

# THE EFFECTIVENESS OF SPECTROSCOPY IN DETECTING THE SWELLING CLAY MINERALS IN SOILS

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## ABSTRACT

Swelling soils may change by up to 150% from their original volume with increasing water content. This yields major geologic hazards and extensive damage worldwide. Swelling is due to presence of clay minerals whose expansion is caused by the chemical attraction of water in between the clay plates. The three most important groups of clay minerals involved in swelling are smectite, illite and kaolinite, here listed from high to low swelling potential. Currently used engineering practice in quantifying soil swelling potential is time consuming and expensive as elaborate laboratory measurements are needed. Spectroscopy provides a rapid and in-expensive alternative to mapping the swelling potential of soils. This, together with the coefficient of linear extensibility (COLE) test method were used to classify a group of soil samples from the Antequera area of southern Spain. Several spectral characteristics were identified as giving good basis for separating the samples in terms of swell potential and the three types of clay minerals. They include asymmetries at the 1400nm, 2200nm and 2340nm wavelength positions, 1<sup>st</sup> and 2<sup>nd</sup> derivatives of the spectra, a unique absorption at 2170nm and a shift at the 1900nm-feature position. Area and Depth whose intensities signify abundance were found to be greatly affect by both masking and band overlaps, making them hard to use as quantitative estimators of the swell potential.

## 1.0 INTRODUCTION

### 1.1 Background and Problem Definition

Expansive soil is a term generally applied to any soil that has a potential for shrinking or swelling under changing moisture conditions. The potential volume change is dependent on the mineralogical composition, clay mineral type and content, and the exchangeable ion. Easy identification of the mineralogy is therefore a priority in classifying potentially expansive soils (Mitchell, 1993). Of greater importance is the clay mineralogy, the major groups of which are, smectite, illites and kaolinite, assignment to which is based on their engineering properties especially their critical significance in the resultant volume change.

Presence of substantial levels of these minerals is of great concern in any infrastructure development due to the destructive nature of the great volume changes associated with the addition and removal of water more so to the highest swelling type the smectites. Determining their presence and relative abundance is therefore one of the most crucial field investigations in infrastructure development and in taking remedies where the infrastructure is already in place.

In conventional engineering, presence of these minerals has been inferred from their properties or through expensive laboratory analysis. Among the laboratory-based methods include X-ray diffraction (XRD) and microscopic examination. Due to the elaborate nature and cost of mineral identification using these methods, indirect methods for evaluating the swell potential

have been devised and include; Atterberg limits, Free swell, Colloid content tests among others.

Spectrometry offers a fast and inexpensive method of recognising the presence, type and abundance of these minerals. Significant spectral information found in the short wave infrared (SWIR) spectral region has been identified as diagnostics for clay minerals (Clarke et al, 1997). In this paper the capability of the laboratory spectrometry in the SWIR spectral region to identify presence of the three types of clay minerals has been elaborately shown.

## **2.0 MATERIALS AND METHODS**

### **2.1 Data Acquisition**

#### **2.1.1 Soil Sampling Site Selection**

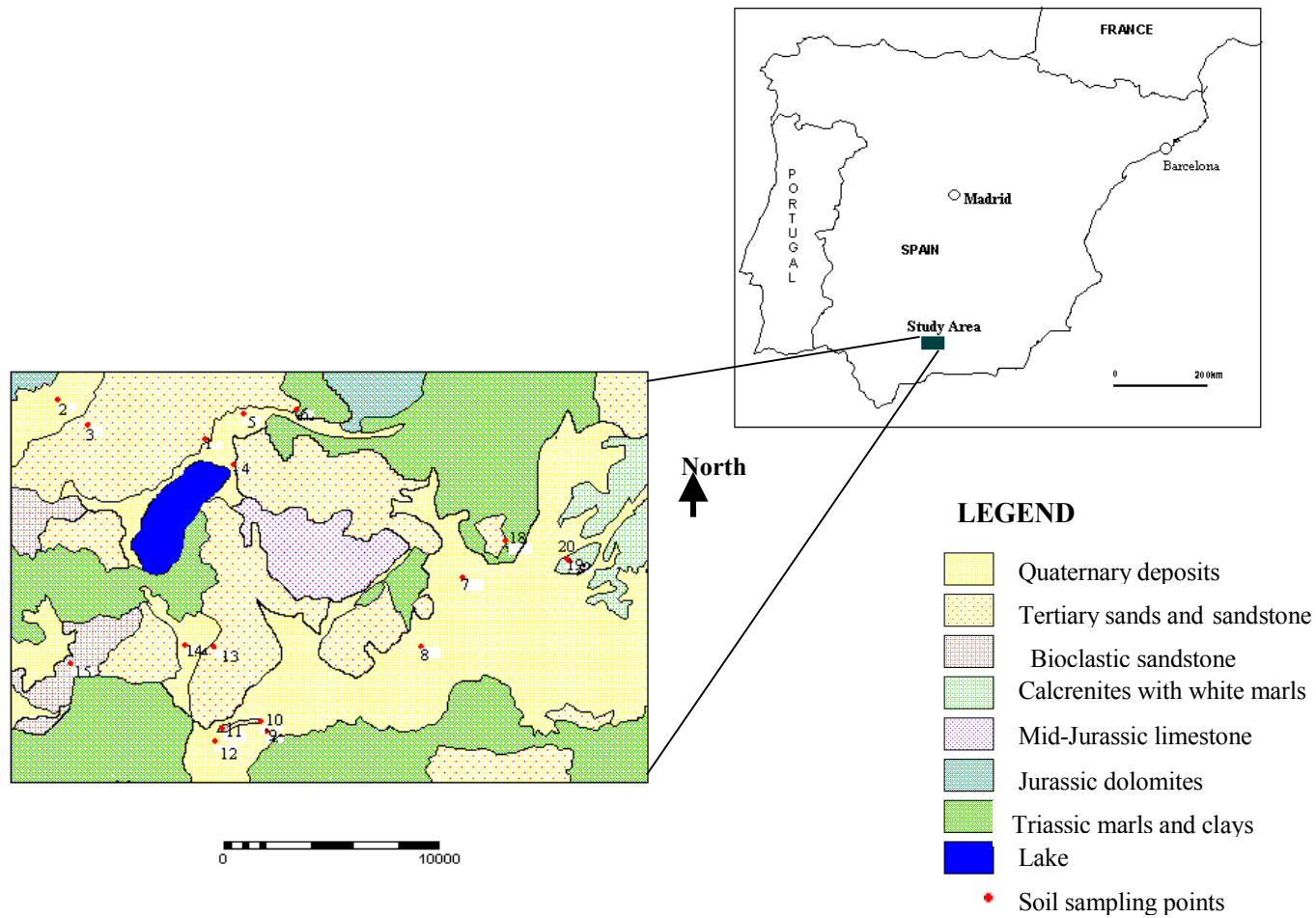
Sampling sites in Antequera, southern Spain (see figure 1) were carefully selected, in order to have good representative samples. This was done through the use of an existing soil database of the area, obtained from the Soil Science Division of the International Institute for Aerial Survey and Earth Sciences (ITC). The cation exchange capacity (CEC) values of the soils in the database were used in selecting sites with low, moderate and high swelling potential soils. To obtain the CEC values due to the clay fraction, a correction for that due to the organic matter was done,

$$CEC_{\text{clay}}=100/\%Clay*[CEC_{\text{soil}}- (3.5 * \%Carbon)] \quad [1]$$

The obtained CEC value was then taken to be that due to the present clay minerals.

#### **2.1.2 Sample Collection**

Sample collection was carried out in the month of October 1998 when the weather was generally dry. Samples were collected from the surface soils, mainly from land prepared for the planting season. Proper location of the specific previously selected soil-sampling site was done using the global positioning system (GPS). This enabled the collection of samples as close as possible to the locations where the previous soil samples used in the estimation of the cation exchange capacity (CEC) had been collected.



**Figure 1.** Geology map of study area showing soil sampling locations.

### **2.1.3 Laboratory Procedures**

Laboratory procedures involved the swell potential determination and acquisition of the spectral data of the collected soil samples. Swell potential was by coefficient of linear extensibility (COLE) clod test procedure and the saturated soil pastes linear extensibility test (LE). Spectral data acquisition was done using a portable field spectrometer.

#### ***2.1.3.1 Linear Extensibility (LE) Test - Saturated Paste Procedure***

Paper cups were filled with 100g of each of the obtained soil samples. Distilled water was then carefully added to the soils, and constantly stirred until pastes slightly drier than saturation were obtained and the cups then sealed tightly to avoid any moisture loss during the stabilisation period. The pastes were then left to equilibrate for twenty-four hours and readjusted to the proper moisture content where necessary. It was ensured that the surface of the pastes was smooth after repeatedly tapping the cups on the table. In cases where the right proportions were not met either soil or water was added for adjustments.

Upon meeting these requirements the pastes were then loaded on shrinkage moulds of semi-circular cross section and 8cm length. They were then flattened evenly on the surface using a light metal sheet, which ensured the flatness of the surface. Their lengths were precisely taken with a Calliper to obtain length at saturation. The pastes were then left to dry for at least 24hours after which the lengths were measured again. Changes in length were recorded for each sample. Similar procedure was repeated on other samples, which were instead oven dried at 105<sup>0</sup>C for 24hours.

#### ***2.1.3.2 Coefficient of Linear Extensibility (COLE) - Coated-Clod Procedure***

In this test, natural clods of about 10 to 25cm<sup>3</sup> (fist size) were used. One side of each clod was flattened with sandpaper for good contact with the sandbox later in the test. The clods were then tied with fine copper wire in a loop and dipped in a saran-ethyl ketone of 1:5 solution and dried in air for one day. Weights of the clods were determined in the air and in water. The clods were then saturated with water by hanging in the water for fourteen days. Weights were again taken both in air and water prior to which they were quickly treated with a hair drier to remove the surface water. The clods were then placed in a sand-kaolinite box at 1/3 bar tension where the flat surface was allowed to touch the surface of the sand for fourteen days. On the fourteenth day the weights of the clods were again taken both in air and in water. Finally the clods were oven-dried at 110<sup>0</sup> C for one day and the weights taken in air.

#### ***2.1.3.3 Spectroscopic Data Acquisition***

Spectra of the samples were collected using PIMA (Portable Infrared Mineral Analyser) spectrometer that covers the spectral range between 1.3 and 2.5µm with an average resolution of 7-10nm and sampling interval of 2nm. In total 198 spectra of the soil samples were taken, representing the 22 sampled locations.

## **2.2 Data Analysis**

### **2.2.1 Engineering Quantitative Analysis**

Soil scientists have used the linear extensibility clay content ratio test in identifying the dominating clay minerals in soils. The procedure as described by the American National Soil Survey Laboratory (1981) was used to group the collected soil samples (table 1). Swell potential assignment was given based on the works of Parker et al, (1977) and Simon et al. (1985) for the COLE and LE respectively.

**Table 1.** Relationship between the LE/clay content ratio and Mineralogy (After Nelson & Miller, 1992).

LE/Percent clay	Mineralogy
> 0.15	Smectites ( montmorillonite)
0.05-0.15	Illites
< 0.05	Kaolinites

### 2.2.2 Spectral Analysis

The sensitivity of spectroscopy to subtle changes in crystal structure and chemistry with changing clay mineralogy was the basis for wavelength position analysis. Presence and shifts of absorption features at particular wavelengths associated with the minerals under study was used in determining their presence and influence in the heterogeneous soil. Asymmetry of the absorption features on the other hand was used as a discriminating parameter for the three clay mineral groups under study based on the differences reported by Van der Meer (1998). Depths and areas which are known to be dependent on the abundance of the absorbing material (Clark, 1997) were used in quantifying the interpreted clay minerals. Increase in the absorption depth was attributed to increase in the abundance of that particular mineral responsible for the absorption while decrease was attributed to decreased proportions of that particular element. Manipulations of the obtained spectra by getting the first and second derivatives were also used to give some information lacking in the original spectra.

## 3.0 RESULTS AND DISCUSSION

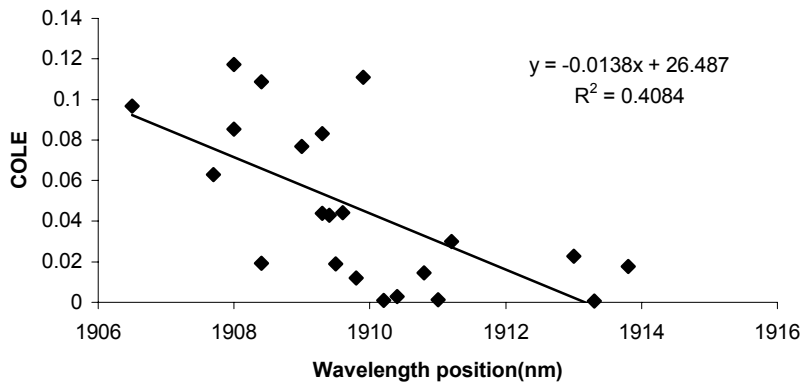
### 3.1 Spectroscopy and Swell Potential

#### 3.1.1 Absorption Feature position

Presence and characteristics of absorption features at several wavelength positions were observed to be significant and are given in table 2. Water absorption features were among the most significant probably due to the bound water in the lattice of clay minerals in question. Whereas the 1400nm did not show notable differences between the samples in the wavelength position, 1900nm feature did show differences in position between the collected soil samples. One group of samples had the feature at around 1905nm whereas the other had it at around 1915nm. This was attributed to probable differences in the bound water of the present minerals, excess moisture having been removed through oven drying at 105<sup>0</sup>C for 24hours. Tendency to the lower wavelength was attributed to probable presence of higher amount of water bearing montmorillonite to give what Hunt and Salisbury (1970) described as a very strong molecular water band at 1899nm. The correlation between this wavelength position and the observed COLE is as seen in figure 2. Though weak it shows a negative relationship where increase in the high swell potential mineral results in shift towards lower wavelength position.

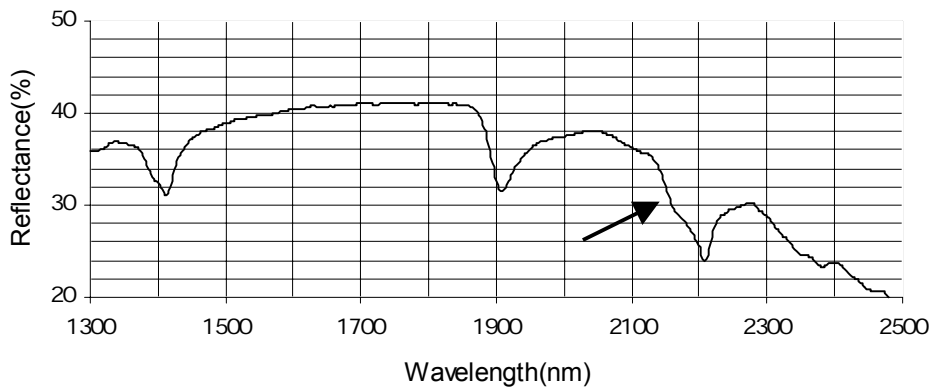
**Table 2.** Grouping according to presence or absence of absorption features

Swell potential	High	Moderate	Low
<b>Wavelength</b>			
1400-1420nm	Present	Present	Present
1900-1910 nm	Present	Present	Absent
1910-1920 nm	Absent	Present	Present
2160-2170 nm	Absent	Present/Absent	Present
2200-2210 nm	Present	Present	Present
2340-2350 nm	Absent	Present	Present



**Figure 2.** Relationship between the 1900nm-wavelength position and Coefficient of Linear Extensibility (COLE)

Another significant presence was a feature at the 2160-2170nm region found in a small group of samples. This feature has for long been associated with high presence of Al-OH typical of kaolinite. Samples observed to possess it were mainly those observed to show low swell potential. Its significance in presence of kaolinite can be observed in figure 3 where the feature gives the spectrum a shoulder next to the 2200nm feature position



**Figure 3.** Example of kaolinite dominated soil sample showing the characteristic shoulder at the 2170nm.

All the obtained samples possessed a feature at the 2200nm wavelength position, a position known to signify more than 20% clay content (Stoner and Baumgardner, 1980). However differences in precise position and other parameters of the feature were observed to separate soil samples. Two clusters, one between 2203-2206nm and the other between 2207-2208nm were observed. These clusters were believed to signify differences in clay mineralogy among the soil samples.

### 3.1.2 Band Asymmetry

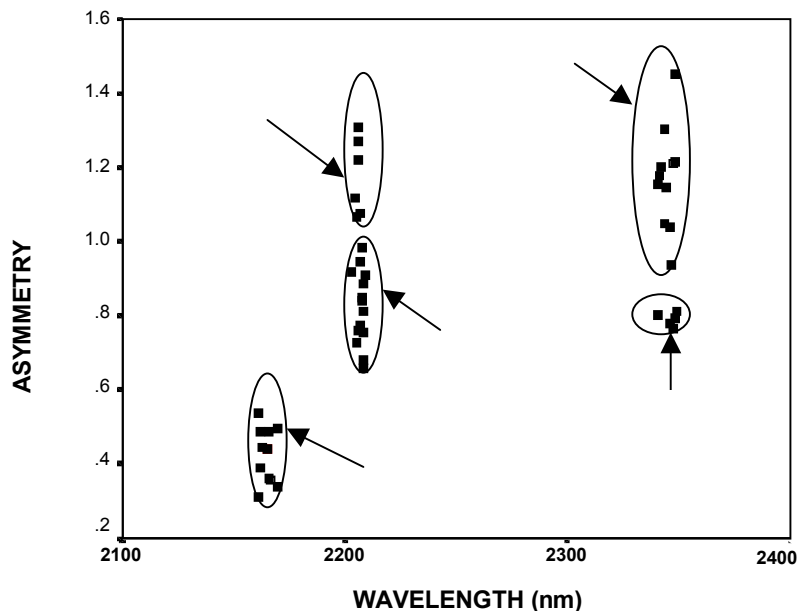
Asymmetries greater than one at the 1400nm and at several other positions in the wavelength range between 2200 and 2500nm in clay mineralogy are mainly associated with high presence of kaolinite. The most significant are those due to doublets (characteristics of kaolinite) at 1400nm and 2200nm.

Asymmetries at mainly three wavelength positions (see table 3) were observed to separate obtained soil samples into two groups, one with the asymmetries greater than one and the other less than one.

**Table 3.** Relationship between swell potential and asymmetry

Swell Potential	High	Moderate	Low
Wavelength(nm)			
1410-1420	<1	>1	>1
2200-2220	<1	<1	>1
2340-2350	<1	>1	>1

Based on van der Meer (1998) conclusions and supported by the swell potential values, kaolinite domination was observed to result in asymmetries greater than one while domination by the other two gave less than one asymmetries at these wavelength positions. An exception was observed to be the 2340nm position where some samples believed to have high contents of illite gave asymmetries greater than one. A summary of asymmetry relationship with observed swell potentials is as shown in figure 4.



**Figure 4.** Clusters of the used soil samples based on wavelength position and asymmetry spectral characteristics and their relationship with swell potential values.

### 3.1.3 Derivatives

Derivative functions are frequently used in the analysis of high-resolution spectral measurements of soils. The derivatives suppress the flat part of the spectrum and enhance the absorption bands. By taking the first derivatives of the spectra two sets of samples emerged, one had values above the zero threshold at 1880-1890nm wavelength range while the other returned zero in all wavelengths. The second derivative was found to show the same trend, though it further separated the samples. Values above the threshold were mainly for those samples observed to have high swell potential and were taken to contain higher quantities of smectite. This could be due to higher amounts of water in the lattice of the smectite lacking in the case of the other two. Russell (1987) has described the wavelength position as the water bending mode of montmorillonite.

### 3.1.4 Relative-quantitative Estimation (Absorption Depths and Areas)

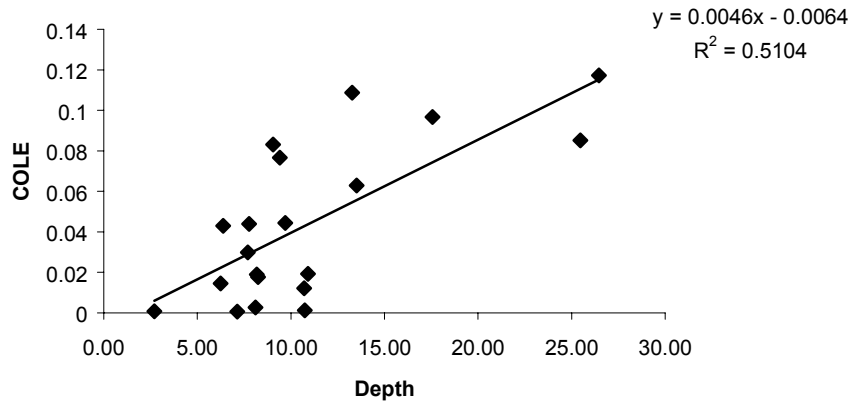
Area and depths are the quantitative estimators of the mineral associated with a particular absorption feature. However, other factors such as presence of organic matter, carbonates, and moisture together with the grain size greatly affect the obtained depths and areas. This making use of these parameters only relative.

The 1400 and 1900nm depths and areas give a quantitative index of the available water in the minerals composing the soil (assuming total elimination of excess moisture by oven drying). The depths and areas of these two wavelength positions were found to vary among the soils in such a way as to show differences in mineralogical composition. For the 1900nm, depths were such that those recognised to shift to the lower wavelength generally gave higher depths. The 1400nm position was however not as evident. This could be due to its being a hydroxyl band rather than molecular water band.

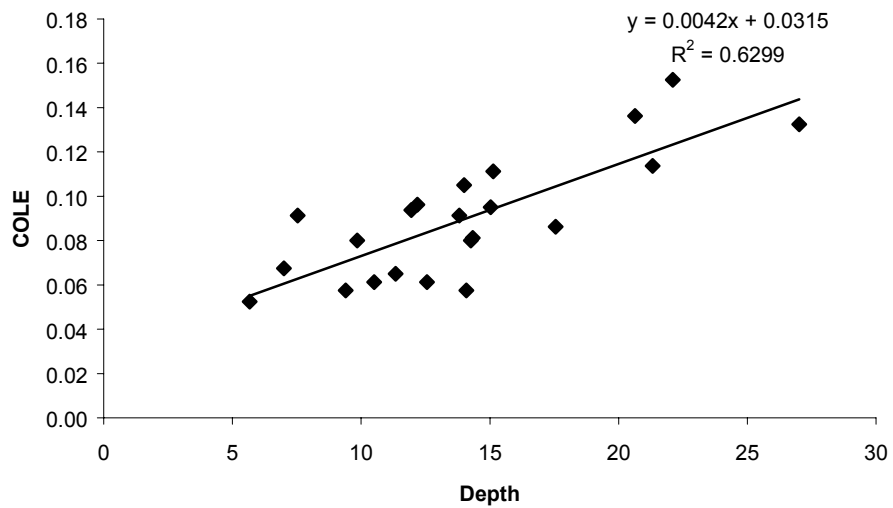
Though it has been associated with the strong presence of the smectite group of minerals (Chabrilat *et al*, 1997), the 2200nm feature can be described as complex due its presence whenever either of the clay minerals under study are encountered. This coupled with masking by organic matter and moisture could explain its quantitative indicators relatively poor correlation with the obtained linear extensibility values.

Effects of present organic matter and moisture are best illustrated by the correlations given in figures 5, 6, 7 and 8. Figure 5 shows relationship between depth of the 2200nm feature and COLE values (for the collected samples) before correction for moisture, whereas figure 6 shows the relationship after oven drying the samples. Figure 7 shows correlation with LE before correction for greater than 2% organic matter content (threshold to substantially affect spectrum) while figure 8 shows the relationship after the correction. There is a marked improvement upon collection for both the moisture and organic matter content.

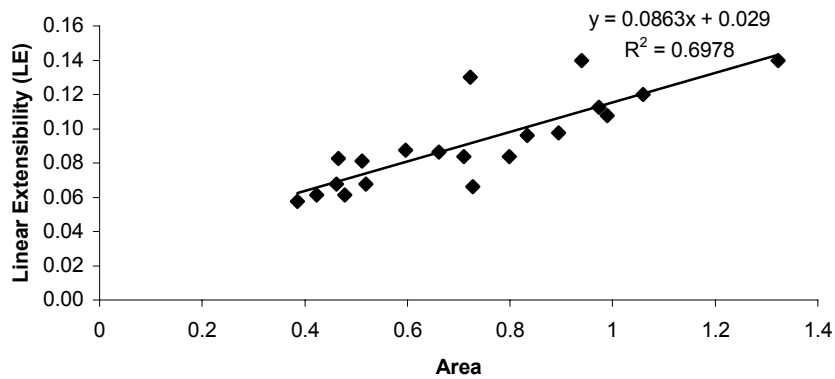




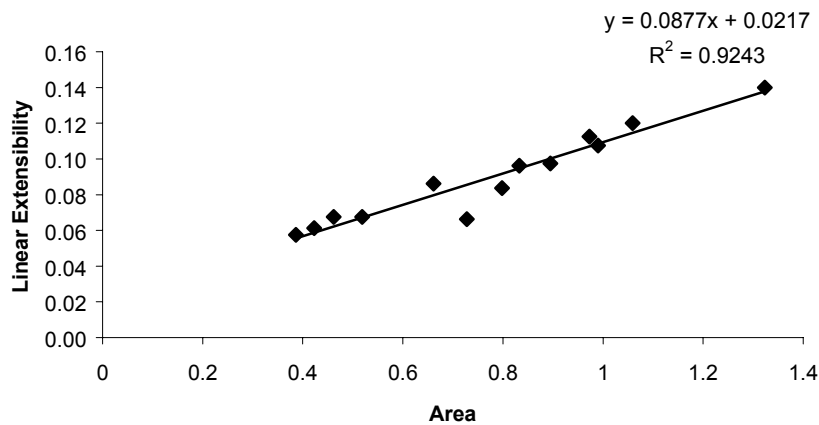
**Figure 5.** Relationship between the COLE and depth at the 2200nm absorption feature as at field moisture content.



**Figure 6.** Relationship between the COLE and depth at the 2200nm absorption feature after oven drying at 105°C for 24 hours



**Figure 7.** Relationship between area and LE at 2200nm before correction for >2% organic matter.



**Figure 8.** Improved relationship between area and LE at 2200nm on correction for >2% organic matter.

### 3.2 Classification

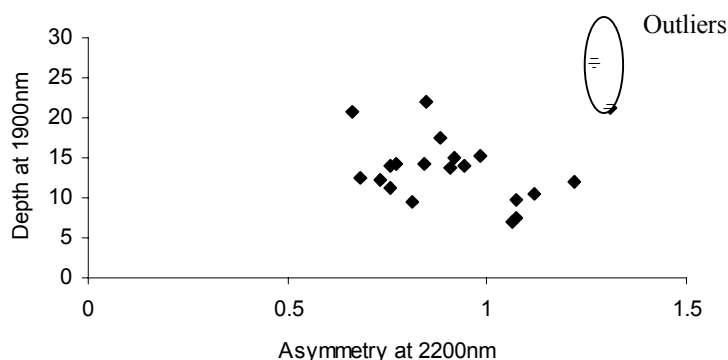
Classification of the soil samples was done based on both the obtained qualitative aspects of the spectra and the engineering characteristics, in the form of LE and COLE.

#### 3.2.1 Spectroscopic indices based classification

For the spectral classification, combinations of the qualitative indicators interpreted to signify domination of one of the three clay mineral types were used.

Kaolinite dominated soils were classified as those having asymmetries greater than one at the 1400nm and 2200nm and grouping in the samples with values below the zero threshold at the 1890nm of the first and second derivatives. They had the 1900nm wavelength position shifting to higher wavelengths relative to those with higher quantities of smectites. Illite dominated soils were found to be the most difficult to characterise. However they were classified as those with greater than one asymmetry at the 2340nm coupled with less than one asymmetries at the 2200nm. Their first and second derivatives were also below the zero threshold.

Samples classified as having significant amounts of smectites are those observed to have had asymmetries at 1400nm, 2200nm and 2340nm less than one and their first and second derivatives at the 1890nm having values higher than the zero threshold. Their 1900nm wavelength feature position had a shift to lower wavelength relative to those of kaolinitic composition. Where the characteristics are closely related to two of the minerals, it indicates presence of the two minerals in substantial proportions. This could be as a result of mixed layer or intimate mix of the separate minerals which have been described to resemble (Crowley *et al*, 1988). Examples of this are samples from location 17 and 18, which had close relationships to both kaolinite and smectites. By comparing the depths at the 1900nm and obtained asymmetries at the 2200nm (figure 9) they stand out as outliers from the general trend of decrease in the water feature depth with increase in asymmetry at the 2200nm. This signifies a strong presence of both the smectite and kaolinite groups probably in equal proportions, where strong presence of smectite is indicated by greater depths at the 1900nm whereas high presence of kaolinite is signified by the greater than one asymmetry at 2200nm.



**Figure 9.** Asymmetry at 2200nm relationship with depths at 1900nm

### 3.2.2 Engineering classification

Many disparities were observed to exist between the engineering classifications. The differences in conditions at which the swell potential values are obtained is a key player to these disparities. Whereas the COLE was performed under set standard conditions, LE was done under no restraining conditions. The CEC on the other hand is based on chemical analysis, which have been described by Mitchell, (1993) as, though of high order of accuracy, the accuracy does not extend to the overall compositional analysis of the soil in terms of components of interest in understanding behaviour. Chemical analysis of the solid phase does not indicate the organization of the elements into crystalline and non-crystalline components

### 3.2.3 Comparison of the classifications

The integration of the engineering properties with the spectral interpretations was based on the assumptions of the dependence of swell potential on the clay mineralogy. A clear relationship can be observed between the two (see table 4). Samples consisting of higher quantities of kaolinite and smectites were seen to separate from both approaches while those interpreted to consist of higher illite lacked proper distinction.

**Table 4.** Comparison between dominating clay mineral and the swell potential estimates.

SAMPLE NUMBER	DOMINATING MINERAL (SPECTROSCOPY)	SWELL POTENTIAL (COLE)	SWELL POTENTIAL (LE)	SWELL POTENTIAL (CEC)
1	Illite	Low	Low	Moderate
2	Illite	High	Moderate	Moderate
3	Smectite	High	High	High
4	Illite	Low	High	High
5	Kaolinite/Illite	Low	Low	Moderate
6	Illite/kaolinite	Low	Moderate	Moderate
7	Smectite	high	High	High
8	Illite	Moderate	Low	Low
9	Illite/kaolinite	Moderate	Low	Moderate
10	Kaolinite	Low	Low	Moderate
11	Illite	Low	Low	Low
12	Smectite/Illite	High	High	High
13	Kaolinite/Illite	Low	High	High
14	Kaolinite	Low	Moderate	Moderate
15	Illite	Low	High	High
16	Smectite	High	Low	Low
17	Kaolinite/smectite	High	High	High
18	Kaolinite/smectite	High	High	High
19	Smectite/Illite	Moderate	High	High
20	Smectite	High	High	High
21	Illite	Low	low	Moderate
22	Kaolinite/Illite	Low	low	Moderate

#### 4.0 CONCLUSIONS

Spectroscopy is a relatively new tool that has yet got a long way to go before becoming fully operational in engineering applications. Here it has been shown to give fairly good information on the clay mineralogy of soil and swell potential based on the interpreted spectral properties of the three basic clay minerals. It shows a potential in identifying the presence of kaolinite, illite and smectites, the most influential clay minerals in determining the engineering properties of soils more so the swelling capacity. The most significant of the obtaining absorption features include 1400nm, 1900nm, 2200nm and 2350nm whose characteristics define the present clay minerals. The first and second derivatives of the spectra also give a good basis for their discrimination where higher presence of lattice water in minerals is evidenced by greater than zero thresholds at 1890nm wavelength position. Establishing an empirical relationship between the swell potential and spectroscopic indicators however need take into consideration other parameters more so organic matter and moisture content which affect the quantitative spectroscopic estimators.

## 5.0 REFERENCES

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

Ben-Dor E and Banin A., 1994. Chemical analysis of semi-arid soils using reflectance spectra in the visible and near infrared (0.4-1.1 $\mu$ m) region. The Tenth Thematic Conference on Geologic Remote Sensing, 9-12 May 1994 (San Antonio, Texas), pp. II: 121-131.

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 (1-2.5 $\mu$ m). The 5<sup>th</sup> International Colloquium, Physical Measurements and Signatures in Remote Sensing, 14-18 January 1991 (Courchevel, France), pp. 159-163.

Chabrilat, S., Goetz, A.F.H., Olsen, H.W. and Noe, D.C., 1997. Field spectrometry techniques for identification of expansive clay soils. The 12<sup>th</sup> International Conference and Workshops on Applied Geologic Remote Sensing, 17-19 November 1997 (Colorado), pp. I: 141 -148.

Chabrilat, S., Goetz, A.F.H., Olsen, H.W. Kronsley L, and Noe, D.C., 1999, Use of AVIRIS hyperspectral data to identify and map expansive clay soils in the front range urban corridor in Colorado. The 13<sup>th</sup> International Conference and Workshops on Applied Geologic Remote Sensing, 1-3 March 1999 (Vancouver, British Columbia, Canada), pp. I: 390-397.

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, pp.10635-10644.

Clark, R.N., and Roush, T.L., 1984. Reflectance spectroscopy quantitative analysis techniques for remote sensing applications. *Journal of Geophysical Research*, 89, pp.6329- 6340.

Clark R. N and Roush T.L., 1984. Reflectance spectroscopy: quantitative analysis techniques for remote sensing applications. *Journal of Geophysical Research*, 89, pp. 6329-6340.

Condit, H.R., 1970. The spectral reflectance of American soils. *Journal of Photogrammetric Engineering and Remote Sensing*, 36, pp. 955-966.

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), pp. I: 597-606.

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

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

Schafer W.M and Singer J.M., 1976. A new method of measuring shrink-swell potential using soil pastes. *Soil Society of America Journal*, 40, pp. 805-806.

Stoner E.R., and M.F. Baumgardner.,1981. Characteristic variations in reflectance of surface soils. *Soil Science Society of America Journal*, 45, pp. 1161-1165.

Van Der Meer, F., 1994. Extraction of mineral absorption features from high spectral resolution data using non-parametric geostatistical techniques. *International Journal of Remote Sensing*, 15(11), pp. 2193-2214.