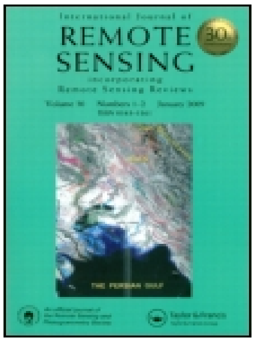

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Classification of soils based on engineering indices and spectral data

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Abstract. This study sought to establish diagnostic spectral characteristics in the short-wave infrared (SWIR) that could be used to classify soils in terms of their swelling potential. Three widely accepted soil-swelling indices, i.e. Atterberg limits, cation exchange capacity (CEC) and coefficient of linear extensibility (COLE), were used as controlling parameters to identify these spectral parameters. The results show that several spectral absorption feature parameters, namely position, depth and asymmetry, can be used in the classification on the basis of the discrete thresholds of these indices. The results show potential application of soil spectral characteristics in the construction industry and add a physical basis to the identification of clay mineral types dominant in engineering soils from currently used indices.

1. Introduction

Soil swelling is a major engineering problem and ranks high among the natural hazards. It is the process where the soil changes in volume with changing moisture conditions and has been attributed to be mainly due to the presence of clay minerals, which are susceptible to penetration of their chemical structure by water molecules (Carter and Bentley 1991). Several other factors, i.e. the soil water chemistry, amount of non-clay material and initial moisture content, among others, also play some role in the resulting volume changes, though not to the same degree as that of the clay mineralogy.

The level of water penetration among the clay minerals varies with their crystal structures, a characteristic that allows grouping them into a few groups, which has been found convenient since members of the same group generally have similar engineering properties (Mitchell 1993). Three structural groups are described for engineering purposes, i.e. kaolinite, illite and smectite, whose presence in substantial amount results in low, moderate and high volume changes respectively.

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Most swelling potential estimation methods have therefore aimed at recognizing the clay minerals and associated soil properties, examples of which are those used in this study [i.e. the Atterberg limits, the cation exchange capacity (CEC) and the coefficient of linear extensibility (COLE) tests]. The Atterberg limits measure the range at which a soil remains plastic with increasing moisture and is based on plasticity being unique to soils with clay mineral particles (Head 1992). Plastic index (PI), the difference between the liquid limit and the plastic limit, is the parameter of interest and the ratio between the PI and the percentage clay fraction has been found to be more or less constant for each clay type. The CEC on the other hand is a measure of the quantity of exchangeable cations required to balance the negative charge on the surface of clay particles and is therefore an indicator of clay mineral type (Nelson and Miller 1992). COLE measures the change in length of an unconfined clod with changing moisture content and has in the past been used to estimate clay mineral types (Nelson and Miller 1992).

The above discussion shows the importance of identifying the type of clay mineral in swelling potential estimation. It is therefore prudent to assume that a method that can directly ascertain the type of clay mineral could go a long way to increase the ability to classify soil swelling potential. Reflectance spectroscopy offers such a possibility.

Reflectance spectroscopy offers a new science that can be used to derive significant information about mineralogy with little or no sample preparation and is based on the principle of absorption feature mapping, which is physically based and exploits the fact that many minerals exhibit absorption bands that are diagnostic of mineral type and composition (Mustard and Jessica 1999). The key features used in this mapping are the position, shape and relative strength (depth) of the absorptions, which are characterized and then compared and analysed in the context of spectral libraries. This makes its application here all the more important since it has been established as an excellent tool for clay mineralogy (Clark 1999) based on their diagnostic fingerprints in the short-wave infrared (SWIR). It offers a more fundamental method on the basis of its capacity to identify the clay mineral type and content and thus has the potential to increase the accuracy of the swelling potential classification schemes.

In this Letter we report on the findings using PI, CEC and COLE, together with the absorption feature mapping to establish spectral parameters that could be used to characterize soils in terms of clay mineralogy and swelling potential. The result is a unified swelling potential classification based on the clustering of the engineering indices and the spectral parameters.

2. Materials and methods

The methodology sought to establish spectral parameters that could be used in classification of soil swelling potential. The well-established combined classification schemes of Pearring (1963), Holt (1969) and Hamberg (1985), using the engineering index properties of COLE, PI, and CEC, were used to help identify these parameters.

Soil samples collected from areas with known varying degrees of swelling potential were used in the study and were subjected to the preparations as required for each of the engineering indices used (see quoted references for details on each index).

The PI was obtained through the procedures described by Head (1992) and CEC through the mechanical extractor method described by Reeuwijk (1995).

COLE was obtained through the procedures as in Nelson and Miller (1992) and clay content was obtained through the pipette method as given in Reeuwijk (1995).

PI and CEC were converted to activity (A_c) and cation exchange activity (CEA_c) respectively by division with the clay percentage (see Nelson and Miller 1992 for details), to enable the engineering classifications.

2.1. *Spectral data acquisition*

Spectra of split samples of those used for the engineering tests (passing the <2 mm sieve and oven dried at 105° C) were obtained using the Portable Infrared Mineral Analyser (PIMA) upgrade spectrometer which has an instantaneous field of view (IFOV) of approximately 2 mm by 10 mm and an average spectral resolution of 7–10 nm covering the spectral range between 1300–2500 nm.

Absorption feature mapping as described by Mustard and Jessica (1999) was used for the interpretations where differences in the parameters of the absorption features, i.e. position, asymmetry, area and depth, were used to group the samples into classes based on their differences.

2.2. *Classification*

The soils were classified into the classes as given in the work of Pearring (1963), Holt (1969), Hamberg (1985) and Nelson and Miller (1992), whose classification charts are made on the basis of the resulting CEA_c, A_c COLE and deduced mineralogy. This was followed by a classification based on these indices and the spectral parameters where the *K*-means cluster algorithm (SPSS 1999) was used. The cluster method is based on identifying relatively homogeneous groups of cases.

3. Results

3.1. *Spectral analysis*

Characteristic differences were observed among the soil samples on the basis of their absorption feature parameters. Figure 1 illustrates some of these differences that are visually recognizable such as depths at the 1900 nm and the characteristic kaolinite diagnostic doublet at the 1400 nm and 2200 nm. However, other less visually evident differences were observed and included, among others, the precise position of the water absorption feature (1900 nm) that was found to be mostly between 1914–1918 nm for samples with the kaolinite diagnostics and near or at 1909 nm in samples with the feature intense in depth and sharpness associated with the presence of structured water, in abundant smectite.

Asymmetry at both the 1400 nm and the 2200 nm features was the other parameter observed to give an indication of the soil differences, with the kaolinitic type giving larger values (mostly greater than one) with sharp and well-defined minima at the longer wavelengths of the doublets. Kruse *et al.* (1991) established asymmetry at 2200 nm to be useful in predicting the relative amounts of kaolinite in kaolinite/smectite clay mixtures.

The order in which the depths at 1400 nm, 1900 nm and 2200 nm increased was also found to be important and was 2200 nm > 1400 nm > 1900 nm in kaolinitic samples and the reverse for smectitic samples as seen in figure 1.

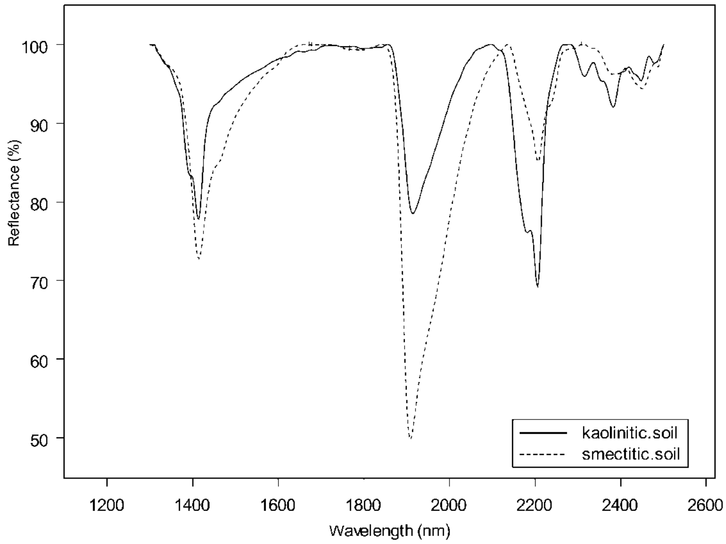

Figure 1. Spectra of soil samples rich in smectite and kaolinite showing characteristic differences used in the interpretation.

3.2. *Classification*

The resulting classes on the basis of the engineering indices and their deduced mineralogy are as shown in figures 2 and 3 where the soils can be seen to represent the various swelling potential levels on the basis of these schemes. Figures 4 and 5 illustrate the introduction of the spectral parameters to the engineering classifications, where asymmetry at 1400 nm is used. They give an indication of the potential in using the spectral diagnostic parameters in a complementary role to the swelling potential classifications by adding value to these indices on the basis of their capacity to identify the clay mineralogy.

The results of the cluster analysis, where all the absorption feature parameters

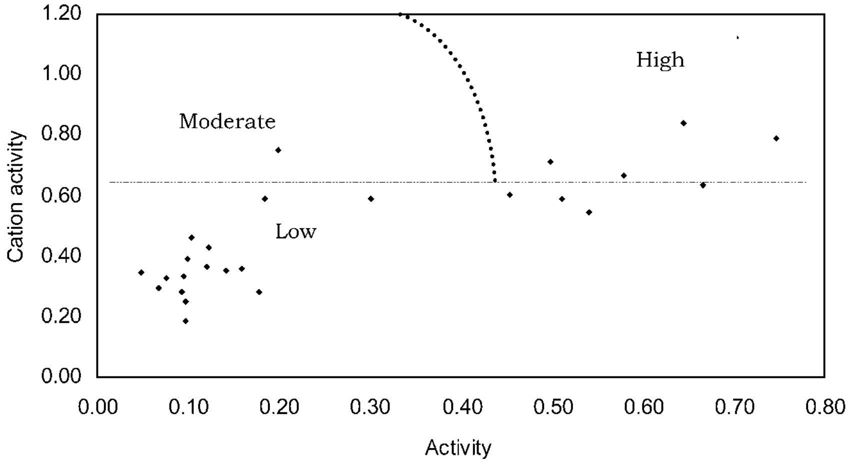

Figure 2. Modified (Nelson and Miller 1992) swelling potential classification.

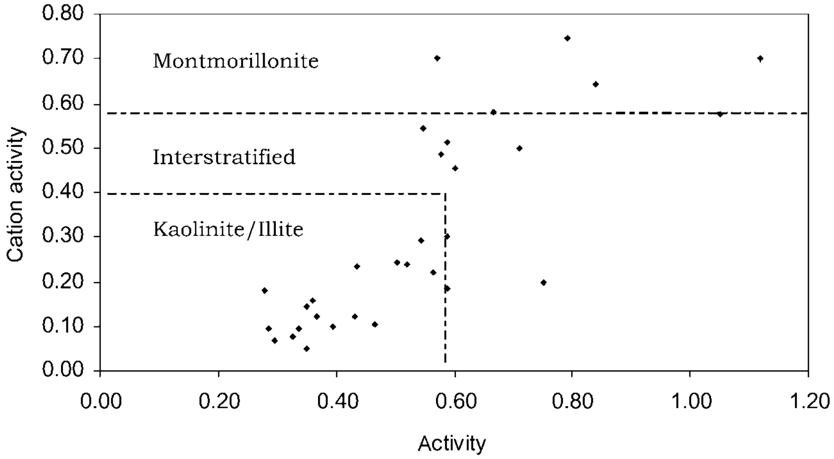

Figure 3. Modified mineralogical estimation chart based on Pearring (1963) and Holt (1969).

observed to give characteristic differences in the absorption feature mapping were used, is given in table 1 and gives an indication as to the differences among the samples in terms of clay mineralogy and swelling potential levels. The results show that samples of high swell potential grouped in the first cluster whereas those of moderate and low potential grouped in the second and third clusters respectively. However, although there is a clear separation between low and high swelling potential samples from both the engineering and spectral characteristics, this cannot be said to be the case for the moderate swelling group. This is evident from the distance between the cluster centres (table 2), which shows a large separation between class 1 and 3 the extreme end-members but less so for the medium class.

Figure 6 gives an indication of the clustering among the samples within the three groups where parameters from both the engineering and spectral data are used to give a visual impression of the applicability of this method.

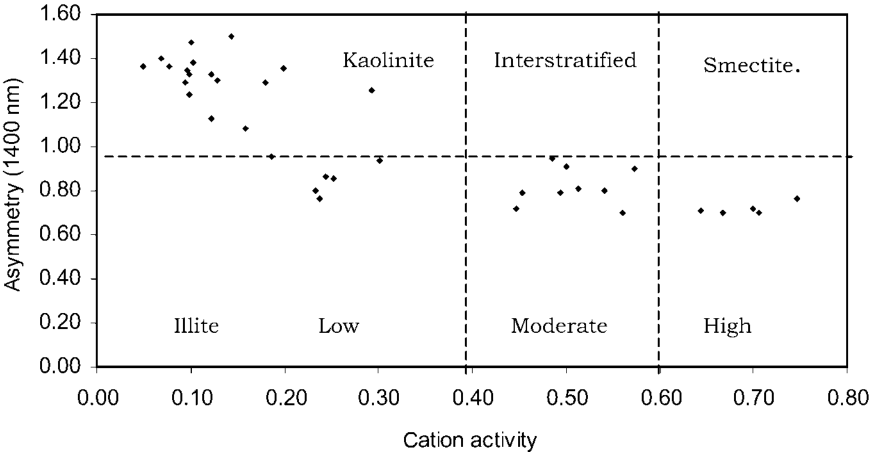

Figure 4. Estimated mineralogy and swell potential based on CEA_c and 1400 nm asymmetry.

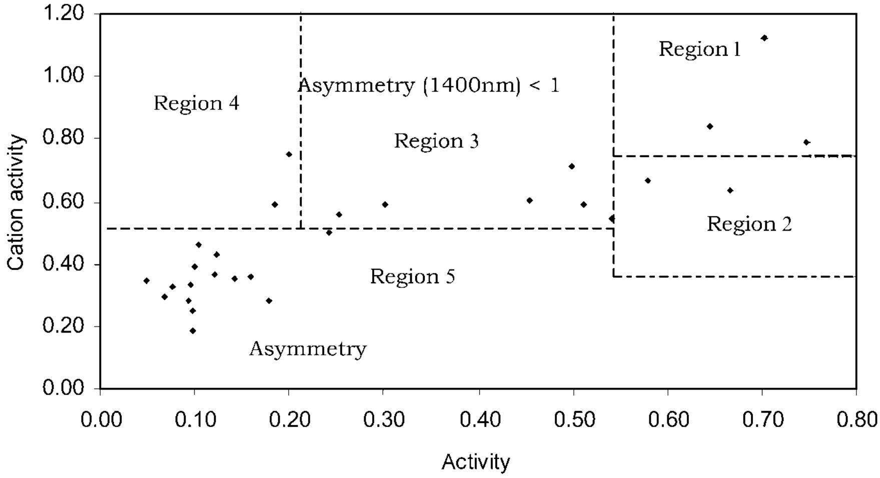

Figure 5. Classification based on modified Hamberg (1985) COLE value chart and asymmetry (1400 nm).

4. Discussion

The results show that clay mineralogy has great influence on the resulting spectral parameters of soils. The intense depths and sharpness of the 1900 nm water feature in smectitic soils can be attributed to the influence of large surface areas resulting from smectite's small size and susceptibility to isomorphous substitution, thus possession of a substantial amount of structured adsorbed water relative to those rich in especially kaolinite due to kaolinite's larger particle size and lack of substitution. Kaolinitic soils on the other hand possessed larger amount of hydroxyl (OH), based on kaolinite's 1 : 1 (silica : aluminium) structure, which probably made

Table 1. Final cluster centres.

	Cluster centres		
Parameter	1	2	3
COLE	0.128	0.072	0.014
Plasticity index (PI)	34	23	17
Cation exchange capacity (CEC)	26.95	14.85	6.56
Asymmetry (1400 nm)	0.7662	0.9490	1.3440
Feature position (1900 nm)	1909.2	1910.8	1914.4
Depth of feature (1900 nm)	0.0963	0.0730	0.0441
Asymmetry (2200 nm)	1.0731	1.1672	1.4573
Depth (2384 nm)		0.0091	0.0115

Table 2. Distances between final cluster centres.

Cluster	1	2	3
1		11.203	27.306
2	11.203		16.305
3	27.306	16.305	

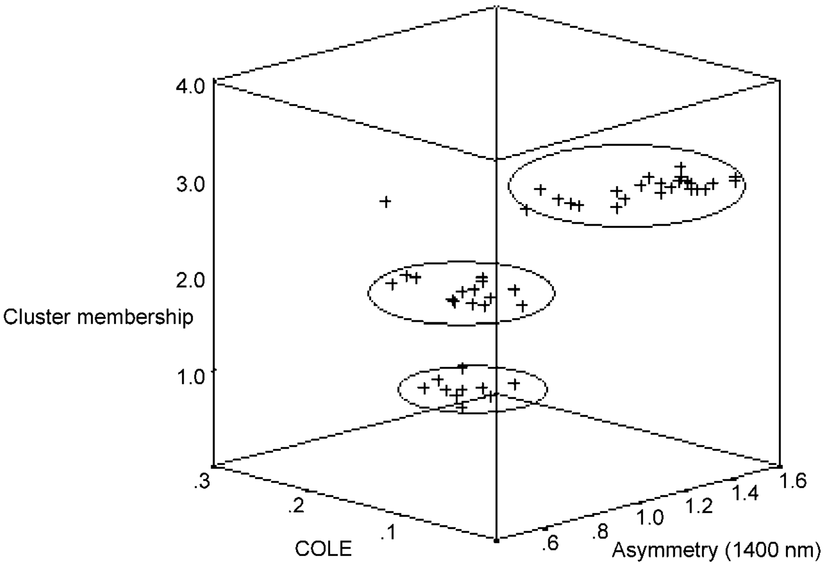

Figure 6. Cluster memberships based on engineering indices and spectral parameters.

them have enhanced 1400 nm and the 2200 nm bands resulting in their observed higher asymmetries. These factors could also probably explain the order of increase in depths of the three features as observed in the results. The presence of the subtle 2384 nm in kaolinitic samples goes further to emphasize the potential of reflectance spectroscopy in discriminating among soils on the basis of their clay mineralogy.

These interpretations are given more weight by the observed relationship between these diagnostic spectral parameters and the three engineering indices. 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 and reflect the covariance between the soil physical/chemical properties and their spectral response.

The results are promising and give an indication of the potential role that reflectance spectroscopy could play as a primary or complementary tool in the determination of soil swelling potential.

5. Conclusions

The results show that absorption feature parameters consist of information which, with proper calibration, can be used to differentiate soils on the basis of their engineering properties. The covariance between the soil properties without a primary response in the soil spectra (such as the engineering indices used) with those possessing such a response (i.e. the clay mineralogy) makes it possible to use the spectral diagnostics of the primary response factors to obtain information on such properties. They show that reflectance spectroscopy is a powerful tool that adds value to the existing swelling potential classification schemes, in that it adds a physical basis on the swelling potential causative factors through the identification of the clay mineral types. The results lay the foundation for establishing a faster method of characterizing soil in terms of susceptibility to swelling, and with the building of a large database with varieties of representative soils could result in the establishment of a method to determine the swelling potential *in situ*.

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