DETERMINATION OF SOIL ACTIVITY IN KENYAN SOILS FROM SPECTROSCOPY

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ABSTRACT:

Soil activity is a term generally applied to the ability of a soil to take in and dispose water under changing moisture conditions. It is due to presence of clay minerals with a net negative charge to neutralise which, water is attracted to the mineral surface. The water molecules are incorporated in the clay structure in between the clay plates and with increased water; both the exchangeable cations and the clay surfaces are hydrated resulting in further separation of the clay plates and swelling of the soils. This has come to be referred to as soil activity. Swelling soils are a major engineering problem and have been estimated to rank first of all the natural hazards in terms of damage to structures, and more so light buildings and pavements making their detection to be one of the most important site investigations in the construction industry. Methods of determining the soil activity have been developed over the years most of which utilise the soil physical properties as indices. Among these are Atterberg limits and cation exchange capacity (CEC) tests. These methods are time consuming and at times expensive. While this might not be a big problem in the industrialised world it is a great challenge in the developing world and at times lead to construction without proper site investigations more so if such construction is of light structures. In this paper we report on the findings of an approach in which spectroscopy was used to address the soil activity in a set of samples collected from areas of known soil activity in Kenya. The Methylene blue absorption (MBA) and the Atterberg limits were used to determine the soil activity, results of which were correlated with identifying parameters from laboratory spectral analysis. The outcomes are relationships between the soil activity and their spectral indicators and lay the foundation for a rapid method of estimating soil activity based on their optical properties.

1. INTRODUCTION

One setback in classification of expansive soils has been the lack of a standard definition of swell potential (Nelson and MIller, 1992). Not only do sample conditions vary in the different swell tests used, but also testing factors over a wide range of values. In all cases however, the term swelling potential refers to the relative capacity for the soil to change in volume with added moisture.

Several underlying factors affect the swelling potential, and include; clay mineral composition, amount of non-clay material and moisture. Clay mineralogy plays the most significant role by determining both the surface area and charge density to neutralize which, water molecules attach on the clay surface. This governs the engineering and optical properties of the soil. In terms of optical, it determines the strength of the water absorption features in the soil spectrum and has been found to have an overall effect on the whole soil spectra (Ben-Dor *et al.*, 1999). Quantification of this water is therefore a semi-quantitative estimate of the soil activity.

The term chromophore has been used to describe parameters and substances (chemical or physical) that significantly affect the shape and nature of a soil spectrum (Ben-Dor et al., 1999). Discrete absorption bands, caused by chemical activity allow unique identification of many of the soil chromophores, among which are the adsorbed water and thus the clay minerals dominant in a soil. However due to complexity of the chromophores, assessment of reflectance properties by physical theories or models is very difficult (Liang and Townshed, 1996), though such models have been proposed by among others Hapke (1986) and Jacquemoud et al. (1992). Empirical quantitative approach has been found to be a better alternative to derive this information from soil spectra.

Such methods are based on the simple idea that photons obey Beer's law for a given path length within the surface studied and are dependent on absorption coefficients and the concentrations of the material. Under ideal conditions estimations on the concentration of the material can be estimated. Thus under such conditions the empirical relationship between the chemical/physical properties and reflectance can provide quantitative information on these soil properties.

Here we report on the relationships between classifications based on the soil activity as the chromophore and its optical spectral indicators by use of the Near Infrared reflectance analysis (NIRA).

NIRA has been used as a quantitative laboratory approach by among others Ben-Dor et al. (1997) and is widely accepted in many disciplines (Norris, 1988). The method assumes that a concentration of a given constituent is proportional to the linear combination of several absorption features.

The method has a strong spectroscopy foundation though no physical or chemical assumptions are made (Ben-Dor et al., 1999).

2. MATERIALS AND METHODS

Synthetic mixtures of kaolinite and smectites to represent varying surface activity were used to obtain a relative guide to those of the soil samples. The minerals were mixed quantitatively between 0-100% and spectra obtained for each mixture. Their results were used to analyze those of a total of 47 soil samples with varying degree of activity and obtained from

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areas in central Kenya dominated by kaolinite and montmorillonite.

To obtain the engineering indices, the methods described by Nelson and Miller (1992) were adopted where the obtained plastic index (PI) and cation exchange capacity (CEC) were converted to activity and cation activity respectively by division with the clay content of each sample.

Spectra of split samples, of those used in the engineering tests at oven-dried state, were measured using the Portable Infrared Mineral Analyser (PIMA) upgrade spectrometer. The spectrometer has an instantaneous field-of-view (IFOV) of approximately 2 by 10mm, an average spectral resolution of 7-10nm and a sampling interval of 2nm. It covers the spectral range between 1.3 and 2.5µm.

To obtain the representative spectral indices the NIRA approach was adopted where calibration and validation phases were used. The calibration was used to obtain the most representative multivariate linear regression models to predict the soil activity through manipulation of the spectral data. The validation phase involved use of a separate set of samples that had not been used in the calibration stage so as to test the validity of the obtained models. Calibration and standard error of prediction were used to gauge the validity of the estimates by obtaining the standard error of calibration according to Davies and Grant (1987) method, i.e.

$$SEC = \sqrt{\frac{\sum (C_m - C_p)^2}{N_{c-n}-1}} \qquad (1)$$

where:

C_m = value measured by the engineering tests,
C_p = predicted value on the basis of the spectral analysis,
N_c = number of samples in the set and
n = the number of terms in the prediction equation.

Validation was by use of samples not in the calibration stage but from the same origins. The standard error of performance (SEP) was obtained from these samples.

$$SEP = \frac{\sqrt{\sum (Cm - Cp)^2}}{N_v - 1} \qquad (2)$$

where:

N_v = the total number of tested samples at this stage.

Two independent empirical models were developed. The obtained models were then characterized on the basis of changing clay mineralogy composition as established in the synthetic models. The physical understanding of the spectral features established as representative was then sought.

In utilising these observations other parameters known to have effect on the soil spectra such as the grain size and moisture content were kept uniform.

3. RESULTS

3.1 Spectral Indicators

Figure 1 shows the changing spectral characteristics with changing percentages of montmorillonite and kaolinite. The increasing inter-lattice water is seen in the 1900nm feature and indicates weakening of interlayer bonds as a function of disorder and the development of interlayer spaces that accommodate water as montmorillonite increases. The kaolinite doublet in both the 1400nm and 2200nm region softens and broadens from sharp, well-defined minima to a shoulder as the ratio of octahedral structure to that of tetrahedral structure decreases. This is reflected by the changing asymmetry values at both positions. The depths at the two positions also decrease whereas that at the 1900nm increases with increasing montmorillonite. Presence of the two minerals in soils influences these parameters in the same manner (Figure 2).

3.2 Soil Activity

Asymmetry (1400nnm and 2200nm) and position (1900nm) gave negative weights (Table 1) in the obtained activity model. This was attributed to the changing ratios described in the synthetic mixture results. Decrease in kaolinite and increase in montmorillonite as represented by activity values resulted in disorder at the two wavelength positions due to increased substitution as montmorillonite increased and thus a decrease in asymmetry as the soil activity increased. The position of the 1900nm on the other hand shifted to lower wavelengths as activity increased due to order in the adsorbed water.

The depth at 1900nm however showed a positive weight, which can be attributed to increased surface area available for wetting with increasing amount of montmorillonite thus resulting in higher amounts of adsorbed water and strength of the water feature.

3.3 Cation Activity

Model	Weighted coefficients	Partial correlation
Constant	31.8	
Asymmetry (1400)	-0.323	-0.77
Position (1900)	-0.016	-0.73
Depth (1900)	0.017	0.59
Asymmetry (2200)	-0.092	-0.753

Table 1. Model to predict soil activity

Cation activity reflects hydration of both the surface of clay particles and the exchangeable cations. Table 2 shows the obtained model coefficients, with the spectral features being the same as those of activity. This confirms the two as representing the same chromophore.

As can be observed from Table 3 the models make good prediction since both the calibration and prediction errors are relatively low thus emphasising the basis for the selected parameters to represent the process of soil activity. The error of prediction for the cation activity is higher than that of activity and could be attributed to the fact that whereas activity is entirely dependent on the available clay surface, cation activity is dependent on the hydration of both the cations and the negatively charged clay surface.
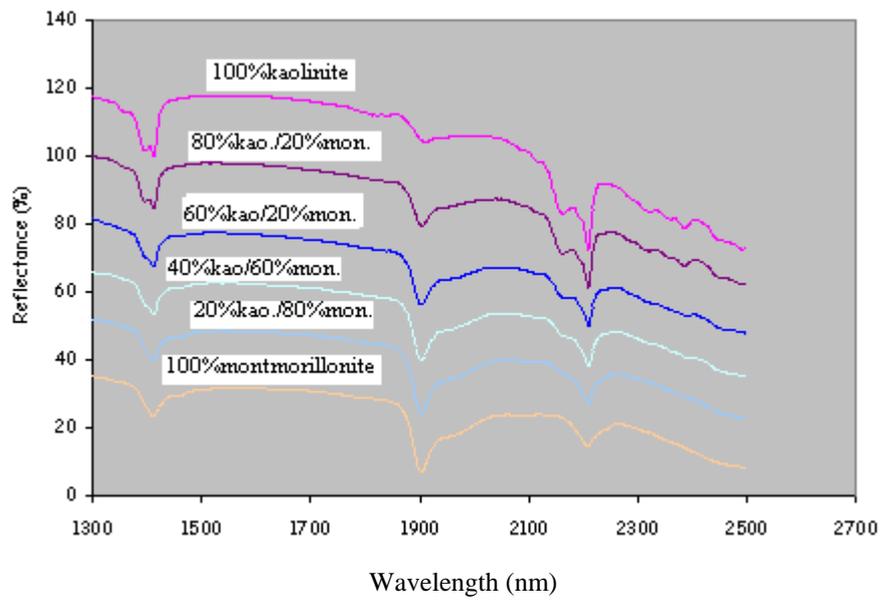
Wavelength (nm)

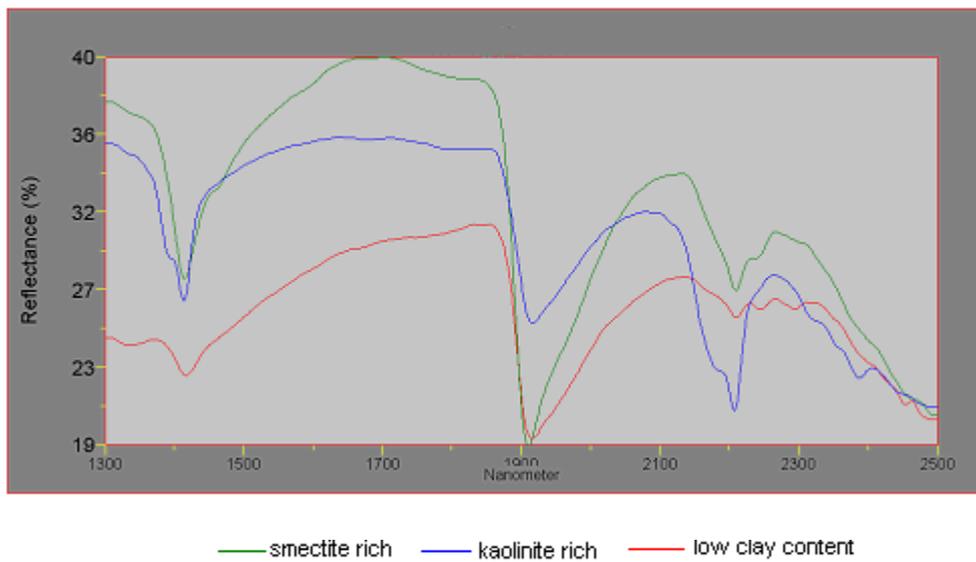Figure 1. Changing parameters with changes in kaolinite/montmorillonite

Figure 2. Spectra of some of the soil samples showing characteristic differences used in the interpretation

Model	Coefficients	Correlations
Constant	47	
Asymmetry (1400)	-0.12	-0.73
Position (1900)	-0.024	-0.66
Depth (1900)	0.16	0.72
Asymmetry (2200)	-0.21	-0.76

Table 2. Model to predict soil activity

Property	Nc	Nv	SEC	SEP
Activity	30	17	0.57	2.66
Cation activity	30	17	0.59	13.4

Table 3. Calibration and prediction errors

4. DISCUSSION

The soil activity is greatly influenced by the clay component whose behaviour is dependent on its surface charge. This charge is reflected in the amount of adsorbed inter-lattice water and thus affects order in the crystal structure of the soil and has an overall influence on the soil spectrum.

Soil activity can therefore be determined from a few key absorption feature parameters. The ordering in the structure is well represented by the strong negative relationship between activity and asymmetry at 2200nm and 1400nm, and in the absence of hygroscopic water, by the sharpness of the feature at 1900nm. Importance of these parameters in its determination from spectra is further emphasized by the synthetic mixture results.

These observations agree with those of Kruse et al. (1991) who established asymmetry at 2200nm as enough to predict the relative amount of kaolinite in a soil consisting of kaolinite and smectites. They also confirm those of Hauff (2000) of finding absorption depth at 1900nm as a good semi-quantitative estimator of smectite content as reflected by its relationships with activity and the percentages of montmorillonite and kaolinite in the synthetic mixtures.

The results also show that, at low water quantities, the water is tightly held by clay giving it a form different from free water as seen in the negative relationship between the 1900nm-feature position and activity. The feature sharpness and lower wavelength position in the presence of higher amounts of montmorillonite reflects order in structure due to greater influence of the electrostatic forces. This agrees with the observations of Graham et al. (1964) whose Nuclear magnetic resonance (NMR) data results showed distinct phases of crystalline hydrates and order in structure at low water contents.

5. CONCLUSIONS

The models show that although the soil is a complex material and in that case soil spectra, a remarkable amount of information whose physical basis is well understood is hidden in the reflected and absorbed photons and under controlled conditions, can be retrieved.

From the models it is established that the water representative absorption features are central to estimation of soil activity. Whether in the lattice form as is the case with 2200nm and 1400nm or in adsorbed, as is the case with 1400nm and 1900nm the features are central to its determination. The models though not conclusive establish an easier method of quantifying soil activity and with added information could lead to very conclusive quantification.

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