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Engineering Geology

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Engineering Geology 72 (2004) 1–8
ENGINEERING GEOLOGY
www.elsevier.com/locate/enggeo

A unified swelling potential index for expansive soils

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Received 25 October 2002; accepted 10 July 2003

Abstract

Soil swelling is a term generally applied to the ability of a soil to undergo large changes in volume due to increased moisture content. Several commonly used swelling potential indices, namely Atterberg limits, coefficient of linear extensibility (COLE), cation exchange capacity (CEC) tests and saturated moisture content test (SP) were used to estimate the swelling potential of a group of soil samples representing the whole range of swelling potential. Correlations between the various indices and the potential volume change were obtained and used to determine the potential of each to be included in the establishment of an expansive soil index (ESI), a summation of the indices. The outcome is a set of reliable soil-swelling indices for different levels of risk.

Keywords: Swelling soils; Expansive soil index; Clay minerals; Potential volume change

1. Introduction

One setback in classification of expansive soils has been the lack of a standard definition of swell potential (Nelson and Miller, 1992) since not only do sample conditions vary in the different swell tests (i.e. disturbed or undisturbed samples), but also testing factors over a wide range of values. Thus, whereas Holtz (1959) referred to swell potential as the volume change of air-dried undisturbed sample, Seed et al. (1962) defined it as change in volume of a remoulded sample. It is therefore not to be unexpected that disparities occur in classifications when these indices are applied, making it difficult to use one method to conclusively state the nature of the expansiveness of a soil. Many examples abound where either of the indices has been described to best represent the swelling potential. McCormack and Wilding (1975) described clay content to be as reliable in predicting swelling potential as the Atterberg limits in soils dominated by illite, but Yule and Ritchie (1980) and Gray and Allbrook (2002) reported there being no relationship between clay percentage and soil swelling. Gill and Reaves (1957) described cation exchange capacity (CEC), saturation moisture and plastic index (PI) as some of the most representative properties in the estimation of swelling potential having established them as highly correlated

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doi:10.1016/S0013-7952(03)00159-5

to the specific surface area. Snethen et al. (1977) evaluated 17 swelling indices and concluded that liquid limit (LL) and PI are the best indicators of potential swell and Parker et al. (1977) concluded swell index (Lambe, 1960) and PI as superior to other indices. Schafer and Singer (1976) on their part found clay type rather than the clay content as more important. Karathanasis and Hajek (1985), in their study, found smectite content as the only consistent soil property that significantly correlated with laboratory-measured shrink–swell potential. It therefore becomes necessary to establish ways of using these indices to obtain a relative standard of characterizing swelling potential.

Thomas et al. (2000) discussed the importance of such a method and went further to describe the need to use a combination of methods in order to obtain proper estimates of swelling potential. Others have designed classification schemes based on two or three indices where discrete thresholds are used to group the soils into swelling potential, among them are Pearring (1963) and Holt (1969) who developed classification schemes, which combine engineering properties and cation exchange capacities to classify soils in terms of swelling potential and the dominant clay minerals. McKeen and Hamberg (1981) and Hamberg (1985) extended these concepts to obtain new schemes to include coefficient of linear extensibility (COLE) and later Thomas et al. (2000) used summation of indices to obtain three swelling potential indices to characterize sites.

These works provide an insight into the importance of using combinations of available measurements, i.e. physical/chemical, and mineralogical in classifying the soil vulnerability to swelling and highlights the complexity of swelling potential estimation. We propose to integrate the works of Hamberg (1985) with those of Thomas et al. (2000) where we use the clay content as a normalizing parameter to the establishment of singular expansive soil indices (ESI) dependent on the available indices for swell potential ratings at building sites.

2. Materials and methods

2.1. Sampling sites selection

Sampling sites were carefully selected based on three physiographic zones of the study area (Table 1) and falling in the humid, sub-humid and semi-arid tropical climatic regions (Scott, 1963), with samples collected to properly represent a wide variation in swelling properties and different parent materials consisting mainly of volcanic rocks and basement system rocks. The samples consisted mainly of kaolinite and smectites as the dominant clay minerals dependent on the zone.

Table 1
Soil classifications (FAO, 1998), parent material and average swelling potential of selected soil series

Physiographic zones	Parent material	Classification	Swell potential
High ground (volcanics)	Tuffs, trachytes	Kaolinitic, Nitisols, and Ferrasols	Low
Plains	Tuffs, trachytes, phonolites	Smectitic, Vertisols	High
High ground (basement rocks)	Granitoid gneiss, undifferentiated gneiss	Kaolinitic, Acrisols, Luvisols and Ferrasols	Low

2.2. Laboratory analysis

The samples were sieved to remove coarse fragments >2 mm prior to analysis for the various indices. Table 2 provides a summary of the applied methods and the obtained soil properties (swelling indices). The Atterberg limits (PL, PI, LL) were measured by BS1377: Part 2:1990 method (Head, 1992), PSD was through the pipette method (Reeuwijk, 1995), while CEC was through NH_4OAc pH 7 mechanical extractor (Reeuwijk, 1995) and the methylene blue absorption spot test methods (Verhoef, 1992). Exchangeable bases were estimated by the atomic absorption spectrometer method while COLE was by the clod test method (Nelson and Miller, 1992) and SP was calculated as the difference in weight between saturation and oven dry state. Skempton (1953), Pearring (1963) and Holt (1969) methods of using clay content to normalize PI and CEC were used to obtain Activity (A_c) and cation exchange activity (CEA_c), respectively. A similar procedure was used to obtain the linear extensibility percentage due to the clay (LEP_c) from COLE and Saturated standard moisture (SSP) from the SP. The COLE value was also converted to a potential volume change (PVC) index as per the

Table 2
Soil properties measured and the methods used

Soil property	Method	Reference
CEC (sum of cations)	NH_4OAc pH 7 (mechanical extractor method) and methylene blue spot method	Reeuwijk, 1995; Verhoef, 1992
pH-H_2O	pH measures at 1:1 soil/water suspension	Reeuwijk, 1995
Particle-size distribution (PSD)	Pipette method (%)	Reeuwijk, 1995
Coefficient of linear extensibility (COLE)	COLE clod procedures	Nelson and Miller, 1992
Exchangeable bases: Ca, Mg, Na, and K	Atomic absorption spectrophotometer	Reeuwijk, 1995
Saturated moisture content	Saturation and oven drying at 105 °C	
LL, PI, PL	BS1377: Part 2: 1990 method	Head, 1992

method of Parker et al. (1977). The PVC was assumed to be near ideal representation of the natural volume changes due to the preserved structure resulting from the relatively undisturbed nature of the clod and the ideal pressure under which the clods were saturated.

2.3. Statistical analysis

Correlation and regression are useful statistical techniques to identify related variables. Correlation compares individual variables with one another and calculates estimates of the strength, or magnitude, of the statistical relationship and is used in this study. Pearson's correlation coefficients of the relationships between the various properties indices and the obtained PVC were used to select the most significant normalized indices for inclusion in a unified Expansive Soil rating (ESI).

3. Results

The soil samples consisted of a wide range of swelling potential levels. Soils grouping in the low swelling category were generally of orange, brown to reddish color, interpreted to reflect high contents of iron oxides due to high levels of weathering and good drainage. They had kaolinite as the dominant clay mineral and were those from zones 1 and 3. High swelling samples were gray dark gray to black in colour and were all from the physiographic zone 2 in low lying plains with restricted drainage and were smectitic. Soils with inter-mediate swelling potential consisted of both varieties but mostly along the footslopes of zone 1 and some from young volcanic soils of shallow depth in zone 2 where the soil depth was less than 30 cm.

Table 3 gives the statistics of the various measured soil properties showing the samples to consist of a wide range of clay contents (3% and 82%) but a mean of 45% and thus the soil population could be described to be mainly of a clay texture. The means of the Atterberg limits (the LL, PL and PI) and saturated moisture contents were also high.

Liquid limit was highest in the plain soils, low to moderate in the volcanic (zone 1) and low in the basement (zone 3) soils. This was assumed to reflect the trend in smectite content and to show some

Table 3
Statistics (sample size, mean, and the range) of the properties in the used soil

Soil property	n	Mean	Minimum	Maximum	Standard deviation
CEC, meq/100 g	47	36	4	60	13
COLE	47	0.089	0.014	0.195	0.05
Saturated moisture (%)	47	56	26	91	17.2
Liquid limit (%)	47	53	24	82	15
Plastic limit (%)	47	29	15	40	6.3
Plastic index (%)	47	24	10	47	9.1
Activity	47	0.641	0.196	1.422	0.27
Cation activity	47	0.405	0.052	1.141	0.25
% Volume change	47	29	16	67	14.9
pH (H_2O)	47	6	5	9	0.82
	47				
Clay (%)	47	45	3	82	17.6
Silt (%)	47	20	2	48	11
Sand (%)	47	32	6	91	17.7
Exchangeable base	47				
Ca	47	13.12	0.14	39.5	12.9
Mg	47	3.712	0.118	12.69	3.4
Na	47	0.671	0.04	2.466	0.63
K	47	1.15	0.02	4.55	0.95

Table 4
Correlation between estimated percentage volume change and swelling potential indices

Correlations (*r*)	Percent volume change (PVC)
Plasticity index (PI)	0.71
Liquid limit (LL)	0.77
Plastic limit (PL)	0.66
Cation exchange capacity (CEC)	0.84
Saturated moisture (SP)	0.75
% Clay	0.25
Na^+	0.03
K^+	0.23
Ca^{2+}	0.77
Mg^{2+}	0.69
CEA_c	0.72
A_c	0.65

influence from the clay content. Plasticity index followed the same trend giving an indication that soil with high layer charges can retain plasticity over a wider moisture range than their counterparts with less layer charge. The saturated paste average was also significantly high showing similarity with the liquid limit obtained averages.

Average CEC was significantly high with a dynamic range, between 6% and 60%. Ca^{2+} and Mg^{2+} were dominant as the exchangeable bases with the Ca^{2+} average slightly higher. Na^+ and K^+ averages were low. The pH ranged between moderately acidic (5.0) to alkaline (9) though with an average of slightly acidic, whereas organic matter was generally low (0.5–6%).

Table 4 gives the relationships between the measured soil properties and the estimated PVC. There was strong correlation with some (CEC, PI, LL, SP, Mg^{2+} and Ca^{2+}), portraying them as good in its estimation. The others, i.e. the clay content, pH and the exchangeable bases Na^+ and K^+ gave poor correlations. The poor predictive power of clay content in particular contradicts findings by McCormack and Wilding (1975) who described it as the important in potential volume change estimations though it probably vindicates observations by Parker et al. (1977) of the clay type rather than content to determine the PVC. The exchangeable Na has also been described as good in the estimation of swelling potential (Anderson et al., 1973) but was in this case found to be a poor estimator, a fact that probably

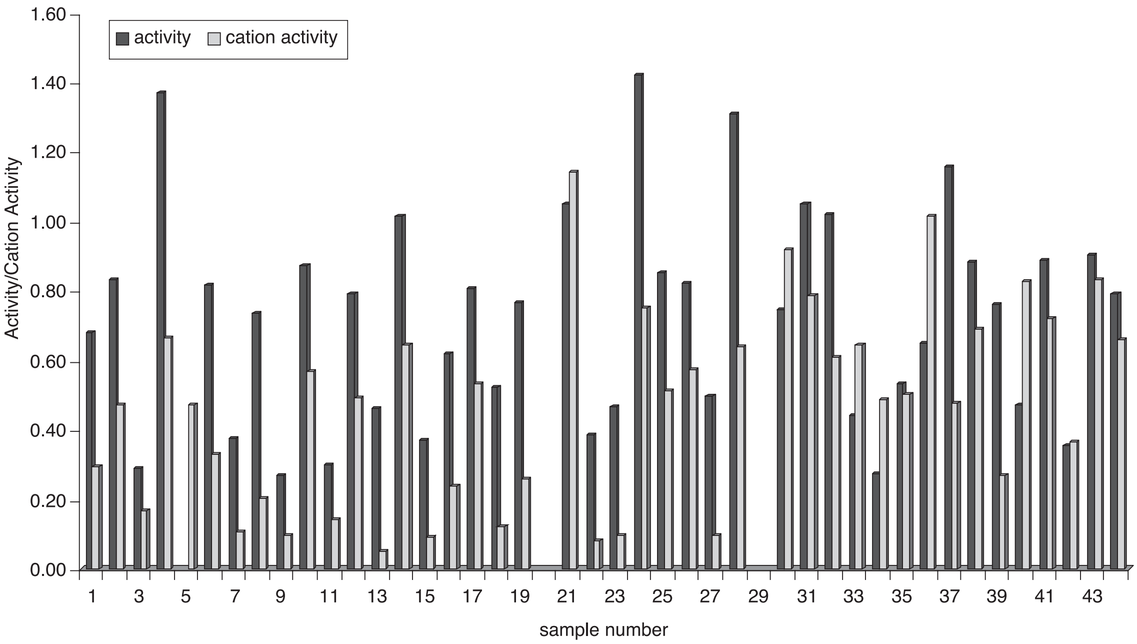

Fig. 1. Discrepancies in classifications based on activity and cation activity.

further show the difficulties in universally applying one particular method, emphasizing instead the need to use a combination of indices to draw meaningful conclusions.

The normalized properties, which provided indices based on the activity of clay content, gave generally good correlations with the PVC though not necessarily improving significantly the originally obtained indices (Table 4) but having the added advantage of probably giving information on a more fundamental relative difference among the soils and generally described to be the driving force behind soil swelling, the clay type (Carter and Bentley, 1991). Skempton (1953) established activity to change little in the presence of a particular clay mineral type and Pearring (1963) and Holt (1969) found the cation exchange activity to be important in assignment of a soil to a dominant clay type.

Overestimation/underestimations occur in single index classifications (Shepherd and Markus, 2002). Figs. 1 and 2 give examples of such discrepancies where Fig. 1 shows activity to overestimate the swelling potential relative to cation activity based on Hamberg (1985) thresholds of >0.5 for high, 0.2–0.5 for moderate and <0.2 for low swelling classes. Fig. 2 shows similar discrepancies between SP and LL, which theoretically should be close since they represent the point of change from plastic to liquid phase. To overcome this, combination of the indices could be used to establish thresholds of high, moderate and low swelling potential classes, as is the case in Table 5 based on normalized indices, thus providing a tool with a potential to establish a more reliable classification.

Table 5
Modified Nelson and Miller (1992) swell potential and clay mineral type allocation

Activity	Cation activity	LEP	SSP	Swell potential class	Mineral assignment
>0.5	>0.5	>0.15	>1.0	High	Smectite >50%
0.3–0.5	0.3–0.5	0.05–0.15	0.5–1.0	Moderate	Mixed minerals or Illite >25%
<0.3	<0.3	<0.05	<0.5	Low	Kaolinite >50%

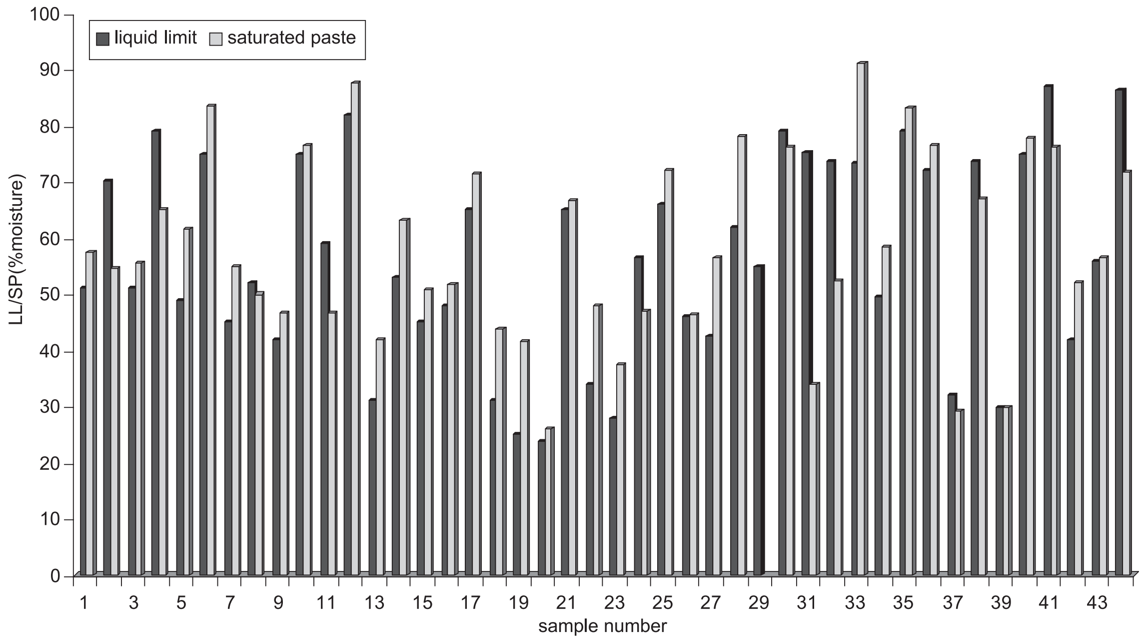

Fig. 2. Discrepancies in saturated paste and liquid limit classifications.

Table 6
Classification thresholds based on ESI

ESI-1	ESI-2	ESI-3	Rating	Mineralogy
< 1.15	< 1.10	< 0.5	Low	Kaolinite
1.15–2.15	1.1–2.0	0.5–1.0	Moderate	Illite/mixed layer minerals
>2.15	>2.0	>1.0	High	Smectites

3.1. Proposed unified expansive soil index

By using the concepts of Thomas et al. (2000) of summation, and that of Hamberg (1985) for normalization, unified swelling potential ratings (ESI) (Table 6) were obtained:

$$\mathrm{ESI}-1 = A_c + \mathrm{CEA}_c + \mathrm{SSP} + \mathrm{LEP}_c \quad (1)$$

$$\mathrm{ESI}-2 = A_c + \mathrm{CEA}_c + \mathrm{SSP} \quad (2)$$

$$\mathrm{ESI}-3 = \mathrm{SSP} \quad (3)$$

These indices reflect the number of available measurements and should be used for different levels of risk estimation with the third index used as a fast reconnaissance field index and the first for more elaborate site investigation. Due to the lack of measurements on LEP_c in most cases, the alternative ESI-2 and ESI-3 could be used and were highly correlated with ESI-1. Fig. 3 shows the relationship between ESI-1 and ESI-2 that shows it to well represent the obtained swell rating. Table 7 gives the correlations between the two ESI ratings in which the PVC parameter was not used, and PVC and shows them to be good in its estimation. The indices not only show a standardized swelling potential index but also a potentially less expensive method to identify the dominating clay mineral type.

Table 7
Correlations between PVC and ESI indices

Correlations coefficients (*r*)	Percent volume change (PVC)
ESI-2	0.79
ESI-3	0.81

4. Discussion

This method presents a reliable way of estimating the swelling potential of soils based on a combination of usually readily available soil property data in soil science databases. Disparities among the indices in their predictive powers show the need to use their combinations where possible in order to obtain more representative swelling potential index.

The strong correlations between the PVC and a select group of the indices and poor correlations with others among which was the clay content show the central role played by the clay mineral type and the variability of the methods in different soils, thus showing the need to use more than one method in

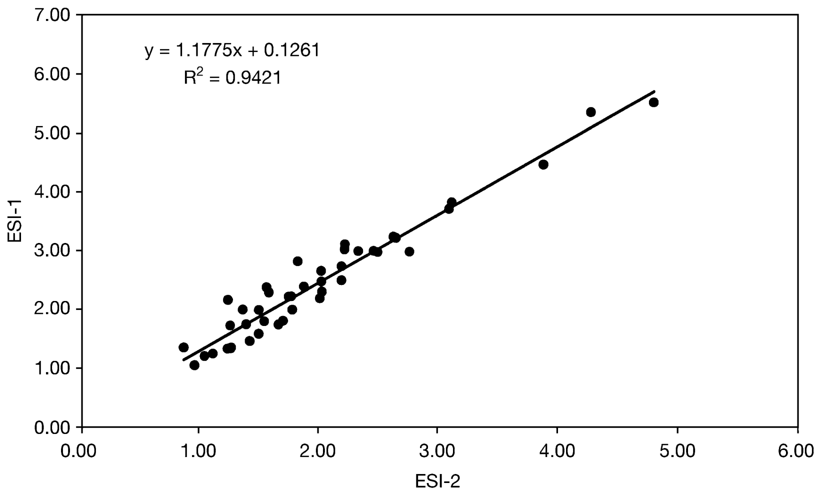

Fig. 3. Relationship between ESI-1 and ESI-2 showing significant correlation.

drawing conclusions as to the swelling potential level of a soil. The fact that the most highly correlated indices were those closely associated with clay type (CEC, PI, SP and LL) is an indicator of the central role played by the dominant clay type in determining the resulting potential volume change. Ben-Dor et al. (1999) described the affinity of water in soils to vary with clay type and to decrease in the order smectite>illite>kaolinite due to variation in the specific surface area which Thomas et al. (2000) reported to be highly correlated to these indices. Yule and Ritchie (1980) described CEC to integrate the amount and activity of clay present in a soil and Amer and Al-Rawas (1999) described active clays to have greater influence on the swelling behaviour than any other factor describing smectites as the most active and responsible for swelling problems.

Relatively strong correlation with divalent exchangeable cations (Ca^{2+} and Mg^{2+}) and lack of it for monovalent (Na^{+} and K^{+}) cations contradicts reported strong correlation between exchangeable sodium (Al-Rawas, 1999) and COLE, instead it confirms the observed lack of relationship by Gray and Allbrook (2002). Though the normalized indices do not drastically improve the relationships for the various indices, they probably present more universally applicable indices based on their associated assignment to a fundamental soil property, the clay mineralogy (Franzmeier and Ross, 1968; Parker et al., 1977). Carter and Bentley (1991) described activity to change little for each clay type and the activity values assigned to the various clay minerals to hold true not only for the minerals but soils in which they form the clay fraction. This makes the proposed combination not only fundamentally based but also reliable by providing a useful tool for establishing compositional differences among soils.

5. Conclusions

The results show soils swelling potential to be mainly dependent on the clay type and thus indices indicative of the clay type would generally be good in the establishment of a unified expansive index. The normalized indices gave a more fundamental way of characterizing the soil swelling potential by providing indication as to the dominant clay mineral type and thus a universally applicable index due to the generally little variation in such indices among the clay minerals. The results also show some of the commonly measured soil properties, readily available in most soil science databases, such as CEC, saturation moisture content and clay content when used in combination to lead to reliable estimates of the swelling properties.

Acknowledgements

The authors wish to thank the Netherlands government for providing the funds to carry out the research. They wish to acknowledge the laboratory staff of the Delft technical University for their help in the laboratory mechanical tests and also Iraj Manucherri and de Smeth for their assistance in the wet chemistry analysis at the ITC, laboratory Enschede. They also wish to thank the two anonymous reviewers for their positive criticism in making the manuscript better for a wider audience.

References

Al-Rawas, A.A., 1999. The factors controlling the expansive nature of the soils and rocks of northern Oman. Eng. Geol. 53, 327–350.

Anderson, J.U., Elfadil, F.K., O'Connor, G.A., 1973. Factors affecting the coefficient of linear extensibility in Vertisols. Soil Soc. Am. J. 37, 298–299.

Ben-Dor, E., Irons, J.R., Epema, G.F., 1999. Soil reflectance. Remote Sensing for the Earth Science, 3rd ed. Manual of Remote Sensing, vol. 3.

Carter, M., Bentley, S.P., 1991. Correlations of Soil Properties. Pentech Press, London, UK.

Franzmeier, D.P., Ross Jr., S.J., 1968. Soil swelling: laboratory measurements and relation to other soil properties. Soil Sci. Soc. Am. Proc. 32, 573–577.

Gill, W.R., Reaves, C.A., 1957. Relationships of Atterberg limits and cation-exchange capacity to some physical properties of soil. Soil Sci. Soc. Am. Proc. 21, 491–494.

Gray, C.W., Allbrook, R., 2002. Relationships between shrinkage indices and soil properties in some New Zealand soils. Geoderma 108 (3–4), 287–299.

Hamberg, D.J., 1985. A simplified method for predicting heave in expansive soils. MS thesis, Colorado State University, Fort Collins, CO, USA.

Head, K.H., 1992. Manual of Soil Laboratory Testing, 2nd ed., vol. 1. Pentech Press, London.

Holt, J.H., 1969. A study of physico-chemical, mineralogical and engineering index properties of fine grained soils in relation to their expansive characteristics. PhD Dissertation, Texas A&M Univ., College Station, TX, USA.

Holtz, W.G., 1959. Expansive clays—properties and problems. Q. Colo. Sch. Mines 54 (4), 89–117.

Karathanasis, A.D., Hajek, B.F., 1985. Shrink–swell potential of montmorillonitic soils in udic moisture regimes. Soil Sci. Soc. Am. J. 49, 159–166.

Lambe, T.W., 1960. The Character and Identification of Expansive Fed. Housing Admin. Rep. 701. U.S. Gov. Print. Office, Washington, DC.

McCormack, D.E., Wilding, L.P., 1975. Soil properties influencing swelling in Canfield and Geeburg soils. Soil Sci. Soc. Am. Proc. 39, 496–502.

McKeen, R.G., Hamberg, D.J., 1981. Characterization of expansive soils. Transportation Research Record, vol. 790. Transportation Research Board, USA, pp. 73–78.

Nelson, J.D., Miller, D.J., 1992. Expansive Soils: Problem and Practice in Foundation and Pavement Engineering. Wiley, New York.

Parker, J.C., Amos, D.F., Kaster, D.L., 1977. An evaluation of several methods of estimating soil volume change. Soil Soc. Am. J. 41, 1059–1064.

Pearring, J.R., 1963. A study of basic mineralogical, physical–chemical, and engineering index properties of laterite soils. PhD Dissertation, Texas A&M Univ., College Station, TX, USA.

Reeuwijk, L.P., 1995. Procedures for soil analysis, Technical paper 9. International Soil Reference and Information Centre, The Netherlands.

Schafer, W.M., Singer, M.J., 1976. Influence of physical and mineralogical properties on swelling of soils in Yolo County, California. Soil Sci. Soc. Am. J. 40, 557–562.

Scott, R.M., 1963. The soils of the Nairobi–Thika–Yatta–Machakos area. DOS for Kenya Government.

Seed, H.B., Woodward Jr., R.J., Lundgren, R., 1962. Prediction of swelling potential for compacted clays. J. Soil Mech. Found. Div., Am. Soc. Civ. Eng. 88 (SM3), 53–87.

Shepherd, K.D., Markus, G.W., 2002. Development of reflectance spectral libraries for characterization of soil properties. Soil Sci. Soc. Am. J. 66, 988–998.

Skempton, A.W., 1953. The colloidal activity of clay. Proceedings of the Third International Conference on Soil Mechanics and Foundation Engineering, London, vol. I, pp. 57–61.

Snethen, D.R., Johnson, L.D., Patrick, D.M., 1977. An evaluation of expedient methodology for identification of potentially expansive soils. Soil and Pavements Laboratory, U.S. Army Eng. Waterway Exp. Sta., Vicksburg, MS, Rep. No. FHWA-RE-77-94, NTIS PB-289-164.

Thomas, P.J., Baker, J.C., Zelazny, L.W., 2000. An expansive soil index for predicting shrink–swell potential. Soil Sci. Soc. Am. J. 64, 268–274.

Verhoef, P.N.W., 1992. The methylene blue adsorption test applied to geomaterials. Memoirs of the Centre of Engineering Geology in the Netherlands, Delft, vol. 101.

Yule, D.F., Ritchie, J.T., 1980. Soil shrinkage relationships of Texas vertisols: 1 small cores. Soil Sci. Soc. Am. J. 44, 1285–1291.