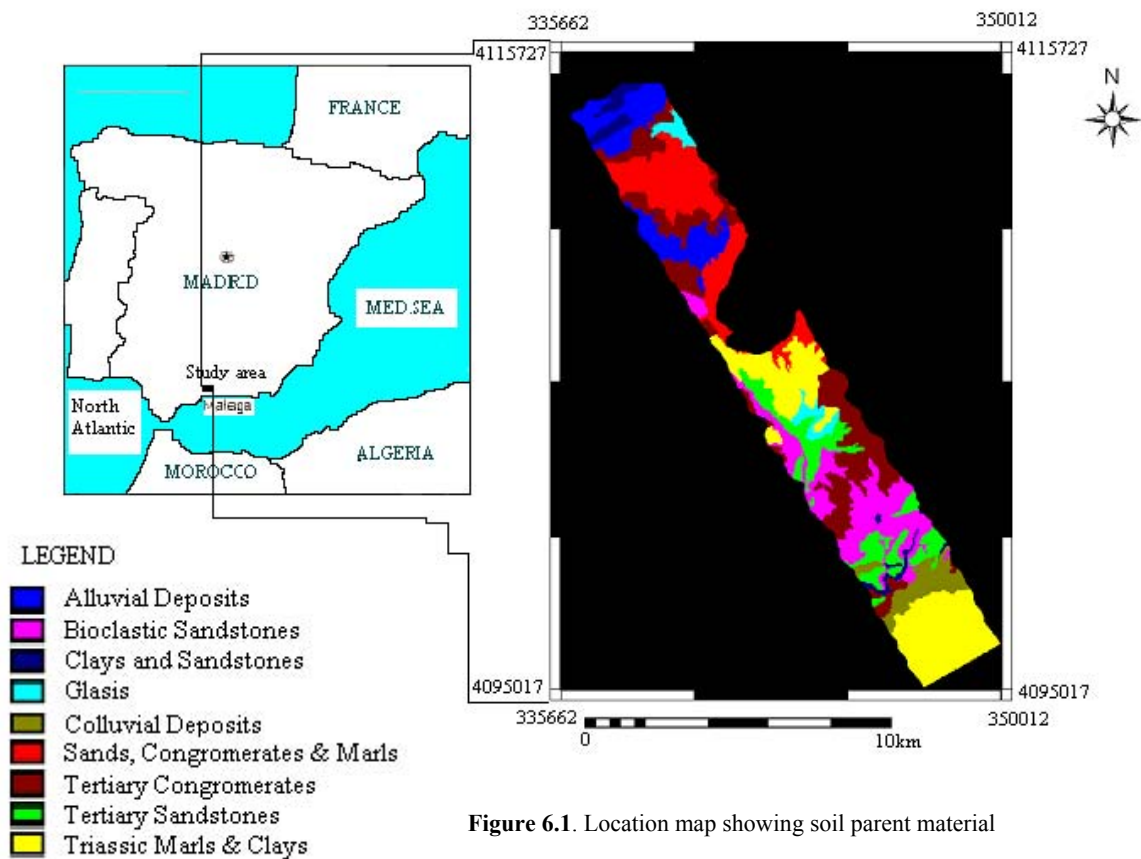


Figure 6.1. Location map showing soil parent material

## 6.2 Materials and Methods

### 6.2.1 Data Acquisition

Sampling sites were selected based on previously determined cation exchange capacity (CEC) values, in an existing soil database of the area, in the Soil Science Division of the International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, in the Netherlands. The sites were selected to represent a wide range of soils based on the CEC values. At each site three bulk and six clod samples were collected from the surface soils (0-20cm) within a five-meter radius at the same time in June 2001 when airborne hyperspectral data was acquired and field spectral measurements made. Proper location of the selected sites was done using the global positioning system (GPS) in order to obtain samples as near to the existing data as possible. Other ancillary information, of each site, i.e. description of the soil, and percentage cover of in terms of soils and vegetation was also recorded. Extra sites were also randomly selected and added to the previously selected sites.

### *Physicochemical data*

The particle size distribution (PSD) analysis, CEC, COLE and SP were obtained from split samples of those collected. Particle size analysis was by the pipette method while CEC was through the mechanical extractor method (Reeuwijk, 1995). COLE was through the clod test method (Nelson and Miller, 1992) while SP was taken as the difference in weight between saturation and oven dry states of the samples. The obtained clay content was then used to normalize the other indices so as to obtain thresholds within which to assign the soils to a swelling potential class.

### *Spectral data acquisition*

In the laboratory spectra of split samples of those used for the physicochemical tests (passing the < 2 mm sieve and oven dried at 105<sup>0</sup>C) were obtained using the PIMA (Portable Infrared Mineral Analyser) upgrade spectrometer and GER 3700. Both of which have an average spectral resolution of 10 nm. The PIMA covers the spectral range between 1300 nm and 2500 nm and GER 3700 between 400nm and 2500nm. Field measured spectra data at selected sites during the flight represented the field spectral data. The DAIS hyperspectral data was acquired on 28 June 2001 at an altitude of 10 000 feet (providing a pixel size of approximately 5 m×5 m). The sensor is sensitive to the visible (VIS), near infrared (NIR), short wave infrared (SWIR) and thermal infrared (TIR) spectral regions (0.4–14 nm) consisting of 79 channels with a bandwidth ranging from 0.9 nm in the VIS to 60

nm in the TIR. The image scene covered an area of 21km by 3 km in a northwest southeast direction and in this paper, only the reflective portion of the electromagnetic radiation was used covering the VIS-SWIR (0.4–2.5 mm) spectral region with 72 spectral bands.

### *6.2.2 Data analysis*

Analysis of the spectral data was by use of two techniques found to adequately represent information in the spectra i.e. absorption feature mapping (Mustard, and Jessica 1999) and the derivative analysis where finite approximation method was used (Tsai and Philpot, 1998). Classification of the soils in terms of swelling potential classes was based on the established thresholds of the three measured properties (see chapter 3). These thresholds provide a measure of the clay influence relative to sand and silt contents.

#### *Statistical analysis*

K-means cluster algorithm was used to establish spectral parameters with a potential to give information on the measured properties using the laboratory and field spectral data. The method is based on identifying homogeneous groups of cases within a heterogeneous data (SPSS, 1999) followed by establishing cluster centres for each cluster. The clusters were set at 3 and the initial centres as the three established thresholds in Table 6.1 for the physicochemical properties. Resulting spectral parameter assignments were made based on their association with these centres and assumed to provide information on differences in the measured properties among the soils.

The second stage involved the use of factor analysis to establish quantitative assignments to the simultaneous variation in both the spectral parameters and physicochemical properties by assigning the factor scores of the factor with strong assignments from the measured properties to a normalized scale. Factor analysis is based on common factors analysis, where elements on the principal diagonal are the communalities, which means that only the common variance of the variables are analyzed. Thus, it has the advantage of removing the unique factors of each variable and optimizing the information content based on the common factors. This enables interpretation of factors in terms of their contributing variables. Here the factor with maximum contribution from the measured physicochemical properties was assigned to represent compositional differences and thus to varying swelling potential levels. Spectral parameters with strong loadings from this factor were

assumed to show strong correlation to the compositional factors contributing to the differences in the measured physicochemical values.

#### *Image data analysis*

The atmospheric correction was performed with the Atmospheric/Topographic Correction (ATCOR4) model for wide FOV airborne imagery (Richter et al, 2001) prior to the introduction of the data in the combined analysis. The visible (VIS) to near infrared (NIR) i.e. 0.49-1  $\mu\text{m}$ , short wave infrared SWIR-1 (1.5-1.8  $\mu\text{m}$ ) were good, however problems existed with the spectrometers in the region 1.948-2.179  $\mu\text{m}$  that made the data not useful. There was noise in 2.317 – 2.395  $\mu\text{m}$  region that was minimized by use of the moving average smoothing technique before analysis. Extracted pixels spectra at each of the sampling locations were used together with the resampled field and laboratory spectra for the statistical analysis. Resulting spectral assignments were then used on a pixel-by-pixel basis on the whole image.

#### *Geological map units' integration*

We used a generalized parent material map as an additional information source for classification. The generalization process comprised of merging smaller adjacent units to the various major units that resulted in the parent material map (Figure 6.1).

### **6.3 Results**

Table 6.1 gives the summarised dynamic range of the physicochemical properties and statistics of the laboratory analytical data of the used samples, showing a relatively wide variation in the three properties. The mean for SP (50%) was relatively high as would be expected for clay soils though not as high as in soils of generally high swelling properties as previously established among the Kenyan samples.  $\text{CEA}_c$  (0.41) and LEP (0.053) averages were also moderate thus classifying the soil population as of moderate activity. This was attributed to the soils generally having illite as the dominant clay type with those of high swelling in the population being of an illite/smectite inter-layering. Domination of illite promotes low to moderate swelling properties whereas swelling resulting from the interlayer type of minerals depends on which of the two forms the higher percentage.

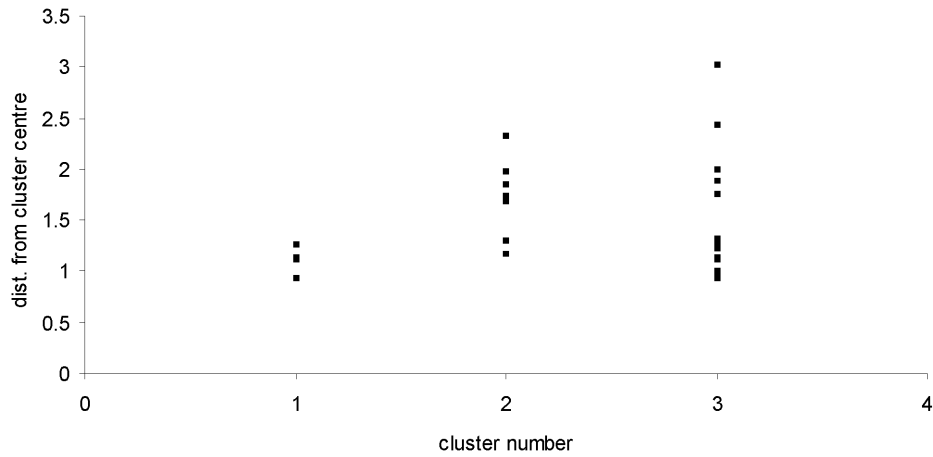
**Table 6. 1.** General information on engineering indices

Property	Minimum	Maximum	Average	Standard Deviation.
Saturated paste	28	76	50	0.33
CEA <sub>c</sub>	0.12	0.7	0.41	0.12
LEP	0.01	0.108	0.053	0.39

Table 6.2 provides the cluster centres based on the absorption feature parameters of the laboratory and field spectra and the three swelling indices. Figure 6.2 shows the spread of samples in each cluster from their cluster centres based on the Euclidean distance where only a few samples seem to be significantly different from their means and in the 3<sup>rd</sup> cluster, thus showing each cluster to properly represent the assigned threshold. The results show that though other sources of variability between the soils are likely, the spectral variability seemed to give a good indication of the compositional differences and thus provide a good source of information on the swelling potential of the soils based on the three measured properties. Samples of high swell potential and assigned to abundant smectite in Table 3.2 grouped in the second cluster whereas those of moderate and low potential grouped in the first and third clusters respectively further proving the previously established spectral parameters potential in discriminating soils on the basis of their swelling potential.

**Table 6.2.** Final Cluster Centers

Parameter	Clusters		
	1	2	3
Asymmetry 1400	1.0796	.8989	1.0336
Depth 1900	0.0481	0.0865	0.0399
Wave position 2200	2207.30	2218.29	2206.37
Asymmetry 2200	0.96	0.62	1.15
CEA <sub>c</sub>	0.41	0.6	0.23
SP	52.7	75.9	28.2
LEP	0.05	0.09	0.02



**Figure 6.2.** Variation in distance to cluster centers among used soil samples

However, even though there is a clear separation between low and high value classes based on both the measured physicochemical properties and spectral parameters, this cannot be said to be the case for the moderate value group as evident from the distance between the cluster centres (Table 6.3) probably showing two clusters as more appropriate. This resulted in the use of two clusters for the image data with much better results.

**Table 6.3** Distances between Final Cluster Centers

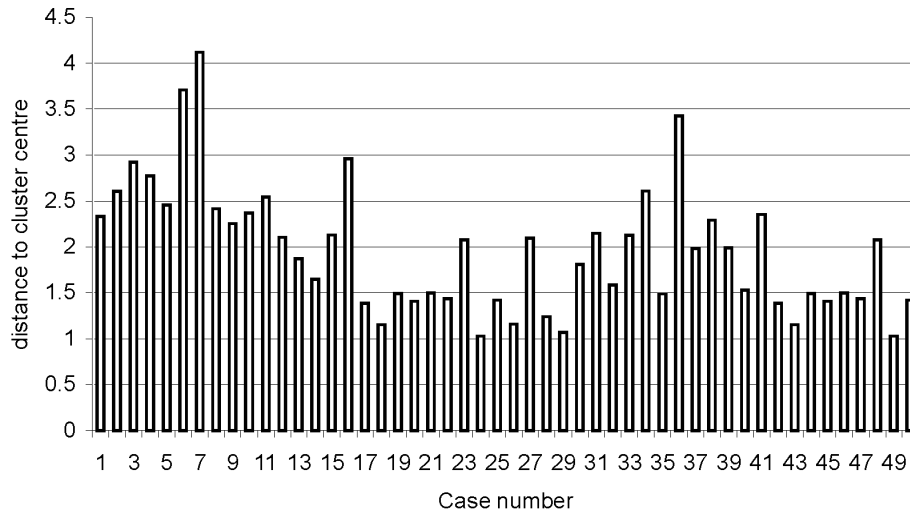
Cluster	1	2	3
1		25.392	14.298
2	25.392		38.724
3	14.298	38.724	

Similar relationships were sought from the DAIS image data where re-sampled field and laboratory spectral data were used together with extracted pixel spectra of the various sampling sites. They gave an indication of similar differences among the soils by separating the samples into two clusters based on the 1<sup>st</sup> derivative peaks intensities at several wavelengths ( $p < 0.01$ ) that included; 551nm, 1606nm, 1698nm, 2151nm, 2252nm, 2193nm, 2304nm and 2342nm. These peak positions are in spectral regions, which have been assigned to spectral anomalies in clay minerals reflectance and to the presence of Al-OH and Mg-OH in dioctahedral and trioctahedral clays (Hunt, and Salisbury 1970). Table 6.4 provides the final cluster centres after 25 iterations of both the spectral parameters and the measured properties among the soil samples. Figure 6.3 gives an illustration of the samples distribution in terms of distance from their respective cluster centres where only a few samples are seen to be at great distances from their centres thus appearing as offshoots in what is generally a distribution well within short Euclidean distances.

**Table 6.4.** Final Cluster Centers

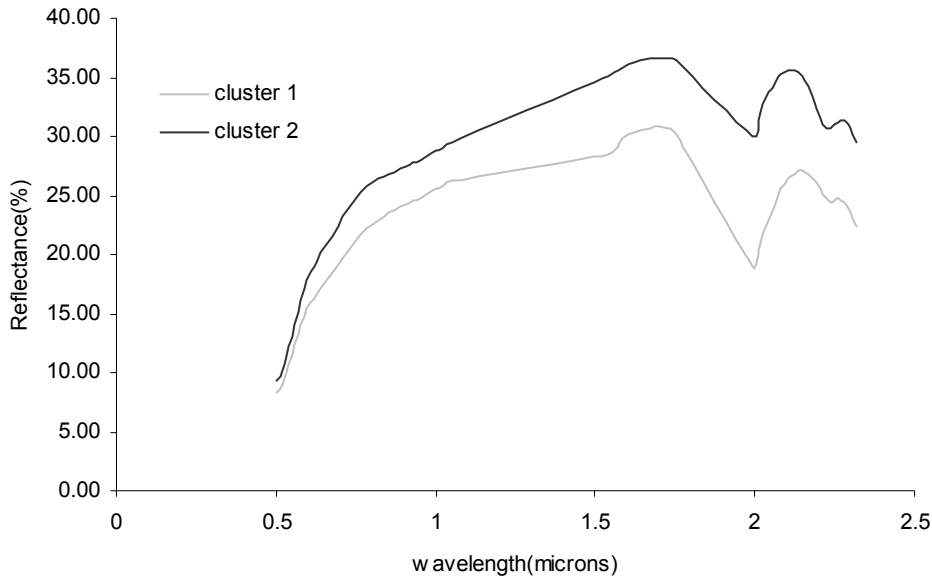
1 <sup>st</sup> derivative peak	Cluster	
	1	2
R_551	10.966	17.812
R_1606	3.047	-1.874
R_1698	2.745	1.414
R_2151	-2.518	1.220
R_2193	-6.867	-3.548
R_2252	-7.649	-5.872
R_2304	-10.441	-4.502
R_2342	-2.331	-8.026
LEP	.07	.02
SP	67.33	42.25
CEA <sub>c</sub>	0.7	0.2





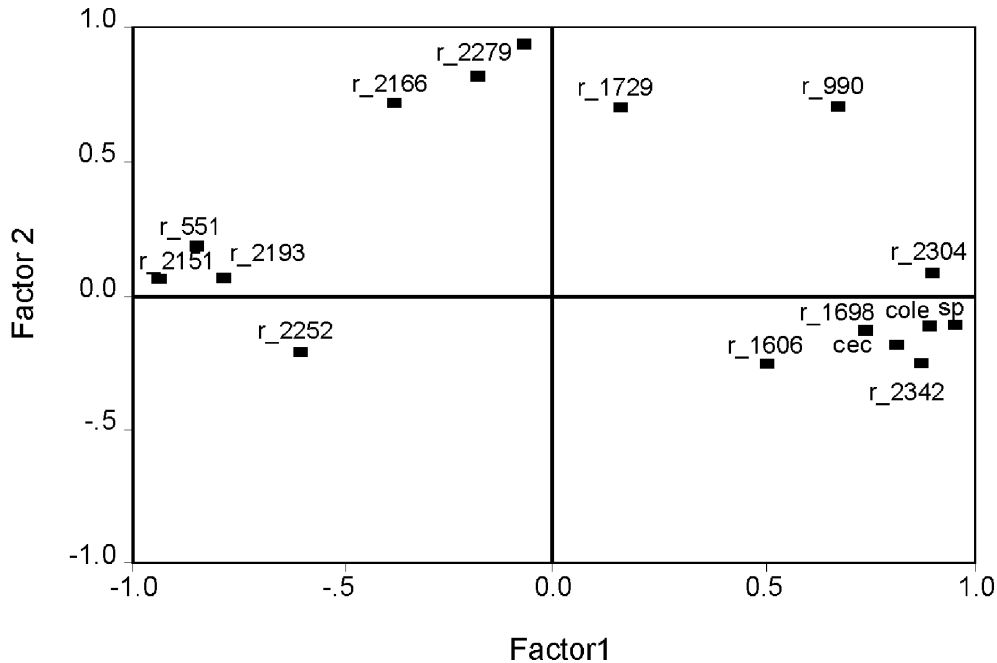
**Figure 6.3.** Variation in distance to cluster centers in DAIS extracted pixel data

Figure 6.4 gives an illustration of the resampled average spectra of soils in each of the two clusters where it is evident that the spectrum of cluster 1, comprising of the generally higher swelling soils based on the used indices shows a generally lower albedo at all wavelengths relative to that of cluster 2. This is as would be expected for soils with significant contents of the high swelling smectites which possess structural water that could explain the lower reflection relative to those in the second cluster presumed to consist of lower swelling potential minerals soils whose albedo is generally higher based on their lack of such water. The general slope of the spectra is also different with that of the first cluster being gentler and the outline of the hydroxyl feature at the 2200nm being more pronounced in the second cluster. Though the parameters of the feature could not be give the characteristic difference its greater intensity in this second cluster of significance. It is important to point out here that of the samples used in this classification only less than 10% were misclassified thus showing the selected spectral assignments as good in the characterization of the soils on the basis of the three swell indicator properties.



**Figure 6.4.** Average spectra of low and high properties value soils

The second stage involved quantization of these relationships based on the factor analysis statistical procedure where the factor extraction was done with criteria that the minimum acceptable eigenvalue must be greater than 1 (Kumru and Bakac, 2003). The first two factors explained more than 87% of the variance where factor 1 grouped the measured physicochemical properties with some of the spectral parameters both of which had high factor loadings. The second factor had loadings from mainly spectral parameters not found in the cluster analysis to closely relate to the measured properties and thus was interpreted to consist of insignificant information as to their variability (Figure 6.5). Spectral parameters with high factor loadings in factor 1 were therefore interpreted to represent the reflectance spectral information with a strong indication as to the variation in the three properties that based on previous results show an indication of mineralogical and thus swelling potential differences.



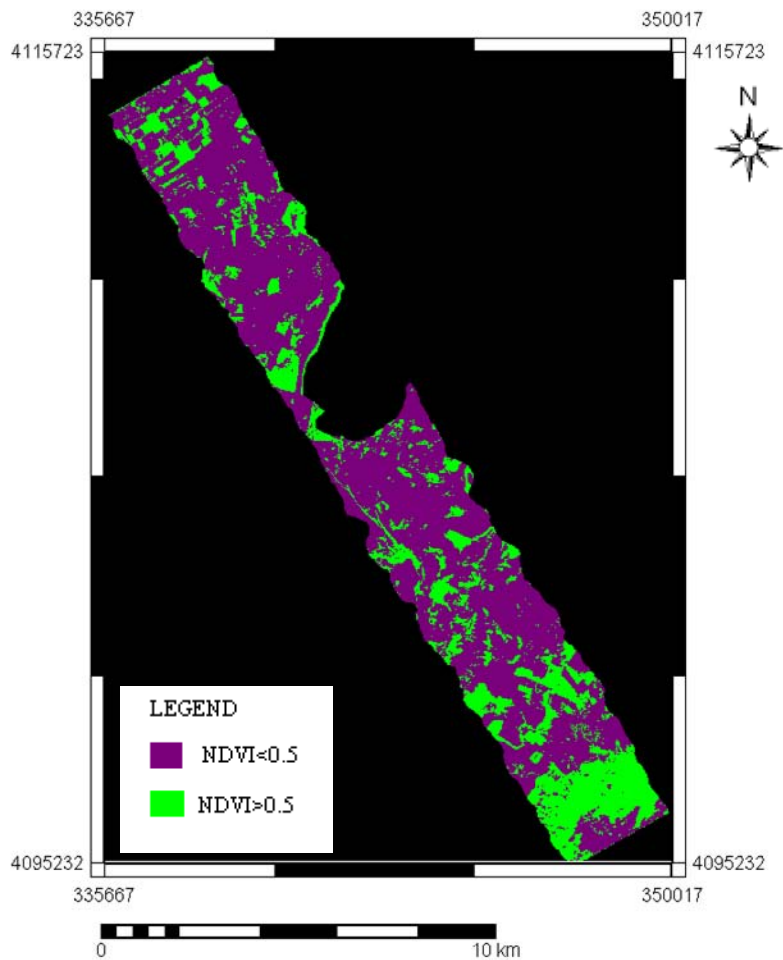
**Figure 6.5.** DAIS data reduction to obtain spectral calibration wavelengths

The loadings for this common factor from the three indices were; COLE (0.86), CEC (0.76), SP (0.92) and 551nm(-0.82), 1606nm(0.52), 1698nm(0.75), 2151nm(-0.88), 2252nm(-0.55) 2193nm(-0.7), 2304nm(0.94) and 2342nm(0.77) for the spectral parameters with a strong showing in the factor. This confirmed the cluster membership assignments and led to the conclusion that the factor could be used to explain variation in the soil swelling properties in the soil population, by assigning the soil samples to their factor scores.

The results also show the loadings to portray the information as coming mainly from wavelength positions associated with strong presence of clays rich in Al-OH (2151nm, 2193nm) and Mg-OH (2304nm) cited in many writing as a reflection of the strength of the combination of fundamental OH stretching ( $\nu$ ) and bending ( $\delta$ ) modes of OH-metal-OH bonds in the octahedral and trioctahedral positions respectively. High albedo in clays could also be assigned to one of the other significant positions (1698nm) also described by Beck et al, (1976) as best for mapping clay content in surface soils. It has also in other studies been established

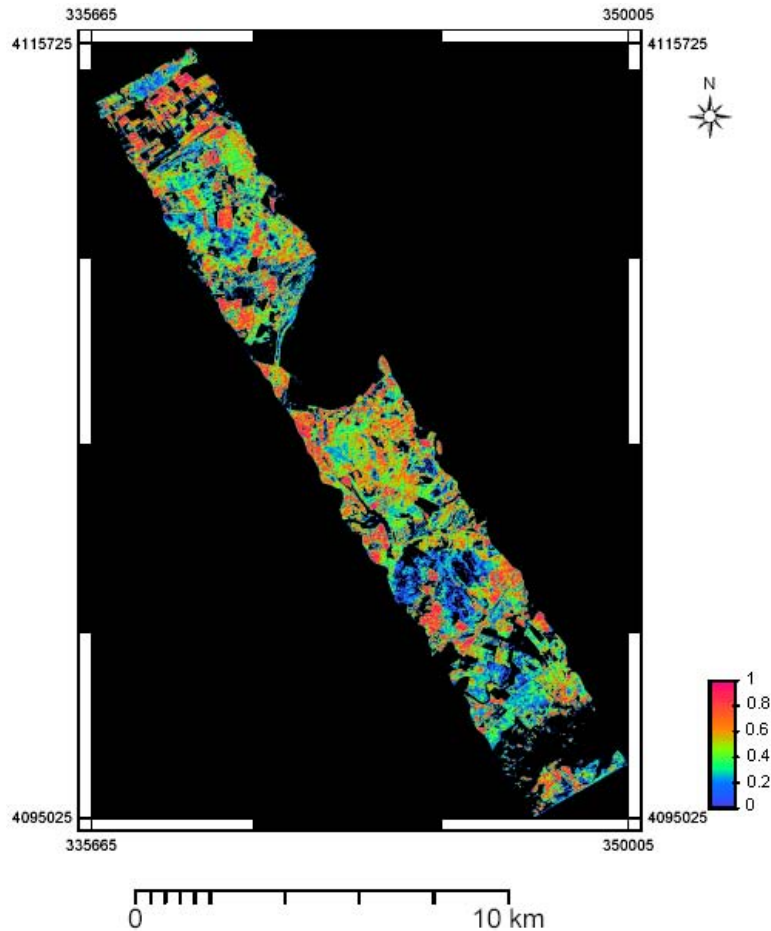
to show strong correlation with CEC (one of the three measured physicochemical properties) a fact that has been attributed to CEC being closely related to soil constituents that exhibit spectral behaviour, the clay type (Stoner 1979). 2252nm that was relatively weaker in the results has been associated with Fe-OH, though its significance could also probably reflect the presence of ferric iron in well-drained soils with a low swelling potential. Karmanov (1970) attributed the reflection intensity at the 551nm region to iron hydroxides containing water.

Part of the study area was covered with vegetation that could have influence on the classification results. This was overcome by application of masking based on reported discriminating indices for high vegetation cover and percentages at which a vegetation cover can be assumed to have little or no influence on the soil signature. At a vegetation cover as high as 15% surfaces have been described to appear as soils (Girard-Ganneau 1975) whereas vegetation cover in excess of 40% makes the spectral behaviour that of vegetation. Masking of vegetation was therefore done based on these assumptions and that of Orueta, et al, (1998) who reported a threshold of NDVI of 0.5 as enough to separate areas of little or no vegetation cover from those in which vegetation would interfere with the establishment of soil surface properties. The image was thus classified into vegetated and scarcely vegetated/bare soil regions by use of the Normalised Difference Vegetation Index (NDVI) threshold (Figure 6.6) which left significantly large areas for classification.



**Figure 6. 6.** Criteria for masking Areas with heavy vegetation (NDVI)

Figure 6.7 shows the resulting classification of the image based on the obtained results where the factor scores of the spectral data manipulations and the measured properties were used. Classification was by assigning the selected spectral parameters weights based on their contribution to the established common factor which was normalised into the 0 to 1 range i.e. 0 to 0.4 for low, 0.4-0.7 (moderate), and > 0.7 (high) based on the field-collected samples results.



**Figure 6.7.** Classification based on spectral parameters and measured properties.

The results gave a fair indication of the measured property differences (Table 6.5) in the area based on field knowledge i.e. classifying the soils into mainly low and moderate property values that are characteristic of the area. However, misclassifications did occur as would be expected probably due to variations resulting from other sources of variability in the spectral data. The highest misclassification occurred in the high swell potential category probably due to the lower presence of these type of soils in the area as is evident from the accuracy figures. The results however seem to indicate that despite what could have been other sources of variability, the composition differences influencing the soil physicochemical properties seem to play a significant role in their spectral characteristics that can be used to obtain information on their differences despite the classification having only considered the spectral information. This probably

confirmed observation by Baumgardner et al, (1985) that soil patterns remain visible with drainage and moisture holding capacity differences influencing their overall reflectance.

**Table 6.5.** Error matrix, user's accuracy (UA) and producer accuracy (PA) of the classification

	Low	Moderate	High	Accuracy
Low	13224	4092	6056	0.56
Moderate	8480	3172	2932	0.58
High	2836	916	2032	0.35
RELIABILITY	0.55	0.39	0.20	

Average Accuracy = 49.67 %

Average Reliability = 38 %

Overall Accuracy = 42.3 %

This indicates that in addition to absorption features, changes of the spectral slope can play a significant role in the estimation of soil properties from hyperspectral data with much lower spectral band numbers relative to those regularly used in the laboratory and field measurements. Thus, though the hyperspectral data might not give as precise measurements as the laboratory procedures, it could be a good tool for quick assessment on the surface properties and thus a start to more detailed assessment in the field or laboratory. Similar procedures for soil property estimations, have in the past been applied (Ben Dor et al, 2002) to a relative degree of success, making the obtained results significant. However, caution should be taken when using such information since spectral noise can be introduced into the results due to amplification of noise by the various manipulations, which could lead to irrelevant band assignments.

Incorporating the parent material map to stratify the image where the parent material prior probability based on known presence among the laboratory-measured data was used did not improve the classification much probably signifying the need to study in detail variation within the various strata in relation to other factors that maybe having an influence on the spectral data. However, moderate to relatively high property values soils was observed to fall mainly into marls, clays, and alluvial deposits which form the greater part of the low lying areas.

## **6.4 Discussion**

The laboratory results show the soil compositional differences to have great influence on the resulting spectral parameters that can be used to classify them on the basis of their associated property differences. The differences in the absorption feature parameters in terms of strength of the hydroxyl (OH) and molecular water features relative to the presence of clay minerals with a potential to influence the measured swelling potential indicator properties were seen in the variations in depths, asymmetries and position shifts which as previously described is a function of the soil clay mineralogy and their structural differences which as seen in the established classification tables result in surface area differences a key to the variation in the used soil physicochemical properties. The clusters give an estimation of the discrete boundaries within which spectral parameters can be used to classify soils in terms of their swelling potential based on these classes and reflect the covariance between the physicochemical properties and the spectral response of the used soils. Montgomery and Baumgardner, (1974) reported the potential of using spectral data to establish soil properties resulting from soil constituents with obvious spectral character and went further to describe this as being pronounced for CEC, which seem to be the case here.

This seems to be evident even in the airborne image data where significance of the spectral derivatives could be attributed to the manipulations enhancement of weak absorption (De Jong, 1994) and at the same time suppression of physical influences (Chang, et al, 2001). This could have provided clearer information on the absorption mechanism by minimizing interference from properties such as the soil surface roughness and other physical properties. The results are also in line with Muller and Decamps, (2000) observations of remotely acquired spectral data providing information on underlying processes bringing about the soil composition differences such as the soil internal drainage. Thus the generally high reflectance at all wavelengths by the presumed well-drained soils and lower reflection by the poorly drained soils could be attributed to this as has been previously documented by Baumgardner et al, (1985). Most of the established significant wavelengths have also been described to provide important information on soil water and mineralogy (Banin, and Amiel, 1970; Ben-Dor, and Banin, 1994; Goetz, et al, 2001; Downey, and Byrne, 1986) further confirming the approach as viable in soil property studies. However the conclusions by Stoner (1979) and Schreier (1977) of parent material being a key component in the resulting soil spectral characteristics did not seem to give significant improvement in this case.

The results thus provides a strong case for the potential application of remote sensing to soil properties estimation more so those related to presence of clay minerals and their interaction with moisture. They give an indication of the



potential role of reflectance spectroscopy as a primary or complementary tool in such determinations, though they also show the limitations of hyperspectral data relative to laboratory data in terms of information content.

## **6.5 Conclusions**

The results show that the laboratory established spectral parameters to show potential differences in the soil composition, can also be obtained from remotely sensed data with proper calibration and used to differentiate soils based on their physicochemical properties. This could easily be attributed to the covariance between the soil properties without a primary response in the soil spectra (used indices) with those possessing such a response (the clay mineralogy and soil water) making it possible to use the spectral diagnostics of the primary response factors to obtain information on their co-varying properties. The resolving capacity of the airborne data was however insufficient to resolve some of the most diagnostic spectral parameters established in laboratory data to provide details as to the molecular structural differences among the compositional elements. This probably calls for the applications of higher bandwidths in the airborne data acquisition that would resolve some of these unique feature parameters. Even though other sources of variability could have been in play, the results confirm reflectance spectroscopy as a tool that adds value to the existing soil properties classifications schemes by filling the information gap as to causative compositional factors. They also add a physical basis of diagnostic differences in terms of clay mineral in the reflected soil spectra and thus lay the foundation of establishing a faster method of characterizing soil in terms of mineralogy and their related properties such as swelling.

## CHAPTER 7

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### **LANDSAT TM WHAT ROLE IN SWELLING SOIL MAPPING?**

*Based on: Kariuki P.C., Woldai, T., and Van der Meer, F.D, Is There A Role For Remote Sensing In Mapping Swelling Soils? Asian Journal of Geoinformatics, (submitted)*

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*“We are not permitted to choose the frame of our destiny. But what we put into it is ours” –  
Dag Hammarskjold*

## **Abstract**

Use of satellite images during the early stages of mineral exploration has been very successful in pointing out the presence of minerals important in identification of swelling soils namely smectites, illites and kaolinite. Here several methods were used for spectral enhancement of an Enhanced Thematic Mapper image (ETM+) to evaluate the possibility of separating surface soils based on the presence of these minerals in an area in central Kenya, where swelling soils are a major problem in the ever-expanding urban centres in the vicinity of Nairobi city. The enhancement techniques included; principle component analysis, band rationing, and minimum noise fraction. Characteristic differences were apparent in vegetation related indices and soil brightness in the various enhancements which was attributed to drainage and topographic differences having influence on the two. Micro-topography in the form of gilgai found exclusively in the poorly drained soils were observed to confirm the established differences interpreted from the vegetation and soil brightness. The swelling potential distribution map based on these image interpretations was found to generally agree with the soil classification map of the area confirming the potential of the TM image in mapping soil characteristic differences.

## **7.1 Introduction**

Expansive soil identification is mainly done based on aerial photography coupled with field observations where the surface expression in the form of cracking and mulch or popcorn surface are used. However, advancement of remote sensing systems both in terms of spatial and spectral resolutions has added a possibility of using these systems in the identification of these soils where their diagnostic spectral parameters, based on their clay mineralogy, and spatial patterns can be established.

General remote mineral identification has developed over the years since the launch of the first Landsat satellite in 1972 with the vibrational transitions in hydroxyls of clay minerals being the most notable reflectance anomaly in the short wave infrared (SWIR) region between 1.1 and 2.5 $\mu\text{m}$  in these sensor systems. The Landsat Thematic Mapper (TM) has two bands in the region of interest, consisting of high reflectance (1.65 $\mu\text{m}$ -TM5) and absorption anomalies (2.2 $\mu\text{m}$ -TM7) for the clay minerals (Goetz and Rowan 1983). The satellite has four bands in the visible region with TM3 (0.6 $\mu\text{m}$ ) showing high reflectance for iron oxides and strong absorption for vegetation. The typical feature for vegetation is at TM4 (0.78-0.9 $\mu\text{m}$ ) that also contains absorption anomaly for iron oxides. This makes TM helpful in mapping vegetation, iron oxides, and clay minerals a fact that probably

led Goetz *et al*, (1981) to describe the series of Landsat to provide extensive soil mapping capabilities. Westin and Frazee (1976) used such data based on tone, color, land use and drainage patterns to obtain a soil map whereas Kirschmer *et al*, (1978) and Agbu *et al*, (1990) used similar logics to establish soil composition and classification maps respectively. Riaza *et al*, (2000) and Ruiz-Armenta and Prolledesma (1998) on their part managed to map stages of iron and clay weathering and the spectral response of hydroxyl and iron oxides. All of which gives an indication as to the potential application of Landsat imagery in soil mapping.

The spatial resolution of the TM imagery (30m) has generally been described as too coarse for meaningful surface spatial patterns mapping. However, the improved spatial resolution of band 8 in the new satellite the Enhanced Thematic Mapper (ETM) offers a better source of spatially discernable features information, as is the case with gilgai topography that range in diameters at between 20-50m and in terms of height 15-30cm based on their significance in the recognition of high swelling soils.

Gilgai describes a terrain of low relief in *Vertisols* characterized by the presence of hollows, rims, and mounds, as formed by alternating periods of expansion during wet season and contraction (with deep cracking) during hot, dry season. Eldelman and Brinkman (1962) related them to shearing force in the underlying clay while Knight (1980) suggested that their micro highs form from cumulative internal vertical movements along small oblique slips immediately associated with major crack zones. White and Bonestell (1960) on their part suggested gravity as the cause while Beckmann *et al* (1973) and Elbersen (1983) attributed the linear type to immature rill erosion. The soil on the mounds has properties, which are more like subsoils (i.e. lighter colour and higher salinity) whereas those in the depressions consist of dark accumulation material, a characteristic that brings about vegetation differences (Stephen *et al*, 1956) and which is expected to bring tonal differences on an image. The topography has been widely mapped in Australia and is recognized as a surface expression of high swelling soils due to its presence only in such soils. Their surface expression on the image could thus provide a good source of information on these soils. With the ever-increasing spatial resolution data from satellites, such as the Interferometric SAR (InSAR) that allows measuring surface topography with meter accuracy and differential interferometry (Van der Meer, 1999) such spatial patterns could in future be used with a great element of success.

Here a prelude to such an application combining the spectral differences and recognition of these features is discussed where the ETM panchromatic band (spatial resolution 15m) is used to delineate the gilgai pattern and the enhanced

spectral differences to obtain recognisable compositional differences resulting in the classification of the image into a swelling potential map.

## 7.2 Materials and Methods

The six none thermal bands of an enhanced TM imagery acquired on 21 February 2000 were used for the spectral manipulations where univariate and multivariate image statistical analysis were used to assess redundancies in the data. This was followed by use of commonly used enhancement methods to maximize information content before the interpretation. The enhancements included; band ratios, minimum noise fraction (MNF), principal component (PC) analysis and Tasseled cap transformation (TCT).

Band ratios has been described to overcome the shadow and topography effects thus allowing spectral characteristics differences to be established. MNF which is a cascaded principal component transform (Green *et al.* 1988) that selects new components in order of decreasing signal to noise ratio and was taken to determine the inherent dimensionality of the image data by segregating and removing noise. It divides the data into two parts: one part associated with large eigen values and coherent eigen images, and a complimentary part with near unity eigen values and noise dominated images. By using only the coherent portions, the noise was assumed to have been separated from the data. The PC analysis was in two stages, one based on all the available bands, and the other on selected bands based on their known anomalies in the presence of vegetation and hydroxyl bearing minerals (Crosta and Moore 1989). This allowed identification of the principal components that contained spectral information about these materials, as well as the contribution of individual original bands to the components in relation to their spectral response thus indicating whether they were represented by bright or dark pixels based on the sign and magnitude of the eigenvectors.

TCT is an orthogonal transformation that is used to enhance separation between soils and vegetation through the determination of three indices namely; soil brightness, greenness and a third feature associated with soil moisture (Crist and Cicine, 1984). The 1<sup>st</sup> index which is a soil band that includes soil reflectance or brightness information, is a weighted sum of all bands in the direction of principle variation in soil reflectance and was used to locate bare soil areas. The greenness axis describes the contrast between the near infrared and the visible bands and was used to confirm vegetated areas whereas the third component contrasts mid

infrared reflectance with visible and near infrared reflectance and was important in confirming the separation of areas into vegetated and bare soil units.

Visual interpretation was also done on the panchromatic band to delineate the gilgai area. Field visits were used to assess the obtained results where locations identified on the image to consist of the various spectral and spatial assignments were confirmed and soil samples collected for further analysis in the laboratory. Detailed field description of the soils was also carried out and the contrasting physical differences recorded. The combined information was then used to produce a swelling soil distribution map of the area.

## 7.3 Results

### 7.3.1 Univariate and multivariate statistics

The results of the univariate analysis are as shown in Table 7.1 and show TM-2 to have the smallest variance attributed to its low contrast among the surface cover in the image. TM-5 had the largest variance which was interpreted as due to the large differences in the spectral response of the various materials contained in the image. The other four bands gave moderate variance relative to the two and could therefore be said to show significant contrast in the scene surface materials.

**Table 7.1:** Univariate analysis on the six bands of the TM image

Band Number	TM1	TM2	TM3	TM4	TM5	TM7
Mean per band	89.88	42.06	56.74	71.97	133.90	64.11
Std. per band:	20.93	13.77	19.53	15.98	33.96	20.38
Variance	437.95	189.55	381.32	255.37	1153.46	415.15

The multivariate statistics (Table 7.2) indicate bands TM-1, TM-2, and TM-3 as highly correlated, and therefore their information content as independent sources redundant to some extent. There was also a high correlation between band 5 and 7 probably due to their dependence on the soil reflectance differences. The lowest correlation was between TM-4 and TM-7 (49%) followed by that between band 5 and band 4 (51%) making these the most important in establishing differences in spectral information in the surface materials within the study area.

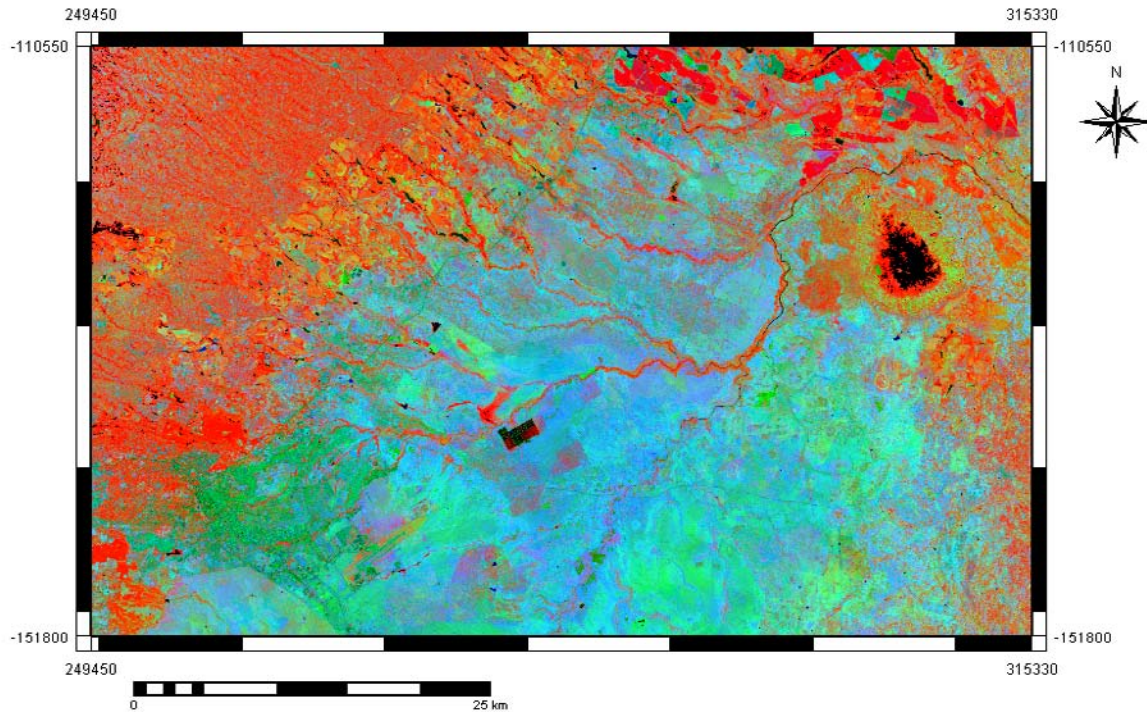
**Table 7.2.** Correlation Matrix for study area

	TM 1	TM 2	TM 3	TM 4	TM 5	TM 7
TM 1	1.00	0.95	0.93	0.56	0.67	0.76
TM 2	0.95	1.00	0.96	0.66	0.68	0.79
TM 3	0.93	0.96	1.00	0.60	0.81	0.89
TM 4	0.56	0.66	0.60	1.00	0.51	0.49
TM 5	0.67	0.68	0.81	0.51	1.00	0.95
TM 7	0.76	0.79	0.89	0.49	0.95	1.00

### 7.3.2 Band Rationing

The important band ratios were TM4/TM3 (for vegetation), TM3/TM1 (iron oxides), and TM5/TM4 (hydroxyl bearing clays). Though TM5/TM7 is conventionally used to show clay mineral presence (Riaza et al, 2000), it was here observed not to give much in terms of information probably due to the previously observed high correlation. Figure 7.1 gives a color composite of the important ratios, TM4/TM3, TM5/TM4 and TM3/TM1 in red (vegetation), green (hydroxyl) and blue(iron oxides) respectively. (Rowan et al, 1977).

Vegetation was strong mainly to the northwest and east and gave an indication of strong correlation with the topography and thus drainage differences (see Figure 7.8 for a perspective view) and along the drainage channels, which is expected due to proximity to water. Vegetation was poor in the plains to the centre of the area, which instead gave a strong green colour thus probably indicating exposed soils with high hydroxyl presence. The iron assigned blue was also evident in the plains along drainage channels and on the fringes at the contact between the plains the higher grounds. The strong presence along drainage channels could be due to transported materials making the use of this ratio difficult. The composite image thus provided an indication of the clear difference in terms of the soil units based on the interpreted drainage and topography as established by the vegetation cover. Better drainage on the high grounds was interpreted to probably result in the heavy vegetation cover and thus probably of lower swelling potential properties. Poor drainage on the other hand in the low-lying plains was interpreted as the cause of the poor vegetation and thus the stronger index of exposed soil. Thus based on these ratios the image was subdivided into at least two soil units.



**Figure 7.1.** Color composite of band ratios (TM4/3, TM5/4 and TM3/1)

### 7.3.3 Minimum Noise Filter (MNF)

Van der Meer and De Jong (2000) established MNF to improve cover estimates relative to the original TM band data. Table 7.3 gives summarized statistics of the MNF transformation where the first four bands, with large Eigen values were taken to represent the spectral information, contained in the images (Boardman and Kruse, 1994). The first image consisting of the highest variance was interpreted to represent variation in albedo. The second had strong negative loading from band 5 and was thus assigned to show hydroxyls as dark pixels. The third gave a strong negative loading from band 4 and was assigned to vegetation. Other images were found to consist of noise and thus not useful in the interpretation. The results of the MNF were thus found not to add any significant information relative to that in the band ratios since the established cohesive image differences were similar to those in the ratios.



**Table 7.3:** Statistics of the MNF transformation Images

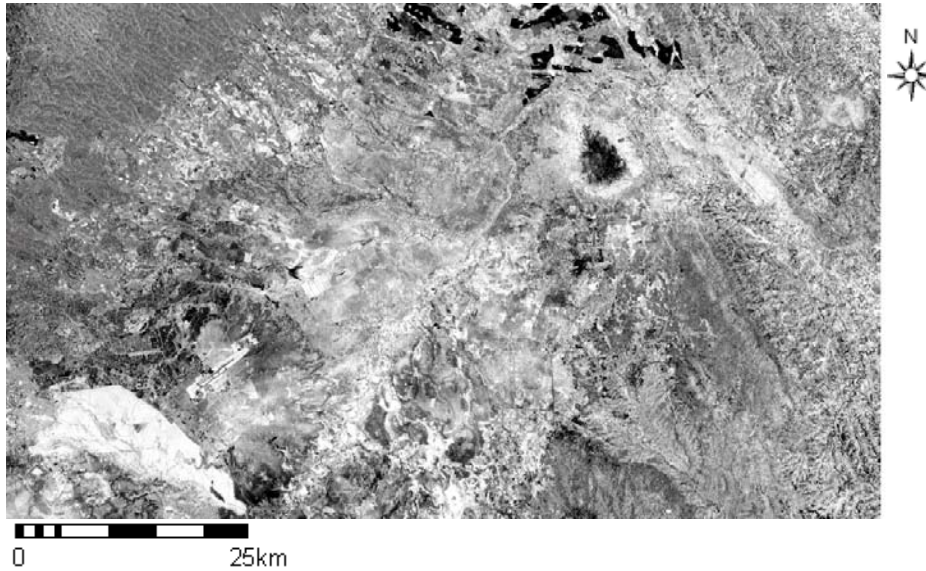
Band	Min	Max	Stdev	Eigenvalue
1	-51.38	81.83	12.69	161.15
2	-15.19	73.69	6.11	37.33
3	-26.55	30.16	4.24	17.95
4	-64.92	22.92	3.6	12.94

#### 7.3.4 Principal Component Analysis

Principal component transformation results, using the six optical bands (TM-1, TM-2, TM-3, TM-4, TM-5, and TM-7) is as shown in Table 7.4. The first (PC1) assumed to consist of information on the albedo and topography had the major contribution from TM-5 (66.7%) whereas PC2 had a strong negative contribution from TM-5 and thus was assigned to the anomalous reflectance of exposed soil hydroxyl bearing minerals. PC3 was assigned to vegetation due to strong loadings from TM-4 (91%) and PC4 to transported loose material as bright pixels, (Figure 7.2) due to their location in the image, i.e. mainly along the drainage channels. PC5 and PC6 were incoherent and therefore not useful. The transformations did not also seem to add much to what had been established by the band ratios.

**Table 7.4.** Principal component analysis of the study area

	TM1	TM2	TM3	TM4	TM5	TM7	Eigen values (%)
Pc 1	0.371	0.249	0.383	0.206	0.667	0.408	82.30
Pc 2	0.546	0.360	0.297	0.307	-0.601	-0.168	10.87
Pc 3	0.315	0.061	0.167	-0.914	-0.104	0.151	5.39
Pc 4	0.562	-0.209	-0.369	-0.029	0.360	-0.611	0.93
Pc 5	0.368	-0.262	-0.569	0.136	-0.213	0.639	0.39
Pc 6	0.113	-0.832	0.527	0.093	-0.091	0.013	0.12



**Figure 7.2.** 4<sup>th</sup> principal component showing loose sediments as bright pixels

### 7.3.5 Crosta Technique

This technique was applied to bands 1,4,5 and 7 selected on the basis of the spectral characteristics associated with presence of the OH and the vegetation, to establish any marked improvement on the information content relative to the six-band analysis (Table 7.5). However, the four band principle components did not seem to add much information missing in the six band components.

**Table 7.5.** PCA on four bands for hydroxyl mapping

Input Bands	TM1	TM 4	TM 5	TM7	Eigen values
PC1	0.389	0.222	0.767	0.459	82.52
PC 2	0.682	0.568	-0.448	-0.103	10.21
PC 3	0.574	-0.786	-0.161	0.163	6.33
PC 4	-0.232	0.098	-0.429	0.867	0.95

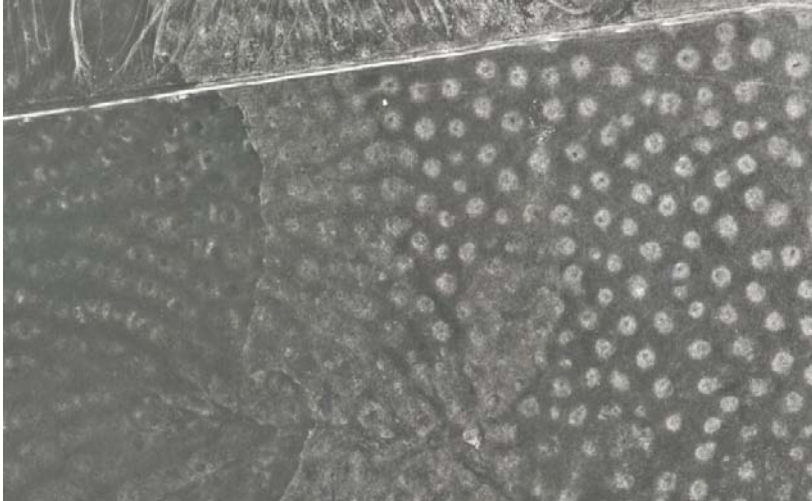
### 7.3.6 Tasselled Cap Transformation (TCT)

This procedure confirmed the interpretations from the various enhancement based on its robustness in separating vegetation and bare soil where areas with high values for soil brightness assignment were those established in the other analysis to consist of strong hydroxyl assignments and the greenness index matching those assigned to vegetation in such enhancements. The third index supposed to give indication of areas with low reflectance resulting from soil moisture was found not useful.

Field visits established areas assigned to good drainage and thus healthy vegetation to consist of kaolinitic red soils also rich in iron oxides and those assigned to bare soil and exposed hydroxyl of dark grumosolic soils where the dominant clay mineral consisted of notronite. These soils had grass and scattered *acacia drepanolabium* as the vegetation cover.

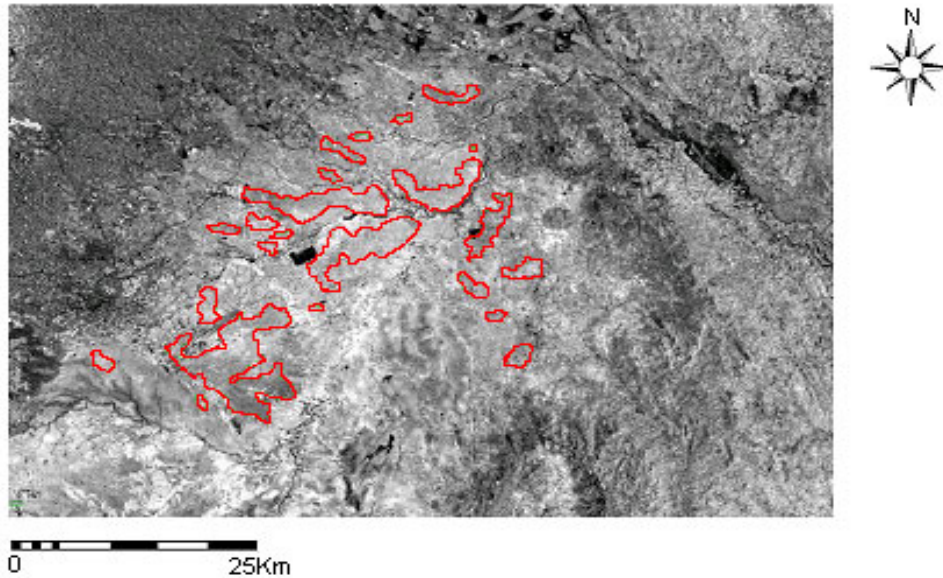
### 7.3.6 Visual image interpretation

Visual interpretation of the surface textural differences (see example Figures 7.3) in the image was found to result in a gilgai micro-topography distribution map, based on reflectance contrast between the micro highs and lows and was restricted to soils in the centre of the study area interpreted from the spectral enhancements as of poor drainage. The linear pattern to the left bottom of the figure was in a sloping surface along a drainage channel that is indicative of change in slope relative to the right side where the mounds stand out as bright mini hills in a background of depressions, which have a dark tone. Stephen et al, (1956) attributed the brightness of the mounds to their possession of properties similar to those of underlying soil, relative to the micro lows which are usually more moist and support healthier vegetation. Beckmann et al (1973) and Elbersen (1983) described such linear patterns to signify rill erosion along the micro lows during the wet seasons. Though very clear in the image these differences were not as clear in the field where vegetation cover tended to mask out observable differences. In terms of the classification given by Beckmann et al (1973), the gilgais were interpreted to be of the normal type.



**Figure 7.3.** The gilgai topography in the area from an aerial photograph  
1:20 000 scale

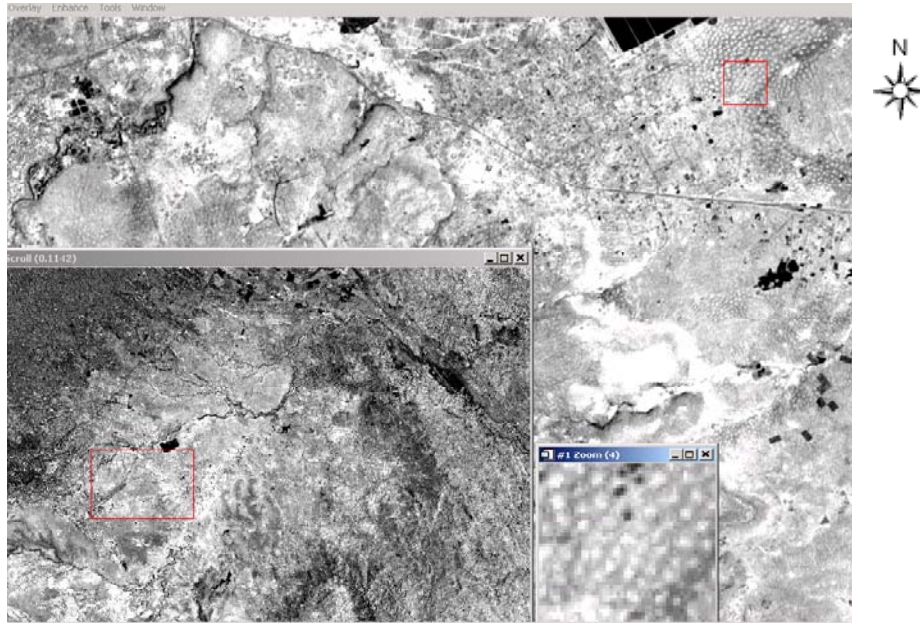
Figure 7.4 shows the resulting map based on the image interpretations and field verifications where they range in size in terms of heights (15-30cm) and diameters (20-50m). The fieldwork also confirmed the interpreted polygons to be all within the high swelling soil variety based on other identifying properties among which were wide cracks (>5cm), slickensides at depth and surface mulch. Evidence from the field also pointed to the fact that churning process could have caused Ca concretions to appear on the surface in the mounds, giving them a lighter colour where exposed which probably explains their brightness in the image relative to the shelves (depressions). This has also been reported in other areas where they are prominent and seems to support Isbell (1996) conclusions of the soil on the mounds having a lighter colour and carbonate presence. It is also worth noting that they were all found to be within the areas established in the spectral assignments to consist of poor drainage, low topography and poor vegetation growth. Stephen, et al, (1956) described their presence as prove of the presence of swelling clays and alluded to their influence on the natural vegetation describing the slightly higher mounds as somewhat better drained than the surrounding flats leading to the vegetation differences.



**Figure 7.4.** The gilgai topography spatial distribution in the study area (red polygons)

Several methods have been established for quantitative analysis of the gilgai distribution patterns and their significance to soil properties (Webster, 1977). Among these are simple micro-relief factor, specific micro relief factor, slope variation, structural homogeneity, and avoidance factor (Russell and Moore, 1972).

The structural homogeneity factor ( $K$ ) that measures the tendency of repeatability was used over a 1km radius in the six major polygons established in the satellite image. Figure 7.5 shows the area (inset) and the zoom window used to obtain the  $K$  parameter for each of these polygons. Table 7.6 gives the results showing generally moderate values in most polygons though with one polygon, (that in the field was found to show prominence in the micro relief) giving a relatively higher value thus a more uniform distribution of the features. However, the overall value of  $K$  was concluded to show a relatively homogeneous spacing among the polygons probably establishing the swelling in the soils to be near uniform and being subjected to similar formation mechanisms.



**Figure 7.5.** Study area image inset with zoom showing the individual mounds used to estimate K

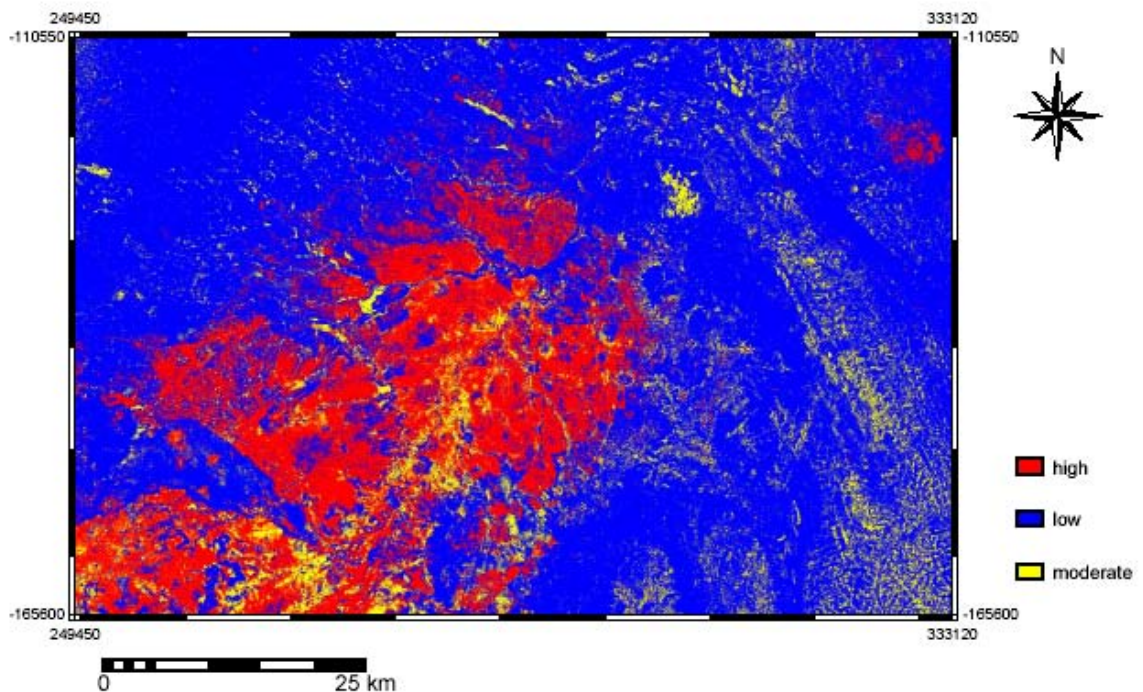
**Table 7.6.** Micro relief parameter (Russell and Moore, 1972)

Polygon	Range	K	Rank
1	3-6	0.17	1
2	10-11	0.13	4
3	6-10	0.15	2
4	8-11	0.13	4
5	7-9	0.13	4
6	8-13	0.14	3

The parameter provides a basis to compare the gilgais with those in other areas and thus enable extraction of information on environmental factors, making their identification in the image significant. Further and more detailed analysis should be appropriate in future for a follow up on these results. In this more attention should

be given to the differences not only in the distances but in all the other micro relief parameters such as the heights and compositional differences to enable add value to their importance as comparative tools for swelling potential differences and their relationships with environmental factors.

Based on this and the interpreted spectral differences a swelling potential map was established. Figure 7.6 shows this resulting swelling potential classification map where the spectral contrasts (vegetation distribution and drainage/ topography differences) and gilgai (exclusive presence in swelling soils) were used.



**Figure 7.6.** Swell potential classification map based on spectral and micro-relief interpretations

### 7.3.7 Relationships with soil distribution map

An overlay of the soil distribution map over the established swell potential differences based on the image interpretations is given in Figure 7.7. It shows the interpretations to confirm the soil characteristic differences and the correlation between the interpreted spectral/spatial satellite imagery with the field based soil map is clearly very good.

The midsection, found in the image to consist of the combination of gilgai, high soil brightness and poor vegetation coincide with the poor drainage and low topography in the soil map whereas high topography and good drainage coincide with the heavily vegetated areas and low soil brightness. In the overlay blue, and cyan are areas with soils of low swelling potential, red and shades of pink of high swelling potential, confirmed by the gilgai polygons (green) and classified as *Vertisols* in the field soil classification map (see figure 1.1).



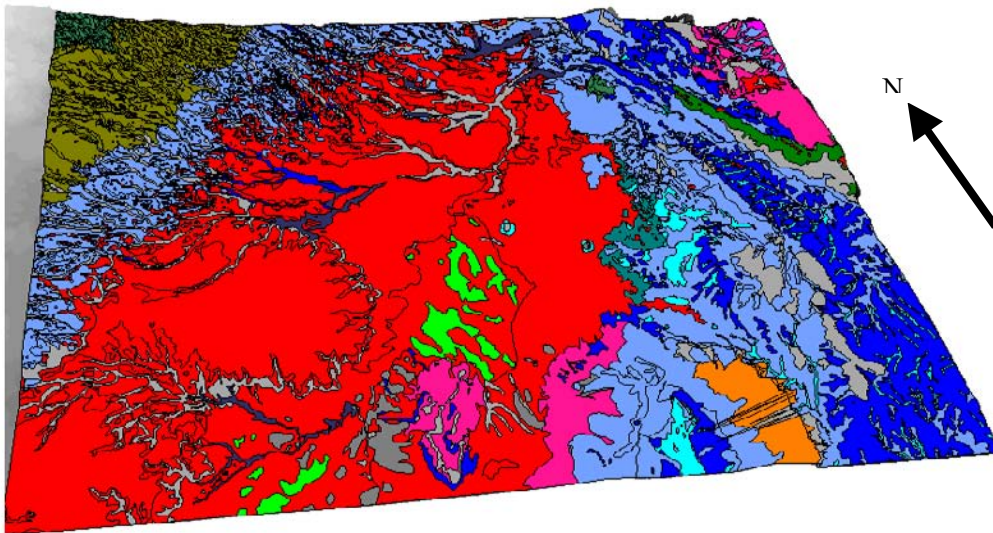
**Figure 7.7.** Overlain layers of gilgai soil and interpreted swelling based on spectral data (soil map 50%transparent)

Figure 7.8 gives a perspective view of the soil map showing the major soil units that shows an indication of topomorphic and lithomorphic (Jewitt et al, 1979; Murdoch, 1970; Comerma, 1985) influence on the soil swelling differences. The former seems to be the overall overriding factor, with soils in the franks of the plain (midsection) being of low swelling variety and of similar physical characteristics despite the northwest being of volcanic origin (see table 1.3) and those to the east of metamorphic origin. The plains are generally of high swelling potential though there is significant lithomorphic influence at the fringes of the plains where they form contact with the low swelling variety (based on laboratory



tests). Those at the contact with the basement rocks derived soils have a higher content of sand (average 45%) and a lower swelling potential relative to those in the volcanic areas which are of higher clay content (average 65%) and a higher swelling. A small high swelling unit (red) at the extreme northeast of the area seems to be more of a topomorphic unit. These soil differences on the basis of lithology and topography also seem to confirm the image interpretations in terms of drainage and topography and the resulting variation in vegetation growth to thus the soil swelling potential differences.

Lithomorphic *vertisols* have been described as less deep and at times better drained than topomorphic *vertisols* (Siderius, 1987), a fact that leads to the later possessing better developed profiles and recognisable surface features among which is widespread deep cracking during the dry season. This could also probably explain the significant selective presence of the gilgai features, whose observation probably gives an indication as to the soil differences in terms of depth, origin and level of swelling, which have been described significant in the mapping of *vertisols* properties (Mahmoud 1985; Beckman et al, 1984). Further studies on variability within these soil units might be needed in the future to better understand these differences. Such a study could conclusively establish presence of gilgai to indicate significant variation within the *vertisols* as pertains to depth and swelling potential levels. This could save on high sampling densities and extensive laboratory analysis based on the ease of these features identification from the imagery.



**Figure 7.8.** Perspective view of DEM wrapped with the soil distribution map

## **7.4 Discussion**

The various enhancement methods seemed to retain spectral features typical of soil differences even in the presence of vegetation, making the use of vegetation differences good in the classification. The spectral anomalies were strong enough and allowed the deduction of the soils compositional differences based on the vegetation coupled with topography and drainage. The results thus seemed to support Lee et al, (1988) conclusions of the soil brightness index to contribute most to Landsat image soil classification accuracy and those of Weismiller et al, (1977) describing Landsat imagery and topographic data as sufficient in making a soil inventory. They also seemed to agree with Lewis et al (1975) and Westin and Lemme, (1978) conclusions that soil differences can be interpreted from the image patterns resulting from differences in vegetation. They also confirm Baumgardner et al, (1985) conclusions of soil drainage being specific and indicative of the local landscape and thus to have a strong influence on the soil surface reflectance properties. The lack of clear Iron oxides anomalies expected in areas subject to weathering and good drainage could have been complicated by the significant vegetation presence.

The internal processes of shearing and expansion in the high swelling variety were manifested on the soil surface morphology as seen in the presence of gilgai which Newman (1983) describing as “chimney” or “diapir” structures due to plastic extrusion resulting from large disparities in the densities of adjacent materials within the soil profile. Eldelman and Brinkman (1962) on their part advanced the theory of gilgai resulting from sedimentation followed by periods of drying and wetting between which materials are deposited into the cracked surfaces that could explain their presence mainly in deep soil profiles. Driese et al, (2000) established significant differences in the soil physiochemical properties at the micro-highs and shelves and attributed it to overall wetter soil conditions and variable reduction/oxidation under the shelves relative to the micro-highs (puffs) which instead behave as evaporative "wicks" that draw moisture and soluble phases towards the soil surface, thus their lighter color. Macdonald et al, (1999) described their uneven vegetation growth to be due to these soil moisture variations and this could probably explain their clarity and ease of identification in the image. Continuous reworking on the soils seems not to completely obliterate them as seen in the K factor of the various locations some of which are under cultivation probably indicating rejuvenation, making them the more important for swelling soils mapping from remote sensing imagery.

The results make a preliminary case for combined use of these spatially resolvable surface features and spectral reflectance manifestation of drainage and topography from vegetation to assign soils to swelling potential classes, providing yet another dimension to the use of Landsat satellite imagery in the mapping of soil properties. The integrated soil and topographical maps strengthened the case for these interpretations thus confirming the imagery to be a good source of soil information. Future work should involve the use of higher spectral resolution (unfortunately missing in the time frame of this research) to establish whether more information as to the soil differences could be established from satellite imagery.

## **7.5 Conclusions**

It has here been established that combined use of the surface expression of internal soil mechanisms and spectral enhancement tools of low resolution Landsat image can result in the identification of soils susceptible to swelling. The spectral information was useful in establishing the topographic and associated drainage differences seen in vegetation and soil spectral assignments such as the brightness index. The surface manifestations of the internal forces in high swelling soils and their origins can be deduced from various surface features such as gilgai making satellite imagery important in the identification of swelling soils based on its wider view relative to any field based method. However, further research might be needed to confirm the presumed differences in the overall physicochemical properties between the soils and to better understand the gilgai phenomenon.

## CHAPTER 8

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### **NMR AND INDUCED POLARISATION TO ESTIMATE SWELLING PARAMETERS**

*Based on: Kariuki P.C., Jean Roy, and Van der Meer, F.D. Nuclear Magnetic Resonance (NMR) and Induced Polarisation (IP) to Estimate Selected Soil Properties: Pore size, Moisture and cation exchange capacity (CEC). Journal of Applied Geophysics, (submitted)*

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*"The further backward you look, the further forward you see." – Sir Winston Churchill,  
British Statesman (1874-1965)*

*and*

*"What on earth would man do with himself if something did not stand in his way?" – H. G.  
Wells, English writer*

## Abstract

A set of soil samples from Spain and Kenya consisting of a broad range of textural distributions and mineralogy were used in the acquisition of Nuclear Magnetic Resonance (NMR) response and induced polarization (IP) signal to evaluate their relationships with pore/grain size, moisture content, and cation exchange capacity (CEC). NMR decay times analysis gave relatively good moisture estimates whereas their amplitudes gave an indication of the relative contribution of assigned soil water type and thus mineralogical differences. IP gave a strong correlation with the soil CEC (read clay type) at moistures above a 25% threshold for most soils. The two methods were thus established as good in indicating the soil differences based on clay mineralogy.

## 8.1 Introduction

Particle size distribution, moisture holding capacity and cation exchange capacity (CEC) are three soil properties regularly used to determine the suitability of soils for civil engineering works based on their potential to give an indication as to soils swelling potential characteristics. Their measurements usually require field sample collections, and in cases where detailed information at depth is required core sampling, followed by tedious laboratory procedures that are expensive both in terms of cost and time. There is therefore the need to continue searching for field-based methods of determining these properties with a view to reducing costs and establishing faster representative methods, with which to characterize soils in terms of these properties. Nuclear magnetic resonance (NMR) and Induced polarization (IP) provide two such methods whose combination could be used in the estimations of the three properties in the field at varying depths. NMR can be calibrated to estimate moisture and pore/grain size distribution and IP to obtain information on CEC, found in many studies as a good index of the soil swelling properties (Thomas et al, 2000; Parker et al, 1977; Kariuki et al, 2003).

NMR refers to a physical principle, the response of nuclei to a magnetic field when the magnetic nuclei interact with externally applied magnetic fields that are switched on and off producing measurable decay signals whose period is called the relaxation time  $T_2$ . For most elements, the detected signals are low, but hydrogen has a relatively large magnetic moment that can be maximized and measured by tuning NMR instruments to its Larmor frequency. When water is present in natural materials such as soils, the speed of relaxation of its hydrogen ions ( $H^+$ ) depends on how frequently it can collide with the surfaces of the particles thus is a function of the surface to volume (s/v) ratio of the pores within which the ions reside. Collisions are less frequent in large pores (small s/v) and more frequent in small pores (large

s/v) resulting in long and short relaxation times respectively (Kenyon et al, 1995). This theoretically makes it possible to establish the different soil water types based on the interpretation of the relaxation time lengths by assuming that the signal is a sum of single exponentials (Kenyon et al, 1989). The total signal amplitude of decay times on the other hand is proportional to the number of hydrogen nuclei present and thus could be used to estimate the moisture content in a soil lacking in ferromagnetic minerals.

Yaramanci et al, (1999) insinuated that at saturation, the number of decay times ( $T_2$  components) could be used to give an indication of the pore and particle sizes distribution while their total amplitudes could be used to estimate the moisture content in a sample. The derived  $T_2$  components can also be interpreted in terms of, clay bound, capillary bound and free pore water and the response calibrated to estimate the various moisture types (Yaramanci et al, 2002). This makes NMR not only a tool of estimating the pore and moisture contents but also the differences in clay mineralogy among soils based on the differences in terms of clay bound water strength at times referred to as the irreducible water saturation. Thus by separating the irreducible from the other soil waters there is the possibility of establishing the pore size and thus grain size distributions for different soils. This principle has been used to study physical, chemical, and biological properties of matter in the fields of medical imaging (MRI), oil exploration (NMR logging), Geophysical prospecting (proton magnetometer) and direct water exploration (MRS). Application in soil science however has been limited (Kenyon, et al, 1995), even though Anderson and Hopmans (1994) described magnetic resonance imaging as also applicable to soil studies.

Use of IP technique on the other hand, over the past 30 years has been proven as one of the most successful geophysical methods in mineral exploration. It has however increasingly found use in other areas more so in environmental studies such as saline intrusion mapping (Seara and Granda, 1987) and the detection of clay units (Illiceto et al, 1982; Vinegar and Waxman, 1984). It has also been successfully used in geothermal (Reynolds, 1997), oil and gas exploration (Sternberg and Oehler, 1990). In soil study, it has been used to obtain diagnostic clay mineral signature (Klien and Sill, 1982), making it a potential tool to obtain information on soil clay mineralogy based on its high correlation with CEC thus is a potential tool to measure their related soil properties.

IP in soil is due to the soils fixed electrical charges where the pore structure is lined with a coating of minerals having ion exchange capacity (clay) whose exchangeable ions go into solution when the minerals electrolyse due to addition of

polar fluids such as water. This leaves behind mineral particles that carry a net negative charge that form highly charged immobile anions blocking free ion flow through the pore. This causes areas of abnormally low and high gradient on either side of a clay anion and is dependent on the ion-exchange properties of the clays. It is therefore a source of information on the soil CEC (Worthington and Collar, 1984). Vacquier et al, (1957) found the IP to be roughly proportional to the ion exchange capacity of the constituent clay and Parkhomenko (1971) reported the fixed clay content IP to be greater for clays having higher ion exchange activities. Worthington and Collar (1984) went further and established a generalised equation for such estimation in which site-specific constants are needed. Other factors however influence the resulting IP among which is moisture, salinity and particle size distribution. Ways of reducing such influence has been the subject of research one of which is that by Slater and Lesmes, (2002) where normalization with resistivity is done resulting in the reduction of the influence from salinity and leading to stronger relationships between structural properties (clay) and IP measurements. This makes the normalised IP a parameter with a potential at estimating the soil CEC thus associated properties such as the swelling potential, the overall subject of the current research.

This paper reports on the findings in a laboratory setting on a study that sought to establish the potential of the two discussed methods. The main objective was to assess the performance of the methods on soils of known compositional differences thus their ability to yield this important soil information. The other objective was to establish their complimentary role to other methods of soil suitability determinations and thus their future application in non-intrusive investigation on soil compositional differences.

## **8.2 Materials and Methods**

### *8.2.1 Sampling sites selection*

Two zones soils falling in the temperate Mediterranean (southern Spain) and humid tropical (central Kenya) type of climate were used for this study. Fifty soil samples carefully selected based on existing soil information were used to represent a wide variation in the parent materials and the properties under study. The Spain samples were from sedimentary rocks consisting of limestones, dolomites and marls and those from Kenya were mainly from volcanic and basement system metamorphic rocks.

The samples were representative in terms of mineralogy where, Illite was the main clay mineral type in the Spain samples with mixed layer smectite/illite being the other dominant assemblage. Kenyan samples consisted mainly of kaolinite and smectite rich soil varieties dependent on the topographic position on the landscape from which a sample was obtained.

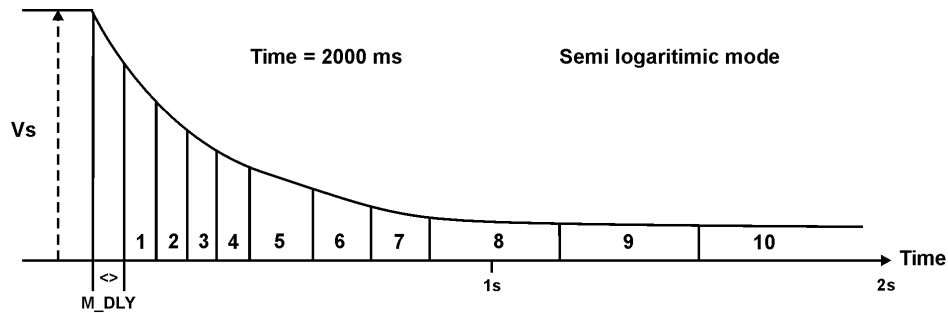
### *8.1.2 NMR data acquisition*

The 50 samples were split into two subsets with each comprising of enough representative samples from each region. One subset was saturated and the other moistened to known moistures below saturation prior to signal acquisition. Acquisition of the NMR response was by use of a laboratory NMR MARAN (Resonance Instruments Witney UK) Spectrometer at an observation frequency of 10.1 MHz in which the system was programmed to perform  $T_2$  measurements using a CPMG pulse sequence (Carr and Purcell, 1954; Meiboom and Gill, 1958). The response was first obtained for the empty sample holders (this was to enable adjust the dead time to remove the container response), followed by measurements of the response of three sets of saturated glass bead sizes with known porosity for the calibration in moisture estimation. Response was finally measurements for the fifty samples.

### *8.1.3 IP data acquisition*

In the IP measurements, a Time Domain procedure that combines resistivity and chargeability measurements was applied where an IRIS ELREC-6 receiver was used. Samples were first placed in plastic tubes of 17 mm diameter and 200 mm length with two holes at a spacing of 66mm apart on the upper part of the tubes into which two receiver electrodes were placed and the voltage between them measured and displayed in terms of apparent resistivity and chargeability values. The measurement was fully automated through the control of a microprocessor which does automatic self-potential correction, digital stacking for signal enhancement and error display in case of procedure troubles. The current injection was through copper electrodes at the two ends of the container tubes and was from an IP-TX transmitter that generates a square pulse electric current that is fed to the current electrodes. Chargeability measurements were made on ten consecutive windows after the current was switched off. The total chargeability as determined in this work is taken as the average values measured in these ten time windows (Figure 8.1). Accuracy of the instrumentation was of the order 0.1mV/V.





**Figure 8.1:** Decay curve sampling mode. It shows 10 IP windows (ELREC-6 manual).

To enable a coherent signal, resistance of below 15Kohms is needed for stable IP measurement. De-ionized water was therefore gradually added at increments of 5ml to initial moisture contents that enabled this goal to be achieved prior to any recording of reading for each sample. Subsequent steps consisted of gradual addition of moisture at the same rate and subsequent measurements of IP and resistivity. This was repeated until saturation for each sample. Determination of the moisture state for each measurement was relative to the soil dry mass;

$$W = \frac{M_w}{M_s} * 100 \quad (8.1)$$

Where,  $W$  is the % moisture,  $M_w$  the mass of water at each step, and  $M_s$  the mass of dry soil.

By using de-ionized water it was assumed that the salinity influence on the obtained IP values was minimized leaving the influence from the ionic dissolution from the exchangeable sites of the constituent clay minerals. This was presumed to provide a more reliable charge estimation by the freeing of the exchangeable cations without introduction of more heterogeneous cations as would be the case if tap water was to be used.

### 8.1.4 Data Analysis

#### NMR Data

The SPLMOD program (Provencher and Vogel, 1983) was used to resolve the exponential decay curves into  $T_2$  components taken to represent the contribution by the different soil waters (Figure 8.2) where a threshold of three standard deviations was used as the cut-off for a component to be considered valid. The components were assigned to various established time thresholds (i.e. clay bound  $<3\text{ms}$ ,  $>3$   $<33\text{ms}$  capillary and  $>33\text{ms}$  free pore water) as established by Kenyon, (1997). Their total amplitudes were used to study the relationships with the independently established moisture resulting from oven drying the samples at  $105^\circ\text{C}$  for 24hrs. The individual amplitudes were used to establish contributions of the various water types to the total decay. Relationships with the various particle sizes were also sought to evaluate whether there was any relationship between the water distribution and the soil texture.

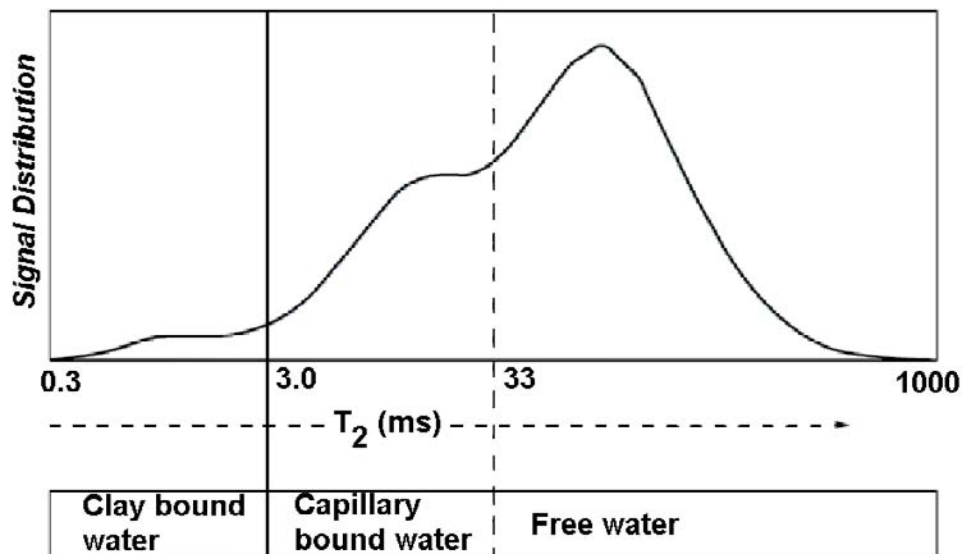


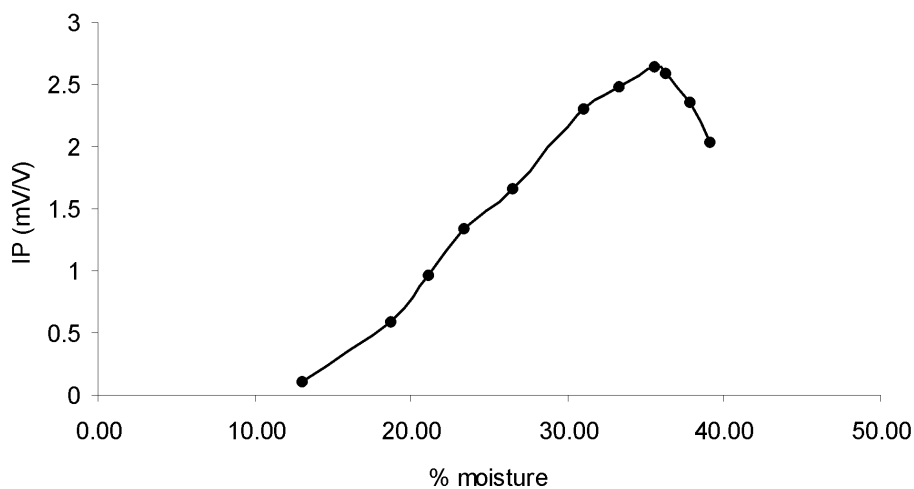
Figure 8.2. Pore size as a function of relaxation time (after Schlumberger Inc.)

The amplitudes of the various  $T_2$  components less the irreducible moisture in the form of clay component amplitude were also established relative to the known moisture of the various diameters saturated glass beads previously discussed from

which a simple linear calibration model had been obtained based on their total  $T_2$  amplitudes and known moisture.

#### *IP-Data*

The changes in obtained IP with moisture were analysed and the moisture content at which the maximum (peak) IP was reached for each sample established (Figure 8.3). This peak is assumed to represent the total release of exchangeable cations. Correlations between the IP values at the various moisture contents and CEC (independently obtained through  $\text{NH}_4\text{OAc}$  pH 7 mechanical extractor method (Reeuwijk, 1995)) were also established. These were then used to assess the relationship between IP and CEC with the aim of establishing the potential application of IP in deriving the estimation of CEC, a key soil property in the determination of the compositional differences among soils and their related properties at different moisture conditions. This would be useful in practical application as is usually the case in the field where the moisture contents of the soil is not uniform. Trials of the IP measurement of structural changes at depth have proven useful (Slater and Lesmes, 2002).

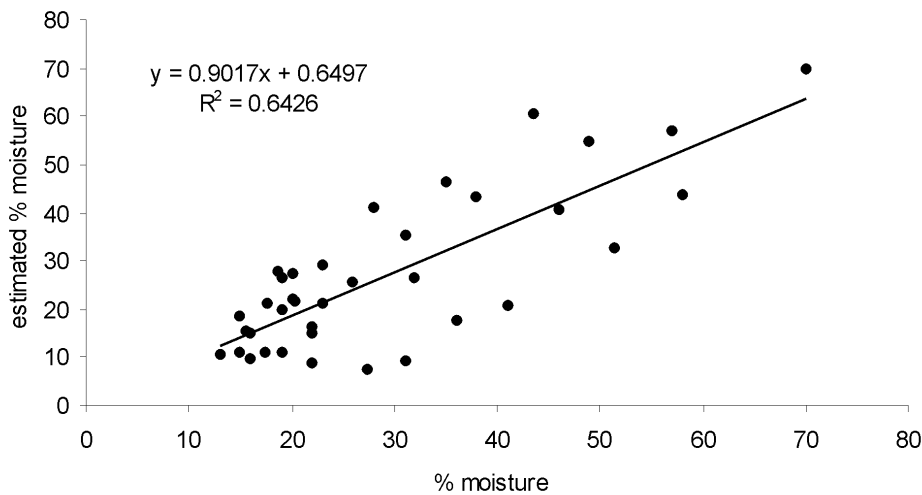


**Figure 8.3.** Changes in IP with increasing moisture for one of the sample note the presence of a peak at 36% moisture

### 8.3 Results

#### 8.3.1 Estimation of pore size, CEC and moisture from NMR

The moisture contents estimate from the NMR response amplitudes gave a good correlation with the true moisture (Figure 8.4). This confirmed the possibility of using the summed NMR amplitude to estimate moisture relative to known moisture, as was the case by calibrating the amplitudes with the known saturated glass beads estimates. The spread in data was attributed to the possibility that some of the amplitudes could have been left out in the decay components where the tail of the decay was not analysed to the times it flattened out due to the limitations of the equipment to pick out these minute amplitudes. Contribution from the non-reducible water could also have affected the relationship though even removal of the fast decay component did not improve the results significantly.



Prammer et al. (1998) found that the average  $T_2$  value was generally higher in the samples with smectite as the dominant mineral and to have a linear relationship with the available moisture (Figure 8.5). Thus, samples with higher smectites content are more likely to possess greater overall decay times relative to those with the other minerals at saturation.

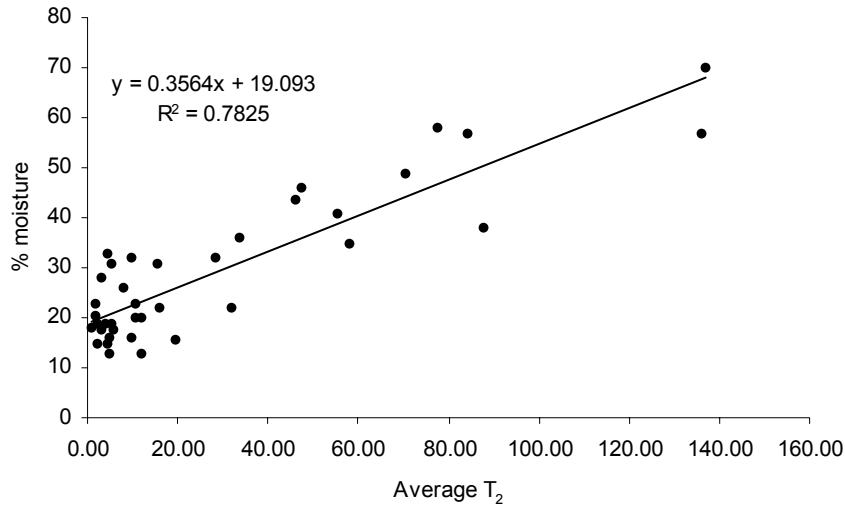


Figure 8.5. Average T<sub>2</sub> relationship with moisture

Table 8.1 gives a summary of the available T<sub>2</sub> components for the saturated samples where those rich in smectites were observed to show presence of both the short and a relatively long decay time component in the range assigned to free pore water (Kenyon et al, 1995) i.e. <1ms and >100ms. The longer component was assumed to probably represent the response of the interlayer water that can take several molecular layers dependent on the amount of expandable clay present in a sample. Graham et al, (1964) working with hydrated silicate minerals established the water attraction to clay surfaces to vary where it is tightly held at low quantities giving it a form different from free water and thus a comparatively very fast decay time and at higher contents to enable interlayer cations to form diffuse double layers which lack structure. This results in molecular motion that is not much different from that in free water (Mitchell, 1993). This could probably explain the presence of this longer decay component in smectite rich samples and absence in the others. However, it is worth noting that when dealing with a field based measurement free water is usually assigned to decay times in excess of 600ms (Schirov et al, 1991).

**Table 8.1.** T<sub>2</sub> component distribution among saturated samples

Sample number	% Moisture	% Clay	Dominant clay	No. of comp.	T <sub>2</sub> (ms)	T <sub>2</sub> (ms)	T <sub>2</sub> (ms)	T <sub>2</sub> (ms)
9	33	68	Smectite	4	157	23	3.3	0.69
25	35	41	Smectite	4	198	28	4.8	0.97
31	33	72	Kaolinite	2			8	0.91
32	31	19	Kaolinite	2			9	1.3
			Smectite/	4	242	33	5.9	1.1
33	49	71	Kaolinite					
34	58	27	Smectite	4	248	53	7.5	1.02
35	57	57	Smectite	4	351	75	11.1	1.02
			Kaolinite/	3		84	15	1.8
36	36	52	Illite					
37	70	56	Smectite	4	448	86	13.1	1.02
38	46	86	Kaolinite	2			18	1.84
			Kaolinite/	3	149		16	1.34
39	41	42	Smectite					
40	57	71	Smectite	4	269	57.6	9.3	0.92
42	38	36	Smectite	4	280	61	9.6	0.99
43	46	54	Smectite	4	150	33	5.5	0.91

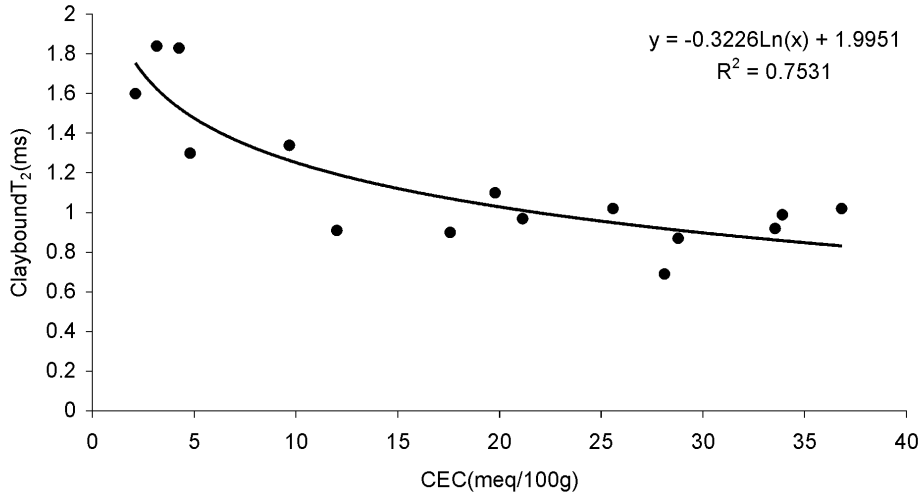
Table 8.2 gives correlations between the individually assigned water type amplitudes and the various particle sizes where the shortest component assigned to clay bound water, gave a strong positive correlation with the clay content and negative correlation with the sand content but poor correlations with silt. The others gave positive correlations with sand and negative correlations with the clay content but again poor correlations with silt. These results probably attest to Yaramanci et al, (2002) conclusions that T<sub>2</sub> relaxation relates to the grain size of a material and those of Woessner (1980) of linear relationship between the relaxation rates and amount of dry clay per water volume. Lack of correlation with the silt could however not be explained.

**Table 8.2.** Relationships between particle sizes and T<sub>2</sub> component amplitudes for saturated samples

Relative amplitude	r (%Clay)	r (% Silt)	r (% Sand)
Clay bound	0.9	0.02	-0.81
Small pore	-0.84	0.27	0.83
Medium pore	-0.76	0.05	0.89
Free pore water	-0.72	0.082	0.74

Based among others on Kenyon (1997) assignments, the amplitudes seem to show an indication of the grain distribution. This is expected based on the fact that adsorbed water is more in less compacted soils relative to that of high clay soils which probably explains the negative relationship between the clay content and the water assigned to pore water and the opposite effect for sand. The positive correlation for the clay bound component with clay percentage could be attributed to the relatively higher surface area in abundant clay thus more likely higher clay bound water.

Prammer et al (1996) described the number of available exchange sites as proportional to a clay's specific surface ratio and the  $<3\text{ms}$   $T_2$  component as an indicators of CEC where a samples with  $T_2 < 1\text{ms}$  is likely to have smectite dominance, 1-2ms illite and  $> 3\text{ms}$  little or no CEC. They established laboratory and field data to consistently show  $T_2$  relaxation times in this range to be a function of the clay morphology and water content. Correlation between this component position and the independently obtained CEC for the saturated samples was relatively strong but non-linear (Figure 8.6) probably providing an indication as to the potential of NMR to also provide some information on the clay mineralogy differences among the samples. It shows the value to generally decrease with increase in the CEC where most samples with high CEC values have the component at less than 1ms vindicating these assertions. All the samples in this test were however found to have the value in the range between  $< 2\text{ms}$  thus within the range of clay mineral presence according to their assignments. This relationship was however reduced drastically when samples below saturation were included ( $r^2=0.48$ ) probably due to the described influence of moisture on this position. A larger number of samples might be needed in any future study to further establish these related mineralogical differences based on CEC.



**Figure 8.6.** Relationship between CEC and shortest T<sub>2</sub> component

### 8.3.2 Estimation of CEC from IP

In their analysis Vinegar and Waxman (1984) established polarisation as due to concentration gradients arising from two mechanisms: clay cations displacement and electrolyte blockage by the clay site membranes both of which are proportional to the cation exchange capacity per unit pore volume. Thus multiplying the displaced cations by their equivalent conductance gives the specific conductance of the clay exchange cations that is directly correlated with the CEC. The specific conductance of the charged sites can be similarly obtained. They established a model that sums the two in series resulting in an equivalent conductance  $\lambda$  (see Vinegar and Waxman, 1984 for details) representing the coefficients of the two in relation to the CEC and established contribution by both displaced cations and charged sites as equal. They drew conclusions that IP is directly proportional to CEC and weakly proportional to the salinity. They established a general equation for the IP (commonly referred to as quadrature conductivity), which for water-saturated samples is given as;

$$C_Q = 1/F_q \lambda Q_v \quad (8.2)$$

Where  $F_q$  is the formation factor a function of the resistivity of the sample and  $Q_v$  is the cation exchange capacity of the sample per unit pore volume.  $\lambda$  consists of



coefficients for both the available cations equivalent ionic conductance and that of the electrolyte solution where in this case was distilled water.

It follows then that in the case of unknown formation factor the relationship can be established as;

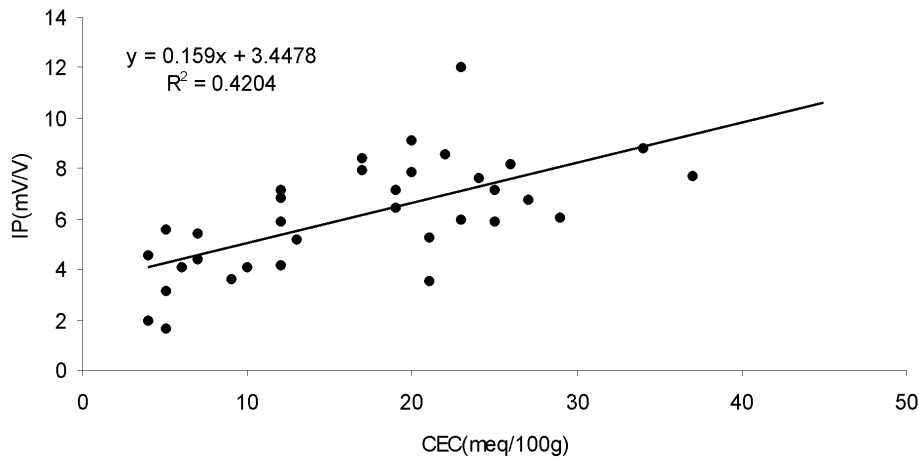
$$C_Q F_q = \lambda Q_v + b \quad (8.3)$$

Where  $b$  is the intercept of the relationship to account for the differences in conditions. They thus established regressions at different salinities between the measured IP and the functions of CEC. In our case, such relationships were established at different moisture contents with the aim of obtaining empirical models to represent CEC from IP measurements.

Parkhomenko (1971) described induced polarization to increase with increasing moisture to an optimum saturation beyond which it starts to decrease. He described the peak as significant in the estimation of CEC i.e. low in samples with high CEC and greater in those with low CEC. The moisture content at which this peak was obtained was however observed to give no particular trend based on known compositional differences though giving some significant correlation between the IP and the independently established CEC (Figure 8.7). Lack of trend in the moisture content at which the peak occurs could be due to other factors such as the salinity and composition of the exchangeable cations described by Worthington and Collar, (1984) to play some significant role in establishing the position of this peak by shifting it towards lower water contents at low concentration and higher valency respectively. The number of step measurements to sample saturation also varied and was between 4 and 15 giving a trend that seemed dependent on the soil dominant clay type where those of high smectite contents required more steps (average 10) while those with strong kaolinite presence had it an average of 7-8 steps.

Correlations between the IP and CEC based on the previously described generalised model at low moisture were poor with a negative trend that seems to agree with observations by various workers. Significant positive correlation was established at moistures of between 20% and 25%, the moisture contents around which the peaks occurred for most samples. After this, the relationships were found to generally improve with moisture, though the data still seemed to spread from the empirical line thus showing other factors to have significant influence on the IP other than the CEC of the soil. The intercept constant has been attributed to residual sample polarisation

from other sources other than clays that is likely due to the heterogeneous nature complexity that is soil.



**Figure 8.7.** Relationships between peak IP and CEC

Slater and Lesmes (2002) suggested normalizing the IP with the resistivity (which is primarily determined by the properties of the electrolyte) to minimize the influence of salinity. The normalization improved the relationships as seen in Figures 8.8 for the above relationship which also showed a decreased intercept difference between the regressed perfect fit ( $r^2=0.67$ ) and that of constrained zero intercept ( $r^2=0.65$ ). Figure 8.9 shows the sustained positive relationship with CEC beyond the peak moisture threshold a fact attributed to Knight and Nur (1987) theory that describe the normalized IP to be insensitive to the effects of partial saturation if sufficient water is available to establish an electrochemical surface phase. This could be very important for field experiments where the moisture conditions vary. Table 8.3 gives the resulting correlations between CEC and both IP and normalized IP at the various moistures beyond the established threshold. They show an increased correlation between the normalised IP and the CEC relative to those of CEC with IP thus giving it as a good source of information on a sample clay activity above the peak threshold. The results are in agreement with Vinegar and Waxman (1984) conclusions that for water bearing samples, the IP is directly proportional to the clay activity parameter and only weakly dependent on the

electrolyte concentration. This provides a good tool of establishing the soil swelling properties as is already seen in the foregoing chapters based on this activity importance among the swelling potential indices.

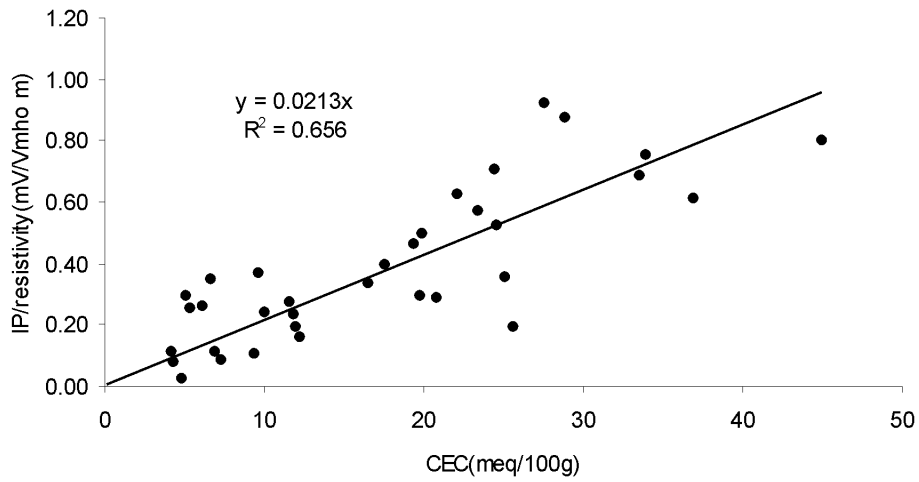


Figure 8.8. Relationships between normalized peak IP and CEC

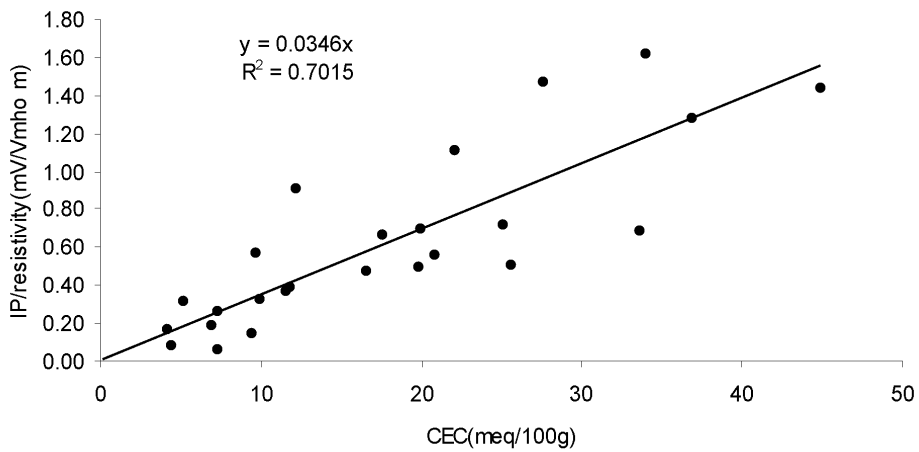


Figure 8.9. Relationships between normalized IP and CEC at 35 % moisture

**Table 8.3.** Relationships between moisture content and IP/normalized IP

Moisture (%)	No. of samples	R <sup>2</sup> for (IP)	R <sup>2</sup> for Normalized IP
0-20	43	0.12	0.01
20-25	43	0.2	0.01
25-30	32	0.25	0.7
30-35	25	0.26	0.71
35-40	16	0.31	0.89
>40	5	0.24	0.94

These simple relationships have established that it is possible to estimate CEC, moisture and the relative soil waters together with grain size distribution in the laboratory based on disturbed field samples from the two geophysical methods. Combining them could provide important information significant in soil swelling potential estimations, where IP could be used in the estimation of CEC whereas proper calibration of the NMR could provide information on the prevailing moisture conditions and thus better judgement on the reliability of the obtained CEC. The results therefore provide a tool for field mapping of not only the three soil properties but also other related soil characteristics if proper calibration could be achieved.

#### 8.4 Discussion

The good correlations obtained between the measured moisture and that based on the T<sub>2</sub> amplitudes show the potential of the NMR signal amplitude as a field tool in providing information on soil moisture estimations. Yaramanci et al, (2002) found it as superior in estimation of water content relative to several other geophysical methods. The trend in the decay time components among the saturated samples show clear differences between soils in terms of their clay mineralogy where significant presence of smectite gave a T<sub>2</sub> component with a longer decay time higher than Kenyon et al, (1995) free water threshold assignment which could be attributed to presence of abundant interlayer water.

The  $T_2$  components amplitudes correlations with the particle sizes, could be attributed to what Liebllich et al, (1994) described as linkage between decay times and grain size distribution which however remains unclear and the variation in their number of seems to confirm what Kenyon (1997) described as representation of the various soil waters and pore sizes. The results thus show a potential application of NMR response in soil moisture estimations and under saturated conditions to give information on their grain sizes based on the resolved  $T_2$  components and amplitudes respectively. More still need to be done if the full potential especially as to the components representing differences in pore sizes were to be fully well understood.

As for the IP, many authors have recognized that the induced polarisation effect is determined by the amount and type of clay together with its ion exchange characteristics (Vacquier et al, 1957; Parkhomenko, 1971; Dakhnov 1962). This could be described to explain the observed strong correlations between the IP and CEC. The IP has also been described to relate to the specific surface area with its peak position described as low in abundant montmorillonite, and higher in illite and kaolinite (Telford et al, 1990). However, this could not be established in the results which probably calls for the interpretation on the peak position to be done bearing in mind that increased salinity shifts it to lower moisture contents.

The weaker relationship when the IP was used without removal of the salinity effect and stronger relationships after normalization with the resistivity shows the need to take salinity into consideration in interpretations a procedure Lesmes and Frye (2001) described to yield a parameter relatively independent of salinity and more sensitive to the clay in the soil. Slater and Lesmes (2002) went further and established the applicability of this parameter in the field. They established measured IP to be insensitive to the clay boundaries with other layers whereas the normalized IP gave a clear boundary for the clays making them draw conclusions that this parameter could distinguish IP effects due to electrolyte controls from those due to clay. This makes it an ideal field measurement for recognizing the presence of compositional clay differences. Its increase at higher moisture contents after a certain threshold confirms what Worthington and Collar (1984) described as an optimum saturation to free enough cations, a point that reflects the peak IP significant in establishing the CEC of a soil. This makes application of the method in soil swelling potential studies even the more possible.

## **8.5 Conclusions**

The results show that IP/NMR can be used to obtain information on soil properties of significant importance in characterizing soils based on clay mineralogy. NMR shows a potential to estimate both moisture and grain size distribution under different moisture conditions and its clay bound component to give an indication as to the clay mineral differences where a position shift gives an indication as to the likely dominant clay mineral type. Normalized IP on the other hand show a potential at estimating CEC upon removal of the influence of some other factors more so salinity. The results are significant because the two methods can be used in the field thus providing potentially faster methods of obtaining these important soil properties.

## CHAPTER 9

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# SYNTHESIS

## Spectroscopy and Theories of Swelling Soils

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*Time is the thief you cannot banish" – Phyllis McGinley, (American poet)*

*and*

*"The secret of being a bore is to tell everything." – Francois Voltaire, French author  
(1494-1778)*

## **9.0 Introduction**

The identification of swelling soils is one of the major factors that must be addressed in the characterization of a site for construction as well as in agricultural production where potential swelling problems may exist (Nelson and Miller, 1992). The problem has stimulated much discussion and numerous hypotheses have been advanced to account for the causative factors resulting in many swelling potential indices and the recognition that no one method is suitable to fully account for the swelling properties of all soils (Thomas et al, 2000). This provides for a need to continually pursue the possibility of establishing new methods, which could bridge the gap associated with the lack of a commonality in the established indices.

It is important at the outset to be clear on the fact that the problem of understanding the swelling potential is complicated. In the first place, swelling is not determined in all cases by the same single factor but it is the outcome of many interacting factors. Secondly whereas one can formulate rules about the contributing factors in all cases each rule has many exceptions. To give but one example, it has been hypothesized that the swelling is a function of the smectite content and increases with increase in its content (Goetz et al, 2001). Though this generally holds true in most occasions, anomalies occur in the event of coating by iron oxides or carbonates thus the total expected swelling is reduced as is the case in some tropical soils (Nevill, 1961), making the mere use of smectite content as an index of the level of swelling alone not to always hold true.

It is evident however, that a complete explanation of soil swelling must involve both the background on the soil source, topographic position and the associated soil forming processes, the former providing information on the parent materials and the later the environment in which the secondary minerals, the key to the swelling properties, formed. Progress in the understanding of the source influence and the topographic contribution has been achieved by the awareness that the source rock compositional primary mineralogy and the environment under which they weather determine the soil secondary mineralogy. This in turn has been established to be the driving force behind the swelling potential differences among soils and to consist of three major groupings namely kaolinite, illite and smectite. This grouping has been established as enough in explaining soils engineering properties (Mitchell, 1993) based on their quantitative abundance and thus have been generally accepted as the basic fundamental compositional parameter that is required to enable classify a soil into a swelling group. In terms of the environmental contribution, the moisture regime prevailing in a site is of critical significance and determines the initial moisture status of the soil and thus its potential capacity to accumulate more moisture.



Pending issues as to the establishment of universally acceptable index based on recognition of all these interacting factors were considered important enough to motivate the current research. For instant in the context of clay mineralogy important questions arise as to what level they can be recognized in a soil matrix and if so their quantification and use in the soil property evaluation. Answering such questions could contribute to optimizing decision making as to site suitability and thus making more reasoned decision as to the mitigation remedies. Other important challenges is how to scale such established methods from a local scale often in a laboratory setting to wider areas using the emerging technological advances in the fields of remote sensing and deep geophysical prospecting. In other words methods aiming at moving the positive outputs from a laboratory based experiment to an operational management process in a site and further to regional application are needed to enable trigger land use planning process based on known scientific facts.

Our research was motivated by the fact that an understanding of swelling soil should rest on how and why it happens and the methods to ascertain this. Further more both the building industry and the agricultural community needs to keep updated on emerging techniques that could hasten their recognition and mapping. Therefore the study aimed at developing methods based on these emerging sciences in recognizing the principle compositional elements of swelling soils and their related physicochemical properties thus attempting to quantify the potential volume changes. This was through known diagnostic spectral parameters of the responsible minerals in optical reflectance, and the influence of these same minerals on other physical properties of soils whose quantitative estimation has been widely used as indicators of the level of potential volume change. Other techniques consisted of the study of the surface morphology of the swelling soils that set them aside from normal soils as evidenced by diagnostic microstructures among them gilgai and other surface manifestations such as poor vegetation growth due to poor drainage. Geophysical methods based on changing magnetic and electrical fields have long been established to have a potential in gathering information on some of the physicochemical properties currently in use as swelling potential indices (cation exchange capacity, grain size distribution and natural moisture contents) and were also studied to establish their potential, based on their applicability in a field setting.

Several steps were necessary to achieve these objectives, based on two case studies so as to account for the potential differences arising from the soils different parent materials and environment of formation. In the proceeding text the different steps in achieving the set objectives are briefly discussed and highlights on the main

findings given. The potential contribution of the different methods and the implications of results findings are also discussed. Conclusions are drawn and some recommendations formulated for future research in order to improve the use of this integrated geo-information, remote sensing and geo technical methods as a land use-planning tool.

### **9.1 Clay mineralogy and associated physicochemical properties**

To proceed with any new method of estimating soil swelling it is important to understand the underlying mechanisms and compositional factors that bring about these changes and their characteristic influence on the various media of measure in this case the reflected light, physicochemical properties and magnetic fields. However any method to measure these factors as previously discussed runs into problems of the factors varying under varying conditions. The presence of some other common soil materials e.g. organic matter and moisture has an influencing effect on the various methods and in particular a masking effect on the spectral reflectance data (chapter 2). Several studies have established quantitative thresholds beyond which correction is needed (Weidong, 2002; Baumgardner et al, 1985). However, despite such shortcomings the clay mineralogy plays the most significant role in swelling soil mapping and its identification and quantification is an obvious choice when trying to establish the potential of such methods. Mere physical observation of a site might not yield such information demanding the application of instruments with high resolving power (chapter 2, 3 and 8).

### **9.2 Spectroscopy and established index relationships**

The variability of swelling potential characteristics in different environments has led to conclusions that no singular index could be applied universally to describe the swelling potential of all soils, though at a local scale, it is generally accepted that the established indices provide adequate information on the compositional differences. This has been the fundamental principle behind most of the currently applied indices, which basically convey the extent to which the indicator minerals are influencing various physicochemical soil properties and thresholds have been established to estimate the abundance of these minerals (chapter 3). In our study statistical analysis established the various indices as closely related (chapter 3) and to also closely relate to particular spectral parameters established in spectral analysis (chapter 2) to relate to clay mineral types. A method for accounting for the varied geotechnical indices and the various indicator spectral parameters in the estimation of swelling potential values was obtained with a representative index

established (chapter 5). At larger scales other sources of information are critical (chapter 6).

### **9.3 Remote sensing and other remote swelling soil mapping**

Satellite images of the Earth have been commercially available since the early 1970s. Despite long standing scientific interest, the potential of remote sensing technology to map soil properties have been little explored. However, use of such data in their identification is important and needed if we are to make fast inventory of soil properties. To monitor and predict soil properties it is necessary to identify physicochemical variables that are measurable with remote sensing instruments and whose change in magnitude is significant enough to be detected. Our results demonstrate that surface expressions of swelling potential differences (chapter 6) may be observed from remotely sensed data in terms of vegetation differences and soil surface morphology and also in the slope of the spectral curve (chapter 5). Furthermore, remote sensing provides synoptic views with more intensive spatial sampling than the sparse point samples traditionally used in field surveys. Global coverage of spaceborne sensors also means that we can obtain estimates of soil properties that are consistent between regions, allowing comparative study across entire gradient of climate and source materials. With remote sensing, we were able to make real progress in understanding the intricacies associated with presence of swelling soils (chapter 6, 7) and in identifying the areas requiring closer scrutiny in any future developments more so construction of roads or buildings. CEC emerged as an important indicator of soil swelling and the possibility to obtain such information under the soil surface is addressed (chapter 8) providing rapid field measurement procedures which could reduce on drilling cost if proper calibration could be achieved.

### **9.4 Conclusions and recommendations**

Based on the discussions above, conclusions could be drawn that the general objectives of the use of integrated methods for potential evaluation of engineering sites were partly achieved. More specifically the methods have enabled establish:

- Diagnostic spectral parameters with a potential application in the recognition of swelling potential differences through the identification of the dominant clay mineral type.
- Surface expressions of underlying soil mechanical systems that could easily be identified on a satellite image.

- Empirical models based on the diagnostic spectral features and established swelling potential indices to obtain quantitative estimation of soil swelling levels
- The potential application of geophysical measurements to estimate CEC, grain size distribution and moisture contents adding to soil swelling potential measuring tools.

Although the study gave some answers to some of the issues raised by the lack of one standard method of estimating soil swelling potential, the following points may be the future direction for further research.

- A more aggressive approach to integrated remote sensing and ancillary information in the development of robust methods of recognizing these soils requires more scrutiny.
- Spatial statistical methods to evaluate the variability of the measured indices within homogeneous units and their potential source of variability need further research.
- Comprehensive libraries on the soils spectral measurements and associated swelling potential levels require building thus minimizing on the uncertainties whenever new sites are to be explored.
- The two geophysical methods established in the laboratory as good in identifying these soils based on CEC, grain size distribution and moisture require further testing in the field to enable obtain calibration parameters.
- Integrating the remote sensing and spectroscopy into the learning of urban planners in areas where such soils exist to enable the exploitation of the full potential of these methods in the updating of existing soil information databases. This would enable sensitize the policy makers to the applicability of new tools which to many have remained as scientists territory that need not be tampered with due to its sophistication.

## REFERENCES

Agbu, P.A., Fehrenbacher, D.F., and Jansen, I.J., 1990, Soil property relationships with SPOT satellite digital data in east central Illinois. *Soil Science Society of America Journal*, 54, 807-812

Alonso, S.M., Rustard, J.R., and Goetz, A.F.H., 2002, Ab initio quantum mechanical modelling of infrared vibrational frequencies of the OH group in dioctahedral phyllosilicates, Part II, main physical factors governing the OH vibrations, *American Mineralogist*, 87, 1224-1234

Amer, A., and Al-Rawas., 1999, The factors controlling the expansive nature of the soils and rocks of northern Oman, *Engineering Geology*, 53, 327-350

Anderson, J.U., Elfadil, F.K., and O'Connor, G.A., 1973, Factors affecting the coefficient of linear extensibility in Vertisols, *Soil Science Society of America Journal*, 37,298-299

Anderson, S.H., and Hopmans, J.W., 1994, Tomography of soil-water root processes. *SSSA Special Publication*, no. 36, ASA/SSSA Inc., 148p

Banin, A., and Amiel, A., 1970, A correlation of the chemical physical properties of a group of natural soils of Israel: *Geoderma*, 3, 185–198

Baumgardner, M.F., Stoner, E.R., Silva, L.F., and Biehl, L.L., 1985, Reflectance properties of soils. *In: N. Brady (Ed.), Advances of Agronomy*, (New York: Academic Press) pp. 1-44

Beck, R.H., Robinson, B.F., Mcfee, W.H., and Peterson, J.B., 1976, Info. Note 081176.Lab Applic. Remote Sensing, Purdue Univ. West Lafayette, Indiana, USA

- Beckmann, G.C., Thompson, C.H., and Richards, B.R., 1984, Relationships of soil layers below gilgai in black earth. In: Properties and utilization of cracking clay soils, eds. J.W. McGarity, E.H. Hault and H.B. So. Reviews in Rural Science No. 5, University of New England, Armidale, New South Wales. pp. 64-72
- Beckmann, G.C., Thompson, C.H., and Hubble, G.D., 1973, Linear gilgai. *Australia Geographer*, 12, 363-366
- Bedidi, A., Cervelle, B., and Madeira, J., 1991, Moisture effects on spectral signatures and CIE-color of laterite soils, In: Proceedings of the 5<sup>th</sup> International colloquium on physical measurements and signatures in remote sensing, Courchevel, France, vol.1, pp. 209-212
- Ben-Dor, E., Patkin, K., Banin, A., and Karnieli, A., 2002, Mapping of several soil properties using DAIS-7915 hyperspectral scanner data: a case study over clayey soils in Israel, *International Journal of Remote Sensing*, 23(6), 1043-1062
- Ben-Dor E, Irons, J.R, and Epema, G.F., 1999, Soil reflectance, Remote Sensing for the Earth Science, manual of remote sensing 3<sup>rd</sup> edition, edited by A.N Rencz, (New York: John Wiley & Sons), pp. 111-188
- Ben-Dor E., Inbar, Y., and Chen, Y., 1997, The reflectance spectra of organic matter in the visible near infrared and short wave infrared region (400-2500nm) during a controlled decomposition process, *Remote Sensing Environment*, 61, 1-15
- Ben-Dor, E., and Banin, A., 1995, Near infrared analysis (NIRA) as a rapid method to simultaneously evaluate several soil properties. *Soil Science Society of America Journal*, 59, 364-372
- Ben-Dor, E., and Banin, A., 1994, Visible and near infrared (0.4-1.1 mm) analysis of arid and semiarid soils. *Remote Sensing of Environment*, 48, 261-274

Ben Dor, E., and Kruse, F.A., 1994, Mineral mapping of Makhtesh Ramon Negev, Israel using GER 63 channel scanner data and linear unmixing procedures. In proceeding of the 10<sup>th</sup> Thematic Conference on Geologic Remote Sensing, San Antonio, Texas, 7-8 May (Ann, Arbor, MI: ERIM), pp.215-223

Ben-Dor E., Banin, A., and Singer, A., 1991, Simultaneous determination of six soil properties from the soil diffuse reflectance spectrum in the near infrared region. Proceedings of the 5<sup>th</sup> International Colloquium-Physical Measurements and Signatures in Remote Sensing, Courchevel, France, 14-18 January 1991 ESA SP-319, (Noordwijk: ESA), pp. 159-163.

Bittick, S.M., Morgan, K.M., and Busbey, A.B., 1994, Preliminary spectral analysis of calibrated reflectance patterns to map the distribution of alluvial fans on the Rosillos laccolith in Brewster County, Texas. 10<sup>th</sup> thematic conference on geologic remote sensing, San Antonio, Texas, 9-12 May (Ann, Arbor, MI: ERIM), pp. II-151-157

Boardman, J. W., and Kruse, F.A., 1994. Automated spectral analysis: A geologic example using AVIRIS data north Grapevine Mountains, Nevada, Proc. 10<sup>th</sup> thematic conference on geologic remote sensing, San Antonio, Texas, 9-12 May (Ann, Arbor, MI: ERIM), pp. I-407-418

Bohn, H.L., McNeal, B.L., and O'Connor, G.A., 1985, Soil Chemistry 2<sup>nd</sup> Edition, (New York: John Wiley)

Bowers, S.A., and Smith, S.J., 1972, *Soil Sci.Soc.Am.Proc.* 36, 978-980

Bowers, S., and R.J. Hanks., 1965, Reflectance of radiant energy from soils, *Soil Science*,100, 130-138

Bridges, E.M., 1997, *World Soils*, (Cambridge: Cambridge University Press)

Carr, H.Y., and Purcell, E.M., 1954, Effects of diffusion on free precession experiments. *Physics Review* 94, 630

Carter M and Bentley S.P., 1991. *Correlations of Soil Properties*, (London: Pentech Press, UK)

Chabrillat, S., Goetz, A. F. H., Krosley, L., and Olsen, H.W., 2002, Use of hyperspectral images in the identification and mapping of expansive clay soils and the role of spatial resolution, *Remote Sensing of Environment*, 82,431-445.

Chabrillat, S., Goetz, A. F. H., Olsen H.W., and Krosley, L., 2001, Field and Imaging Spectrometry for Identification and Mapping of Expansive Soils. In *Imaging Spectrometry: Basic Principles and Prospective Applications*, edited by F.D. van der Meer and S.M. de Jong, (Dordrecht: Kluwer Academic Publishers), pp. 87-109.

Chang, C.W., Laird, D.A., Mausbach, M.J. and Hurburgh C.R. Jr., 2001, Near infrared reflectance spectroscopy-principal components regression analysis of soil properties, *Soil Science Society of America Journal*, 65, pp. 480-490

Clark, R.N., T.V.V., King, Klejwa, M., and Swayze, G.A., 1990, High spectral resolution reflectance spectroscopy of minerals: *Journal of Geophysical Research*, 95 (B8), 12, 653- 680

Clark R. N., 1999, *Spectroscopy of Rocks and Minerals, and Principles of Spectroscopy, Remote Sensing for the Earth Science*, manual of remote sensing 3<sup>rd</sup> edition, edited by A.N Rencz, (New York: John Wiley & Sons), pp. 111-188

Clark, R.N., 1983, Spectral properties of mixtures of Montmorillonite and dark carbon grains: Implications for remote sensing minerals containing chemically and physically adsorbed water, *Journal of Geophysical Research*, 88, 10635-10644

Comerma, J.A., 1985, Vertisols of Venezuela. *Proceedings of the 5<sup>th</sup> International Soil Classification Workshop*, November 1982 Khartoum, Sudan, Soil Survey Administration, Sudan, pp. 153-159



Courault, D., Girard, M.C., and Escadafal, R., 1988, Modélisation de la couleur des sols par teledetection, *Actes du 4e coll.int. Signatures spectrales d'objets en teledetection*, Aussois, Janvier 1988, 357-362

Crist, E.P., and Cicine, R.C., 1984, A physically based transformation of Thematic Mapper- the TM tasseled cap. *IEEE Trans. Geosci. Remote Sens.* GE-22, 256-263

Crosta, A. P., and Moore, J. M., 1989, Enhancement of Landsat Thematic Mapper imagery for residual soil mapping in SW Minas Gerais State, Brazil: a prospecting case history in Greenstone Belt terrain. Proceedings of the Seventh Thematic Conference on Remote Sensing for Exploration Geology, Calgary, Alberta, Canada, 2- 6 October, pp. 1173- 1187.

Crowley J.K and Vergo N., 1999, Visible and Near-Infrared (0.4-2.5 $\mu$ m) Reflectance Spectra of Selected Mixed Layer Clays and Related Minerals, In: The Proceedings of the Sixth Thematic Conference on Remote Sensing for Exploration Geology, Applications Technology Economics Vol. I, 16-19 May 1988, Houston, Texas, pp.597-606

Crowley J.K and Vergo N., 1988, Visible and Near Infrared (0.4-2.5 $\mu$ m) reflectance spectra of selected mixed layer clays and related minerals. The Sixth Thematic Conference on Remote Sensing for Exploration Geology, Applications Technology Economics, 16-19 May 1988 Houston, Texas (Ann Arbor, MI: ERIM), pp. 597-606.

Crowley, J.K., 1986, Visible and near infrared spectra of carbonate rocks: reflectance spectra variations related to petrographic texture and impurities, *Journal of Geophysical Research*, 91, 5001-5012

Curran, P.J., 2001, Imaging spectrometry for ecological applications. *International Journal of Applied Earth Observation and Geo-Information*, 3: 305-312

Da Costa, L.M., 1979, Surface soil color and reflectance as related to physicochemical and mineralogical soil properties, PhD. Dissertation, University of Missouri, Colombia, Mo., 154p

- Dakhnov, V.N., 1962, Geophysical well logging. *Q. Colo. Sch. Mines* 57(2)
- Dalal, R.C., and Henry, R.J., 1986, Simultaneous determination of moisture, organic carbon, and total nitrogen by near infrared reflectance. *Soil Science Society of America Journal* 50:120–123.
- De Jong, S.M., 1994, Applications of reflective remote sensing for land degradation studies in a Mediterranean environment, Ph.D. Dissertation, Utrecht Univ., Utrecht, The Netherlands.
- Downey, G., and Byrne, P., 1986, Prediction of moisture and bulk density in milled peat by near infrared reflectance, *J. Food Agric. Sci.*, 37,231-238
- Driese, S.G., Mora, C.I., Stiles, C. A., Joeckel, R. M., and Nordt, L.C., 2000, Mass-balance reconstruction of a modern Vertisol: implications for interpreting the geochemistry and burial alteration of paleo-Vertisols. *Geoderma*, 95(3-4), 179-204
- Duckworth, J.H., 1998, Spectroscopic quantitative analysis. In *Applied Spectroscopy, A Compact Reference for Practitioners*, edited by J. Workman, Jr., and A.W. Springsteen, (London: Academic Press), pp.93-163
- Duke, E.F., 1994, Near infrared spectra of muscovite, Tschermak substitution, and metamorphic reaction progress: implications for remote sensing. *Geology*, 22, 621-624
- Dumbleton, M.J., 1967, Origin and mineralogy of African red clays and Keuper Marl. *Q.J. Eng. Geol.*, 1,39-45
- Elbersen, W., 1983, Non-glacial types of patterned ground that developed from erosion, *International Training Centre Journal*, 322-333
- Eldelman, C.H., Brinkman, R., 1962, Physiography of gilgai soils. *Soil Science*, 94, 366-370

Emsley, J.W., and Sutcliffe, L.H., 1967, High-resolution Nuclear Magnetic Resonance Spectroscopy (Oxford: Pergamon)

Escadafal, R., 1994, Soil spectral properties and their relationships with environmental parameters- examples from arid regions. In *Imaging Spectrometry- A Tool For Environmental Observations*, edited by J. Hill and J Megier, (Dordrecht: Kluwer Academic Publishers), pp. 71-87

Farmer, V.C., 1974, The layer silicates: In *The Infra-Red Spectra of Minerals*, edited by V.C. Farmer, (London: Mineralogical Society), pp.331-364

Franzmeier, D.P., and Ross, S.J., 1968, Soil swelling: Laboratory measurement and relation to other soil properties. *Soil Science Society of America Journal*, 32,573-577

Gaffey, S.J., 1984, Spectral reflectance of carbonate minerals in the visible and near infrared (0.35-2.55 microns): Applications in carbonate petrology. PhD. Thesis, University of Hawaii, 236pp

Galvao L.S., Marco A.P., And Epiphanio, J.C.N., 2001, Variation in reflectance of tropical soils: spectral-chemical composition relationships from AVIRIS data. *Remote Sensing of environment*, 75, 245-255

Goetz, A.F.H., Chabrilat, S., and Lu, Z., 2001, Field reflectance spectrometry for detection of swelling clays at construction sites, *Field Analytical Chemistry and Technology*, 5(3), 143-155

Goetz, A.F.H., and Rowan, L.C., 1983, Remote sensing for exploration: an overview. *Economic Geology*, 78, 573-590

Goetz, A.F.H. & Rowan, L.C., 1981, Geologic remote sensing, *Science*, 211, 781-791

Gill, W.R., and Reaves, C.A., 1957, Relationships of Atterberg limits and cation-exchange capacity to some physical properties of soil. *Soil Sci. Soc. Am. Proc.* 21, 491-494.

Girard-Ganneau, C.M., 1975, Docteur Ingénieur dissertation, University of Paris-Sud, Centre d'Orsay

Graham, J., Walker, G.F., and West, G.W. 1964, Nuclear magnetic resonance study of interlayer water in hydrated layer silicates. *Journal of Chemical Physics*, 40(2), 540-550

Gray, C.W., and Allbrook, R., 2002, Relationships between shrinkage indices and soil properties in some New Zealand soils, *Geoderma*, 108 (3-4), 287-299

Green, A.A., Berman, M., Switzer, P., and Craig, M.D., 1988, A transformation for ordering multispectral data in terms of image quality with implications for noise removal. *IEEE Transactions on Geoscience and Remote Sensing*, 26(1), 65-74

Green, A.A. & Graig, M.D. 1985, Analysis of aircraft spectrometer data with logarithmic residuals, NASA-JPL Publication 85-41: pp. 111-119.

Hamberg, D.J., 1985, A simplified method for predicting heave in expansive soils, M.S. thesis, Colorado State University, Fort Collins, CO, USA.

Hapke, B.W., 1981, Bidirectional reflectance spectroscopy I. Theory: *Journal of Geophysical Research*, 86, 3039-3054.

Hapke, B.W., 1986, Bidirectional reflectance spectroscopy: 4. The extinction coefficient and the opposition effect, *Icarus*, 67, 264-280

Hauff, P.L., 2000, Manual of Applied Reflectance Spectroscopy With Emphasis on Data Collection and Data Interpretation Using the PIMA-II Spectrometer. Users manual, Spectral international inc. Arvada, CO, USA

Head K H., 1992, Manual of Soil Laboratory Testing (Volume I: Soil Classification and Compaction Tests, (London: Pentech Press)

Holt, J.H., 1969. A study of physico- chemical, mineralogical and engineering index properties of fine grained soils in relation to their expansive characteristics. Ph.D. Dissertation, Texas A&M Univ., College Station, TX

Holtz, W. G., 1959. Expansive clays- properties and problems. Quart. Colorado School of Mines, 54(4), 89-117

Hruschka, W.R., 1987, Data analysis: wavelengths selection methods. In: Williams, P., Norris, K. (eds.), Near Infrared Technology in the Agricultural and Food Industries. American Association of Cereals Chemists, St. Paul, MN, pp.35-55

Hunt, G.R., 1979, Near-infrared (1.3-2.4  $\mu\text{m}$ ) spectra of alteration minerals- Potential for use in remote sensing, *Geophysics* 44, 1974-1986

Hunt, G.R., and Salisbury J.W., 1970, Visible and near-infrared spectra of minerals and rocks, I. Silicate Minerals, *Modern Geology*, 1, 283-300.

Illiceto, V., Santarato, G., and Veronese, S., 1982, An approach to the identification of fine sediments by induced polarisation laboratory measurements: *Geophysical Prospecting*, 30,331-347

Irons, J.R., Weismiller, R.A., and Petersen, G.W., 1989, Soil Reflectance. In Theory and Applications of Optical Remote Sensing, edited by G. Asrar. (New York: Wiley), pp 66-106

Isbell, R.F., 1996, The Australian Soil Classification.,( Melbourne: CSIRO Publishing).

- Ishida, T., and Ando, H., 1999, Use of disjunctive cokriging to estimate soil organic matter from Landsat Thematic Mapper image. *International Journal of Remote Sensing*, 20(8), 1549-1565
- Jewitt, T.N., Law, R.D., and Virgo, K.J., 1979, Vertisol soils of tropics and subtropics: their management and use. *Outlook on Agriculture* 10(1): 33-40
- Karathanasis, A.D., and Hajek, B.F., 1985, Shrink-swell potential of montmorillonitic soils in udic moisture regimes. *Soil Sci. Soc. Am. J.* 49, 159-166
- Kariuki, P.C., and van der Meer F.D., 2003a, Determination of cation exchange capacity from spectroscopy, *International Journal of Remote Sensing*, 24(1), 161-167.
- Kariuki, P.C., and Van der Meer, F.D., 2003b, Determination of soil activity from optical spectroscopy. In *Geoinformation for European-wide Integration*, Editor, T. Benes (Rotterdam: Millpress), pp.587-590
- Karmanov, I.I., 1970, *Sov. Soil Sci.* 4, 226-238
- Kenyon, W.E., 1997, Petrophysical principals of applications of NMR logging, *The Log Analyst*, 38, 21-43
- Kenyon, B., Kleinberg, R., Straley, C., Gubelin, G., and Morris, C., 1995, Nuclear magnetic resonance imaging technology for the 21<sup>st</sup> century. Schlumberger, Oilfield Review
- Kenyon, W.E., Howard, J.J., Sezginer, A., Straley, C., Matteson, A., Horkowitz, K., and Ehrlich, R., 1989, Pore-size distributions and NMR in microporous cherty sandstones, *Trans. Soc. Prof. Well Log Analysts 30<sup>th</sup> Logging Symp.*, paper LL.
- Kirschner, F.R., Kamiinsky, S.A., Weismiller, R.A., Sinclair, H.R., and Hinzl, E.J., 1978, *Soil Science Society of America Journal*, 42, 768-771

- Klien, J.D., and Sill, W.R., 1982, Electrical properties of artificial clay bearing sandstones: *Geophysics*, 47, 1593-1605
- Knight, R.J., and Nur, A., 1987, The dielectric constant of sandstones, and 60kHz to 4kHz. *Geophysics*, 52,644-654
- Knight, M.J., 1980, Structural analysis and mechanical origins of gilgai at Boorook, Victoria, Australia. *Geoderma*, 23, 245-283
- Kruse, F.A., Thiry, M., and Hauff P.L., 1991, Spectral identification (1.2-2.5 $\mu$ m) and characterization of Paris basin kaolinite/smectite clays using a field spectrometer. 5<sup>th</sup> International Colloquium on Physical Measurements and Signatures in Remote Sensing, Courchevel, France, 14-18 January 1991 ESA SP-319 (Noordwijk: ESA), pp. 181-184
- Kubelka, P., 1948, New contributions to the optics of intensely light scattering materials, *Journal of Optic Society of America*, 38, 448-457
- Kumru, M.N., And Bakac, M., 2003, R-mode factor analysis applied to the distribution of elements in soils from the Aydin basin, Turkey, *Journal of Geochemical Exploration*, 77, 81-91
- Lambe, T.W. 1960. The character and identification of expansive Fed. Housing Admin. Rep. 701. U.S. Gov. Print. Office, Washington, DC.
- Lee, K.S., Lee, G.B., and Tyler, E.J., 1988, Determination of all characteristics from Thematic Mapper data of a cropped organic-inorganic soil landscape. *Soil Science Society of America Journal*, 52, 1100-1104
- Lesmes, D.P., and Frye, K.M., 2001, The influence of pore fluid chemistry on the complex conductivity and induced-polarisation responses of Berea sandstone. *Journal of Geophysical Research*, 106, 4079-4090
- Lewis, D.T., Seever, P.M., and Drew, J.V., 1975, *Soil Sci. Soc. Am.Proc.*39, 330-335

Lieblich, D.A., Legchenko, A., Haeni, F.P., Portselan, A.A., 1994, Surface nuclear magnetic resonance experiments to detect subsurface water at Haddam Meadows, Connecticut. Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Boston, vol.2. EEGS, Denver, pp.717-736

Macdonald, B.C.T., Melville, M.D., and White, I., 1999, The distribution of soluble cations within chenopod-patterned ground, arid western New South Wales, Australia. *Catena*, 37, 89-105

Mahmoud, M.A., 1985, Management of vertisols for rainfed crop production in the Sudan. Proceedings of the 5<sup>th</sup> International Soil Classification Workshop, November 1982 Khartoum, Sudan, Soil Survey Administration, Sudan, pp. 317-321

Mathews, H.L., R.L. Cunningham, and G.W. Peterson, 1973, Spectral reflectance of selected Pennsylvania soils. *Soil Science Society of America Journal*, 37, 421-424

McKeen, R.G., and Hamberg, D.J., 1981, Characterization of expansive soils. Transportation. Research. Record. 790, Transportation. Research. Board, USA

McCormack, D.E and Wilding, L.P., 1975, Soil properties influencing swelling in Canfield and Geeburg soils. *Soil Science Society of America Journal*, 39,496-502

Meiboom, S., and Gill, D., 1958, Compensation for pulse imperfections in Carr-Purcell NMR experiments. *Review of Scientific Instruments* 29, 688

Mitchell J.K. 1993, *Fundamentals of Soil Behaviour*, 2<sup>nd</sup> edition (New York: John Wiley & Sons).

Montgomery, O.L., 1976, An investigation of the relationship between spectral reflectance and the chemical, physical and genetic characteristics of soils, PhD thesis, Purdue University.



Montgomery, O.L., And Baumgardner, M.F., 1974, Tech. Rep. 112674. Lab. Applic. Remote Sensing, Purdue Univ., West Lafayette, Indiana, USA

Mulders, M.A., 1987, Remote Sensing in Soil Science, Developments in Soil Science 15, (Amsterdam: Elsevier Publishers)

Muchena, F.N., and Gachene, C.K.K., 1988, The distribution characteristics and classifications of swell-shrink soil in Kenya, In: *Transactions of International Workshop of Swell-shrink Soils. Classification, Management and Use Potential of Swell-shrink Soils*, Nagpur, India, 24-28 October 1988 IWOSS (Rotterdam: A.A. Balkema), pp. 54-58

Muller, E., And Decamps, H., 2000, Modelling soil moisture reflectance, *Remote Sensing of Environment*, 76,173-180

Murdoch, G., 1970, Soils and Land Capability in Swaziland. Swaziland Ministry of Agriculture. 360p.

Mustard, J.F., And Jessica M.S., 1999, Spectral analysis for earth science: investigations using remote sensing data. In Remote Sensing for the Earth Sciences, Manual of Remote Sensing, 3<sup>rd</sup> edn, Vol. 3., edited by A.N. Rencz, (New York: John Wiley and Sons) pp. 251-305

Mustard, J.F. and Pieters, C.M., 1987, Quantitative abundance estimates from bi-directional reflectance measurements, *Journal of Geophysical Research*, 92, 617-626

National Soil Survey Laboratory., 1981, Principles and procedures for using soil survey laboratory data. Unpublished training materials NSSC, SCS, USA.

Nelson J.D and Miller D.J., 1992, Expansive Soils: Problem and Practice in Foundation and Pavement Engineering (New York: John Wiley & Sons)

- Nevill, D., 1961, A laboratory investigation of two red clays from Kenya. *Geotechnique*, 11, 302-318
- Newman, A.L., 1983, Vertisols in Texas. *Soil Survey Horizons*, 24, 8-20
- Orueta, A.P., Pinzon, E.J., Ustin, L.S., And Roberts, D.A., 1998, Remote sensing of soils in the Santa Monica mountains: hierarchical foreground and background analysis, *Remote Sensing of Environment*, 68,138-151
- Parker, J.C., Amos D.F., and Kaster D.L., 1977. An evaluation of several methods of estimating soil volume change. *Soil Science Society of America Journal*, 41,1059-1064
- Parkhomenko, E.I., 1971, Electrification phenomena in rocks (New York: Plenum Press)
- Pearlman, J., Carman, S., Segal, C., Jarecke, P., Barry P.S., Browne W., 2001, Overview of the Hyperion Imaging Spectrometer for the NASA EO-1 Mission, *IGARSS Special Session 40, SS40MO*, Paper 1775,2001.
- Pearring, J.R., 1963, A study of basic mineralogical, physical-chemical, and engineering index properties of laterite soils. Ph.D. Dissertation, Texas A&M Univ., College Station, TX, USA
- Prammer, M.G., Drack, E.D., Bouton J.C., and Gardner, J.S., 1996, Measurements of clay-bound water and total porosity by magnetic resonance logging, paper presented as SPE-36522 at the Annual Technical Conference and Exhibition, Society of Petroleum Engineers, Denver, Colorado, October 1996
- Provencher, S.W., and Vogel R.H., 1983, Regularization techniques for inverse problems in molecular biology. In: Numerical Treatment of Inverse Problems in Differential and Integral Equations, eds. P. Deuffhard & E. Hairer (Boston: Birkhäuser), pp. 304-319.

- Reeuwijk, L.P., 1995, Procedures for soil analysis. Technical paper 9, International Soil Reference and Information Centre, The Netherlands
- Reynolds, J.M., 1997, *An Introduction to Applied and Environmental Geophysics*, (New York: John Wiley and Sons)
- Riaza, A., Mediavilla, R., and Santistieban, J.I., 2000, Mapping geological stages of climate-dependent iron and clay weathering alteration on lithologically uniform sedimentary units using Thematic Mapper imagery (Tertiary Duero Basin, Spain). *International journal of Remote Sensing*, 21(5), 937-950
- Richter R. D., Schläpfer, And Hausold A., 2001, A unified approach to parametric geocoding and atmospheric / topographic correction for wide FOV airborne imagery, Part 1: parametric ortho-rectification process. Proceedings of the Second EARSeL Workshop on Imaging Spectroscopy, ITC, Enschede, The Netherlands, 11-13 July 2002, (Paris: EARSeL), pp.9-15.
- Ross, G.J., 1978, Relationships of specific surface area and clay content to shrink-swell potential of soils having different clay mineralogical compositions. *Canada Journal of Soil Science*, 58, 159-166
- Rowan, L.C., and Mars, J.C., 2002, Lithologic mapping in the Mountain Pass, California area using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data. *Remote Sensing of Environment*, 84(3), 350-366
- Rowan, L.C., Goetz, A.F.H., and Ashley, R.P., 1977, Discrimination of hydrothermally altered and unaltered rocks in the visible and the near infrared multispectral images. *Geophysics*, 42, 522-535
- Ruiz-Armenta, J. R., and Prol-Ledesma, R. M., 1998, Techniques for enhancing the spectral response of hydrothermal alteration minerals in Thematic Mapper images of Central Mexico. *International Journal of Remote Sensing*, 19(10), 1981-2000
- Russell, J.D. 1987, Infrared methods. In *A Handbook of Determinative Methods in Clay Mineralogy*, edited by M.J Wilson, (New York: Chapman & Hall), pp. 133-173

Russell, J.S., and Moore, A.W., 1972, Some parameters of gilgai micro relief. *Soil Science*, 114(2), 82-87

Saggerson, E.P., 1991, *Geology of the Nairobi Area*, 98 (Nairobi: English Press)

Schafer, W.M, and Singer, M.J., 1976, Influence of physical and mineralogical properties on swelling of soils in Yolo County, California. *Soil Science Society of America Journal*, 40,557-562

Schirov, M., Legchenko, A. and Creer, G. 1991, A new direct non-invasive groundwater detection technology for Australia. *Exploration Geophysics*, 22, 333-338

Schlumberger Inc, Appendix B, An Example of the Current State-of-the-Art Geophysical Logging Technology, <http://www.netl.doe.gov/scng/projects/transmission/ngs/asc/pubs/asc98FT30602%20appendix%20B.pdf>

Schreier, H., 1977, Quantitative predictions of chemical soil conditions from multispectral airborne, ground and laboratory measurements In: *Proceedings of the 4<sup>th</sup> Canadian Symposium on Remote Sensing*. Quebec City, Quebec, Canada, pp. 106-112

Scott, R.M., 1963, *The Soils of The Nairobi-Thika-Machakos Area*, edited by E. Bellis, (Nairobi: English Press)

Seara, J.L., and Granda, A., 1987, Interpretation of IP-time domain/ resistivity sounding for delineating seawater intrusions in some coastal areas of the northeast Spain: *Geoexploration*, 24, 153-161

Seed, H.B., Woodward, R.J., and Lundgren., 1963, Prediction of swelling potential for compacted clays. *Trans. of American Society of Civil Engineers*, 128(1), 1443-1477

Seed, H.B., Woodward, R.J., Jr., and Lundgren, R., 1962, Prediction of swelling potential for compacted clays. *Journal of Soil Mech. Found. Div., Am. Soc. Civil Eng.* 88 (SM3), 53-87

Shepherd, K.D. and Markus G. W 2002, Development of reflectance spectral libraries for characterization of soil properties. *Soil Science Society of America Journal*, 66, 988-998

Sherwood, P.T., 1967, Classification tests on African red clays and Keuper Marl. *Q.J. Eng. Geol.*, 1,47-53

Siderius, W., 2002. Antequera Descriptive Legend Soil Map 1:50.000. ITC-DESA (Soil Science), Int. Document, 1<sup>st</sup> draft.

Siderius, W., 1987, Vertisol variability, experimental design and data processing: management of vertisols under semi-arid conditions. Proceedings of IBSRAM, Bangkok, pp. 233-245

Skempton, A.W., 1953, The colloidal activity of clay. In Proceedings of the Third International Conference on Soil Mechanics and Foundation Engineering, London, (vol. I), pp. 57-61

Slater L. and Lesmes D., 2002, IP interpretation in environmental investigations. *Geophysics*, 67, 77-88

Smith, C.W., Hadas, A., Dan, J., and Koyumdjisky, H., 1985, Shrinkage and Atterberg limits in relation to other properties of principal soil types in Israel. *Geoderma*, 35,47-65

Snethen, D.R., Johnson, L.D., and Patrick, D.M., 1977, An evaluation of expedient methodology for identification of potentially expansive soils. Soil and Pavements Laboratory, U.S. Army Eng. Waterway Exp. Sta., Vicksburg, MS, Rep. No. FHWA-RE-77-94, NTIS PB-289-164

- Soil Survey Staff., 1994, Keys to Soil Taxonomy, 6<sup>th</sup> edition, (Blacksburg: Pocahontas Press)
- Sombroek, W.G., Braun, H.M.H., and van der Pouw, B.J.A., 1982, Exploratory soil map and agro-climatic zone map of Kenya, 1980, scale 1:1.000.000. Republic of Kenya, Min. of Agric., National Agricultural Laboratories, Kenya Soil Survey, Exploratory Soil Survey Report No. 1.Nairobi, Kenya.
- SPSS Inc., 1999, SPSS Base 9.0 applications guide, USA, SPSS inc.
- Stephen, I., Bellis, E., and Muir, A., 1956, Gilgai phenomena in tropical black clays of Kenya. *Journal of Soil Science*, 17(1), 1-12
- Sternberg, B. K. and Oehler, D. Z., 1990, Induced-polarization hydrocarbon surveys: Arkoma Basin case histories: Induced Polarization, J. B. Fink, B. K.
- Sternberg, E. O. McAllister and W. G. Wieduwilt, eds., Tulsa, OK, *Soc. Explor. Geophys.* pp. 354-378.
- Stoner, E.R., 1979, PhD. Dissertation, Purdue Univ. West Lafayette, Indiana, USA
- Svanberg, S., 2001, Atomic and Molecular Spectroscopy: Basic Aspects and Practical Applications, 3<sup>rd</sup> Edition (Berlin: Springer)
- Telford, W.M., Geldart, L.P., and Sheriff, R.E., 1990, Applied geophysics, 2<sup>nd</sup> edn, (Cambridge: Cambridge university press)
- Terzaghi, K., 1925, Simplified soil tests for sub grades and their physical significance, Public roads
- Thomas, P.J., Baker J.C., and Zelazny L.W., 2000, An expansive soil index for predicting shrink-swell potential, *Soil Science Society of America Journal*, 64, 268-274.

- Tsai, F., and Philpot, W., 1998, Derivative analysis of hyperspectral data, *Remote Sensing of Environment*, 66,41-51
- Uehara, G., 1982, Soil science for the tropics. Engineering and construction in tropical and residual soils. ASCE Geotech.Div.Spec. Conf., Honolulu, Hawaii: pp. 13-26.
- Vacquier V., Holmes C.R., Kintzinger P.R. and Lavergne M. 1957, Prospecting for groundwater by induced electrical polarisation. *Geophysics*, 23, 660-687
- Van der Meer F. D., and De Jong, S.M., 2000. Improving the results of spectral unmixing of Landsat Thematic Mapper imagery by enhancing the orthogonality of end members. *International Journal of Remote Sensing*, 21(15), 2781-2797
- Van der Meer F. D., 1999, Can we map swelling clays with remote sensing?, *International Journal of Applied Earth Observation and Geoinformation*, 1(1), 27-35
- Van der Meer, F.D., 1995, Spectral reflectance of carbonates mineral mixtures and bidirectional reflectance theory: quantitative analysis techniques for application in remote sensing. *Remote Sensing Reviews*, 13, 67-94
- Vinegar, H.J., and Waxman, M.H., 1984, Induced polarization of shaly sands. *Geophysics*, 49, 1267-1287
- Verhoef, P.N.W., 1992, The methylene blue adsorption test applied to geomaterials. Memoirs of the Centre of Engineering Geology in the Netherlands, Delft, 101
- Webster, R., 1977, Spectral analysis of gilgai soil. *Aust. J. Soil Res.*, 15,191-204
- Weidong, L., Baret, F., Xingfa, G., Qingxi, T., Lanfen, Z., and Bing, Z., 2002, Relating soil surface moisture to reflectance. *Remote Sensing of Environment*, 81, 238-246

Weismiller, R.A., Persinger, I.D., and Montgomery, O.L., 1977, Soil inventory for digital analysis of satellite scanner and topographic data. *Soil Science Society of America Journal*, 41, 1166-1170

Wessman, C.A., 1994, Estimating canopy biochemistry through imaging spectrometry, In *Imaging Spectrometry- A Tool for Environmental Observations*, edited by J. Hill and J. Megier (London: Kluwer Academic Publishers), pp. 57-69

Westin, F.C., and Lemme, G.D., 1978, *Photogr. Eng. Remote Sensing*, 44, 315-325

Westin, F.C., and Frazee, C.J., 1976, *Soil Science Society of America Journal*, 40, 81-89

White, E.M., and Bonestell, R.G., 1960, Some gilgaied soils in South Dakota, *Soil Science Society of America*, 24, 305-309

Woessner, D.E., 1980, An NMR investigation into the range of the surface effect on the rotation of water molecules. *Journal of Magnetic Resonance*, 39, 297-309

Worthington, P.F., and Collar, F.A., 1984, Relevance of induced polarisation to quantitative formation evaluation. *Marine and Petroleum Geology*, 1, 14-26

Yaramanci, U., Lange, G., and Hertrich, M., 2002, Aquifer characterization using surface NMR jointly with other geophysical techniques at the Nauen/Berlin test site. *Journal of Applied Geophysics*, 50, 47-65

Yaramanci, U., Lange, G., Knödel, K., 1999, Surface NMR within a geophysical study of an aquifer at Haldensleben (Germany). *Geophysical Prospecting*, 47, 923-943

Yule, D.F., and Ritchie, J.T., 1980, Soil shrinkage relationships of Texas vertisols: small cores. *Soil Science Society of America Journal*, 44, 1285-1291.



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*REFERENCES*

Zhang, R. Warrick A.W. and Myers D.E., 1992, Improvement of the prediction of soil particle size fractions using spectral properties. *Geoderma*, 52, 223-234

## **CURRICULUM VITAE**

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## BIBIOGRAPHY

Kariuki P.C., and Van der Meer, F., 2003, Cation exchange capacity determination of from spectroscopy. *International Journal of Remote Sensing*, 24(1), 161-167

Kariuki P.C., Van der Meer, F. and Siderius, W., 2003, Classification of soils based on Engineering indices and Spectral Data. *International Journal of Remote Sensing*, 24(12), 2567-2574

Kariuki P.C., Van der Meer, F. and Woldai, T., 2003, Effectiveness of Spectroscopy to Identify Swelling Indicator Clay Minerals. *International Journal of Remote Sensing*, 24 ( ),1-15

Kariuki P.C., and Van der Meer, F.D., 2003, Issues of effectiveness in empirical methods for describing swelling soils. *International Journal of Applied Earth Observation and Geoinformation*, 4(3), 231-241

Kariuki, P.C., and Van der Meer, F.D., 2003, Determination of soil activity from optical spectroscopy. In *Geoinformation for European-wide Integration*, Edited by, T. Benes (Rotterdam: Millpress), pp.587-590

Kariuki P.C., and Van der Meer, F.D, 2003, A unified swelling potential index for Expansive Soils. *Engineering Geology*, (in press)

Kariuki P.C., Jean Roy, and Van der Meer, F.D, Nuclear Magnetic Resonance (NMR) and Induced Polarisation (IP) to Estimate Selected Soil Properties: Pore size, Moisture and cation exchange capacity (CEC). *Journal of Applied Geophysics*, (submitted)

Kariuki P.C., Woldai, T., and Van der Meer, F.D, Is There A Role For Remote Sensing In Mapping Swelling Soils? *Asian Journal of Geoinformatics*, (submitted)

Kariuki P.C., F.D Van der Meer., and T. Woldai, 2000, The effectiveness of spectroscopy in detecting the swelling clay minerals in soils, In: *Proceedings of the Second EARSeL Workshop on Imaging Spectroscopy*, ITC, Enschede, 11-13 July 2000.

Kariuki P.C, T. Woldai & F.D Van der Meer, 2002, Determination of soil activity in Kenyan soils from Spectroscopy, In: *Proceedings of the Dar es Salaam, ISPRS workshop*, 25-28 March 2002.

Kariuki P.C & Van der Meer, F., 2000, Spectroscopy to map swelling potential of soils. *Proceedings Vijfde Nederlands Aardwetenschappelijk Congres*, 20-21 April, Veldhoven, pp. 2-23.

Van Dijk, P., Van der Meer, F. & Kariuki, P. 2000, The mapping of swelling clays with remote sensing potential of high spectral resolution sensors. *Proceedings of the 31<sup>st</sup> International Geological Congress, Rio de Janeiro, Brazil, 6-17 August, 2000 (1 page abstract)*.

Kariuki, P.C., van der Meer F. D., 2003, Swelling Clay Mapping For Characterizing Expansive Soils; Results from Laboratory Spectroscopy and HySens DAIS Analysis. *Proceedings of the Third EARSeL Workshop on Imaging Spectroscopy, DLR, Oberpfaffenhofen*, 13 - 16 May 2003.