

Issues of effectiveness in empirical methods for describing swelling soils

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Abstract

Swelling soils are a major engineering problem and the establishment of new and fast methods for their identification continues to be a major subject of research. Several engineering methods were here used to obtain indices used in the estimation of swelling potential in a group of soil samples with a wide variation in swelling and to classify them into swelling potential classes. The indices were then reduced through factor analysis to obtain a new swell index that was used to obtain the spectral parameters to best correlate with the index where absorption feature mapping, optical density, and derivative spectral data analysis methods were used to establish these parameters. The spectral parameters found to have high correlations with the swell index were then used to establish statistical empirical models to quantify soil swelling from spectral data. The physical understanding of these spectral parameters was also sought and the results show a close relationship between the clay mineralogy related bound water and hydroxyl spectral features in the soil spectra and the swelling index. The bound water parameters gave positive and the hydroxyl related parameters negative correlations to this index. The results confirm the strong influence of the clay mineralogy on the soil properties.

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1. Introduction

Expansive soils are a major engineering problem and their identification and mapping is an important undertaking in the building industry (Nelson and Miller, 1992). The potential volume change (PVC)

is dependent on several physical and chemical properties, among them are clay content, clay mineral type and environmental factors such as the moisture conditions of a site.

Clay mineralogy plays the most important role in controlling these properties where their size and type determine the state of packing, the manner in which the soil particles adhere to one another, and the extent to which the voids or spaces between them are filled with water. The individual clay mineral types exhibit different swelling potentials due to variations in their structures and interlayer bonding (Mitchell, 1993) and

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thus capacity to accommodate water molecules. Smectites and vermiculites undergo more volume changes on wetting and drying relative to kaolinites and illites.

Presence of these minerals even in small amounts influence the overall properties of the entire soil mass (Head, 1992) where presence of smectites leads to soils undergoing high volume changes whereas illites and kaolinite give the soils moderate and low swelling potential, respectively. Recognizing their presence is therefore important in classifying potentially expansive soils (Mitchell, 1993).

Due to problems in performance of structures founded on expansive soils, engineers have made numerous attempts to develop reliable methods for determining the swelling properties of soils where the most successful are based on the determination of factors directly related to the clay mineral composition. Among these are plasticity index (PI), cation exchange capacity (CEC), colloid content and X-ray diffraction (XRD) analysis.

Indices obtained from these methods have been used to establish thresholds within which soils are characterised as dominated by either of these clay minerals. Such include the USA National Soil Survey Laboratory (1981, unpublished) use of linear extensibility (LE) and clay content ratios, Pearring (1963) use of CEC and plasticity and Hamberg (1985) extension of the works of Pearring to include coefficient of linear extensibility (COLE) in establishing classification charts. These charts offer parameters, which could be used to establish the potential application of other methods in the identification and mapping of swelling soils where the clay mineralogy is potentially identifiable. Reflectance spectroscopy is one such method where the clay minerals give diagnostic absorption features in the reflected electromagnetic spectrum.

These features are in the short-wave infrared (SWIR) region (1.3–2.5 μm) of the reflected spectrum, resulting from the vibrational processes of their water and hydroxyl molecules. The precise wavelength position of these features varies among the minerals, depending on the details of the composition, structure, and associated atomic bonding characteristics (Hauff, 2000). Hunt and Salisbury (1970) observed very strong molecular water bands at 1400 and 1900 nm to be due to bound water typical of montmorillonite and strong hydroxyl bands at 1400 and 2200 nm as typical

of kaolinite. Mathews et al. (1973) observed illite to show low absorption for both the water and hydroxyl bands relative to kaolinite and montmorillonite.

Extension of their study in soils include such as that of Mulders (1987) in which he described soils to exhibit reflectance greatly derived from their spectral behaviour, though affected by other constituents such as organic matter and one by Goetz et al. (2001) where they observed second derivatives of the reflectance spectra as good in the estimation of smectites in soils. De Jong (1994) on the other hand used reflectance spectroscopy to draw conclusions that clay is an important parameter in the description of soil properties. In the recent past, spectroscopy has been used in the estimation of soil properties related to the presence of these minerals among them cation exchange capacity (Chang et al., 2001; Kariuki et al., 2003), and particle size distribution (Zhang et al., 1992). Chabrilat et al. (2002) have gone further and applied airborne imaging spectroscopy for the identification of these minerals while Ben-Dor et al. (2002) have used such data to estimate related soil properties of saturated moisture, field moisture capacity and electrical conductivity (EC).

With such applications becoming possible more so the remote based, a need exists to investigate possibilities of establishing diagnostic spectral parameters that would be used not only to recognize these clay minerals in soils, where they form the most important constituents (Bridges, 1997) but also enable determine related physical/chemical properties such as the swelling potential.

Here, we report on the findings in which several widely used and accepted swelling indices were used to obtain a swelling potential index (ESI) that was then used together with spectral parameters to establish empirical models to quantitatively estimate soil swelling based on the spectral information.

2. Materials and methods

2.1. Soil sampling

Stratified random sampling was used based on existing soil and property maps in the selection of sampling locations where soil samples representing the whole spectrum of high to low swelling types and known to

consist of varying abundance of these minerals, were obtained.

2.2. Spectral data acquisition procedures

The samples were oven dried at 105 °C and cooled in a desiccator prior to the spectral data acquisition to eliminate hygroscopic moisture upon which they were then emplaced on crucibles and their surfaces gently flattened ready for the spectral measurements. A portable infrared mineral analyzer (PIMA) upgrade spectrometer was then used to obtain spectra on each of the soil samples where the acquisition port was placed in contact with the sample to avoid atmospheric interference.

The spectrometer covers the spectral range between 1300 and 2500 nm with a 2 nm-sampling interval and 7–10 nm spectral resolutions and measures hemispherical reflectance in 601 continuous spectral channels.

Analysis of the spectra was by the use of several techniques, i.e. absorption feature mapping (Mustard and Sunshine, 1999), band depth normalized with centre (BNC) (Curran, 2001), optical density ($\log 1/R$) (Chang et al., 2001) and the first- and second-derivative analysis (Duckworth, 1998).

The absorption mapping technique is a physically-based method that exploits the characteristic of materials to exhibit absorption bands that are diagnostic of type and composition. It consists of the characterisation of the absorption features based on four parameters namely; wavelength position, depth, width, and asymmetry, where the wavelength position is the wavelength of minimum reflectance and the width, W , is given by

$$W = \frac{\text{Area}_{\text{left}} + \text{Area}_{\text{right}}}{2D} \quad (1)$$

D is the depth of the feature relative to the hull (see Green and Graig, 1985, for details) and area is given by the summation of the $\text{Area}_{\text{left}}$ and $\text{Area}_{\text{right}}$ of the line through the centre of the absorption feature. Asymmetry, S , is the ratio of the $\text{Area}_{\text{left}}$ to $\text{Area}_{\text{right}}$ of the absorption centre:

$$S = \frac{\text{Area}_{\text{left}}}{\text{Area}_{\text{right}}} \quad (2)$$

The BNC method consists of more detailed analysis of the absorption features by measuring the depth

of the waveband of interest from the continuum line, relative to the depth of waveband at the centre of the absorption feature from the continuum line.

$$\text{BNC} = \frac{1 - (R/R_i)}{1 - (R_c/R_{ic})} \quad (3)$$

where R is reflectance of sample at the waveband of interest and R_i that of the continuum line at this wavelength. R_c and R_{ic} are the reflectance at absorption feature centre and that of the continuum line at this centre, respectively.

Derivative analysis method is based on the presumed capability of them removing the baseline effects (Duckworth, 1998) and thus capacity to separate subtle spectral differences (Escadafal, 1994). The first derivative represent slope of the spectral curve at every point whereas the second derivative measures changes in this slope.

2.3. Swelling indices measurement

This consisted of several widely used and recognized engineering and soil science indices representative of the soils physical/chemical properties relationships with the soils swelling potential and described to be an indirect measure of the present clay mineral properties (Mitchell, 1993). They included texture, commonly referred to as particle size analysis (PSD), Atterberg limits (i.e. liquid limit (LL), plastic limit (PL) and the plasticity index). Others included coefficient of linear extensibility, cation exchange capacity, saturation moisture and exchangeable bases.

The procedures for PSD and Atterberg limits were as described in the manual of soil laboratory testing (Head, 1992), CEC and exchangeable bases were through the standard procedures described by Reeuwijk (1995) while COLE was as given by Nelson and Miller (1992). Saturation moisture was obtained through saturating the samples followed by oven drying at 105 °C and using the difference in weight at saturation and oven dry state to estimate the lost moisture. Classification of the soils into swelling potential classes was based on the schemes developed by Pearing (1963); Holt (1969) and McKeen and Hamberg (1981) where the CEC and PI are converted to cation exchange activity (CEA_c) and activity (A_c), respectively by division with the clay content to obtain classification thresholds.

2.4. Statistical analysis and data reduction procedures

Obtained COLE value was converted to a potential volume change (PVC) index as per the method of Parker et al. (1977) and used as the relative parameter to establish the capacity of each of the other indices to predict volume changes in the soils based on Pearson's correlation method. Factor analysis method was then used to reduce the indices into representative factors assumed to optimize the information on the swelling potential based on the used indices.

Factor analysis is based on principal components and common factors analysis, which though based on different mathematical models, can be used on the same data. The difference of the two is that the elements on the principal diagonal are replaced by communalities in the factor analysis, which means that only the common variance of the variables (separated from unique factors) are analysed. Thus, it has the advantage of removing the unique factors. The method is often used in exploratory data analysis to study correlations among large numbers of interrelated quantitative variables by grouping the variables into a few factors where variables in a factor are more highly correlated with one another than to those in another factor. The factors can then be interpreted according to the meaning of the variables contributing to it.

In this case, the common factor interpreted to represent the PVC was used as the expansive swelling index (ESI).

2.5. Quantitative estimation of ESI from spectral features

The multivariate regression analysis was used to obtain spectral parameters representative of the ESI from the spectral parameters based on the near infrared reflectance analysis (NIRA) method. This resulted in simple representative empirical models of the ESI, where it was assumed to be a function of the spectral parameters

Thus,

$$ESI = f(\beta_0 + \beta_1, \dots, \beta_i) \quad (4)$$

where β_0 is the intercept, and β_i is the spectral parameter.

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

3. Results

3.1. Swelling indices analysis

The correlations between the various indices and the estimated PVC (see Table 1) show the potential of each of these indices in its estimation. The factors known to be more directly related to the clay mineralogy type such as plasticity and CEC show high correlations whereas some such as the clay content show poor correlations. This probably showing the volume change to be more related to the clay type rather than content. The exchangeable bases other than Ca^{2+} and Mg^{2+} show relatively poor correlations probably reflecting the environment at which the soils developed.

Fig. 1 gives the classification of the soils based on the previously described classification schemes

Table 1
Correlation between estimated percentage volume change and swelling potential indices

	Correlation (<i>r</i>)
Plasticity index (PI)	0.65
Liquid limit	0.77
Plastic limit	0.66
Cation exchange capacity (CEC)	0.84
Saturated moisture	0.75
Clay (%)	0.25
Na ⁺	0.27
K ⁺	0.14
Ca ⁺	0.8
Mg ²⁺	0.6

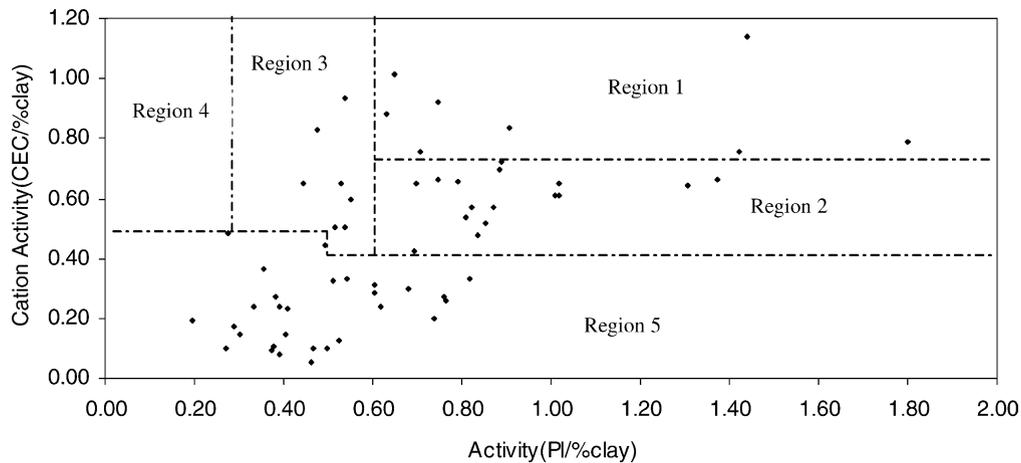


Fig. 1. Modified Hamberg (1985) classification chart.

thresholds given in Table 2. It shows some variations among the indices in their classifications. Regions 1 and 2 are of high, 3 and 4 moderate and region 5 low expansive potential, respectively. The results show relatively good representation of the three swelling potential classes and in clay mineral terms samples in regions 1 and 2 have >50% smectite, regions 3 and 4 >25% illite whereas those in region 5 consist of >50% kaolinite in their clay fractions.

3.2. Data reduction

The factor analysis provided a weighted parameter that best represented the swelling indices minimizing the uncertainty in their classification disparities. Two factors were found to adequately represent the indices variance (Fig. 2), where the first factor was interpreted to represent the swelling and had high loadings from most of the indices, i.e. CEC, PI, LL, PL, Ca²⁺, SP and COLE (the parameter used to calculate the po-

tential volume change) and moderate loadings from Mg²⁺ and K⁺. Exchangeable Na⁺ and percentage of clay were found not to contribute significantly to this factor. The second factor was assumed to represent the residuals resulting from errors.

The obtained common factor scores of the soil samples resulting from the first factor were used in the subsequent analysis as the swelling potential index (ESI).

3.3. Spectral data integration

3.3.1. Optical densities, derivatives and BNC analysis

The optical density gave poor correlations with the established index throughout the spectral range whereas derivatives gave strong correlations (highest $r = -0.8$ at 2200–2260 nm interval for second derivative and $r = -0.73$ and 0.7 at 2100–2200 and 1800–1900 nm intervals, respectively for the first derivative). Fig. 3 gives an example of the differences among the soils in the peak intensities for the first derivative where the soil with high ESI has the bound water peak (1800–2000 nm) intense relative to those with moderate and low ESI values which instead gave their highest peaks at the 2200–2300 nm assigned to the combination of hydroxyl stretching and bending modes (Goetz et al., 2001).

The BNC on the other hand gave significant correlations at the 95% confidence level with ESI over small ranges in the neighborhood of major

Table 2
Swelling and mineralogical classification (Hamberg (1985), Pearring (1963) and Holt (1969))

Swelling class	COLE	CEC/%clay (CEA _c)	PI/%clay (A _c)	Mineralogy (%)
Low	<0.05	>0.4	<0.4	Kaolinite >50
Moderate	0.05–0.07	0.4–0.6	0.4–0.6	Illite >25
High	>0.07	>0.6	>0.6	Smectites >50

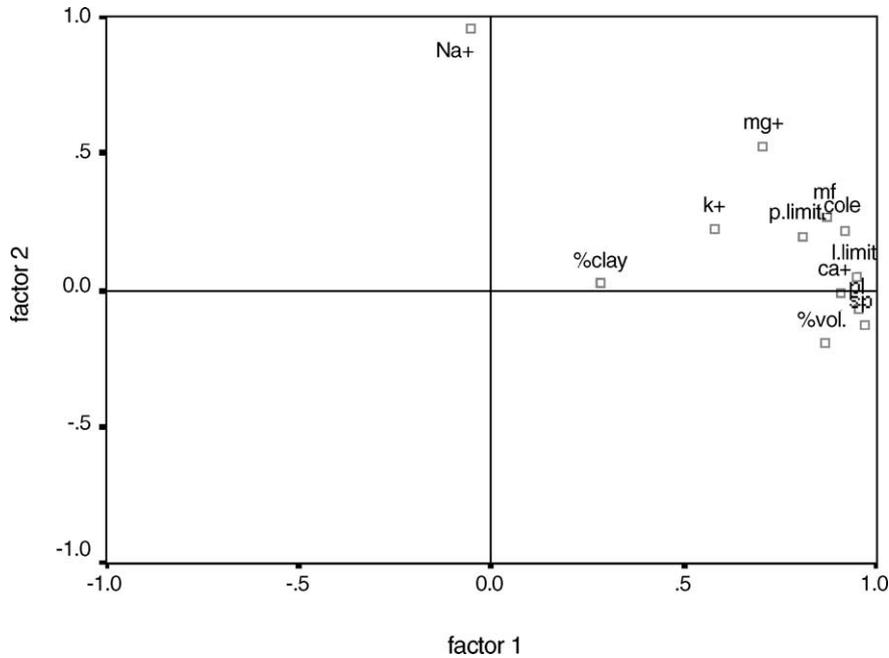


Fig. 2. Common factor scores of the engineering indices.

absorption features. Those found to be of note included 1860–1880 nm ($r = 0.85$), 2160–2220 nm ($r = -0.76$), 2240–2280 nm ($r = 0.6$), 1420–1460 nm ($r = 0.7$) and 1370–1390 nm ($r = -0.73$) that shows a positive relationship with the bound water range and the opposite for the hydroxyl spectral range.

3.3.2. Absorption feature mapping and analysis

Principal components were used to derive maximum information from the absorption feature parameters used in absorption feature mapping. Fig. 4 shows the principal components loadings of the two factors found to explain 95% variance of the spectral

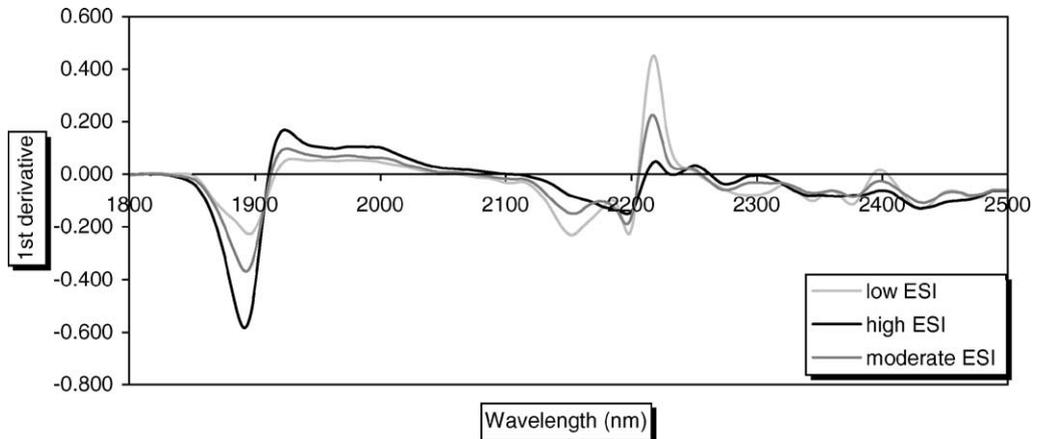


Fig. 3. First derivative spectrum of representative samples of the three ESI classes.

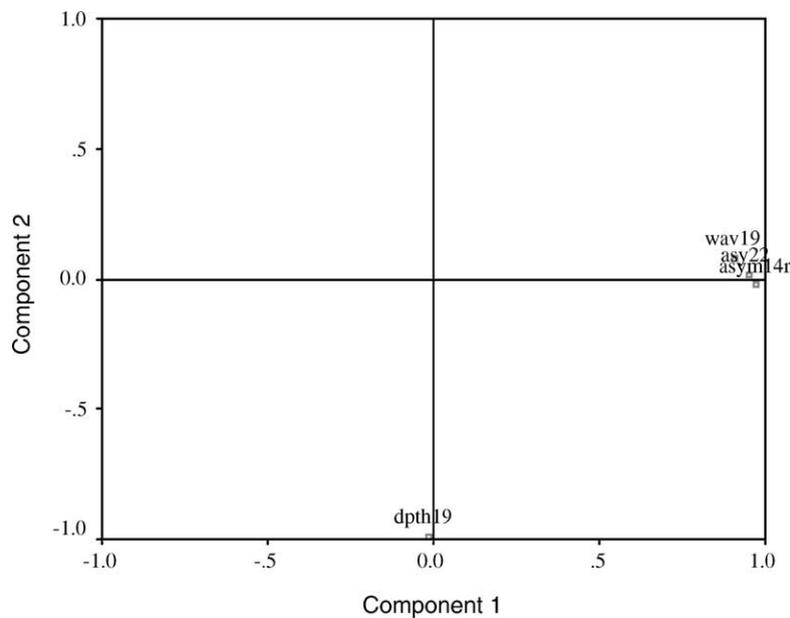


Fig. 4. Results of principal component analysis on soil samples spectra.

Table 3
Significant spectral parameters for ESI estimation models and their statistics

Spectral parameters	Correlation	Contributing parameters	SEC/SEP
Absorption feature parameters	0.82	ln(asy1400), (pos1900), (depth1900), (asy2200)	0.62/1.96
Second derivative	0.84	2180, 1440, 1880, 2240 and 2310	0.44/3.5

information represented by these parameters where width, area and reflectance were found not to give significant relationships with the ESI and are therefore not included. Component 1 had high loadings from asymmetries (1400 and 2200 nm) and the wavelength position at 1900 nm and was assigned to the causative mineralogy crystal structure order. The second factor consisted of the water absorption depth and was interpreted to represent increase in bound water among the soil samples.

3.4. Quantitative estimation of ESI

Table 3 gives the spectral parameters of the two most promising empirical models to estimate the ESI from the various spectral data analysis methods. It shows a strong influence of the bound water content and hydroxyl bonding strength representative parameters on

the obtained models. Fig. 5 shows a validation plot of measured versus the predicted ESI values of the absorption feature parameters model, where it can be observed that most points are within a small range of the 1:1 line. The prediction error (Table 3) also show the model to be a good predictor of the ESI.

4. Discussion

4.1. Engineering methods

The generally strong correlations between the various indices and the established PVC, show a common dependency that based on the results integrating the spectral information could be assigned to the clay mineralogy, a fundamental factor controlling expansive soil behaviour and described by Thomas et al.

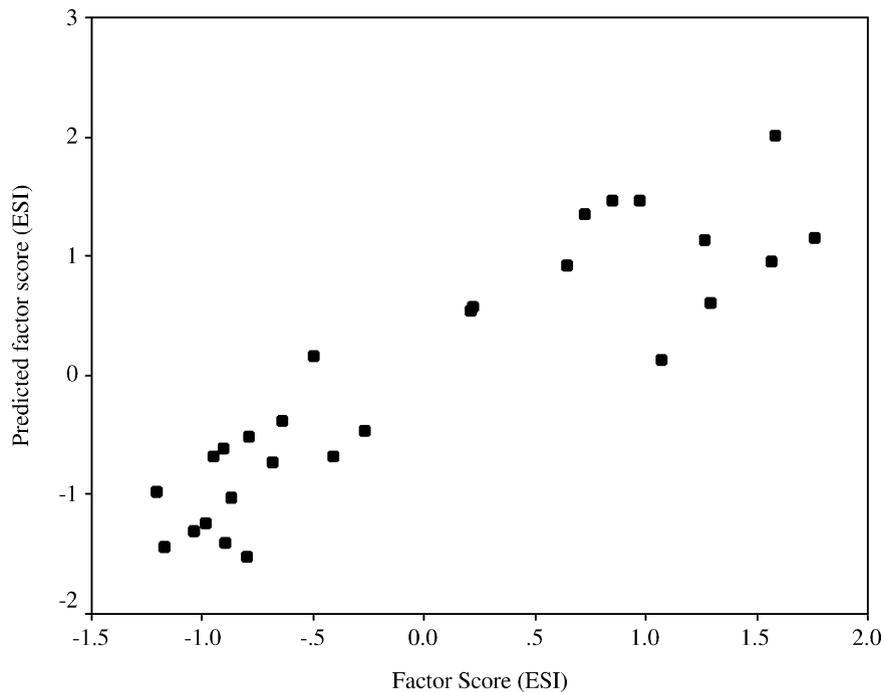


Fig. 5. Predicted vs. true ESI values using the absorption feature parameters empirical model.

(2000) as the most important factor in establishing a swelling index. The disparities in classifying soils on the basis of individual swelling index however can be attributed to the differences in the conditions under which the measurements are made (Nelson and Miller, 1992) and also to the variation in how the soil properties they represent relate to swelling. Whereas some, such as the CEC and PI are direct measures of the clay type and thus the volume change, others such as the clay content (represent all particles less than $2\ \mu\text{m}$) does not represent a direct measure of the clay type, this probably explaining poor relationships of such properties with the PVC and also to the spectral parameters identified as representing the PVC. This makes the use of indices such as clay content alone as an index of PVC a misrepresentation which however when used together with the other parameters, e.g. plasticity (to obtain activity) normalizes the obtained values making them easy to compare as seen in the classification of the soils. This supports the observations of Thomas et al. (2000) that these indices should always be used in combination for meaningful estimation of swelling potential. The data reduction

established such a protocol that integrates the indices and furthers the ideas of Hamberg (1985) and Thomas et al. (2000) by providing a more reliable and unbiased method of combining the indices into a swelling index that compared well with the spectral parameters enabling establish representative swelling models whose physical significance can be explained.

The optical density general decrease with increase in the obtained ESI can be attributed to an increase in bound water and thus an enhancement of the absorption effect at the expense of the scattering effect. The negative relationship between the index and BNC at the 1370–1390 nm could be assigned to the influence of the lattice hydroxyl (OH), described by Farmer (1974) to be strong in the presence of kaolinite, while those at 2160–2220 nm (the combination and bending modes of Al–OH) could be attributed to higher fraction of the octahedral (Al–OH) to tetrahedral (SiO_4) group as ESI decreased which also has been described to reflect the level of substitution of Al^{3+} by Mg^{2+} and Fe^{2+} in hydroxyl bearing minerals (Alonso et al., 2002). The positive correlation at 1440–1460 nm can be attributed to the shoulder of bound water

(Hauff, 2000) and that at the 1870–1880 nm to the water-bending mode described by Russell (1987) and assigned to bound water by Goetz et al. (2001). The positive relationship at 2240–2260 nm could be attributed to increasing levels of Fe–OH to Al–OH ratio as ESI increased since 2240 nm has been established to be diagnostic for Fe–OH (Farmer, 1974) and probably confirms the replacement of Al^{3+} with Fe^{2+} as previously discussed.

The differences observed in the derivatives can also be attributed to these differences in the hydroxyl cations and the abundance of clay bound water based on the derivatives ability to separate overlapping bands and isolate weak features (Wessman, 1994). The subtle differences in the positions and intensity of the peaks seem to show these characteristic differences where the strength of the peaks among the samples tally with the bound water (1800–2000 nm) and hydroxyl (2100–2200 nm) regions described by Goetz et al. (2001).

The results from the absorption feature parameters agree with what Kariuki et al. (2003) described to be changes in surface area and influence of the minerals crystal structure. Thus, the positive correlation of the water feature depth can be interpreted to represent increase in surface area and thus bound water content as ESI increased a fact that supports Ben-Dor et al. (1999) order of increment in surface area, i.e. smectites > ‘illite’ > kaolinite since as seen in the classification there is increased presence of smectite with ESI. This also supports Chabrilat et al. (2001) findings of the feature being diagnostic in the identification of swelling soils. The feature position negative correlation can be said to indicate distinct differences between the soils in terms of their bound water structure a fact that could be attributed to what Kariuki and van der Meer (2003) described as differences in electrochemical forces on the water molecules.

The asymmetries negative correlations at the two Al–OH feature positions probably reflect less substitution of the Al by Mg^{2+} and Fe^{2+} as ESI decreased among the soils since strength of the 2200 nm, has been established to reflect the level of substitution of the Al^{3+} (Alonso et al., 2002) which results in the broadening of the feature. The increasing contents of the more ordered kaolinite (as assigned in the classifications) could be the other reason which would then confirm assertion by Kruse et al. (1991) that asym-

metry at 2200 nm is important in the determination of kaolinite contents ratios to those of smectites in clay soils.

In other studies, spectral data has been found to be a good predictor of some of the swelling indices to levels where r^2 values for measured versus predicted give high values. Such include field moisture predicted at higher than $r^2 = 0.9$ by Dalal and Henry (1986) and CEC by Shepherd and Markus (2002) with an $r^2 = 0.95$. This makes a case for the obtained results and shows that though soil is a heterogeneous mixture thus making the spectral response uncertain, their properties can be estimated from their spectra. The fact that several spectral parameters could give distinct differences among the soil groups, diagnostic of minerals, show the potential of spectroscopy in engineering and soil science.

5. Conclusions

It is clear from the results that clay mineralogy is a major factor in determining both the soil physical/chemical properties and their spectral characteristics. The results show dependence of both on the characteristics of the clay mineralogy in the soil where such properties as higher surface area (related to significant presence of smectites) are seen in the strong positive correlation between ESI and the structural water parameters. Strengthening of the hydroxyl parameters with decreasing ESI, as seen in asymmetries and their related peaks in derivatives can also be concluded to indicate these soil mineralogical differences and supports the conclusions of Mathews et al. (1973) that hydroxyl bands in soils are typically strong in kaolinite relative to smectites.

This leads us to draw the conclusions that spectral parameters are ideal in the estimation of soil swelling properties based on their clay mineralogy and provides a tool from which dominant clay mineral type can be established. It provides a new method by which future mapping of swelling soil will be done bearing in mind the increasing spectral resolution in the family of satellites with the introduction of satellites such as the Hyperion with a 220 contiguous bands and thus capacity to resolve the diagnostic spectral parameters established here to represent significant differences in the soils swelling properties.

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