Evaluation of Soil Expansion Index from Routinely Determined Geotechnical Parameters

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Correlations are essential to obtain information on soil geotechnical parameters, which are costly and time consuming to measure directly, such as expansion potential. A common procedure for evaluating and rating soil expansion potential is the expansion index (EI) test. The purpose in this study was to establish a multivariate regression model to predict soil EI, thereby classify and rate soil expansiveness. Soil samples were collected from the newly planned expressway connecting the city of Addis Ababa with the town of Nazret in Ethiopia. A regression equation was established from liquid limit (LL), plasticity index (PI), and soil fine fraction (percentage of material passing the ASTM 0.075-mm sieve aperture), using a partial least squares (PLS) multivariate calibration method. A coefficient of determination (R^2) of 0.92 accompanied with a root mean square error of prediction (RMSEP) of 9.87, standard error of performance (SEP) of 9.91, offset of 5.31 and bias of 0.04 was obtained. Response surface models showing three-way relationships among the predictors (Atterberg limits and fine fraction) and response variable (EI) may serve as classification systems for evaluating soil expansion potential. Apart from its basic scientific value as a simple method for estimating and rating soil expansiveness, the approach has the advantage of employing easily and routinely determined soil properties, to get information on soil expansion potential at minimal cost and time requirements.

Abbreviations: ASTM, American Society for Testing and Materials; CEC, cation exchange capacity; EI, expansion index; LL, liquid limit; MLR, multiple linear regression; PCR, principal component regression; PI, plasticity index; PLS, partial least squares; RMSEP, root mean square error of prediction; SEP, standard error of performance.

Geotechnical characteristics of expansive soils, with respect to bearing potential, stress and deformation are highly sensitive to variation in moisture regime. Such soils exhibit substantial volume change on alteration of their moisture content. The change in volume is often associated with loss of shear strength and deformation. These phenomena can pose a significant hazard to infrastructures, in particular lightweight structures, founded on such soils. Engineering problems due to expansive soils were reported from different parts of the world (Al-Rawas, 1999; Chen, 1988; Gourley et al., 1993; Morin, 1971; Nayak and Christensen, 1971; Nelson and Miller, 1992; Ramana, 1993; Seed et al., 1962; Shi et al., 2002; Yilmaz, 2006). The damage because of expansive soils worldwide was greater than damage caused by all other natural hazards (Chen, 1988; Nelson and Miller, 1992). Hence, expansive soils are considered hidden hazards.

Identification and quantitative characterization of expansive soils are of critical importance in geotechnical investigations. The purpose is to ensure proper site selection, environmental compatibility, and economical feasibility in designing, construction as well as subsequent performance of infrastructure. Expansive soils can be characterized and classified based on their expansion and shrinkage potentials, measured by methods such as oedometer and triaxial swelling tests, suction, potential volume change (PVC), EI, and coefficient of linear extensibility (COLE) etc. Since several factors should be considered while measuring soil

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Soil Sci. Soc. Am. J. 75:1640–1651
Posted online 11 Aug. 2011
doi:10.2136/sssaj2010.0420
Received 11 Nov. 2010.
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expansion and shrinkage potential, these methods require sophisticated sampling and laboratory procedures. As a result, they are costly and time consuming. Hence, identification and characterization of expansive soils involve the use of correlations and established classification techniques. The bases of these correlations are the dependence of soil expansion and shrinkage potential on soil compositions, mainly clay mineral compositions and content. Soil expansion and shrinkage potential are unique to soils containing expansive crystalline clay minerals, such as smectite, interstratified smectite-illite, illite, and interstratified smectite-kaolinite (Chen, 1988; Karathanasis and Hajek, 1985; Mitchell, 1993; Nelson and Miller, 1992; Thomas et al., 2000; Yerima et al., 1985). Active noncrystalline clay particles such as allophane and imogolite are also responsible for soil swell-shrink susceptibility (Allbrook, 1985; Gray and Allbrook, 2002; Wan et al., 2002; Zehetner et al., 2003). Several indirect relationships and classifications were proposed, mainly based on oedometer, triaxial, suction, potential volume change (PVC), and coefficient of linear extensibility (COLE) methods (Dakshanamurty and Raman, 1973; Erguler and Ulusay, 2003; Erzin and Erol, 2007; Gray and Allbrook, 2002; Kariuki and Van der Meer, 2004; McCormack and Wilding, 1975; Seed et al., 1962; Skempton, 1984; Thomas et al., 2000; Yilmaz, 2006).

Anderson and Lade (1981) proposed the EI test for identifying potentially expansive soils and quantifying magnitudes of volume changes in expansive soils. Zapata et al. (2006) presented one to one correlations among soil EI and PI, fine fraction (material passing the ASTM 0.075-mm sieve aperture), and weighted PI (a product of PI and fine fraction). However, the use of a single index property for estimating and rating potential expansion in soils suffered from overlapping ranges for different magnitudes of expansiveness. Moreover, established thresholds of each index property for a likely extent of volume change differed from one researcher to another adding to the uncertainty as to which class of expansiveness to assign a given soil (Carter and Bentley, 1991; Kariuki and Van der Meer, 2004; Reddy et al., 2009; Thomas et al., 2000). Use of multiple geotechnical parameters might improve prediction ability of models, and better model the noncrisp nature of the relationship among routinely determined geotechnical parameters and soil expansion index.

The objectives in this study were: (i) to determine geotechnical characteristics of the soils and quantify their expansion potential in terms of expansion index, (ii) to establish a relationship among the soil expansion index and routinely determined geotechnical parameters, such as Atterberg limits (LL, PI) and soil fine fraction (percentage of material passing the ASTM 0.075-mm sieve aperture) for indirect estimation of expansion potential, and (iii) to develop a classification technique for rating soil EI, based on these three routinely determined soil geotechnical parameters.

A relationship was established, among the EI and three routinely determined soil geotechnical parameters. A multivariate calibration method, PLS regression (Martens and Naes, 1989; Wold et al., 2001), was used to link the explanatory variables to the response variable. Response surface model swere also used, to illustrate the three-way relationships, among the Atterberg limits and soil fine fractions with EI.

MATERIALS AND METHODS

Study Site

The study was performed in an area located in the central part of Ethiopia (Fig. 1), in the upper valley of the Awash River which drains the northern part of the Rift Valley. Topography ranges from a relatively flat to hilly, undulating, and steep, mountainous terrain. Elevation ranges from 1500 to 2500 m above sea level. Conical-shaped isolated hills of scoria formed during late stages of volcanism are common in the study area. Climate is moderate to wet, with a mean annual rainfall of 1200 mm in Addis Ababa and areas close by, and 870 mm around the town of Nazret. Temperature ranges from 8 to 25°C. Considerable moisture change can occur in the soils, due to heavy rain periods followed by prolonged dry periods. Thus, the soils are susceptible to pronounced volume changes.

The geology (Abebe et al., 1999), around TuluDimtu consists of Tertiary to Quaternary volcanic formations. Figure 1 shows the names of main towns along the existing highway, connecting Addis Ababa with the town of Nazret. The Tertiary to Quaternary volcanic formations include alkaline basalt, spatter and cinder cones, ignimbrite, tuff, rhyolitic flows and domes, and trachyte. Near DebreZeyt, alluvial and lacustrine deposits dominate which include sand, silt, and clay. From DebreZeyt to Modjo town there are lacustrine deposits. After Modjo town, fall and poorly welded pyroclastic deposits are dominant with rhyolitic and trachytic formation intercalations. As the geology of the study area implies, the soils could be derived from a wide range of parent materials, ranging from alkaline to intermediate and siliceous varieties.

Soils in the study area can be classified into vertisols, luvisols, leptosols, phaeozems, andosols, cambisols, fluvisols, and nitosols (Fig. 1). According with FAO (1998), vertisols are clay rich (principally smectite) expanding soils that swell and shrink with change in moisture content. Luvisols are common soil types in flat or gently sloping land, and often derived from a variety of unconsolidated parent material including alluvial, colluvial, and eolian deposits. Luvisols usually exhibit a high cation exchange capacity (CEC) and water retention potential that is associated with accumulation of active clay minerals (Gray and Murphy, 2002). Leptosols are particularly shallow soils over hard rock or unconsolidated gravely material and are common in mountainous areas. Phaeozems are soils that are predominantly derived from basic parent material, and are rich in organic matter. Andosols are young soils in volcanic regions and usually associated with pyroclastic parent materials. Andosols show a low CEC and water retention capacity (Gray and Murphy, 2002) unless allophane or immogolite is present (Gray and Allbrook, 2002; Parfitt and Hemni, 1980; Wan et al., 2002). Cambisols are moderately developed soils derived from a wide range of parent material, and are common in areas where there is active erosion. Fluvisols are young soils common in alluvial deposits; they also occur in lacustrine deposits. Nitosols are deeply weathered soils. These soils are mostly gravelly, and they are characterized by low CEC. The hilly and mountainous terrains of the study area are mainly covered with fresh to partially weathered basalt. From an engineering perspective, soils that are mostly black and contain highly expansive clay minerals are found between

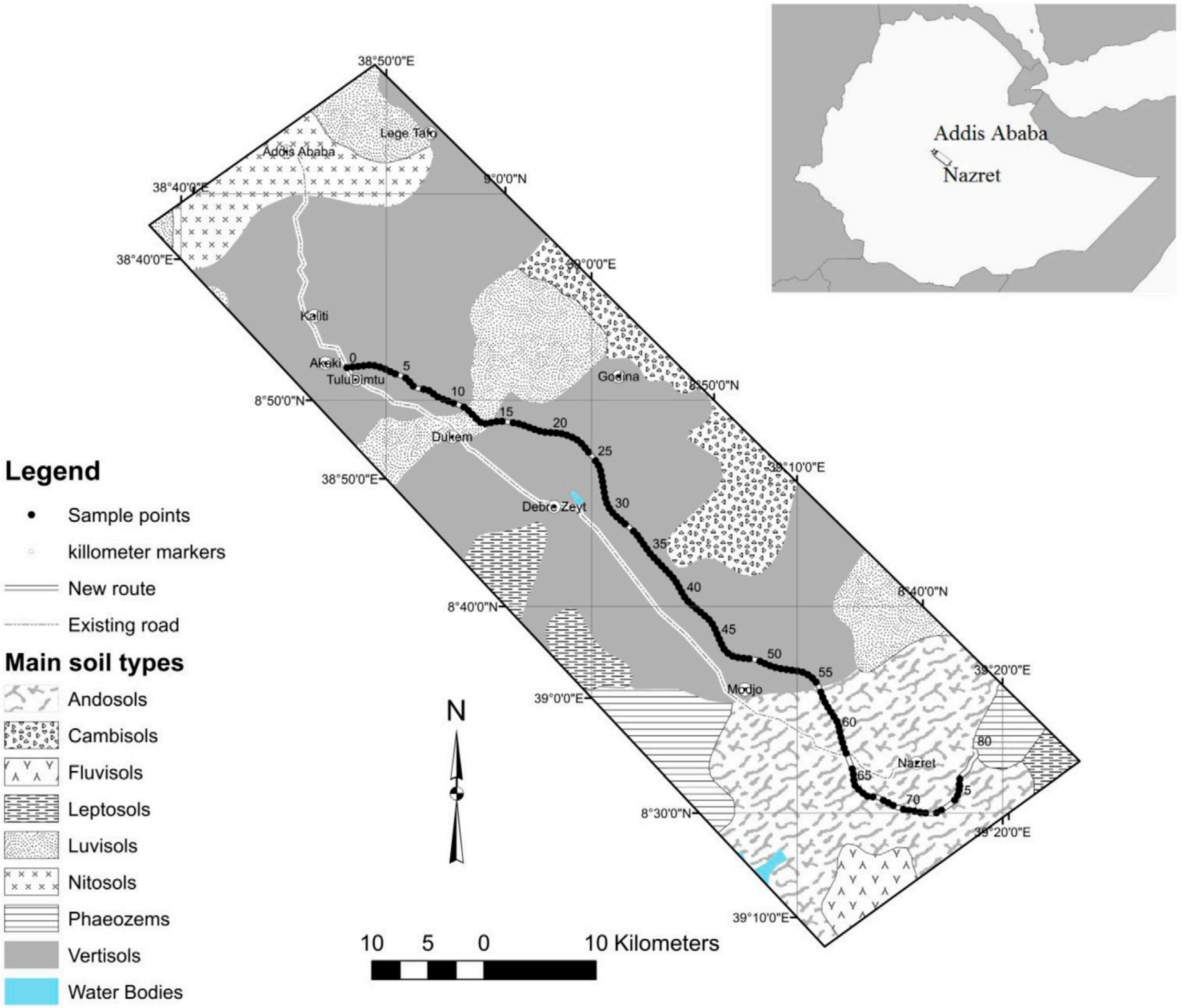


Fig. 1. Location map of the study area, with kilometer markers on the newly planned expressway alignment, showing its length in 5-km intervals. Names of main towns are indicated along the existing highway.

Addis Ababa to Modjo town, and covered an extensive area. These black soils belong to the vertisols family and are commonly known as black cotton soils (ERA, 2002). Apart from Ethiopia, the occurrence of black cotton soils is reported from different parts of the world, e.g., USA, Australia, India, China, Sudan, South Africa, Niger, Chad, Nigeria, Tanzania (Babu et al., 2005; Chen, 1988; Gadre and Chandrasekaran, 1994; Morin, 1971). According to Abebe et al. (1999), the black cotton soils are of alluvial, lacustrine, and colluvial origin.

Soil Sampling

A large part of the newly planned expressway route traverses through vertisols (Fig. 1). Therefore, it was essential to evaluate the swell-shrink potential of the soils to eliminate or minimize detrimental influences of soil volume change in the highway subgrade and the associated adverse impacts on the adjoining environment. Soil samples were collected along the newly planned route from its starting point near TuluDimtu to its ending point at the town of Nazret (Fig. 1). The sampling was part of a comprehensive geotechnical investigation scheme for assessing the suitability and quality of subgrade materials. This detailed investigation was an essential component of the engineering survey for determining the location and design of the expressway. A dense sampling scheme was planned (ERA, 2002), to gather pertinent information on the geotechnical characteristics of the soils to account for optimal location of the route, appropriate foundation and earthworks designs, environmental effect and remedial works. The samples (in total 161) were recovered at every 500-m interval from shallow trial pits of 1-m depth which is commonly the depth at which shallowly founded structures are laid.

Geotechnical Testing

The Atterberg limits: LL, plasticity limits (PL), and PI were determined in accordance with procedures and requirements of the ASTM D4318-05 standard method.

Particle size distribution tests were conducted in accordance with the ASTM D6913–04e1 standard test method, using sieve analysis (for the fraction passing through the ASTM 2-, 0.425-, and 0.075-mm sieve openings). Grading of soils finer than the ASTM 0.075-mm sieve was determined by hydrometer analysis, in accordance with the ASTM D422-63 standard test method.

Expansion indices of the soils were determined in accordance with the ASTM D4829-07 standard test method. The expansion index test was performed on 139 soil samples. The locations of these samples are shown in Fig. 1.

Mineralogical Analysis

Mineralogical compositions of the soils (10 soil samples) were examined using X-ray diffraction (XRD) analysis. The Siemens D5000 X-ray diffractometer was used. Bulk soil samples were analyzed to determine the overall constituents. Clay fractions were analyzed to quantify major, minor, and trace mineral compositions. For this semi-quantitative determination of clay minerals in the clay fraction, the soil samples were treated initially to remove organic matter, iron oxides, and carbonates. The silt and clay fractions were separated by centrifugation. Then, oriented slides were prepared in four different ways; untreated, treated with ethylene glycol vapor, treated with ethylene glycol vapor plus heated at 400 and 550°C, respectively. X-ray fluorescence (XRF) analysis was used to identify the oxides present in the soil samples, and to quantify organic matter content on loss on ignition (LOI).

Multivariate Regression Analysis

Regression analysis is a fundamental statistical tool for exploring possible relationships among explanatory and response variables. In multiple linear regressions (MLR), explanatory variables are assumed to be linearly independent. If explanatory variables are significantly interdependent, the problem of collinearity will arise, which may lead to numerically unstable and spurious estimates of regression coefficients and over fitting (Brereton, 2000; Hair et al., 1987). Two other multivariate regression analyses techniques, principal component and partial least squares regression analyses are widely used to deal with highly collinear variables.

Principal component regression (PCR) analysis decomposes a set of explanatory variables into eigen vectors and scores that are orthogonal to one another, and hence overcome collinearity problems. After achieving an optimal projection of explanatory variables in a few principal components, regressing them against the response variable will be followed in a separate step. Choice of the relevant number of principal components can be a complex process when relevant underlying systematic data structure is small in comparison with noise (Brereton, 2000; Martens and Naes, 1989).

Partial least squares regression analysis, on the other hand, decomposes both explanatory and response variables simultaneously to capture their common structure. Then, project this common structure into a small number of mutually independent factors. In PLS, explanatory variables are decomposed into new coordinates called T-scores. These T-scores are computed in such a way that they also capture part of the structure in the explanatory variables that are relevant to the response. U-scores, on the other hand, summarize part of the structure in the response that is explained by the explanatory variables with a given set of principal components. The decomposition and regression are in a single step, through fewer principal components than is required by PCR (Brereton, 2000; Martens and Naes, 1989; Wold et al., 2001; Yeniay and Goktas, 2002). In PLS, principal components (PLS factors) are extracted in decreasing order of relevance. Hence choice of an optimal number of principal components is not a problem.

The extent and trends of relationships among the soil geotechnical characteristics were examined using a pair-wise correlation analysis. A partial least squares regression analysis was conducted to establish a relationship among the soil expansion index, Atterberg limits (liquid limit and plasticity index) and fine fraction (material passing the ASTM 0.075-mm sieve aperture). The distributions of variables were checked, and appropriate transformations were performed on those variables that showed a skewed distribution. As described by Martens and Naes (1989) and Wold et al. (2001), data were mean centered and scaled to unit variance before the regression analysis to ensure equal influence on the model. A full cross validation procedure was used to calibrate and validate the prediction model. This full cross validation method uses a leave one out principle. One sample will be left out at a time, and the model is calibrated on the remaining samples. There will be N times repeat until every sample is left out once and the model is computed on the remaining samples, and the left out sample is predicted. Model performance indices such as coefficient of determination (R^2), RMSEP, SEP, bias, offset, residual and explained variance plots, were used to evaluate the model performance. As in multiple linear and principal component regressions, the R^2 served to evaluate the goodness of fit. The expected prediction error was assessed by the SEP, and RMSEP. Bias showed interference error, and was computed as an average value of the variation that was not taken into account by the model. The offset showed the point where the regression line crossed the ordinate in the scatter plot summarizing the relationship between measured and predicted values of the response. Thus, it showed deviation from the ideal one to one correspondence.

RESULTS

Geotechnical Characteristics

The soils exhibited a wide range of plasticity character: a liquid limit of 27 to 110%, and plasticity indices of 5 to 70% (Table 1). A majority of soils along the expressway alignment was fine grained (note the mean value of fine fraction in Table 1). Percentage by weight passing the ASTM 0.075-mm sieve aperture ranged from 8% in coarser soils to a 100% in most black cotton soils. Hydrometer analysis conducted on 40 randomly selected soil samples showed a high amount of clay fraction. The clay fraction was higher in those samples obtained from the 0- to 60-km stretch of the expressway route. Clay content in these tested soil samples, ranged from 10 to 60% by weight, with higher proportions recorded in black cotton soils. Figure 2 shows typical particle size distribution curves of soil samples. The ranges in geotechnical properties of the soil samples appeared larger. However, the variability was narrow which tend toward the highly plastic and fine grained geotechnical characteristics. The expansion index of the soil samples, ranged from 1 to 152%, covering the classes of expansiveness very low to very high (ASTM, 2007).

The plasticity chart of the soil samples (Fig. 3) shows that the soil samples were highly plastic, particularly those obtained from the 0 to 60 km of the route. In addition, the majority of the samples (75%) plotted above the ‘A’ line, indicating that they belong to the inorganic clay varieties. On the other hand, the soil samples originated from 60 km up to the end of the route at Nazret town mainly fall within the medium and lower plasticity portions of the plasticity chart. Thus, the susceptibility of the soils to pronounced volume changes is high for those from the 0 to 60 km of the route, while it is low for those from the 60 to 80 km.

Mineralogical Assemblages

The XRD and XRF results, showing the mineralogical assemblages and oxides present in the soils are presented in Tables 2 and 3. The XRD analysis results showed dominance of 2:1 clay minerals. Figure 4 shows XRD patterns of the clay fractions. Smectite (montmorillonite and nontronite) is a major constituent, composing more than 30% by weight in most of the soil samples. Illite-montmorillonite interstratified clay minerals, illite, and kaolinite were also found in the soils, ranging from major (>30%), to moderate (10–30%), minor (2–10%), and trace (<2%) amounts. Apart from the clay minerals, which significantly influence the engineering behavior of expansive soils, associated minerals (Bergaya and Lagaly, 2006) such as quartz, feldspar, and goethite were also identified in the mineralogical assemblage analysis. These original minerals are common soil constituents (Fitzpatrick, 1980; Yong and Warkentin, 1975) but do not contribute to soil expansiveness due to lack of activity. Calcite was found being a minor constituent. Oxides such as SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5, MnO, and Cr_2O_3 were identified from the XRF analysis result (Table 3).

Table 1. Summary of descriptive statistics; minimum, maximum, mean, and standard deviation values of the soils geotechnical parameters, showing that the soil samples exhibited a wide range of properties.

Descriptive statistics	EI†	LL	PI	Fine fraction (% passing ASTM 0.075-mm sieve aperture)
		–% –		
Minimum	1	27	5	8
Maximum	152	110	70	100
Mean	70.8	68.3	34.1	76.7
SD	35.2	22.7	17	22.4

† EI = expansion index; LL = liquid limit; PI = plasticity index.

Montmorillonite $[(\mathrm{Ca, Na})_{0.33}\,(\mathrm{Al, Mg})_2\,(\mathrm{Si}_4, \mathrm{O}_{10})\,(\mathrm{OH})_2\,\mathrm{nH_2O}]$ is a product of weathering of Ca- and Mg-rich parent materials. It is one of the most common smectite minerals found in soils (Galan, 2006). It also forms from weathering of volcanic ashes and primary silicate minerals, such as feldspars, pyroxenes, or amphiboles, under conditions of insufficient leaching of the soil profile due to low permeability and excessive evaporation (Chen, 1988; Fitzpatrick, 1980). As indicated in the summary of its geology, the study area is covered with rocks of volcanic origin. Volcanic debris and alkaline rocks such as basalt is common and abundant. The rainfall is seasonally moderate, where evaporation exceeds precipitation. The geology accompanied with this

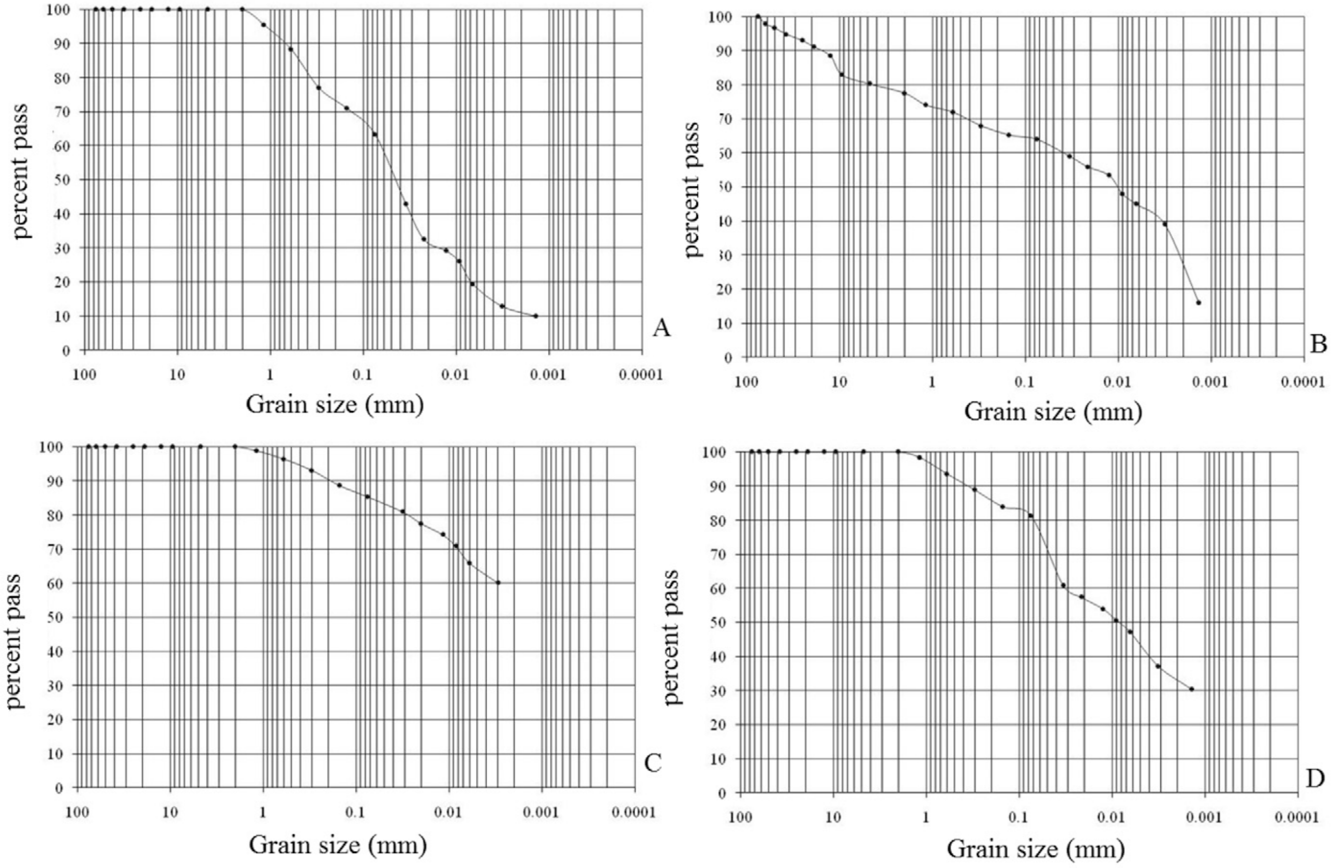


Fig. 2. Particle size distribution curves of selected soil samples, showing grading of soil samples from kilometer (A) 8.5, (B) 28, (C) 57.5, and (D) 71.

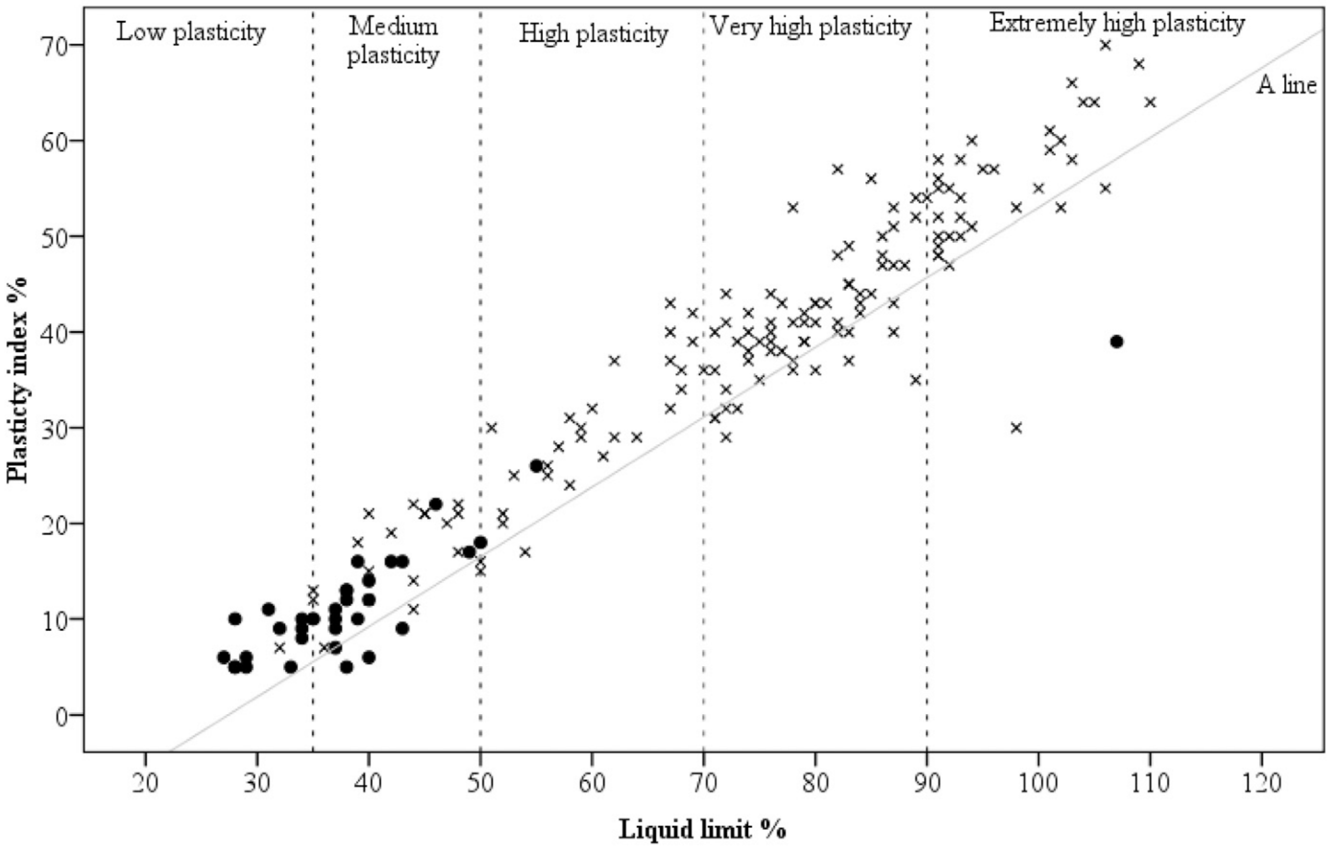


Fig. 3. Plasticity chart of the soil samples with samples divided by their origin: label 'X' showing samples obtained from the 0 to 60 km stretch of the newly proposed alignment, and dark circles indicating samples obtained from the 60 to 80 km stretch of the route.

seasonally moderate rainfall, under poorly drained conditions that can allow retention of Mg and Ca in the soils, can favor the formation of montmorillonite. Nontronite $[(Ca, Na)_{0.66}\ Fe^{3+}{}_4(Si, Al)_8\ O_{20}(OH)_4\ nH_2O]$ is also a common smectite clay mineral found in soils and weathered bedrock. Its formation is similarly favored by alkaline to neutral pH environments, as well as availability of Fe- and Ca-rich parent materials. Thus, formation of nontronite can also be favored by the geology, climatic conditions, and topographic setting of the study area.

Illite $\{(K, H_3O)\ (Al, Mg, Fe)_2\ (Al, Si)_4\ O_{10}\ [(OH)_2\ (H_2O)]\}$ commonly occurs in soils. It can be formed by weathering of silicates, primarily feldspars and micaceous rock-forming minerals such as biotite and muscovite (Galan, 2006). Illite formation is favored in silicic to intermediate geologic environment, where there are high concentrations of Al and K (Fitzpatrick, 1980). These conditions are fulfilled in the study area. Illite regularly appears with smectite (Hower and Mowat, 1966; Mitchell, 1993) forming interstratified smectite-illite clay minerals such as interstratified illite-montmorillonite. This is shown in the XRD

Table 2. Summary of results of the X-ray diffraction (XRD) analysis showing 2:1 clay species dominated in the soil samples in both bulk and clay fractions.

Station	Sample	Mineral assemblage			
		Major	Moderate	Minor	Trace
km					
8.5	Bulk	Montmorillonite	Quartz, calcite, nontronite	Kaolinite, plagioclase, potassium feldspar, illite	brookite, rutile, geothite
	Clay fraction	Montmorillonite	–	Illite, kaolinite, quartz, calcite, potassium feldspar	–
28	Bulk	Montmorillonite	Quartz, nontronite	kaolinite, plagioclase, potassium feldspar, illite	brookite, rutile, goethite
	Clay fraction	Montmorillonite	–	Illite, kaolinite, quartz, calcite, potassium feldspar	–
57.5	Bulk	Montmorillonite	Quartz, nontronite	kaolinite, plagioclase, potassium feldspar, illite	brookite, rutile, geothite
	Clay fraction	Illite/Montmorillonite mixed	–	illite, kaolinite, quartz	–
60	Bulk	Montmorillonite	Quartz, nontronite	kaolinite, plagioclase, potassium feldspar, illite	brookite, rutile, goethite
	Clay fraction	Illite/Montmorillonite mixed	–	Illite, kaolinite, potassium feldspar	–

Table 3. Summary of results of the X-ray fluorescence (XRF) analysis showing oxides in the soil samples.

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3	V_2O_5	LOI†
							–% –						
8.5	46.0	13.8	7.14	2.29	5.66	0.79	1.46	1.14	0.08	0.18	0.02	0.02	21.4
28	50.1	19.0	7.95	1.63	0.30	0.77	1.86	1.22	0.15	0.17	0.01	0.02	13.2
57.5	50.8	15.9	8.46	1.50	1.33	2.16	2.53	1.03	0.04	0.24	0.01	0.02	14.5
60	62.9	13.2	6.82	0.58	0.97	4.53	3.42	0.60	0.06	0.24	<0.01	<0.01	6.86

† LOI = loss on ignition.

analysis result (Table 2 and Fig. 4). Interstratified kaolinite–montmorillonite clay minerals are also common in soils (Yerima et al., 1985).

Kaolinite [$Al_2Si_2O_5\ (OH)_4$] is another commonly occurring clay mineral in soils (Fitzpatrick, 1980; Yong and Warkentin, 1975). It can be derived from almost all silicate minerals. Hence, its formation in the study area can be favored by the environmental conditions. Halloysite [$Al_2Si_2O_5\ (OH)_4\ 4H_2O$] occurs in soils and the uppermost weathered part of the bedrock. Halloysite is a common constituent of various volcanic soils (Takahashi et al., 2001). It can be formed as a result of weathering of Al-rich minerals that are also abundant in the study area and its surroundings.

Estimating Expansion Index

The soil geotechnical parameters were strongly positively correlated at 0.01 significance levels (Table 4). Therefore, collinearity was evident among the explanatory variables. The magnitudes of relationships were higher among the Atterberg limits (LL and PI) and the EI. The fine fraction showed lower correlations with the Atterberg limits and EI. The fine fraction of the soils was likely to contain a large amount of clay minerals. The Atterberg limits reflected high activity (Fig. 3). The XRD results in Fig. 4 and Table 2, on the other hand, showed that the compositions of the soil samples were dominated by 2:1 clay mineral species. This explains the reason why most of the soil samples plotted above the 'A' line, and that they belong to the highly plastic clayey soil varieties. According to Thomas et al. (2000), strong correlations among Atterberg limits are due to the presence of active clay minerals. Thus, the overall strong relationships among the geotechnical parameters were ascribed to the influence of the clay minerals in the presence of active clay minerals and high soil fine fraction content.

Table 5 summarized explained variances in the explanatory (X) and response (Y) spaces. The PLS model accounted for a large percentage of the original variance in the data. Two PLS factors were used. The accompanying RMSEP reached a minimum at the second PLS factor. Thus, the variation in the X-space was directly relevant to the variation in the Y-space. This direct correlation was attributed to common factors, that is, clay mineralogical composition and content, dictating the soil geotechnical parameters.

A regression overview of the actual (measured) vs. predicted EI is presented in Fig. 5. The accompanying summary of model performance indices is also shown. The final equation for estimating the EI from Atterberg limits and fine fraction is given in Eq. [1].

$$\mathrm{EI} = -73.52 + \left(0.392 \times \text{ fine fraction}\right) + \left(1.015 \times \ \mathrm{LL}\right) + \left(0.976 \times \ \mathrm{PI}\right) \qquad [1]$$

All the model terms were statistically significant at a P value of <0.05. This again indicated that the variation in the explanatory variables explained the variation in the response than could be expected due to chance, or that the effect is significant at a 5% level.

The coefficient of determination (R^2), which is a measure of the amount of variation about the mean explained by the model, was large. This showed that the model predicted the response variable well. Besides the large R^2, the RMSEP, SEP, offset, and bias were low. These also showed that the PLS regression model fitted the data appropriately.

There was no apparent deviation from linearity, detected in the PLS analysis result. Examining various plots such as the plot of U-score vs. T-score and residual plots, did not show any nonlinearity. These plots are powerful tools for detecting systematic curvatures. A scatter showing the relationship between the U-score and T-scores is presented in Fig. 6. In addition, the scatter showing the relationship between the measured and predicted expansion index values (Fig. 5), showed no nonlinear pattern in the PLS analysis result. A lack of fit test, which is important for assessing the functional part of the model, was found to be not significant; again indicating that the linear PLS model fitted the data well.

The response surfaces in Fig. 7 illustrated the general trend of the relationship among the Atterberg limits (axes PI and LL) and fine fraction with EI. It appeared that there are no sharply defined boundaries of PI, LL, or fine fraction alone for classifying soils into different expansion index classes.

DISCUSSION

Plasticity is an intrinsic property caused by the presence of active clay minerals in soils (Gourley et al., 1993; Mitchell, 1993; Seed et al., 1962; Snethen, 1975; Thomas et al., 2000; Yong and Warkentin, 1975). Thus, Atterberg limits are indicators of the mineralogical compositions of the fine particles in soils (Al-Rawas, 1999; Chen, 1988; Dakshanamurty and Raman, 1973; McCormack and Wilding, 1975; Ross, 1978; Seed et al., 1962; Skempton, 1984; Snethen, 1975; Thomas et al., 2000). Previous research established the importance of Atterberg limits in indicating soil expansion potential. While high plasticity indicates the presence of active clay minerals (Al-Mukhtar et al., 2010; Al-Rawas, 1999; Carter and Bentley, 1991; Chen, 1988; Dakshanamurty and Raman, 1973; Kariuki and Van der Meer, 2004; McCormack and Wilding, 1975; Mitchell, 1993; Nelson and Miller, 1992; Perloff and Baron, 1976; Seed et al., 1962;

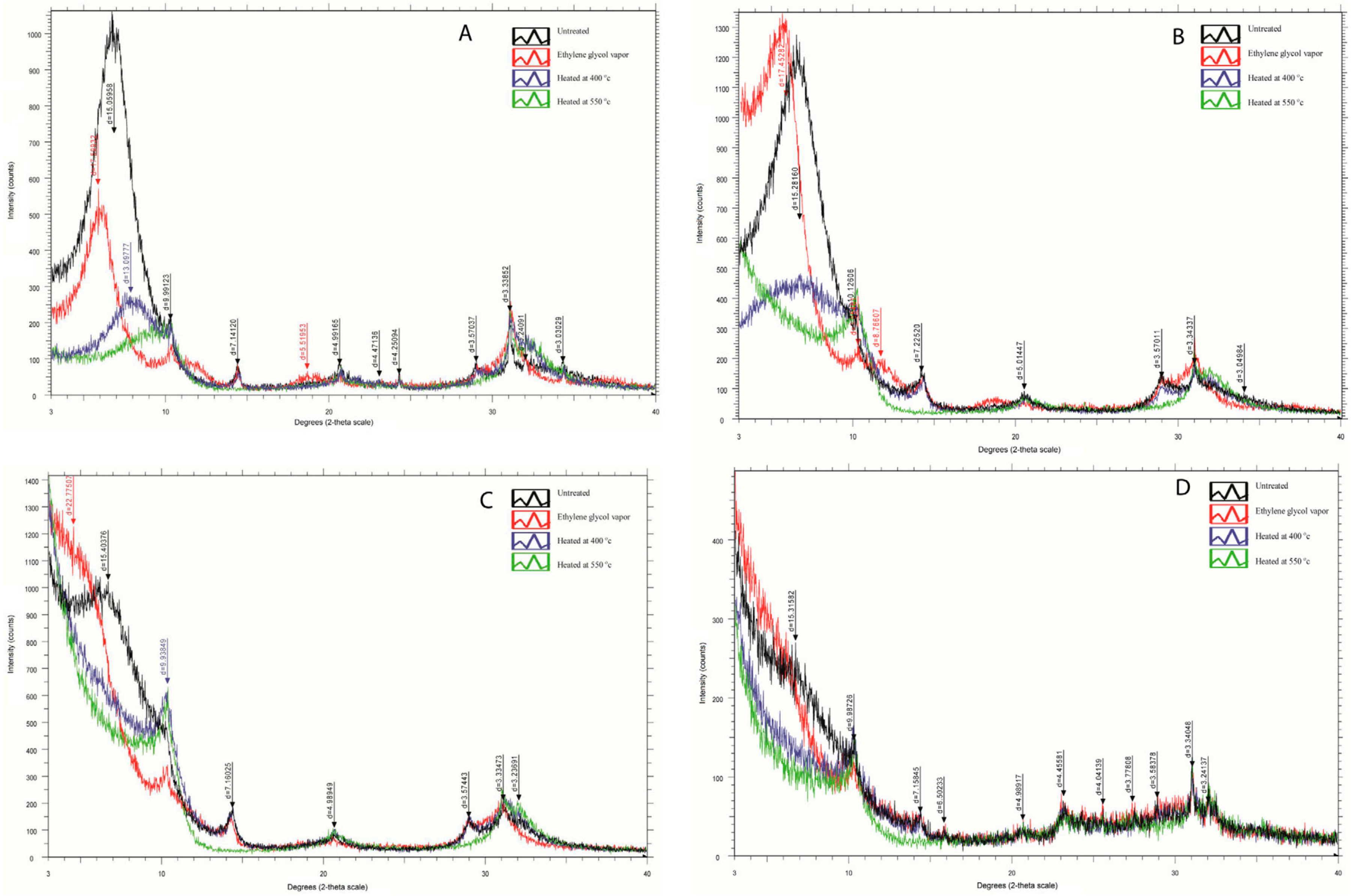


Fig. 4. X-ray diffraction (XRD) patterns of the clay fractions of four soil samples from kilometer (A) 8.5, (B) 28, (C) 57.5, and (D) 60, indicating the presence of expansive clay minerals in the soil samples.

Snethen, 1975; Thomas et al., 2000), nonplasticity often indicates an absence of such clay minerals in soils.

The fine fraction indicates the specific surface area of clay particles within a soil (Carter and Bentley, 1991; Chen, 1988; Kariuki and Van der Meer, 2004). The material passing the ASTM 0.075-mm sieve contain fine sand, silt, and clay fractions of the soil samples. The fine sand and silt fractions may have little effect on soil expansion potential, depending on their mineralogy. Clay content is as significant as Atterberg limits for assessing soil expansiveness (Carter and Bentley, 1991; Chen, 1988; McCormack and Wilding, 1975; Seed et al., 1962; Vaught et al., 2006; Wan et al., 2002). The more clay fraction a soil contains the larger is its expansion and shrinkage potential. This is due to increasing specific surface area, and thereby the water affinity (Bohn et al., 1985; Carter and Bentley, 1991; Chen, 1988; Perloff and Baron, 1976; Seed et al., 1962; Skempton, 1984).

Table 4. Pair-wise correlation matrix among the geotechnical parameters, showing significant correlations among the explanatory variables (liquid limit [LL], plasticity index [PI], and fine fraction).

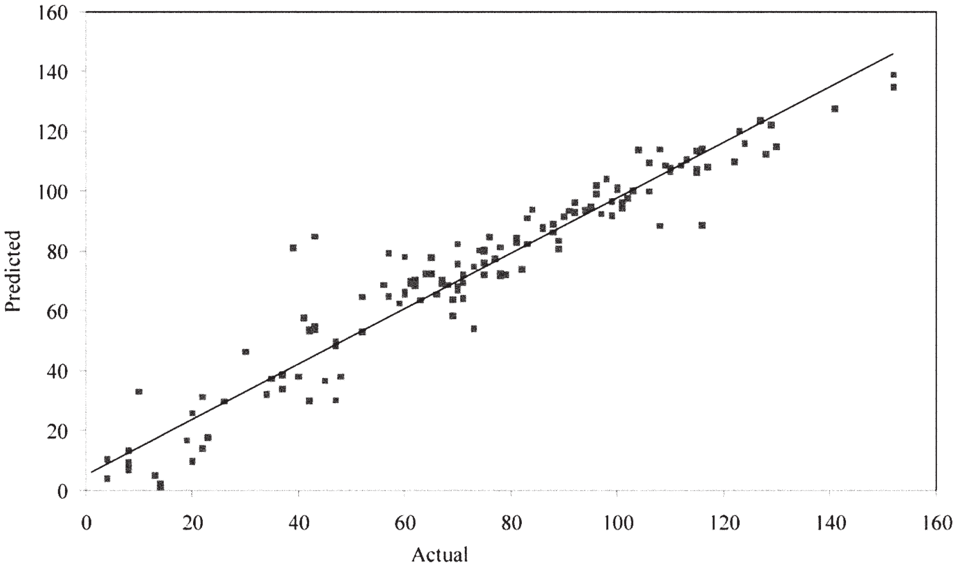
Geotechnical parameter	Fine fraction	LL	PI	EI†
Fine fraction	1			
LL	0.636**	1		
PI	0.643**	0.958**	1	
EI	0.604**	0.844**	0.930**	1

** Correlation is significant at the 0.01 (1%) probability level.

† EI = expansion index.

Table 5. Total amount of variation in the explanatory (X) variables used to explain the response (Y) variable in each partial least squares (PLS) factor used in the analysis, accompanied with root mean square error of prediction (RMSEP) after incorporating each component.

PLS factor	X-explained variance	Y-explained variance	RMSEP
	–% –		
PLS factor _1	54.9	86.4	13.24
PLS factor_2	94.3	92.4	9.87



Root mean square error of prediction (RMSEP)	9.87
Standard error of performance (SEP)	9.91
Offset	5.31
Bias	0.04
R^2	0.92

Fig. 5. Scatter plot showing the relationship between measured and predicted expansion index, with accompanying summary of model performance indices indicating that the model fits the data well and explained a large portion of the variance in expansion index of the soil samples.

The clay mineral composition is much more influential than clay content in dictating soil expansiveness. Several researchers (Al-Mukhtar et al., 2010; Al-Rawas, 1999; Karathanasis and Hajek, 1985; Kariuki and Van der Meer, 2004; Schafer and Singer, 1976; Thomas et al., 2000) demonstrated that soil expansion and shrinkage potential are primarily correlated with smectite content. Compared to their equivalent illite and kaolinite varieties, smectites can cause much more expansion in soils. Smectites have a greater specific surface area (Carter and Bentley, 1991; Ross, 1978) than illite and kaolinite. They also have an open structure which typically accommodates abundant cationic substitution (Farmer, 1974; Yong and Warkentin, 1975). Hence, the dependence of soil expansiveness on clay mineral composition is partly due to the size of the clay mineral, particularly to its specific surface area. Kaolinite, illite, and smectite, in increasing order of activity, are significant with respect to soil expansion potential (Carter and Bentley, 1991; Chen, 1988; Yong and Warkentin, 1975). The ranges of particle thickness, diameter and specific surface area of these three crystalline clay minerals are summarized in Table 6. Noncrystalline clay minerals, allophane and imogolite, are characterized by lesser particle thickness and diameter. These noncrystalline clay minerals have a larger specific surface area (Wada, 1977) than the crystalline clay minerals. Yerima et al. (1985) and Yerima et al. (1987) demonstrated that soil expansiveness depends on mineralogy and clay content. Higher concentration of low to moderately expandable clay minerals behaved similarly as those of the highly expanding clay minerals. They justified this behavior to be a function of specific surface area. Therefore, control of clay fraction on soil expansion and shrinkage potential seems to hold true within the same clay mineral varieties. However, naturally occurring soils are heterogeneous and can be mixtures

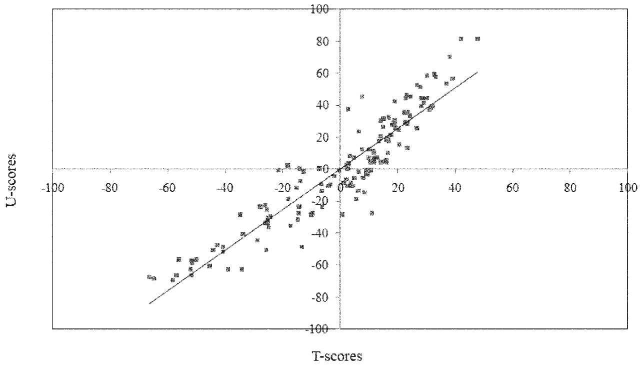


Fig. 6. Scatter plot showing the relationship between T-scores and U-scores from the partial least squares (PLS) modeling, indicating no systematic curvature (nonlinearity) in the data.

of more than one clay mineral. Thus, the increase or decrease in soil expansion potential with clay fraction may not be in direct proportion. Higher correlations among the Atterberg limits and EI (Table 4), and lower (though statistically significant) correlations of those with the fine fraction are considered indicators of the strong influence of clay mineral compositions on soil geotechnical characteristics in the presence of active clay minerals.

In the response surface models (Fig. 7), when the Atterberg limits (axes PI and LL) increased for the same amount of material passing the ASTM 0.075-mm sieve (axis Fine fraction), the EI also increased. A gradual increase was manifested for smaller fractions of material passing the ASTM 0.075-mm sieve. The increase in EI was pronounced with increasing percentage of material passing the ASTM 0.075-mm sieve. As the amount of material passing the ASTM 0.075-mm sieve increased, while the PI or LL terms were fixed, the increase in EI was faint, particularly for lower PI and LL. On the other hand, when both the amount of material passing the ASTM 0.075-mm sieve and Atterberg limits increased (for instance diagonal to axes PI or LL, and fine fraction) the EI showed a prominent increase. The increase in EI along the PI or LL axes can be attributed to possible changes in the compositions of clay minerals from low to moderate and highly expanding varieties. The faint increase in EI of soils along the fine fraction axis, when the PI and LL terms were fixed, can be a result of increasing specific surface area of clay particles probably within the same

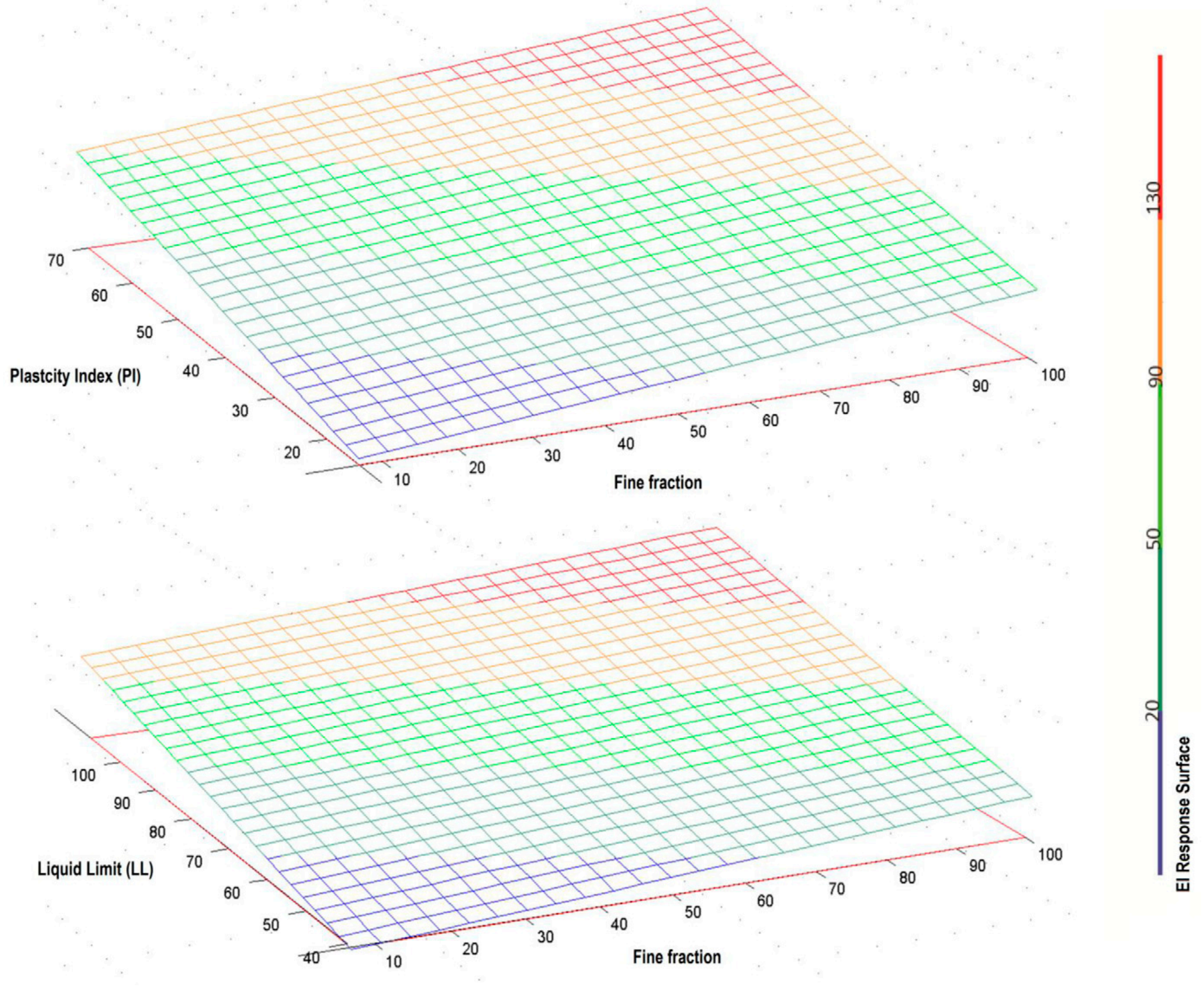


Fig. 7. Response surfaces showing the relationships among percentage of material passing the ASTM 0.075-mm sieve aperture (axis Fine fraction), plasticity index, and liquid limit, with the expansion index represented in varying colors.

clay mineral species. The prominent increase in EI, diagonal to both axes can be ascribed to changes in mineralogy as well as associated increase in specific surface area of clay particles in the soil samples. The response surfaces also illustrated the fuzziness of the soil geotechnical properties, and fuzzy membership of the combinations of these properties with respect to expansion potential. Boundaries for the ranges of each property were fuzzy, and there was a significant overlap of all terms (PI, LL, and fine fraction). It was difficult to assign exact numeric ranges of Atterberg limits and fine fraction with respect to the EI, due to these overlaps. This conforms to earlier observations by Kariuki and Van der Meer, (2004), Reddy et al. (2009), Thomas et al. (2000) who discussed uncertainties of assigning exact numeric thresholds of a single soil property for rating soil expansion potential.

Overall, the findings in this study are in agreement with those of Kariuki and Van der Meer (2004), Nelson and Miller (1992), Reddy et al. (2009), Ross (1978), Schafer and Singer (1976), Seed et al. (1962), Thomas et al. (2000), and Zapata et al. (2006), who concluded that soil expansion potential can be estimated from LL, PI, and soil fine fraction mainly clay fraction. We used fine fraction passing the ASTM 0.075-mm sieve aperture, which is a routinely performed parameter in geotechnical investigations, and easier to determine than clay content. The proposed multivariate regression model showed an improved prediction ability compared to previously proposed univariate regression models, for example, Zapata et al. (2006). In addition, the use of multiple geotechnical parameters enabled modeling the fuzzy interrelationship among the explanatory variables with respect to EI. Both the empirical relationship and response surfaces can provide a reliable estimate of expansion potential of soils. Thus, serve as guides for reliable analysis of design parameters of structures. The reported results can be extrapolated to soils of a similar nature that exist in different parts of the world, for example, soils containing expanding clay minerals derived from similar ranges of parent materials, described in Study Site.

CONCLUSIONS

The purpose of this study was to characterize soils; establish a relationship among the EI, Atterberg limits, and fine fraction passing the ASTM 0.075-mm sieve aperture; thereby proposing an empirical method for evaluating EI. The soils were mostly fine grained, with 2:1 clay minerals dominating their composition. Thus, they were characterized by high plasticity and large susceptibility to pronounced volume changes. The EI ranged from very low to very high. A strong, statistically significant correlation was obtained from the PLS regression analysis. The high coefficient of determination (R^2 of 0.92), low RMSEP (± 9.87%), narrow standard error of performance and negligible bias, showed significant model prediction ability. The fuzziness of soil geotechnical characteristics with respect to expansion potential were modeled by the response surface models, which is attributable to the use of multiple geotechnical parameters in establishing the relationship.

Table 6. Ranges of particle thickness, diameter and specific surface area of kaolinite, illite, and smectite (after Chen 1988); other sources (Yong and Warkentin, 1975) roughly indicate that illite is five times less than the size of kaolinite, and montmorillonite is 50 times less than the size of illite.

Typical properties	Kaolinite	Illite	Smectite (Montmorillonite)
Particle thickness, μ	0.5–2	0.003–0.1	<9.5 Å
Particle diameter, μ	0.5–4	0.5–10	0.05–10
Specific surface area, $m^2\ g^{-1}$	10–20	65–180	50–840

The proposed equation and presented relationships (response surfaces) can serve as classification techniques for identifying, classifying and evaluating expansion potential of soils. This can be particularly useful for preliminary assessment of soil expansion potential in an early stage of a geotechnical investigation, where availability of site information and laboratory test results are limited. The proposed multivariate relation and response surface models can be reasonably valid for other soils of a similar nature. The relations were developed from soils characterized by high LL and PI high percentage of material finer than the ASTM 0.075-mm sieve (up to a 100% with mean value of 76.7%), with most samples having high clay and organic matter content. For wider applications, the established relationship should be tested on soils with a wider range of LL, PIs, particle size distribution, and organic matter content. In general, the approach has an advantage of employing easily and routinely determined geotechnical parameters to derive information on soil expansion potential at minimal cost and time requirements.

ACKNOWLEDGMENTS

The data was kindly provided by the Ethiopian Roads Authority, ERA. The authors would like to express their deepest gratitude to Ato Bekele Negussie (Director of planning in ERA) and the authorities from the previous design and technical support branch for data provision and logistics support during fieldwork times in Ethiopia. Gondwana Engineering PLC is duly acknowledged for carrying out geotechnical tests. Thanks go to Dr. Boudewijn de Smeth of the University of Twente, faculty of Geo-information Science and Earth Observation (ITC), for kindly arranging XRD tests with SGS Canada INC. A discussion with Dr. David Rossiter and comments from anonymous reviewers were useful in improving the manuscript.

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