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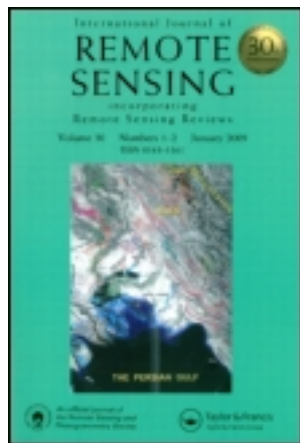
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Effectiveness of spectroscopy in identification of swelling indicator clay minerals

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Abstract. Swelling soils are a major geological hazard worldwide and their identification is a major concern. Swelling is due to the presence of clay minerals with a potential to accommodate water within their crystal structure. Three common groups, namely smectite, illite and kaolinite, have been identified as indicators of high, moderate and low swelling potential soils where in abundance. This study assessed the potential of spectral data as a tool to recognize the presence of these minerals in soils of varying swelling potential collected from the Antequera area of southern Spain, with the aim of establishing spectral parameters that would in future be applied in remote sensing applications for mapping swelling soils. The coefficient of linear extensibility (COLE) and the linear extensibility (LE_{rod}), which are established methods for assessing swelling potential and tentative clay mineral allocation, were used as the controlling methods to classify the soils into swelling potential groups and to assign them to dominant clay mineral types. Several spectral parameters were identified as giving a good basis for assigning the soils to domination by either of these clay minerals, and thus to a swelling potential class based on their diagnostic assignment to hydroxyl (OH) and molecular water vibrational processes in clay minerals. The parameters consisted of asymmetries (1400 nm and 2200 nm) that were strong in the presence of the more ordered kaolinite, wavelength position and depth at 1900 nm in abundant smectites, first and second derivative peaks at or near the molecular water feature and the unique presence of absorptions at 2170 nm and 2340 nm in abundant kaolinite and illite. The results show the potential for using reflectance spectroscopy as a tool in the classification of soils into domination by these indicator minerals and thus into swelling potential classes. However, high organic matter and the presence of moisture were found to affect area and depth intensities and would require consideration in such applications.

1. Introduction

Expansive soil is a term generally applied to soils that have a potential for shrinking or swelling under changing moisture conditions. The potential volume change is dependent on the mineralogical composition, of which the clay

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mineralogy plays the most significant role even when present in small fractions (Head 1992). Their prominent role in the swelling/shrinking characteristics of soils has led to their identification and quantification being described as critical (Mitchell 1993).

The minerals consist of three main groups, smectite, illites and kaolinite, based on properties, crystal structure and capacity to accommodate water within their structure. This has led to their assignment as swelling potential indicators when present in significant amounts where smectite indicates high, illite moderate and kaolinite low swelling potential soils based on their decreasing capacity to accommodate water within their crystal lattice. The easy determination of their presence and abundance has therefore been, and continues to be, a subject of research and many direct and indirect methods have been established to identify and, at times, quantify them in soils.

The most commonly used methods are indirect methods where the minerals' influence on the physical/chemical properties of the soils, such as plasticity, colloid content, linear extensibility (LE_{rod}) and cation exchange capacity (CEC) etc., are used to assign soils to a dominating clay mineral type based on established thresholds within which one of these minerals is likely to be dominant. This is mainly due to expenses involved in detailed quantitative analysis methods such as the X-ray diffraction (XRD) and scanning electron microscope (SEM) examination.

The US Soil Conservation Service, National Soil Survey Laboratory (Nelson and Miller 1992) established a classification scheme that uses the LE_{rod} and clay percentage ratio to assign soils to a clay mineral type (see table 1), while Pearring (1963) and Holt (1969) developed classification schemes that combine engineering index properties and cation exchange capacities to classify soils into regions in a classification scheme assigned to these minerals. McKeen and Hamberg (1981) and Hamberg (1985) further extended this scheme to include the coefficient of linear extensibility (COLE). Such elaborate methods, though relatively cheap, are time-consuming and so the search has continued for easy and cheap methods for the proper identification and, where possible, quantification of these minerals in engineering soils without requiring such elaborate work.

Laboratory, field, airborne and space-borne spectrometry offers such a method since it has the capacity to recognize and quantify these minerals based on their significant spectral information found in the short-wave infrared (SWIR) and described by Clark (1999) as diagnostic. It has in the recent past found widespread use in the estimation of many soil properties including CEC and clay content (Chang *et al.* 2001), particle size distribution (Zhang *et al.* 1992) and organic matter content (Ben Dor *et al.* 1991). Others have gone further and applied airborne imaging spectroscopy (Muller and Decamps 2000, Chabrilat *et al.* 2002, Ben Dor *et al.* 2002) to estimate soil properties. This shows a potential use of not only

Table 1. Criteria for mineralogy assignment from swell indices (after Nelson and Miller 1992).

LE_{rod} /Percent clay	Mineralogy
>0.15	smectites
0.05–0.15	illites
<0.05	kaolinites

laboratory-based but also field and even spaceborne spectrometers to establish soil constituents and associated properties.

This paper reports on the findings where laboratory spectroscopy was used as a first step to establish a method in which field, airborne and space-borne spectral data could be used to recognize the presence and abundance of the three swelling potential indicator clay minerals based on their varied influence on the soil spectra. Two commonly applied and widely accepted swelling potential indices, namely LE_{rod} and COLE, were used to assign the soils to a dominant clay mineral type on the basis of established thresholds which were in turn used to qualify the interpreted spectral assignments to soils being dominated by either of these minerals.

2. Rationale for this study

It has in the recent past been shown that spectral reflectance offers a rapid and inexpensive technique for determining mineralogy on the Earth's surface. Data collected by airborne spectrometers such as Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), Hyperspectral Mapper (HYMAP) and Digital Airborne Imaging Spectrometer (DAIS) have already demonstrated that it is possible to identify certain types of exposed minerals, to label the minerals and determine the fractions of the minerals occurring in small, sub-pixel units (Woldai and Schetselaar 2002). Thus, provided that the non-uniqueness in the solutions obtained from spectral unmixing methods can be constrained, a new type of map, indicating mineral abundance at the surface, can now be made.

Imaging spectrometry or hyperspectral imaging systems, such as the Hyperion and the planned Australia's ARIES-1, using sensors with hundreds of spectral bands provide new space-borne tools in which spectroscopy could be used to obtain compositional information about earth surface materials based on the principles of spectroscopy. Others with less spectral resolution but already operational, such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) with 14 carefully chosen spectral bands including five bands (compared with the single Landsat TM band 7) in the area where hydroxyl (OH) and H_2O bending and stretching can distinguish various clays, makes their use in surface mapping of these minerals all the more possible. This provides a new class of earth observation instruments with the capacity to provide resolution of surface properties from dozens to hundreds of contiguous spectral bands, allowing direct identification of surface mineralogy by comparing pixel spectra and laboratory spectra. This brings the exciting possibility of not only discriminating the materials but actually identifying them and putting a label to the major mineral components present in every pixel of an image. The OH stretch and in-plane bend combination band that occurs near 2200 nm in clay minerals has even been described as observable in imaging spectrometer data (Alonzo *et al.* 2002), allowing their detection and analysis in large natural systems.

With such details readily available from remote sensing, more so for the clay minerals, a need exists to investigate possibilities of establishing diagnostic spectral parameters that would be used not only to recognize their presence and abundance in soils where they form the most important constituents (Bridges 1997) but also to determine associated physical/chemical properties such as the soil swelling potential. This could provide a rapid and less expensive method to map soil properties related to these minerals.

3. Materials and methods

The methodology involved the determination of two swelling potential indices used to classify soils into swelling potential classes and qualitatively assign them to a dominant clay mineral type (Nelson and Miller 1992). This was followed by spectral data acquisition on split samples of those used in obtaining the two indices and their interpretation on the basis of absorption feature mapping procedures (Mustard and Jessica 1999). Organic matter and high moisture contents, two other major soil constituents and known to have a masking effect on the absorption features, were also studied and the complete masking percentage established.

3.1. Data acquisition

3.1.1. Soil sampling site selection

Sampling sites in Antequera, southern Spain (see figure 1) and representing soils of varying swelling properties (from low to high) were selected carefully based on the CEC values, corrected for organic matter.

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

This was from an existing soil database of the area in the possession of the Soil Science Division of the International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, in the Netherlands.

In total, 22 sampling locations were identified from which three bulk and six clod samples (randomly sampled from within a five metre radius) were collected from the surface (0–20 cm) in the month of October 1998 under generally dry

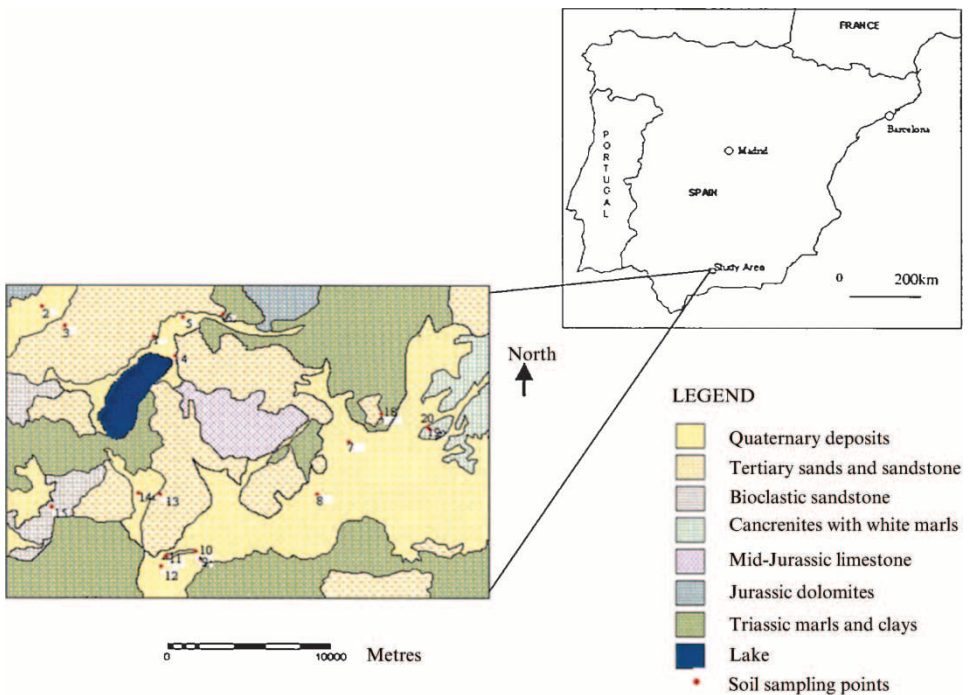


Figure 1. Geology map of study area showing soil sampling locations.

conditions. Proper location of the previously selected sampling sites was done using the Global Positioning System (GPS) in order to obtain samples as near to the existing data as possible.

3.2. Laboratory procedures

3.2.1. Swelling test procedures

Laboratory procedures involved the swell potential determination through the COLE clod procedure (see Brasher *et al.* 1966 for details) and the saturated soil pastes LE_{rod} tests (see Schafer and Singer 1976 for details).

In the LE_{rod} test, 100 g of the obtained soil samples were added into paper cups onto which distilled water was carefully added and stirred constantly to obtain pastes slightly drier than saturation. The cups were then sealed tightly to avoid any moisture loss and left to stabilize overnight. The pastes were then loaded on shrinkage moulds of semi-circular cross-section and 8 cm length and flattened evenly on the surface after which their lengths were precisely measured with a calliper and recorded as the length at saturation. The pastes were then oven dried at 105°C for 24 h and later cooled in a desiccator after which the lengths were measured and the LE_{rod} established

$$LE_{rod} = (L_m - L_d) / L_d \quad (2)$$

where L_m is length at saturation and L_d that at oven dry state.

In the COLE test, natural clods of between 10 and 25 cm³ (fist size) were used where one side 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 left to dry in air for 1 day. Upon drying, weights of the clods were determined in both air and water, and then were saturated with water for 14 days and weights again taken both in air and water prior to which they were quickly treated with a hairdryer 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 14 days, within which time the weight stabilized. On the 14th day, the weights of the clods were again taken both in air and water and recorded as the weight at 1/3 bar tension. The clods were then oven-dried at 105°C and the weights taken in air and water. The difference in weight between saturation at 1/3 bar tension and oven dry state were used to obtain the COLE:

$$COLE = (V_w / V_d)^{1/3} - 1 \quad (3)$$

where V_w is the volume at the 1/3 bar pressure and V_d is the volume at oven dry state.

3.3. Spectroscopy

3.3.1. Data acquisition

A total of 198 spectra were obtained by use of oven dried (at 105°C) split samples of those used in the swelling potential tests. The spectra were obtained in the SWIR range (1300–2500 nm) where a Portable Infrared Mineral Analyzer (PIMA II) spectrometer that had an internal 10 W stable lamp as the light source was used.

The instrument measures when in contact with the material, thus avoiding

interference from atmospheric water vapour and has a signal-to-noise ratio (SNR) of 3500:1–4500:1 and an automatic wavelength calibration that uses a built-in wavelength calibration target. Spectra are calibrated radiometrically during each spectral scan to give a spectral resolution of approximately 7 nm at a spectral sampling interval of 2 nm.

3.4. Data analysis

Data analysis consisted of engineering classification of qualifying the dominant mineral type based on the LE_{rod} :percentage clay, ratio (table 1) and classification into swell potential classes on the basis of the COLE as established by Parker *et al.* (1977).

Spectral data analysis was based on the absorption feature mapping as described by Mustard and Jessica (1999) where differences in the parameters of the absorption features, i.e. position, asymmetry, area and depth, were used and also on the manipulations of the spectra to obtain first and second derivatives.

In the absorption feature mapping, position is taken as the wavelength of the minimum reflection, asymmetry the ratio of area left to that right of the absorption feature minimum. Depth is the difference between the spectrum reflectance at the minimum from the reflectance of the hull at the same wavelength (Green and Graig 1985). Width is determined assuming the absorption feature follows a gaussian shape where the first wavelength to the left or right of the interpolated minimum wavelength at half the depth of the feature is found and the difference between it and the wavelength at the minimum is taken as the half-width of that feature.

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 three minerals were used in interpreting their presence. Asymmetry, an indicator of order in structure (P. Hauff 2000, unpublished), was used as a qualitative indicator and is based on Van der Meer's (1999) assignments. Depths and areas, which are theoretically dependent on the abundance of the absorbing material, were used as a source of information on quantitative abundance of the assigned minerals.

Manipulations of the obtained spectra to obtain the first and second derivatives were also made and assumed to separate overlapping features and background slope (Wessman 1994). Obtained peaks at 1800–1900 nm were interpreted to correspond to bound water in the clay lattice and thus a direct variation in smectite (Goetz *et al.* 2001). Those between 2100 nm and 2300 nm were taken to correspond to the Al-OH combination band and its accompanied variations resulting from substitution.

4. Results and discussion

4.1. Spectroscopy and mineral identification

4.1.1. Absorption feature position

The presence of absorption features at several wavelength positions were observed to be significant in differentiating among the soils on the basis of the presence of the three minerals and are given in table 2. Unique presence at 2160–2170 nm (figure 2) and 2340 nm were interpreted as diagnostic for dominant kaolinite and illite, respectively, and were mainly in samples of low COLE and LE_{rod} :%clay ratio.

Table 2. General groupings based on spectral parameters differences.

Wavelength	Swell potential		
	High (smectitic)	Moderate (illitic)	Low (kaolinitic)
1900 nm (shift)	< 1910	> 1910	> 1910
1900 nm (depth)	intense	broad and shallow	shallow
2160–2170 nm	largely absent	present/absent	present
2340–2350 nm	largely absent	present	present
Asymmetry (2200, 1400 nm)	< 1	varied	mostly > 1
2200 nm (depth)	generally broad	varied	largely intense

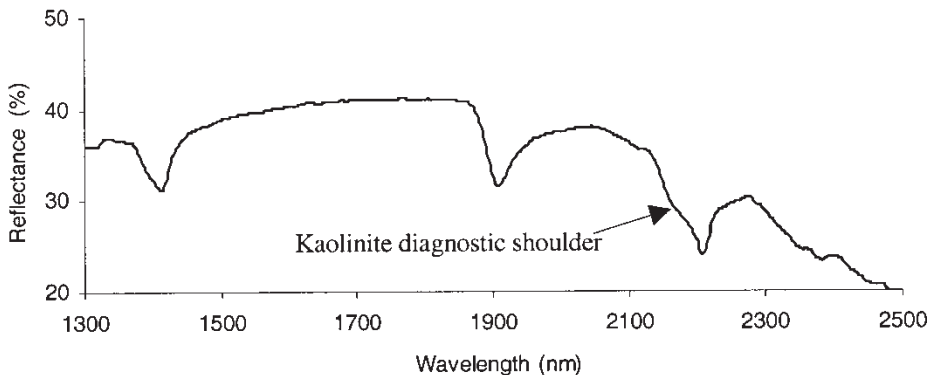


Figure 2. Kaolinite-dominated soil characteristic shoulder at 2170 nm.

The feature at 2160–2170 nm has been assigned to the high presence of Al-OH (P. Hauff 2000, unpublished) and is described as typical of kaolinite in clay mineralogy (Crowley and Vergo 1988). Its significant presence in samples assigned to low swell potential and kaolinite from the engineering indices was therefore interpreted to confirm its importance in assigning a soil to abundant kaolinite. Lack of widespread substitution of the aluminium (Al) by Mg^{2+} and Fe^{3+} in kaolinite may well be the reason behind the strength of the feature in kaolinitic soil due to the availability of Al-OH. Farmer (1974) assigned the feature to a combination ($\nu_{Al-OH-Al} + \delta_{Al-OH-Al}$) of OH-metal fundamentals consisting of stretching and bending modes, respectively.

The feature at 2340 nm has been assigned to illites and muscovite and its presence has been used as a diagnostic method to differentiate between the two and montmorillonite (Clark 1999). Its usually weak and thus its presence reflect a strong presence of illite. It was stronger in samples of low to moderate assignments from the engineering classification schemes therefore confirming its significance in such discrimination.

The precise position of the molecular water feature (1900 nm) gave characteristic differences among the soils probably due to differences in hydration and interlayer water among the soil samples (free pore water was assumed to be eliminated in the drying). It separated the samples into two groups, with one having the feature at between 1905 nm and 1910 nm and mainly consisting of those classified as high swelling and dominated by smectite in the engineering classifications. The other

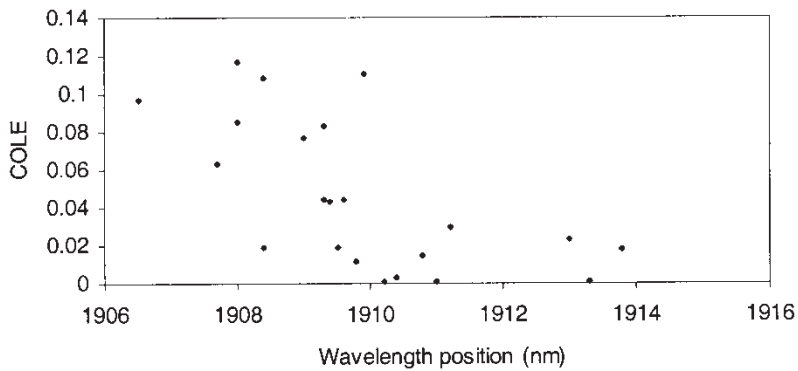


Figure 3. Relationship between the 1900 nm position and COLE.

group had the feature as generally broad and at 1915–1918 nm and consisted of illitic and kaolinitic samples. This was attributed to probable differences in the nature of adsorbed water in the two groups, with the samples with abundant kaolinite and illite having the water mainly on their surfaces and thus subject to lower electrostatic forces; whereas those with abundant smectite had the water in structured position and subject to stronger forces, thus requiring more energy to excite, this probably explaining the sharpness and shift to lower wavelengths for this group of samples. This could also be attributed to the generally higher surface charge in the presence of smectite due to substitution as opposed to the other two, resulting in a higher charge acting on the adsorbed water in smectitic samples. This characteristic is less common in the other minerals and could probably account for the broadness of the feature in the lower swelling group. The regression between the position shift and observed COLE ($r^2 = 0.41$) at the 95% confidence level (figure 3) further attests to these differences.

All samples possessed the 2200 nm Al-OH feature whose variation in position was minimal. The presence of this feature has been described to signify more than 20% clay content (Irons *et al.* 1989), a percentage high enough to have a substantial influence on the soil's physical-chemical properties. The feature at 1400 nm was also observed in all samples and no position shifts were evident to differentiate among the soils. No other feature position was observed to give significant differences.

4.1.2. Band asymmetry

Asymmetries at 1400 nm and 2200 nm (see table 2) were observed to separate the samples based on van der Meer's (1999) scheme, which when observed together with the swell indices gave an indication of differences on the basis of the clay minerals where those of low swell and classified to comprise of kaolinite from the engineering indices generally gave higher asymmetries at the two positions while those of the high swell group and classified as consisting of high smectites had generally low asymmetry values (figure 4). The samples interpreted to consist of high illite content were, however, observed to give no specific trend, with some at high and others at low values.

Based on van der Meer's (1999) conclusions and supported by the swell

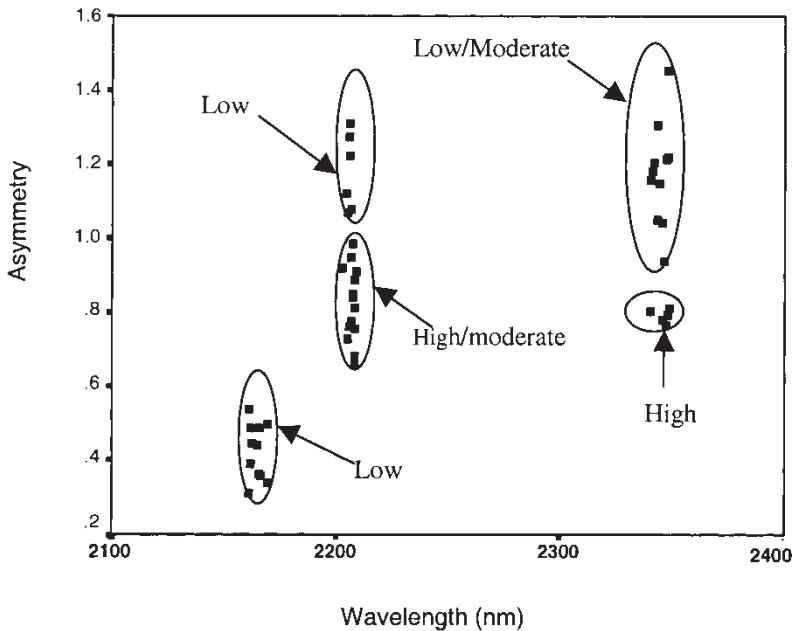


Figure 4. Clusters based on wavelength, asymmetry and swell potential values.

potential classes, it could be concluded that kaolinite was abundant in samples of higher asymmetries, probably due to its characteristic doublets at the two wavelength positions and the general strength of the features in its presence as described by Farmer (1974). Thus, presence of the Al-OH feature at 2170 nm combined with high asymmetry at these two positions is a good indicator of abundant kaolinite in a soil.

4.1.3. Absorption depths

Only two depths were found to vary significantly with the assigned mineral type. The feature at 1900 nm gave stronger intensities for samples assigned to smectites relative to the others whereas that at 2200 nm gave stronger depths in samples assigned to higher kaolinite. This was attributed to the strength of the 1900 nm in abundant smectite due to availability of structural water absent in the other minerals and thus probably low in soils where they are abundant. The differences in the 2200 nm feature can be attributed to the intensity being higher in less presence of substitution by Fe and Mg for Al in abundant kaolinite, a phenomenon more common in smectite and resulting in a general broadening and weakness of the feature. Alonso *et al.* (2002) described the broadening as due to AlFe^{3+} and AlMg^{2+} combination bands being less developed than that of Al^{3+} , whereas Goetz *et al.* (2001) described strength at 2150–2250 nm as more pronounced in low swell potential soils. It should be pointed out, however, that in the strong presence of both kaolinite and smectite the intensity of both the 2200 nm and the 1900 nm features increase substantially.

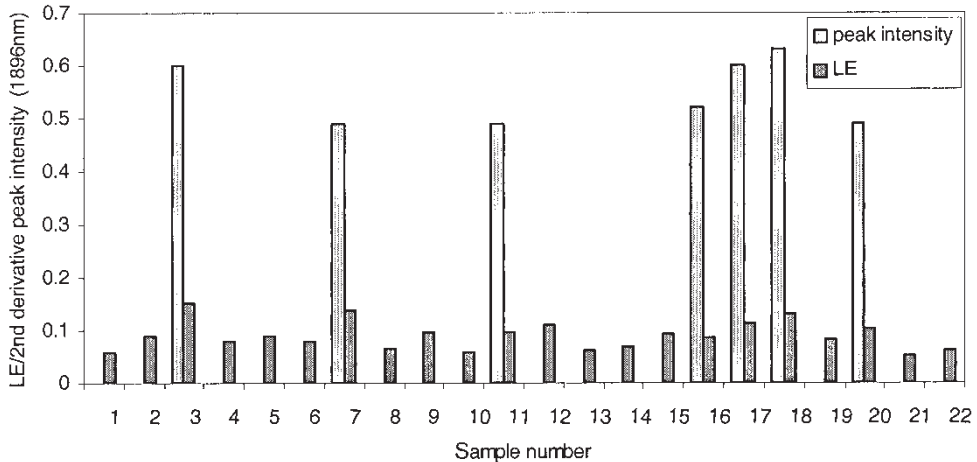


Figure 5. Second derivative water peak (around 1896–1900 nm) and LE_{rod} values among the samples (notice the lack of peaks <0.001 among low swell samples).

4.1.4. Derivatives

Derivatives have been described as best in removing the baseline effects (Duckworth 1998), with the first derivative measuring slope of the spectral curve at every point and the second derivative the change in slope of the curve. The two were observed to enhance only one peak interpreted as the water absorption peak well above the established level of noise and was found only in the high swell potential samples (see figure 5). This supports observations by Goetz *et al.* (2001) in which they established the second derivative of the region between 1800 nm and 2000 nm to give relevant information for the detection and quantification of smectite content corresponding to bound water in the clay lattice interlayer. The fact that the water absorption peaks were more pronounced in high swell potential samples assigned to smectite is significant, and confirms the applicability of this peak to estimate smectite abundance and thus the swell potential class of soils.

4.1.5. Influencing factors

Both organic matter and free water have a masking effect over the entire wavelength region, reducing the intensity of the absorption features. Illustrations of their effects on the intensity of the two quantitative indicators are given in figures 6 and 7. Figure 6 shows an example of this effect where organic matter was observed to result in an exponential decrease in depth intensity of the 2200 nm feature with the relationship giving an $r^2=0.71$. Removal of samples with higher than the 2% organic matter threshold (Baumgardner *et al.* 1985 and the references therein) resulted in varying improvement in the correlation between the depth intensity and the COLE/ LE_{rod} at the various feature positions, the highest of which was that at 2200 nm ($r^2=0.92$ from $r^2=0.69$).

Figure 7 shows the relationship obtained between the field moisture percentage and the difference in depth intensity between this and the oven dry state which clearly show a significant linear ($r^2=0.95$) relationship between increase in moisture and the decrease in depth intensity.

Using increasing moisture and organic carbon on pure minerals of smectites

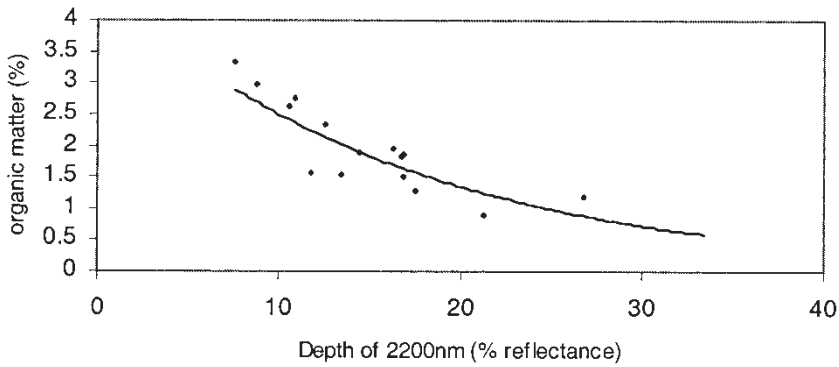


Figure 6. Decrease in depth with increasing organic matter.

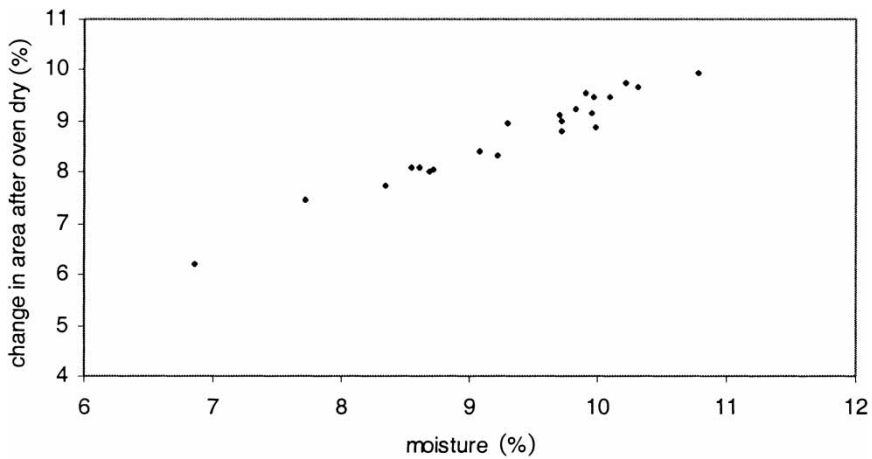


Figure 7. Relationship between % field moisture and differences in depth at 2200 nm between oven dry and field moisture.

and kaolinite and two of the soil samples rich in either of the two minerals helped further understand the influence of the two masking soil constituents.

Complete masking by carbon of the water feature (1900 nm) found in the foregoing discussion as important for both smectite estimation and swell potential class allocation was at 30% and that for the hydroxyl (2200 nm) feature at 15% in pure montmorillonite. Montmorillonitic soil had the water feature completely masked at 15% and the hydroxyl feature at 7% carbon. Complete masking was at 10% for the water feature in pure kaolinite and 25% for the hydroxyl feature, while in the kaolinitic soil the water feature was masked at between 4% and the hydroxyl at 15% carbon. The lower thresholds for complete masking in soils were attributed to the lower signal-to-noise ratio and also interference by other soil constituents.

The water-related features dominated and shifted in position to 1440 nm and 1945 nm at saturation, with a weaker band evident near 1800 nm for both the pure minerals and the representative soils and this was interpreted to be representative of the free water. Transition from this influence to that by adsorbed and hydration water was evidenced by narrowing and sharpening of the 1900 nm feature in

particular, accompanied by a shift in position to lower wavelengths found to be between 1914 nm and 1918 nm for kaolinite/kaolinitic samples and 1908 nm and 1910 nm for smectites/smectitic soil and was observed to be between 10% and 20% moisture. This further confirmed the previous observations of the wavelength position indication of the clay mineralogy differences and confirms observations by Clark (1981) that the change at the water OH absorption is less pronounced for kaolinite than montmorillonite. The 1400 nm feature increased in sharpness with decreasing moisture but position shift was not as dramatic though acquiring shoulders to the right and left of the absorption minima for smectite/smectitic soil and kaolinite/kaolinitic soil, respectively, between 10% and 15% moisture contents.

An interesting observation was that of the depth intensity with changing moisture contents. The kaolinite/kaolinitic soil sample had a linear increase in depths at 1900 nm with moisture to a threshold of about 25%, beyond which there was a sharp drop in depth to a relative constant. This was lacking in montmorillonite/montmorillonitic soil samples where no trend was observable, probably due to interference from structural water. The depth at 1400 nm increased linearly with moisture in all samples to a constant and with a much lower gradient for the smectite/smectitic samples.

Fifteen per cent moisture completely masked the unique and weaker kaolinite feature at 2170 nm, while that at 2200 nm was still evident even at saturation in both pure kaolinite and the kaolinitic soil sample. The 2200 nm feature was completely masked at above 30% and 15% moisture in smectite and smectitic soil, respectively. The feature position was, however, found not to shift with changing moisture, which probably confirms the observation by Ben Dor *et al.* (1999) that free water does not affect the qualitative aspect of the octahedral OH.

From the results it can be argued that the three forms of water, i.e. hydration, hygroscopic and free pore water in soils, and its constituent clay minerals have both the uniqueness (hydration and hygroscopic) and masking (free water) properties. Thresholds at which each of these soil waters influence the soil spectra have been described as different for different soils and to depend on the clay mineralogy (Weidong *et al.* 2002), a fact that is evident in the results. Thus shift to higher wavelengths probably above 1920 nm (the value higher than those of both kaolinitic and smectitic dried samples) at the molecular water feature could be used as an indicator of excess moisture, whereas lower wavelength positions and sharpness could be assigned to indicate more strongly held hydration and hygroscopic water that could yield information on the clay mineralogy and their related properties.

4.2. Classification

Table 3 gives the assignments to mineralogy both from the spectral and the engineering indices where the LE_{rod} , percentage clay ratio was used to assign the samples to a clay mineral type and COLE to a swelling potential class.

The spectral classification assignments are a combination of the indicators observed above to signify abundance of one or the other mineral type where kaolinite is assigned to soils with asymmetries greater than 1 at 1400 nm and 2200 nm, no bound water peaks in the first and second derivatives and with the 1900 nm wavelength position at between 1914 nm and 1918 nm. Soils classified as illite dominated are mainly those that had a strong diagnostic presence of the 2340 nm feature while those classified as smectitic were the ones observed to have

Table 3. Estimation of clay mineralogy from spectral indicators and swell potential indices.

Sample no.	Reflectance spectroscopy assignments	COLE swell potential class assignment	Linear extensibility/%clay mineral assignments
1	illite	low	kaolinite
2	illite/smectite	high	smectite
3	smectite	high	smectite
4	illite	low	kaolinite
5	kaolinite/illite	low	kaolinite
6	illite/kaolinite	low	kaolinite
7	smectite	high	smectite
8	illite	moderate	kaolinite
9	illite/kaolinite	moderate	illite
10	kaolinite	low	kaolinite
11	illite	low	illite
12	smectite/illite	high	smectite
13	kaolinite/illite	low	kaolinite
14	kaolinite	low	kaolinite
15	illite	low	illite
16	smectite	high	smectite
17	kaolinite/smectite	high	smectite
18	kaolinite/smectite	high	smectite
19	smectite/illite	moderate	illite
20	smectite	high	smectite
21	illite	low	kaolinite
22	kaolinite/illite	low	kaolinite

had strong water peaks in the derivatives, had 1900 nm position at between 1905 nm and 1910 nm and mainly lacked the 2170 nm and the 2340 nm features. They also had the 1900 nm feature as intense relative to the 2200 nm depth.

Where these characteristics were closely related to two of the minerals, it was taken to indicate significant presence of both, and is classified as so. This was attributed to the probable presence of mixed layer or intimate mix of the separate minerals, which have been described by Crowley and Vergo (1988) to give similar response.

The close agreement between classifications into clay mineral groups from the swell indices and the spectral parameters with assignments to combination of stretching and bending modes of the hydroxyl and molecular water OH was attributed to the prominent role the clay minerals play in determining both the spectral and engineering properties of soils.

Lack of spectral activity by most of the other major soil constituent minerals make the use of spectral data a powerful tool as a source of information on the dominant clay mineral type and associated physical/chemical properties in soils, provided both the organic matter and free moisture are low in content.

5. Conclusions

Reflectance spectroscopy is a relatively new tool in soil property analysis that has got a long way to go before becoming fully operational in engineering applications. Here it has been shown to give fairly good information on clay mineralogy based on well established threshold assignment to abundance of these minerals in two widely recognized engineering classification methods. The results

show a potential for the application of spectroscopy in the identification and quantification of these minerals in soils. The obtained representative spectral parameters can all be assigned to particular crystal characteristics of these minerals. There are, however, some problems to overcome, especially the presence of significant amounts of smectite and kaolinite together, and significant amounts of free water and organic matter which tend to mask the diagnostic characteristics in the spectra, especially those related to abundance. These are some of the problems that should be addressed in future research when the method is applied on remotely obtained data where the availability of high spectral resolution data is increasingly becoming a reality.

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