

# Quantifying Properties and Variability of Expansive Soils in Selected Map Units

by

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(ABSTRACT)

A study of 12 expansive soils in four major physiographic provinces in Virginia was initiated to examine and quantify the relationship between shrink-swell potential, shrink-swell indices, and soil properties. The *mineralogy classes*, soil series, and (physiographic provinces, parent materials) examined include *smectitic* -- Jackland and Waxpool (Triassic, diabase), Iredell (Piedmont, hornblende); *vermiculitic* -- Kelly (Triassic, thermal shale); *kaolinitic* -- Cecil (Piedmont, granite gneiss), Davidson (Triassic, diabase); and *mixed* -- Carbo and Frederick (Valley and Ridge, limestone), Craven and Peawick (Coastal Plain, fluvial and marine sediments), and Mayodan and Creedmoor (Triassic, sandstones). Three sites in each of the 12 map units were described and major horizons sampled for physical, chemical, and mineralogical laboratory analysis. An expansive soil rating system, termed the *Expansive Soil Index (ESI)*, was developed using the soil properties best correlated with shrink-swell potential. The sum of swelling 2:1 minerals, swell index, liquid limit, and CEC gave expansive soil potential ratings (ESI) for each soil series. The higher the ESI, the greater the shrink-swell potential.

Smectite distributions within the soil profiles were investigated. Smectite concentration in the clay fraction increases with depth in soils formed from diabase and thermally altered shale. Smectite weathers to kaolinite and hydroxy-interlayered vermiculite with increasing proximity to the soil surface thus accounting for the observed decrease in smectite toward the soil surface. The highest amount of smectite from the granite gneiss, limestone, sandstones and shales, and Coastal Plain sediments were in the Bt2 horizon where maximum expression of the argillic horizon occurs. Smectite contents decrease away (upwards and downwards) from the maximum in the Bt2 horizon.

A satellite study focused on locating and quantifying the variability within five map units in the Culpeper (Triassic) Basin in northern Virginia. Variability of the shrink-swell indices and related properties are high in all map units. Dissimilar inclusions could adversely affect foundations if a home is sited on both moderate and high shrink-swell soils. Although there is extreme variability in the map units, the variability occurs within the delineations of each map unit. Each delineation within an individual map unit contains similar levels of variability.

## **DEDICATION**

to my elementary and high school science teachers

**Victor Bridges**

and

**Jeannette Sparks Williams**

for cultivating my observation skills

and igniting my zeal for science

# Table of Contents

Abstract .....	ii
Dedication .....	iii
Table of Contents .....	iv
List of Tables .....	vii
List of Figures .....	viii
Acknowledgments .....	ix
<b>Chapter 1. Introduction .....</b>	<b>1</b>
<b>Chapter 2. Literature Review .....</b>	<b>4</b>
2.1. CLAY MINERALS .....	5
2.1.1. General Overview of Clay Minerals .....	5
2.1.2. Smectites .....	6
2.1.3. Smectite Occurrence .....	7
2.1.4. Transformation and Formation in Soils .....	8
2.2. MECHANICS OF CLAY SWELLING .....	10
2.2.1. Theoretical Aspects .....	10
2.2.2. Water Retention .....	11
2.3. METHODS OF MEASURING SHRINK-SWELL POTENTIAL .....	12
2.3.1. Indirect Measurements .....	12
2.3.2. Direct Measurements .....	15
2.4. DESIGN AND TREATMENT METHODS .....	16
2.4.1. Foundation and Structure Design .....	16
2.4.2. Treatment of Expansive Soils .....	18
2.4.3. Remedial Measures .....	19
2.5. REFERENCES .....	20
<b>Chapter 3. An Expansive Soil Index for Predicting Shrink-Swell Potential .....</b>	<b>26</b>
3.1. ABSTRACT .....	27
3.2. INTRODUCTION .....	27
3.3. MATERIALS AND METHODS .....	29

3.3.1.	Study Design . . . . .	29
3.3.2.	Laboratory Analysis . . . . .	30
3.3.3.	Statistical Analysis . . . . .	31
3.4.	RESULTS AND DISCUSSION . . . . .	31
3.4.1.	Soil Properties . . . . .	31
3.4.2.	Correlation of Shrink-Swell Properties . . . . .	36
3.4.3.	Expansive Soil Index . . . . .	37
3.4.4.	Parent Material Correlation with Shrink-Swell Indices . . . . .	39
3.5.	CONCLUSIONS . . . . .	39
3.6.	REFERENCES . . . . .	41
<b>Chapter 4.</b>	<b>Distribution of Swelling Soils in Virginia as Influenced by Parent Material and Shrink-Swell Potential . . . . .</b>	<b>43</b>
4.1.	ABSTRACT . . . . .	44
4.2.	INTRODUCTION . . . . .	45
4.3.	MATERIALS AND METHODS . . . . .	46
4.3.1.	Study Design . . . . .	46
4.3.2.	Laboratory Analysis . . . . .	47
4.4.	RESULTS AND DISCUSSION . . . . .	48
4.5.	CONCLUSIONS . . . . .	53
4.6.	REFERENCES . . . . .	55
<b>Chapter 5.</b>	<b>Quantifying the Relationship Between Shrink-Swell Indices and Soil Properties of Expansive Soil Map Units . . . . .</b>	<b>57</b>
5.1.	ABSTRACT . . . . .	58
5.2.	INTRODUCTION . . . . .	58
5.3.	MATERIALS AND METHODS . . . . .	60
5.3.1.	Geology . . . . .	60
5.3.2.	Study Area . . . . .	61
5.3.3.	Study Design . . . . .	62
5.3.4.	Laboratory Analysis . . . . .	62

5.3.5. Statistical Analysis . . . . .	63
5.4. RESULTS AND DISCUSSION . . . . .	63
5.4.1. Variability of Shrink-Swell Indices . . . . .	63
5.4.2. Map Unit Composition . . . . .	66
5.4.3. Map Unit Variability . . . . .	66
5.4.4. Prediction of Swell Index . . . . .	68
5.5. CONCLUSIONS . . . . .	69
5.6. REFERENCES . . . . .	71
<b>Chapter 6. Conclusions . . . . .</b>	<b>73</b>
<b>Chapter 7. Summary . . . . .</b>	<b>78</b>
<b>Appendix A. PROCEDURES AND DATA . . . . .</b>	<b>80</b>
A.1. Laboratory procedures . . . . .	81
A.2. Morphological and site descriptions, physical, chemical, and mineralogical soil property data . . . . .	84
A.3. Specific surface areas . . . . .	180
A.4. X-ray diffraction patterns . . . . .	182
A.5. EXPANSIVE SOIL INDEX DIAGRAM . . . . .	186
A.6. STUDY LOCATIONS . . . . .	187
<b>Appendix B. The Unified Soil Classification chart: Relationship between swell index and Atterberg limits . . . . .</b>	<b>188</b>
<b>Vita . . . . .</b>	<b>191</b>

# List of Tables

## Chapter 2

Table 2.1. Chemical composition and layer charge of representative clay minerals . . . . .	6
Table 2.2. Idealized formulas for smectites . . . . .	6

## Chapter 3

Table 3.1. Classification and estimated shrink-swell potential of selected soil series . . . . .	30
Table 3.2. Correlation coefficients for soil properties . . . . .	37
Table 3.3. Expansive soil indices . . . . .	38
Table 3.4. Shrink-swell potential risk of soils as related to parent material . . . . .	40

## Chapter 4

Table 4.1. Classification and estimated shrink-swell potential of soil series . . . . .	47
Table 4.2. Identification and quantification of clay mineral suites (<2 $\mu\text{m}$ ) . . . . .	49
Table 4.3. Identification of sand mineral fractions (0.1 - 0.5 mm) . . . . .	51

## Chapter 5

Table 5.1. Average, minimum, and maximum values and coefficient of variability of map units for selected shrink-swell indices . . . . .	64
Table 5.2. Composition of soil map units . . . . .	67
Table 5.3. Probability and percent total variation contributed by map units, delineations, and profiles of swell index and properties correlated with swell index . . . . .	67
Table 5.4. Correlations (R) between soil properties and swell index . . . . .	69

# List of Figures

## Chapter 3

Figure 3.1.	Relationship between clay content and estimated shrink-swell class . . . . .	32
Figure 3.2.	Relationship between CEC and estimated shrink-swell class . . . . .	32
Figure 3.3.	Relationship between liquid limit and estimated shrink-swell class . . . . .	33
Figure 3.4.	Relationship between plasticity index and estimated shrink-swell class . . . . .	34
Figure 3.5.	Relationship between COLE and estimated shrink-swell class . . . . .	35
Figure 3.6.	Relationship between swell index and estimated shrink-swell class . . . . .	35
Figure 3.7.	Relationship between swelling 2:1 mineral content and estimated shrink-swell class . . . . .	36

## Chapter 5

Figure 5.1.	Study area in Culpeper Basin, Fauquier County, VA. . . . .	61
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# CHAPTER 1

## Introduction

Expansive soils, or shrink-swell soils, cause billions of dollars of damage to in the United States each year, second only to insect damage (Krohn and Slosson, 1980). Once thought to be a problem only in arid and semi-arid vertic soils, shrink-swell damage has become a significant concern in clayey Alfisols and Ultisols in the humid southeastern United States. Concrete basement walls will move and floors will crack because of this phenomenon. Heaving by swelling soils can also cause slope failures, roads to buckle, driveways to shift, and structural walls can collapse.

No one method of soil analysis estimates shrink-swell potential accurately for all soils. Soil scientists recognize that shrink-swell behavior can be predicted by examining a combination of physical, chemical, and mineralogical properties. Determining these properties and establishing a shrink-swell model that can be extrapolated across the same or similar parent materials is needed.

This research focused on defining and quantifying the soil properties correlated with shrink-swell potential for 12 major benchmark soils in four physiographic provinces in Virginia. This dissertation is a collection of three research projects examining different aspects of identifying shrink-swell soil behavior each based on a separate set of objectives. The objectives of each project are:

Chapter 3. Quantify properties and shrink-swell indices of 12 expansive soils in four major physiographic provinces in Virginia; correlate shrink-swell potential with soil properties and shrink-swell indices; develop an expansive soil rating system using soil properties correlated with shrink-swell potential; and develop shrink-swell risk categories for soils within different parent materials.

Chapter 4. Identify and quantify distribution of swelling clay minerals within soil profiles in 12 expansive soils.

Chapter 5. Obtain quantitative estimates of shrink-swell indices and soil properties of 5 expansive soils in the Culpeper Basin; partition variability into map unit components, i.e., among map units, between

delineations within a map unit, between profiles within a delineation;  
and determine best predictors or indicators of shrink-swell potential.

# **CHAPTER 2**

# Literature Review

## 2.1. CLAY MINERALS

### 2.1.1. General Overview of Clay Minerals

Charge distribution and cation species determine the swell potential of a soil clay mineral. Clay minerals have a net permanent negative charge (layer charge) resulting from vacancies or solid state substitutions of cations in the tetrahedral and octahedral layers (Table 2.1). *Kaolinite*, a 1:1 phyllosilicate, has very little tetrahedral or octahedral substitution. Low charge afforded by low substitution is enhanced by hydrogen bonding between the tetrahedral and octahedral layers. This bonding holds 1:1 layers tightly together leaving little to no interlayer space for adsorption of cations or water (Dixon, 1989). Thus, kaolinite is a non-expansive mineral. *Mica* is a 2:1 clay mineral with extensive solid state substitution of  $\text{Al}^{3+}$  for  $\text{Si}^{4+}$  in the tetrahedral layers. This substitution gives mica a layer charge of about 2. Non-hydrated  $\text{K}^+$  binds adjacent tetrahedral layers because it is of the correct size and coordination to occupy the “holes” in the tetrahedral layer electrostatically cementing the adjacent layers (Fanning et al., 1989). Although mica has a high layer charge, the tight bonding afforded by the K causes the mica to behave similarly to a kaolinite. The layers are bound together tightly allowing for little to no interlayer space for adsorption of cations or water. Thus, mica is a non-expansive mineral. *Vermiculite* does not have as much tetrahedral substitution of  $\text{Al}^{3+}$  for  $\text{Si}^{4+}$  as does mica and thus has a layer charge of 1 to 2 (Douglas, 1989). As a result, the interlayers of vermiculite are accessible to both cations and water. However, interlayer expansion is limited because vermiculite can adsorb only two layers of water. Conversely, montmorillonite, is a highly expansive mineral. Most of the ionic substitution occurs in the octahedral layer, giving smectites a lower layer charge than vermiculite averaging about 0.5 to 1. The charge density decay resulting from the distance between the octahedral substitution and the interlayer gives montmorillonite the potential to adsorb many layers of water (Borchardt, 1989). Soils with high Al contents, including most soils in the southeastern U.S., have *hydroxy-interlayered vermiculite* (HIV) or *hydroxy-interlayered smectite* (HIS) as dominant clay minerals. These minerals possess very little potential to shrink and swell (Barnhisel and Bertsch, 1989).

**Table 2.1. Chemical composition and layer charge of representative clay minerals.**

Mineral	Chemical Formula	Charge per unit cell		Layer Charge
		Tetrahedral	Octahedral	
		<i>equivalents mole<sup>-1</sup></i>		
Kaolinite	Si <sub>4</sub> Al <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>	0	0	0
Montmorillonite	Ca <sub>0.66</sub> Si <sub>8</sub> (Al <sub>3.34</sub> Mg <sub>0.66</sub> )O <sub>20</sub> (OH) <sub>4</sub>	0	-0.66	-0.66
Vermiculite	Ca <sub>1.48</sub> (Si <sub>7.12</sub> Al <sub>0.88</sub> )(Al <sub>2.8</sub> Mg <sub>0.6</sub> Fe <sub>0.6</sub> )O <sub>20</sub> (OH) <sub>4</sub>	-0.88	-0.60	-1.48
Muscovite	K <sub>2</sub> (Si <sub>6</sub> Al <sub>2</sub> )Al <sub>4</sub> O <sub>20</sub> (OH) <sub>4</sub>	-2.0	0	-2.0
Chlorite	Mg <sub>0.6</sub> Al <sub>3.8</sub> (Si <sub>7.8</sub> Al <sub>0.2</sub> )(Al <sub>3.6</sub> Mg <sub>0.4</sub> )O <sub>20</sub> (OH) <sub>4</sub>	-0.2	-0.4	-0.6

**2.1.2. Smectites**

Smectite is the generic name given to all expanding 2:1 phyllosilicates with a layer charge of 0.4 to 1.2 (Bailey, 1980). The basic structure of a 2:1 mineral is an octahedral sheet that shares oxygen atoms between two tetrahedral sheets. In smectites, cation substitution occurs in either the octahedral sheet, the tetrahedral sheet, or both. These substitutions determine the properties and chemical composition of the smectites. Dioctahedral smectites — montmorillonite (Mg-rich), beidellite (Al-rich), and nontronite (Fe-rich) — generally form as a result of geochemical and pedochemical weathering. Trioctahedral smectites — hectorite (Li-rich), saponite (Mg-rich), and saunonite (Zn-rich) — rarely survive pedogenesis, i.e., they are found in geologic sediments or arid soils and are rarely found in soils of ustic and udic moisture regimes. Most soil smectites are called montmorillonites even though significant tetrahedral Al substitution and Fe octahedral substitution can occur (Borchardt, 1989). Table 2.2 gives idealized formulas for the smectites.

**Table 2.2. Ideal formulas for smectites.**

Subgroup	Species	Idealized Formula
Dioctahedral	Montmorillonite	Ca <sub>0.66</sub> H <sub>2</sub> O[(Si <sub>8</sub> )(AlMg) <sub>0.66</sub> O <sub>20</sub> (OH) <sub>4</sub> ]
	Beidellite	Ca <sub>0.66</sub> H <sub>2</sub> O[(Si <sub>7.34</sub> Al <sub>0.66</sub> )(Al <sub>4</sub> )O <sub>20</sub> (OH) <sub>4</sub> ]
	Nontronite	Ca <sub>0.66</sub> H <sub>2</sub> O[(Si <sub>7.34</sub> Al <sub>0.66</sub> )(Fe <sub>4</sub> <sup>3+</sup> )O <sub>20</sub> (OH) <sub>4</sub> ]
Trioctahedral	Saponite	Ca <sub>0.66</sub> H <sub>2</sub> O[(Si <sub>7.34</sub> Al <sub>0.66</sub> )(Mg <sub>6</sub> )O <sub>20</sub> (OH) <sub>4</sub> ]
	Hectorite	Ca <sub>0.66</sub> H <sub>2</sub> O[(Si <sub>7.34</sub> Al <sub>0.66</sub> )(Mg <sub>5.34</sub> Li <sub>0.66</sub> )O <sub>20</sub> (OH) <sub>4</sub> ]
	Sauconite	Ca <sub>0.66</sub> H <sub>2</sub> O[(Si <sub>6.8</sub> Al <sub>1.2</sub> )(Zn <sub>4</sub> Mg <sub>2</sub> )O <sub>20</sub> (OH) <sub>4</sub> ]



Soil smectites are naturally saturated with  $\text{Ca}^{2+}$  or  $\text{Mg}^{2+}$  in systems with  $\text{pH} > 6$ . However, in acid soils,  $\text{H}_3\text{O}^+$  destroys edges in the smectite structure releasing  $\text{Al}^{3+}$ . Thus, acid smectites are generally Al-saturated. Subsequent hydroxylation of  $\text{Al}^{3+}$  produces hydroxy Al polymers in the interlayers leading to the formation of pedogenic chlorite (Borchardt, 1989). Partial crystallization of Al polymers drastically reduces the magnitude of negative charge and causes a significant reduction in internal surface area (Inoue and Satoh, 1993).

### **2.1.3. Smectite Occurrence**

More than 2.4 million  $\text{km}^2$  (240 million ha) of Vertisols (clayey soils high in smectite) are distributed throughout the world (Buol et al., 1997). Extensive areas occur in Australia (80 million ha), India (73 million ha), Sudan (50 million ha), Egypt, Ethiopia, Chad, Ghana, Cuba, Puerto Rico, and Taiwan. The largest area of Vertisols in the United States is in the southern states where over 10 million ha of the Houston Black clay (Ustic Pellustert) dominates the landscape. Over 2.8 million ha of clayey, smectitic soils have been described in the western U.S. including 1 million ha in California. Winter rains cause extensive areas of landsliding in these areas (Borchardt, 1989). Vertisols generally develop in seasonal drying environments where precipitation ranges from 250 to 1000 mm (10 to 40 inches) per year, mean annual temperatures are between 4 and 18 °C (40 to 65 °F), and elevations ranging from 90 to 2250 m (300 to 7500 feet) above sea level (Buol, et al., 1997).

Soils that are not classified as Vertisols but have smectite as the dominant clay mineral species also occupy extensive acreages. Smectite is a principle clay mineral in the midwestern U.S. and is directly inherited from the parent material of certain loess deposits (Kleiss and Fehrenbacher, 1973). More than half of the soils in the desert and semi-arid areas of the U.S. are dominated by smectite.

Appreciable amounts of smectite exist in soils in any of the four B's: 1) basins, 2) B horizons, 3) super B horizons, and 4) in basic rock-derived soils (Jackson, 1965). In each of these environments high Si and basic cations occur; conditions necessary for smectite formation and/or preservation. Leaching is often at a minimum (Jackson and Sherman, 1953).

Basic rocks containing high Fe and low Al often weather to a Fe-smectite (Borchardt, 1989). Rocks high in Mg, such as serpentine, might be expected to favor formation of saponite, a trioctahedral smectite. Instead, an Fe-rich smectite forms illustrating the principle that only dioctahedral smectites crystallize under the low temperatures and pressures of soil environments

(Wildman et al., 1968). Smectite occurrence in basin environments does not imply that it has formed in situ. Reduced leaching simply protects smectite from weathering (Borchardt, 1989).

The B horizons of many soils in humid climates contain smectite even though they are well drained. The concentrations and potentials of Si, Al, or Mg may be high enough to preserve smectite rather than providing conditions necessary for formation. In these environments, smectite may be a transitory weathering product (Borchardt, 1989).

Smectites also occur in sedimentary deposits. In ocean basins, smectite can accumulate by either of two methods: 1) fine particles transported from the mouths of streams by ocean currents (Cole and Shaw, 1983) and 2) as authigenic nontronite formed from hydrothermal deposits such as basalt or volcanic ash (Hein, et al., 1979). Smectite does not survive in sediments that have undergone burial at depths greater than about 4 km (Weaver, 1959) or that have experienced metamorphism (Borchardt, 1989). Thus, smectite does not comprise a large portion of shale and limestone formed in deep ocean sediments or of metamorphic rocks.

Smectite commonly occurs in fresh water sediments and high smectite contents in these sediments reflect the smectite contents of the soils from which they were derived (Johns and Grim, 1958). Thus, loess from fresh water sediments typically contains high amounts of smectite (Ruhe, 1984).

#### **2.1.4. Transformation and Formation in Soils**

The polygenetic nature of soils makes it difficult to determine if soil smectites originate from transformation of other minerals or precipitation as smectite (Borchardt, 1989).

Depotassication of mica can lead to the formation of smectites (Crawford et al., 1983). Smectites that form from the weathering of mica are termed transformation smectites (Robert, 1973). Vermiculite may transform from mica initially but is considered an unstable intermediate especially with trioctahedral members such as biotite (Kittrick, 1973). The alteration of trioctahedral micas to vermiculite is easy, but not alteration all the way to smectite. Dioctahedral micas (e.g., illite and glauconite) alter to smectite easier than trioctahedral micas because tetrahedral aluminum is often less in dioctahedral micas as compared to trioctahedral members (Robert, 1973). The pedogenic transformation of mica to vermiculite are, in order: 1) depotassication, 2) dealumination of the tetrahedral sheet, and 3) silication of the tetrahedral sheet (Fanning et al., 1989; Komarnei, et al.,

1985). Unless these changes occur, micas will not have the low charge characteristics necessary for them to behave as smectites. Environmental conditions that favor mica transformation to smectite are 1) temperatures and pressures low enough to destabilize the tetrahedral Al in micas (Jackson, 1963), 2) low  $K^+$  concentration, 3) high Si concentrations, and 4) low Al concentrations. At pH's greater than 6 or 7, these conditions exist and soils are likely to contain smectite. At pH values less than 6, mica weathers to vermiculite and then kaolinite (Ismail, 1970) or directly to kaolinite (Harris et al., 1985). Two Aqualfs in Ohio exhibited a weathering sequence involving the transformation of clay mica to vermiculite to a low charge vermiculite/high charge smectite (Ransom et al., 1988).

Low and high charge smectites have been reported in acidic Ultisols and Alfisols in Mississippi (Nash, 1979), Alabama (Karathanasis and Hajek, 1983) and Texas (Senkayi et al., 1985), in Mollisols in Iowa (Laird et al., 1988), and in Aridisols in California (Reid et al., 1996). High-charged smectites, identified as beidellite, were present in surface horizons and proposed to be developed from the weathering of mica. Conversely, the low-charge smectites, identified as montmorillonite, occurred only at depth and were theorized to be inherited from montmorillonites in the parent material (Nash, 1979; Reid et al., 1996; Senkayi et al., 1985).

Smectites that precipitate from soil solutions are called neogenetic smectites. Most clay minerals form in upper horizons where factors of soil formation are most intense. Neogenetic smectites, however, tend to form deep within soil profiles. Under restricted drainage, smectite may form from soil solution in any parent material that contains the necessary components. Montmorillonite will form in restricted drainage environments with high Mg, such as in mafic rocks. As a soil becomes more leached, smectite exists only in microenvironments surrounding individual grains containing Mg (Borchardt, 1989). In well drained environments, smectites tend not to precipitate because intense leaching removes Mg from solution (Eswaran, 1979). Smectites will persist in environments with pH's as low as 3.6 but only if Si and Mg solution concentrations are high in restricted leaching conditions (Karathanasis and Hajek, 1984).

In highly leached, moderately acidic soils ( $pH \approx 5$ ), which are low in organic matter, smectites are transformed into pedogenic chlorites or hydroxy-interlayered vermiculite or hydroxy-interlayered smectite (Barnhisel and Bertsch, 1989; Rich, 1968). In very intense weathering conditions, evidence exists for the direct transformation of montmorillonite to kaolinite (Altschuler et al., 1963;

Karathanasis and Hajek, 1983; Wilson and Cradwick, 1972). Hydroxy-Al interlayers in montmorillonites have been reported to be more stable than in vermiculites (Carstea et al., 1970b).

## 2.2. MECHANICS OF CLAY SWELLING

### 2.2.1. Theoretical Aspects

Although all clays shrink and swell with changes in moisture content, none approach the magnitude of shrinking and swelling exhibited by smectites. Small size, large internal surface area, and diffuse negative layer charge allow smectite to absorb several times its weight in H<sub>2</sub>O (Borchardt, 1989).

The fundamental concept of clay swelling is the balancing of forces of interaction among the clay surface, ions, and water, however agreement about the most appropriate model of clay expansion has not been reached (McBride, 1989). Interlayer expansion of smectites has been commonly attributed to electrostatic repulsive force between double layers of adjacent platelets. However, diffuse double layers appear not to develop extensively at the clay surface and is attributed to the lack of dependence of smectite double layer potentials on solution electrolyte concentrations (Chan et al., 1984). Low (1981) observed that zeta potentials (the potentials at shear planes) of Na-saturated smectites were much lower than expected if the Na<sup>+</sup> ions were fully dissociated from the clay surfaces. (A shear plane is the plane separating water adsorbed to the clay particle from bulk water.) Conversely, the double layer potential on mica surfaces was observed to be dependent on Li<sup>+</sup> and Cs<sup>+</sup> exchange cations (Pashley, 1981). Shear planes can explain this apparent dichotomy (McBride, 1989). If the shear plane extends 1 nm or further from the clay surface, the dissociation of exchange cations would not generate large zeta potentials because most of the ions would remain inside the shear plane. Low surface potentials measured for Ca<sup>2+</sup> saturated clays confirm the divalent ions reside largely inside the shear plane (Chan et al., 1984).

Layer silicates have a maximum hydration state beyond which they do not expand and which can be explained by H-bonding (Farmer and Russell, 1971). Interlayer expansion is initially driven by the hydration energy of exchangeable cations. The hydration H<sub>2</sub>O is a dielectric link to the clay surface, transferring the charge from the cation to the surface O atoms via the H<sub>2</sub>O dipoles. The tetrahedral negative charge in vermiculite is distributed over a few surface O atoms so that an energetically favorable arrangement occurs with a H<sub>2</sub>O layer only 2 layers thick. In smectites, the

octahedral negative charge is distributed more diffusely favoring a more extended arrangement of dielectric linkages and thus greater interlayer spacing.

Swelling pressures were once attributed to the osmotic pressure created by cations (Sposito, 1973) and thus related to the double layer theory of clay expansion. However, Low and Margheim (1979) proposed that swelling pressure, although probably possessing a small osmotic component, is primarily due to a reduction in the potential energy of the interlayer water as a result of its interaction with adjacent clay layer surfaces. In reality, both theories are probably correct. In environments with high water contents and large interlayer distances, the double-layer theory provides the best explanation for soil swelling (Borchardt, 1989; Thomas and Moody, 1962). However, at low to moderate interlayer distances, several montmorillonites with widely varying charge densities produced nearly identical swelling pressures supporting the potential energy reduction theory (Viani et al., 1983). Low (1980) concluded that swelling was primarily due to interaction between clay layer surfaces and water.

Other swelling mechanisms proposed are crystal strain relaxation and entrapped air pressures. Terzaghi (1927) proposed that the elastic rebound of crystals distorted during compression would result in expansion upon unloading. Swelling may also result from the buildup of pressure in trapped air of an advancing wetting front (Emerson, 1964; Parker et al., 1980, 1982).

In general, a montmorillonite saturated with a divalent cation, such as  $\text{Ca}^{2+}$ , will swell by 100%, or from 1 nm to 2 nm (Norrish, 1954). Conversely, a montmorillonite saturated with a monovalent cation, such as  $\text{Na}^+$ , swells to infinity. However, soil smectites do not exhibit as much expansion as Na-saturated smectites because of 1) interstratification with nonexpansive clay minerals and 2) soil systems are rarely monoionic and are typically saturated with either  $\text{Ca}^{2+}$  or  $\text{Mg}^{2+}$  (Borchardt, 1989).

### **2.2.2. Water Retention**

The number of adsorbed  $\text{H}_2\text{O}$  layers between the smectite layers is related to the x-ray diffraction spacings of smectite (Barshad, 1949). The hydration  $\text{H}_2\text{O}$  associated with an exchangeable cation forms the first layer with subsequent layers held with less energy (Barshad, 1960). Adsorbed  $\text{H}_2\text{O}$  has greater viscosity, lower vapor pressure, lower freezing point, and higher density than normal  $\text{H}_2\text{O}$  (Low and White, 1970).

## **2.3. METHODS OF MEASURING SHRINK-SWELL POTENTIAL**

Many tests and methods have been developed or modified for estimating shrink-swell potential. These include both indirect and direct measurements. Indirect methods involve the use of soil properties and classification schemes to estimate shrink-swell potential. Direct methods provide actual physical measurements of swelling.

### **2.3.1. Indirect Measurements**

Presently, no one method of soil analysis estimates shrink-swell potential accurately for all soils. Soil scientists recognize that shrink-swell behavior can best be predicted by examining a combination of physical, chemical, and mineralogical soil properties. Determining these properties and establishing a shrink-swell model that can be extrapolated across the same or similar parent materials is needed.

Smectite content is universally recognized as the soil property controlling shrinking and swelling behavior in soils and sediments (Borchardt, 1989; Davidson and Page, 1956; Franzmeier and Ross, 1968; Karathanasis and Hajek, 1985; Schafer and Singer 1976; Yaalon and Kalmar, 1972). The mechanisms of swelling behavior in smectite were discussed in the a previous section. The focus of this section will be to discern the relationship between soil properties, including mineralogy, and shrink-swell behavior.

Most of the studies concerning expansive soils have been conducted on Vertisols and high base, smectitic soils. In these studies a number of parameters has been identified as correlated with swelling. Potential volume change of expansive soils in the western U.S. has been linked to clay content and plasticity index (Holtz and Gibbs, 1956). The variation in swelling of Hapludalfs in Ohio was related to clay content, in a study where all other parameters were held constant (McCormack and Wilding, 1975). Swell potential of montmorillonitic soils in southern Ontario are correlated with clay content and specific surface area (SSA) where SSA explained more of the variability in shrink-swell potential than did clay content (Ross, 1978). In Usterts and Torrerts of arid regions, swell potential, as measured by the coefficient of linear extensibility (COLE), was related to the fine clay content and exchangeable Na percentage (Anderson et al., 1973). Schafer and Singer (1976) determined that the percent of expandable clays explained most of the variability in swelling potential in Yolo County, California soils. Shrink-swell potential in kaolinitic and mixed mineralogy soils and

acid montmorillonitic soils are often more difficult to predict. Franzmeier and Ross (1968) observed that soils having equal amounts of kaolinite and montmorillonite behaved like montmorillonitic soils whereas soils with appreciable amounts of montmorillonite had wide ranges in swelling potentials. They postulated that the variability was related to the amount of clay and the soil fabric. Acid montmorillonitic and mixed mineralogy Alfisols and Ultisols in Alabama showed weak correlations between COLE and potential volume change (PVC) (Karathanasis and Hajek, 1985). Higher Al saturations may contribute to resistance of the clay minerals to dehydrate. Acid conditions were found to favor interlayer formation with Al and Fe in montmorillonite (Carstea et al., 1970a) and inhibit swelling (Rich, 1968). Iron coatings have also been found to reduce swell potential (Davidson and Page, 1956). In a study of Alabama soils ranging from kaolinitic Davidson (Kandiudult) to montmorillonitic Houston (Hapludert), cation exchange capacity (CEC) was highly correlated with specific surface area (SSA), -1500 kPa moisture content, and plasticity index (Gill and Reaves, 1957).

Plasticity index — the difference between liquid limit and plastic limit — is the most commonly used indicator of soil expansive behavior. The Atterberg limits, which include liquid limit, plastic limit, and plasticity index, define moisture content boundaries between states of consistency in soils (Casagrande, 1948). Liquid limit is the moisture content at which a soil begins to flow. Typically, clayey soils dominated by smectite will adsorb more water than clayey soils consisting of mostly non-expansive clays (kaolinite, mica, HIV/HIS) or limited expansion minerals (vermiculite). The plastic limit is the moisture content at which a soil stiffens from a plastic to a semirigid and friable state. In practice, plastic limit is the water content at which a sample of soil can be rolled in a 3-mm diameter thread without breaking. It thus characterizes the lower end of the range at which a clayey soil is in a plastic state (Hillel, 1980). Soils with high specific surface areas, e.g., smectitic soils, can retain water at a much lower moisture content than can kaolinitic or micaceous soils, and thus will have lower plastic limits. Plasticity index is the difference between the liquid limit and plastic limit. It generally indicates a soil's potential plasticity and is widely used in engineering classification systems (Casagrande, 1948).

Plasticity characteristics and volume change behavior of soils are theorized to be directly related to the amount of colloidal particles ( $< 1 \mu\text{m}$ ) in soils (Anderson et al., 1973; Nelson and Miller, 1992). For this reason, Atterberg limits and clay content have been combined into a single

parameter called the Activity Ratio ( $A$ ) developed by Skempton (1953). The activity ratio, sometimes called the activity index, is defined as follows:

$$\text{Activity } (A) = \frac{\text{Plasticity index}}{\% \text{ clay}}$$

Skempton proposed three classes of clays according to the activity ratio as follows: inactive,  $A < 0.75$ , normal,  $A$  between 0.75 and 1.25, and active,  $A > 1.25$ . Active clays provide the most potential for expansion. A Ca-saturated montmorillonite has an estimated activity ratio of 1.5, whereas a Na-saturated montmorillonite has an activity ratio greater than 7. Kaolinite has estimated activity of about 0.3 and mica (illite), an activity of about 1. However, as with most soil systems, the activity classification scheme does not accurately estimate shrink-swell potential in mixed mineralogy soils. Parker et al. (1977) found that the activity index was too imprecise for both mixed and montmorillonitic mineralogy soils to be useful. However, Schreiner (1988) observed consistent trends in soil and bentonite/sand mixtures using activity index as an indicator of shrink-swell potential.

The cation exchange capacity (CEC) has been used to estimate shrink-swell potential, in addition to approximating Atterberg limits and other engineering properties of a soil. CEC is related to amount and type of clay present in a soil. As clay content and swelling clays increase in a soil, CEC should elevate and be reflected in an increase in shrink-swell potential. An Alabama study conducted by Gill and Reaves, 1957 a high correlation between CEC and plasticity indices of clayey Ultisols, Alfisols, and Vertisols was observed. Karathanasis and Hajek (1985) observed that CEC was correlated with the coefficient of linear extensibility (COLE) in soils with vertic characteristics in montmorillonitic soils in Alabama. Four Texas Vertisols (Beaumont, Houston Black, Lufkin, and Miller series), with CEC values ranging from 34 to 60  $\text{cmol}_c \text{ kg}^{-1}$ , paralleled an increase in swelling pressure (Davidson and Page, 1956).

As can be surmised from the discussion above, several physical, chemical, and mineralogical soil properties influence shrink-swell behavior, with no one property accurately predicting shrink-swell potential for all soil types. Often, most expansive soils are clayey with high CEC's, high SSA's, and high liquid limits. Smectite typically comprises a significant portion of the soil clay fraction.



### 2.3.2. Direct Measurements

Several laboratory methods have been developed to directly determine the swelling a soil undergoes as moisture content changes. These include free swell, expansion index, California Bearing Ratio (CBR), potential volume change (PVC), and coefficient of linear extensibility (COLE).

One of the more simple procedures is the *free swell* test (Holtz and Gibbs, 1956). A small sample (10 cm<sup>3</sup>) of dry soil passing the No. 40 sieve is added to a graduated cylinder and filled with water. The free swell is determined by comparing the initial volume with the final volume. Bentonite will swell between 1200 to 2000%. Soils having free swell values greater than 100% are considered potential problems, whereas soils with free swell values below 50% probably do not exhibit appreciable volume changes. However, Dawson (1953) reported free swell values of about 50% of several Texas clays showed extensive expansion.

The *expansion index* (EI) test is used in California to evaluate building sites (Nelson and Miller, 1992). Soil passing a No. 4 sieve is compacted into a consolidometer ring and a 6.9 kPa surcharge is applied. Volume change is measured over a 24-hour period. The EI is calculated follows:  $EI = 100\Delta h \times F$ , where  $\Delta h$  is percent swell and  $F$  is the fraction passing the No. 4 sieve. EI values less than 50 are considered to have low expansion potential, and EI's greater than 91 have the high expansion potential.

The *California Bearing Ratio* (CBR) procedure is used extensively in highway design (Nelson and Miller, 1992). Vertical swell is determined by measuring the penetration resistance. Soils are compacted into CBR cylinders and soaked in water for several days. The samples are drained and the penetration test is performed.

*Potential volume change* (PVC) was developed by Lambe (1960) for the Federal Housing Administration. A remolded soil sample is compacted in a consolidometer ring at 2600 kJ m<sup>-3</sup>. Water is added to the sample and the swell, measured as pressure against a proving ring, is determined for several hours. The primary advantage of the PVC method is its simplicity and speed. The primary disadvantage is that the test uses a remolded sample and thus should be used to estimate approximate shrink-swell behavior and cannot be used in foundation design.

The coefficient of linear extensibility (COLE) is used routinely by the National Soil Survey Laboratory to characterize shrink-swell potential of soils (Soil Survey Staff, 1996). Undisturbed soil

samples (clods) are coated with a flexible plastic resin that is impermeable to liquid water, but permeable to water vapor. The clods are brought to field capacity (-33 kPa) and weighed in air and water to determine weight and volume using Archimedes principle. The clods are then oven-dried and weight and volume measurements determined again. The change in volume from field capacity to the oven-dry state is COLE and is calculated by

$$COLE = (DB_D/DB_M)^{0.33} - 1$$

where  $DB_D$  is bulk density of the oven dry sample and  $DB_M$  is bulk density of the sample at field capacity (Brasher et al., 1966; Grossman et al., 1968).

## 2.4. DESIGN AND TREATMENT METHODS

### 2.4.1. Foundation and Structure Design

Soils shrink and swell because the moisture content changes from dry to moist and vice versa. Thus, **shrinking and swelling can be reduced if the moisture content is kept stable**. Major damage can be avoided if a few precautions are taken to ensure that the soil under the foundation does not experience excessive moisture changes. Inexpensive and simple preventive measures to remove water away from the foundation may save thousands of dollars in costly repairs post-damage. The following guidelines were obtained from the internet site of the Department of Building and Safety for the city of Torrance, California<sup>1</sup>.

“1) Proper drainage after a rain is the most important single factor. Rainfall should run away from the foundation as quickly as possible following a storm. Regrading of the lot and/or installation of a drainage system may be necessary to alleviate drainage problems.

2) Installation of rain gutters and downspouts can help in the elimination of drainage problems, but be sure that the downspout outlet does not discharge close to the structure, as this could cause a problem. The discharge point should be on walkways, driveways, or other paved areas away from the building. Drainage should then flow directly to the street.

3) In the summer, water your lawn lightly two or three times a week. Heavy watering is not recommended as this could saturate the foundations. However, it should be emphasized that a uniform moisture condition around foundations should be maintained throughout the year. This will

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<sup>1</sup>[www.ci.torrance.ca.us/city/dept/bldg/soilguid.htm](http://www.ci.torrance.ca.us/city/dept/bldg/soilguid.htm)

prevent periodic drying (shrinkage) and wetting (expansion) which will cause damage to structures.

4) Planting trees (even small ones) within about ten feet from the house is not recommended. Trees extract moisture from soil causing shrinkage. Greater separation is appropriate for larger trees. Plants that require a large amount of moisture are also not recommended near buildings.“

Damage from shrinking and swelling soils can also be reduced or prevented with proper foundation design. The initial additional cost of a properly designed foundation offsets the potential for extensive damage to the structure without reinforced foundations. Several design alternatives are discussed below and were obtained from Chen (1988) and Nelson and Miller (1992).

*Drilled pier and beam.* Drilled pier and beam systems are designed to isolate the structure from expansive soil movements. The primary advantage is that it can be used for a variety of soils. The complexity of the design and construction is a major disadvantage. Additional cost is moderate to high. Risk assessment is low for soils of low to high expansion potential.

*Stiffened slab-on-grade.* Designed to provide a rigid foundation to protect the structure from differential soil movement. Advantage is that no specialized equipment is required for construction. However, the procedure is not applicable for basements and configuration of the structure must be simple. Additional cost is low to moderate. Risk assessment is low for soils of low to moderate expansion potential. Low to moderate risk is presumed for soils of high expansion potential.

*Monolithic wall and slab.* Designed to provide a rigid foundation to resist differential soil movement. Primary advantage is that construction is simple. However, the procedure is ineffective in highly expansive soils. Additional cost is low. Risk assessment is low for soils of low to moderate expansion potential and high for soils with high expansion potential.

*Modified continuous footings, walls, and basement construction.* Design to provide a rigid foundation to resist differential soil movement. Requires no specialized equipment and construction is simple. Like monolithic wall and slab, modified footings are ineffective in highly expansive soils. Additional cost is minimal.

In the Rocky Mountain area pier and grade beam construction is common. Expansive soils are primarily restricted to the upper zone of weathered shales and clays. In the southeastern U.S., stiffened slab-on-grade construction is widely used. The active clay zones in soils in this area are deeper and wetter than those associated with western areas. Basements are uncommon because of shallow water tables.

#### 2.4.2. Treatment of Expansive Soils

Many treatment procedures are available for stabilizing expansive soils (Chen, 1988; Nelson and Miller, 1992). *Removal* of expansive soil and replacement with a non-expansive material is a common method of reducing shrink-swell risk. If the expansive soil or stratum is thin, then the entire layer can be removed. However, frequently the soil or stratum extends to a depth too great to remove economically. *Prewetting* a site to increase to moisture content can eliminate an expansive soil problem if the high moisture content can be maintained. Soils with low hydraulic conductivity may take years to prewet and conversely soils with high hydraulic conductivity may never sufficiently wet. *Lime stabilization* has been used extensively in highway projects. The addition of lime creates several stabilizing reactions. The solubility of silica is increased in a higher pH environment and silica becomes available as a cementing agent. The lime also provides a divalent cation that can form Ca-silicates and Ca-Al hydrates that increase soil strength. The presence of organics, sulfates, and some iron compounds can inhibit lime stabilization reactions. *Fly ash* (product of coal combustion) has also been used instead of lime as a stabilizing agent. Swell potential of soils has been reduced in expansive soils; the reduction is attributed to bonding of soil particles to the fly ash resulting in flocculation (Ferguson, 1993).

### **2.4.3. Remedial Measures**

The absence of preventive measures may result in structural damage. If the structure is not condemned as unsuitable, remedial measures can be applied (Nelson and Miller, 1992). *Underpinning* consists of installing new foundation elements to provide additional support and generally involves installing piers in a stable soil zone. Underpinning can be done with a variety of foundations including continuous footings and slab-on-grade foundations. *Post-tensioning* consists of placing cables, attached to steel brackets, on inside and outside foundation walls.

## 2.5. REFERENCES

- Altschuler, Z.S., E.J. Dwornik, and H. Kramer. 1963. Transformation of montmorillonite to kaolinite during weathering. *Science* 141:148-152.
- Anderson, J.U., Kamal Elfadil Fadul, and G.A. O'Connor. 1973. Factors affecting the coefficient of linear extensibility in Vertisols. *Soil Sci. Soc. Am. Proc.* 37:298-299.
- Bailey, S.W. 1980. Summary of recommendation of AIPEA nomenclature committee. *Clays Clay Min.* 28:73-78.
- Barnhisel, R.I. and P.M. Bertsch. 1989. Chlorites and hydroxy-interlayered vermiculite and smectite. p. 729-788. *In* J.B. Dixon and S.B. Weed (ed.) *Minerals in soil environments*. 2<sup>nd</sup> ed. Soil Sci. Soc. Am. Book Ser. No. 1. Madison, WI.
- Barshad, I. 1949. The nature of lattice expansion and its relation to hydration in montmorillonite and vermiculite. *Am. Min.* 34:675-684.
- Barshad, I. 1960. Thermodynamics of water adsorption and desorption on montmorillonite. *Clays Clay Min.* 8:84-104.
- Borchardt, G. 1989. Smectites. p. 675-727. *In* J.B. Dixon and S.B. Weed (ed.) *Minerals in soil environments*. 2<sup>nd</sup> ed. Soil Sci. Soc. Am. Book Ser. No. 1. Madison, WI.
- Brasher, B.R., D.P. Franzmeier, V. Valassis, and S.E. Davidson. 1966. Use of saran resin to coat natural soil clods for bulk density and water retention measurements. *Soil Sci.* 101:108.
- Buol, S.W., F.D. Hole, R.J. McCracken, and R.J. Southard. 1997. *Soil genesis and classification*. 4<sup>th</sup> edition. Iowa St. Univ. Press, Ames.
- Carstea, D.D., M.E. Harward, and E.G. Knox. 1970a. Comparison of iron and aluminum hydroxy interlayers in montmorillonite and vermiculite. I. Formation. *Soil Sci. Soc. Am. Proc.* 34:517-521.
- Carstea, D.D., M.E. Harward, and E.G. Knox. 1970b. Comparison of iron and aluminum hydroxy interlayers in montmorillonite and vermiculite: II. Dissolution. *Soil Sci. Soc. Am. Proc.* 34:522-526.
- Casagrande, A. 1948. Classification and identification of soils. *Trans. Am. Soc. Civil Eng.* 113:901-931.

- Chan, D.Y.C., R.M. Pashley, and J.P. Quirk. 1984. Surface potentials derived from co-ion exclusion measurements on homoionic montmorillonite and illite. *Clays Clay Min.* 32:131-138.
- Chen, F.H. 1988. *Foundations on expansive soils*. Elsevier Publ., Amsterdam.
- Cole, T.G. and H.F. Shaw. 1983. The nature and origin of authigenic smectites in some recent marine sediments. *Clay Min.* 18:239-252.
- Crawford, T.W., Jr., L.D. Whittig, E.L. Begg, and G.L. Huntington. 1983. Eolian influence on development and weathering of some soils of Point Reyes Peninsula, California. *Soil Sci. Soc. Am. J.* 47:1179-1185.
- Davidson, S.E. and J.B. Page. 1956. Factors influencing swelling and shrinking in soils. *Soil Sci. Soc. Am. Proc.* 20:320-324.
- Dawson, R.F. 1953. Movement of small houses erected on an expansive clay soil. *Proc. 3<sup>rd</sup> Intl. Conf. Soil Mech. Found. Eng.* 1:346-350.
- Dixon, J.B. 1989. Kaolin and serpentine group minerals. p.467-525. *In* J.B. Dixon and S.B. Weed (ed.) *Minerals in soil environments*. 2<sup>nd</sup> ed. Soil Sci. Soc. Am. Book Ser. No. 1. Madison, WI.
- Douglas, L.A. 1989. Vermiculites. p. 635-674. *In* J.B. Dixon and S.B. Weed (ed.) *Minerals in soil environments*. 2<sup>nd</sup> ed. Soil Sci. Soc. Am. Book Ser. No. 1. Madison, WI.
- Emerson, W.W. 1964. The slaking of soil crumbs as influenced by clay mineral composition. *Aust. J. Soil. Res.* 2:211-217.
- Eswaran, H. 1979. The alteration of plagioclases and augites under differing pedo-environmental conditions. *J. Soil Sci.* 30:547-555.
- Fanning, D.S., V.Z. Keramidas, and M.A. El-Desoky. 1989. Micas. p. 551-634. *In* J.B. Dixon and S.B. Weed (ed.) *Minerals in soil environments*. 2<sup>nd</sup> ed. Soil Sci. Soc. Am. Book Ser. No. 1. Madison, WI.
- Farmer, V.C. and J.D. Russell. 1971. Interlayer complexes in layer silicates. The structure of water in lamellar ionic solutions. *Trans. Faraday Soc.* 67:2737-2749.
- Ferguson, G. 1993. Use of self-cementing fly ashes as a soil stabilization agent. p. 1-14. *In* K.D. Sharp (ed.) *Fly ash for soil improvement*. Am. Soc. Civil Eng. Geotech. Pub. 36.

- Franzmeier, D.P. and S.J. Ross, Jr. 1968. Soil swelling: Laboratory measurement and relation to other soil properties. *Soil Sci. Soc. Am. Proc.* 32:573-577.
- Gill, W.R. and C.A. Reaves. 1957. Relationships of Atterberg limits and cation-exchange capacity to some physical properties of soil. *Soil Sci. Soc. Am. Proc.* 21:491-494.
- Grossman, R.B., B.R. Brasher, D.P. Franzmeier, and J.L. Walker. 1968. Linear extensibility as calculated from natural-clod bulk density measurements. *Soil Sci. Soc. Am. Proc.* 32:570-573.
- Harris, W.G., L.W. Zelazny, J.C. Baker, and D.C. Martens. 1985. Biotite kaolinization in Virginia Piedmont soils: I. Extent, profile trends, and grain morphological effects. *Soil Sci. Soc. Am. J.* 49:1290-1297.
- Hein, J.R., H.-W. Yeh, and E. Alexander. 1979. Origin of iron-rich montmorillonite from the manganese nodule belt of the North Equatorial Pacific. *Clays Clay Min.* 27:185-194.
- Hillel, D. 1980. *Soil physics*. Academic Press, New York.
- Holtz, Wesley G. and Harold J. Gibbs. 1956. Engineering properties of expansive clays. *Trans. ASCE* 121:641-677.
- Inoue, K. and C. Satoh. 1993. Surface charge characteristics of hydroxyaluminosilicate- and hydroxyaluminum-montmorillonite complexes. *Soil Sci. Soc. Am. J.* 57:545-552.
- Ismail, F.T. 1970. Biotite weathering and clay formation in arid and humid regions, California. *Soil Sci.* 109:257-261.
- Jackson, M.L. 1965. Clay transformations in soil genesis during the Quaternary. *Soil Sci.* 99:15-22.
- Jackson, M.L. and G.D. Sherman. 1953. Chemical weathering of minerals in soils. *Adv. Agron.* 5:219-318.
- Johns, W.D. and R.E. Grim. 1958. Clay mineral composition of recent sediments from the Mississippi River delta. *J. Sediment. Petrol.* 28:186-200.
- Karathanasis, A.D. and B.F. Hajek. 1983. Transformation of smectite to kaolinite in naturally acid soil systems: Structure and thermodynamic considerations. *Soil Sci. Soc. Am. J.* 47:158-163.
- Karathanasis, A.D. and B.F. Hajek. 1984. Evaluation of aluminum-smectite stability equilibria in naturally acid soils. *Soil Sci. Soc. Am. J.* 48:413-417.



- Karathanasis, A.D. and B.F. Hajek. 1985. Shrink-swell potential of montmorillonitic soils in udic moisture regimes. *Soil Sci. Soc. Am. J.* 49:159-166.
- Kittrick, J.A. 1973. Mica-derived vermiculites as unstable intermediates. *Clays Clay Min.* 21:479-488.
- Kleiss, H.J. and J.B. Fehrenbacher. 1973. Loess distribution as revealed by mineral variations. *Soil Sci. Soc. Am. J.* 37:291-295.
- Komarneni, S., M.L. Jackson, and D.R. Cole. 1985. Oxygen isotope changes during mica alteration. *Clays Clay Min.* 33:214-218.
- Krohn, J.P. and J.E. Slosson. 1980. Assessment of expansive soils in the United States. p. 596-608. In D. Snethern (ed.) *Proc. 4<sup>th</sup> Intl. Conf. on Expansive Soils*, Denver, CO. Am. Soc. Civil Eng., New York.
- Laird, D.A., T.E. Fenton, and A.D. Scott. 1988. Layer charge of smectites in an Argialboll-Argiaquoll sequence. *Soil Sci. Soc. Am. Proc.* 52:463-467.
- Lambe, T.W. 1960. The character and identification of expansive soils, soil PVC meter. Federal Housing Administration, Tech. Studies Program, FHA 701.
- Low, P.F. 1980. The swelling of clay: II. Montmorillonites. *Soil Sci. Soc. Am. J.* 44:667-676.
- Low, P.F. 1981. The swelling of clay: III. Dissociation of exchangeable cations. *Soil Sci. Soc. Am. J.* 43:651-658.
- Low, P.F. and J.F. Margheim. 1979. The swelling of clay: I. Basic concepts and empirical equations. *Soil Sci. Soc. Am. J.* 43:473-481.
- Low, P.F. and J.L. White. 1970. Hydrogen bonding and polywater in clay-water systems. *Clays Clay Min.* 18:63-66.
- McBride, M.B. 1989. Surface chemistry of soil minerals. p. 35-88. In J.B. Dixon and S.B. Weed (ed.) *Minerals in soil environments*. 2<sup>nd</sup> ed. Soil Sci. Soc. Am. Book Ser. No. 1. Madison, WI.
- McCormack, D.E. and L.P. Wilding. 1975. Soil properties influencing swelling in Canfield and Geeburg soils. *Soil Sci. Soc. Am. Proc.* 39:496-502.
- Nash, V.E. 1979. Mineralogy of soils developed on Pliocene-Pleistocene terraces of the Tombigbee River in Mississippi. *Soil Sci. Soc. Am. J.* 43:616-623.
- Nelson, J.D. and D.J. Miller. 1992. *Expansive soils: Problems and practice in foundation and*

- pavement engineering. John Wiley & Sons, New York.
- Norrish, K. 1954. The swelling of montmorillonite. *Discuss. Faraday Soc.* 18:120-134.
- Parker, J.C., D.F. Amos, and D.L. Kaster. 1977. An evaluation of several methods of estimating soil volume change. *Soil Sci. Soc. Am. J.* 41:1059-1064.
- Parker, J.C., D.F. Amos, and L.W. Zelazny. 1982. Water adsorption and swelling of clay minerals in soil systems. *Soil Sci. Soc. Am. J.* 46:450-456.
- Parker, J.C., L.W. Zelazny, and D.F. Amos. 1980. Swelling components of compacted Ca-montmorillonite. *Clays Clay Min.* 28:135-141.
- Pashley, R.M. 1981. DLVO and hydration forces between mica surfaces in  $\text{Li}^+$ ,  $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{Cs}^+$  electrolyte solutions. *J. Colloid Interface Sci.* 83:531-546.
- Ransom, M.D., J.M. Bigham, N.E. Smeck, and W.F. Jaynes. 1988. Transitional vermiculite-smectite phases in Aqualfs of southwestern Ohio. *Soil Sci. Soc. Am. J.* 52:873-880.
- Reid, D.A., R.C. Graham, L.A. Douglas, and C. Amrhein. 1996. Smectite mineralogy and charge characteristics along an arid geomorphic transect. *Soil Sci. Soc. Am. J.* 60:1602-1611.
- Rich, C.I. 1968. Hydroxy interlayers in expansible layer silicates. *Clays Clay Min.* 16:15-30.
- Robert, M. 1973. The experimental transformation of mica toward smectite: Relative importance of total charge and tetrahedral substitution. *Clays Clay Min.* 21:167-174.
- Ross, G.J. 1978. Relationships of specific surface area and clay content to shrink-swell potential of soils having different clay mineralogical compositions. *Can. J. Soil Sci.* 58:159-166.
- Ruhe, R.V. 1984. Clay-mineral regions in Peoria loess, Mississippi River basin. *J. Geol.* 92:339-343.
- Schafer, W.M. and M.J. Singer. 1976. Influence of physical and mineralogical properties on swelling of soils in Yolo County, California. *Soil Sci. Soc. Am. J.* 40:557-562.
- Schreiner, H.D. 1988. Identification and classification of expansive soils. p. 23-29. *In* C.V.J. Varma (ed.) *Proc. 6<sup>th</sup> Intl. Conf. on Expansive Soils*. New Dehli, India.
- Senkayi, A.L., J.B. Dixon, L.R. Hossner, and L.A. Kippenberger. 1985. Layer charge evaluation of expandable soil clays by an alkylammonium method. *Soil Sci. Soc. Am. J.* 49:1054-1060.
- Skempton, A.W. 1953. The colloidal activity of clays. *Proc. 3<sup>rd</sup> Intl. Conf. Soil Mech. Found. Eng.* 1:57-61.
- Soil Survey Staff. 1996. Soil survey laboratory methods manual. *Soil Survey Invest. Rpt. No. 42*,

- Ver. 3. National Soil Survey Center, Lincoln, NE.
- Sposito, G. 1973. Volume changes in swelling soils. *Soil Sci.* 115:315-320.
- Terzaghi, K. 1927. Soil classification for foundation purposes. *Trans. 1<sup>st</sup> Intl. Cong. Soil Sci.* 4:127-157.
- Thomas, G.W. and J.E. Moody. 1962. Chemical relationships affecting the water-holding capacities of clays. *Soil Sci. Soc. Am. Proc.* 26:153-155.
- Viani, B.E., P.F. Low, and C.B. Roth. 1983. Direct measurement of relation between interlayer force and interlayer distance in the swelling of montmorillonite. *J. Colloid. Interface Sci.* 96:229-244.
- Weaver, C.E. 1959. The clay petrology in sediments. *Clays Clay Min.* 6:154-187.
- Wildman, W.E., M.L. Jackson, and L.D. Whittig. 1968. Iron-rich montmorillonite formation in soils derived from serpentine. *Soil Sci. Soc. Am. J.* 32:787-794.
- Wilson, M.J. and P.W. Cradwick. 1972. Occurrence of interstratified kaolinite-montmorillonite in some Scottish soils. *Clay Min.* 9:435-437.
- Yaalon, D.H. and D. Kalmar. 1972. Vertical movement in an undisturbed soil: Continuous measurement of swelling and shrinking with a sensitive apparatus. *Geoderma* 8:231-240.

# CHAPTER 3

# **An Expansive Soil Index for Predicting Shrink-Swell Potential**

## **3.1. ABSTRACT**

Soil properties indicative of shrink-swell potential were studied for 12 soils encompassing several parent materials in Virginia. Soils are rated from moderate to very high shrink-swell potential. The *mineralogy classes*, soil series, and (parent materials) examined include *smectitic* -- Iredell (hornblende gneiss), Jackland and Waxpool (diabase); *vermiculitic* -- Kelly (thermal shale); *kaolinitic* -- Cecil (granite gneiss) and Davidson (diabase); and *mixed* -- Carbo and Frederick (limestone), Craven and Peawick (Coastal Plain sediments), and Mayodan and Creedmoor (Triassic sandstones). Soil properties measured were swell index, coefficient of linear extensibility (COLE), particle size distribution, CEC, liquid limit, plasticity index, and clay mineralogy. Soils with estimated high or very high shrink-swell potential were clayey, with clay contents exceeding 60%. These expansive soils also exhibited high CEC ( $>15 \text{ cmol}_c \text{ kg}^{-1}$  soil), high liquid limits ( $> 70$ ), and appreciable swelling 2:1 mineral content ( $> 15$  percent montmorillonite +  $\frac{1}{2}$  vermiculite on whole soil basis). An expansive soil rating system, termed the *Expansive Soil Index (ESI)*, was developed using the soil properties most correlated with shrink-swell potential. The sum of swelling 2:1 minerals, swell index, liquid limit, and CEC gave expansive soil potential ratings (ESI) for each soil series. The higher the ESI, the greater the shrink-swell potential. Where less detailed information is required, such as for initial feasibility studies, an ESI consisting of liquid limit and CEC is recommended. Finally, the soils were grouped into risk categories based on parent material to allow for classification of similar soils into the ESI rating system. Soils with restricted drainage formed from mafic rocks, carbonate parent material, and metamorphic shales are at high risk for expansive soil behavior.

## **3.2. INTRODUCTION**

Expansive soils may occur throughout Virginia but they especially pose a problem where rapid urbanization and development are occurring. As development extends into these areas, identification and quantification of the soil properties that define shrink-swell potential are essential to evaluate properly the stability of a soil as a foundation material.

The USDA-Natural Resources Conservation Service (NRCS) determines shrink-swell potential using the linear extensibility percent (LEP) which is based on the change in length of an unconfined clod as moisture content is decreased from a moist to a dry state (Soil Survey Staff,

1996). The four shrink-swell potential classes are: LEP < 3% -- low; 3 to 6% -- moderate; 6 to 9% -- high, and > 9% -- very high. Occasionally shrink-swell classes are estimated from accessory soil characteristics such as field-determined plasticity and stickiness and texture. Thus, accurate quantitative measures of linear extensibility are not always available.

Presently, no one method of soil analysis estimates shrink-swell potential accurately for all soils. Soil scientists recognize that shrink-swell behavior can best be predicted by examining a combination of physical, chemical, and mineralogical soil properties. Determining these properties and then establishing a shrink-swell model that can be extrapolated across the same or similar parent materials is needed.

Most of the studies about expansive soils have been conducted on Vertisols and high base, montmorillonitic (smectitic) soils. In these studies several parameters has been identified as correlated with swelling. Potential volume change of expansive soils in the western U.S. have been linked to clay content and plasticity index (Holtz and Gibbs, 1956). The variation in swelling of Hapludalfs in Ohio was related to clay content, in a study where all other parameters were held constant (McCormack and Wilding, 1975). Swell potential of montmorillonitic soils in southern Ontario were correlated with clay content and specific surface area (SSA), and SSA explained more of the variability in shrink-swell potential than did clay content (Ross, 1978). In Usterts and Torrerts of arid regions, swell potential, as measured by the coefficient of linear extensibility (COLE), was related to the fine clay content and exchangeable sodium percentage (Anderson, et al., 1973). Schafer and Singer (1976) determined that the percent of expandable clays explained most of the variability in swelling potential in Yolo County, California soils. Shrink-swell potential in kaolinitic and mixed mineralogy soils and acid montmorillonitic soils are often more difficult to predict. Franzmeier and Ross (1968) observed that soils having equal amounts of kaolinite and montmorillonite behaved like montmorillonitic soils whereas soils with appreciable amounts of montmorillonite had wide ranges in swelling potentials. They postulated the variability was related to the amount of clay and the soil fabric. Acid montmorillonitic and mixed mineralogy Alfisols and Ultisols in Alabama showed weak correlations between COLE and potential volume change (PVC) (Karathanasis and Hajek, 1985). Higher Al saturations may contribute to resistance of the clay minerals to dehydrate. Acid conditions were found to favor interlayer formation with aluminum and iron in montmorillonite (Carstea, et al., 1970) and

inhibit swelling (Rich, 1968). Iron coatings have also been found to reduce swell potential (Davidson and Page, 1956). In a study of Alabama soils ranging from kaolinitic Davidson (Kandiudult) to montmorillonitic Houston soils (Hapludert), cation exchange capacity (CEC) was highly correlated with specific surface area (SSA), -1500 kPa moisture content, and plasticity index (Gill and Reaves, 1957).

As can be surmised from the discussion above, several physical, chemical, and mineralogical soil properties influence shrink-swell behavior, with no one property accurately predicting shrink-swell potential for all soil types. Often most expansive soils are clayey with high CEC's, high SSA's, and high liquid limits. Smectite typically comprises most of the soil clay fraction.

Our study was undertaken with the hypothesis that no one soil property or expansive soil test can precisely predict shrink-swell potential for all soils. However, a set of soil properties that estimates shrink-swell behavior can usually be determined for clayey soils with kaolinitic, mixed, or smectitic mineralogy formed from a variety of parent materials. The objectives of our study are (1) to quantify properties and shrink-swell indices of 12 expansive soils in four major physiographic provinces in Virginia, (2) to correlate shrink-swell potential with soil properties and shrink-swell indices, (3) to develop an expansive soil rating system using soil properties correlated with shrink-swell potential to evaluate each soil's propensity to be expansive, and (4) to develop shrink-swell risk categories for soils within different parent materials.

### **3.3. MATERIALS AND METHODS**

#### **3.3.1. Study Design**

Twelve map units in four physiographic provinces in Virginia comprised the study. These clayey soils have estimated moderate to very high shrink-swell potential with varying amounts of expanding 2:1's, interlayered 2:1's, mica, and kaolinite. Estimated shrink-swell potential of each of the soils for initial placement into expansive soil classes was obtained from the USDA-NRCS database (Table 3.1). All soils are classified (Soil Survey Staff, 1997) as fine with mineralogy classes encompassing kaolinitic, vermiculitic, smectitic, and mixed families (Table 3.1).

Map units in this study were delineated in accordance with procedures of the National Cooperative Soil Survey (Soil Survey Staff, 1993). Three delineations in each of the twelve map units were selected from soil survey maps. One pedon within each delineation was excavated to 1.8 m for

a total of three pedons per map unit. The most representative pit face was described and sampled. Data from the mid-argillic horizon are presented in this paper since this at the depth that foundations are typically installed (0.5 to 0.9 m).

**Table 3.1. Classification and estimated shrink-swell potential of selected soil series.**

Physiographic Province	Parent Material	Soil Series	Classification†	Shrink-Swell Potential‡
Valley and Ridge	limestone	Frederick	mixed, Typic Paleudult	high
		Carbo	mixed, Typic Hapludalf	very high
Piedmont	granite gneiss	Cecil	kaolinitic, Typic Kanhapludult	moderate
	hornblende gneiss	Iredell	smectitic, Typic Hapludalf	very high
Triassic Basins	diabase (diorite)	Jackland	smectitic, Aquic Hapludalf	very high
		Waxpool	smectitic, Aeric Ochraqualf	very high
		Davidson	kaolinitic, Rhodic Kandiudult	moderate
	thermal shale	Kelly	vermiculitic, Aquic Hapludalf	high
	sandstone/shale	Creedmoor	mixed, Aquic Hapludult	high
		Mayodan	mixed, Typic Hapludult	high
Coastal Plain	marine	Craven	mixed, Aquic Hapludult	moderate
	fluvial	Peawick	mixed, Aquic Hapludult	high

†All soils are in the fine family particle-size class (350 to 600 g kg<sup>-1</sup> clay).

‡Soil Survey Staff. 1997. Map unit interpretation records database.

### 3.3.2. Laboratory Analysis

Samples were air-dried, ground, and sieved to remove coarse fragments greater than 2 mm. Laboratory analyses include particle size distribution, CEC, Atterberg limits, potential volume change (PVC), and clay mineralogy. Particle size distribution by pipette and CEC were done by National Cooperative Soil Survey laboratory methods (Soil Survey Staff, 1996). Atterberg limits (liquid limit, plasticity index) were measured by ASTM method D4318 (American Society for Testing and Materials, 1993). Potential volume change was determined by the method of Lambe (1960). Shrink-swell potential was determined on each sample based on PVC data. Shrink-swell potential classes are



low (<81 kPa), moderate (81-153 kPa), high (153-225 kPa), and very high (>225 kPa) (Soil Survey Staff, 1993). Mineralogical composition was determined by x-ray diffraction and thermal methods. Free Fe oxides were removed with dithionate-citrate-bicarbonate (Mehra and Jackson, 1960). Sand was removed by sieving, and the clay fraction was separated from silts by centrifugation (Jackson et al., 1950). Oriented mounts of the clay fraction were prepared by the method of Rich (1969) and saturated with KCl and MgCl<sub>2</sub>-glycerol (Whittig and Allardice, 1986). Clay minerals were identified with a Scintag XDS 2000 x-ray diffractometer with Cu-K $\alpha$  radiation. Thermal analysis of the clay fraction was accomplished with a Dupont 990 Differential Scanning Calorimeter. Quantitative estimates of kaolinite and gibbsite were obtained by measuring endothermic peak areas. Quantitative estimates of other clay fractions were determined by proportioning integrated peak areas of x-ray diffractograms, using kaolinite as an internal standard. Swelling 2:1 minerals were estimated by summing the smectite content and ½ of the vermiculite content, since expansion is limited to two water layers for vermiculite.

### **3.3.3. Statistical Analysis**

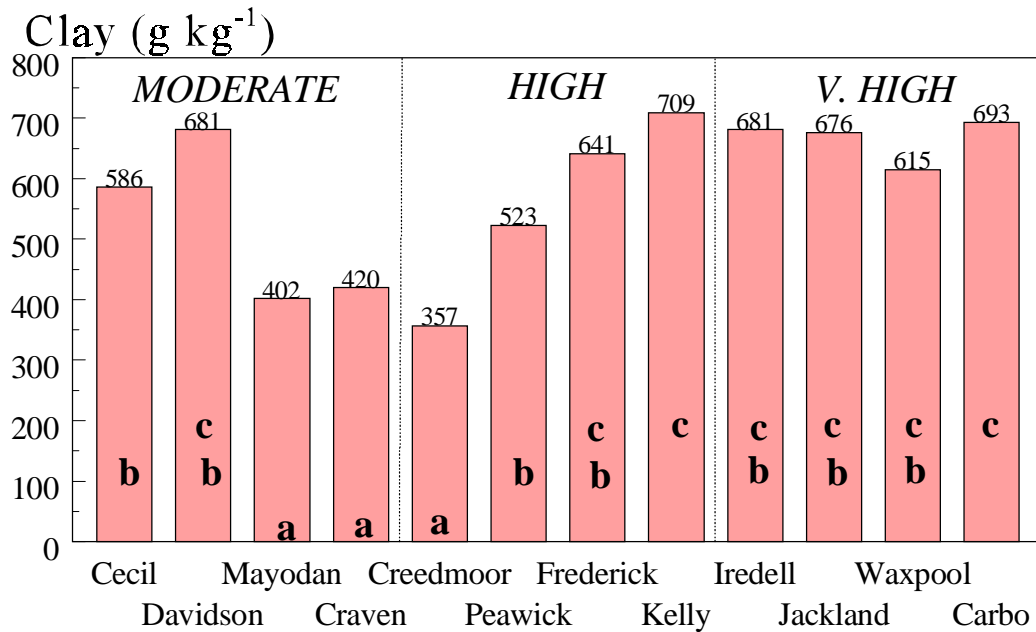
Significantly different means of Bt horizon soil properties were separated by least significance difference at the 0.05 level. The Pearson product moment correlation coefficient between variables was used to examine the relationships between soil properties.

## **3.4. RESULTS AND DISCUSSION**

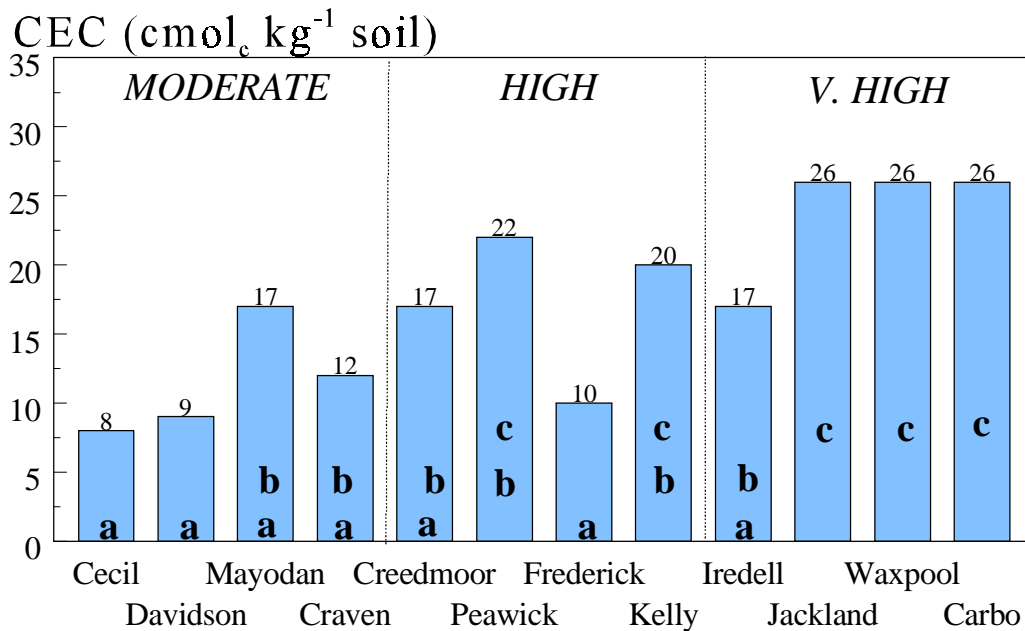
### **3.4.1. Soil Properties**

The Bt horizons of all 12 soils were clayey with clay contents ranging from 360 to 690 g kg<sup>-1</sup> (Figure 3.1). Estimated high and very high shrink-swell soils had similar clay contents except Creedmoor that had a much lower clay content. Moderate shrink-swell soils, Cecil and Davidson, also had high clay contents similar to the more expansive soils. Thus, no apparent relationship between clay content and susceptibility to shrink-swell behavior was observed.

A partial trend in shrink-swell behavior can be observed with CEC. High and very high shrink-swell soils generally had higher CEC's than the moderate soils (Figure 3.2). However, Frederick had significantly lower CEC and behaves or belongs in same class as the moderate shrink-



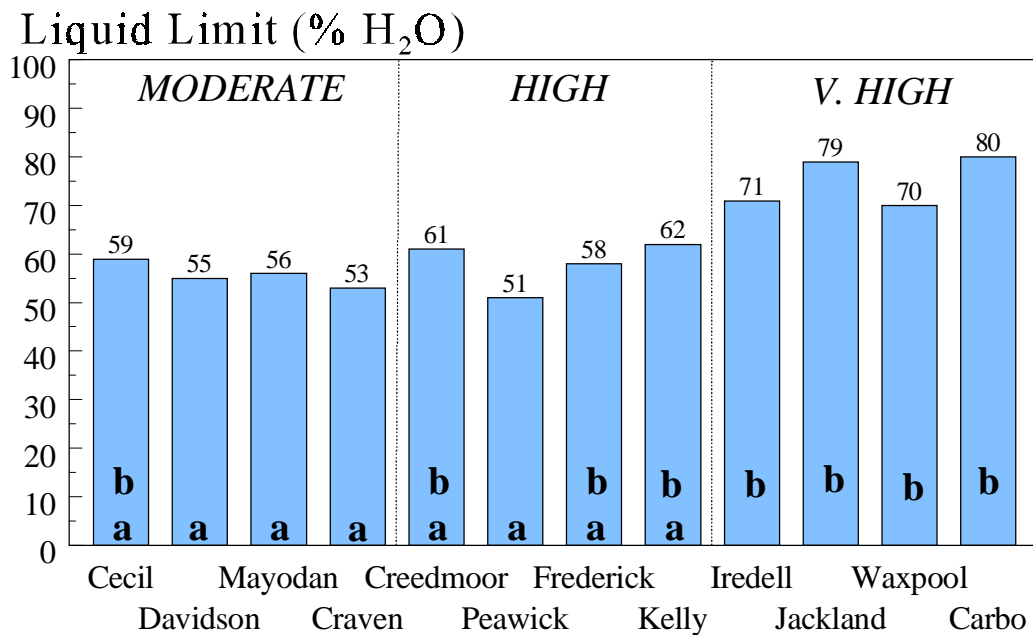
**Figure 3.1. Relationship between clay content and estimated shrink-swell class. Means (above bars) followed by the same letter are not significantly different at the 0.05 level.**



**Figure 3.2. Relationship between CEC and estimated shrink-swell class. Means (above bars) followed by the same letter are not significantly different at the 0.05 level.**

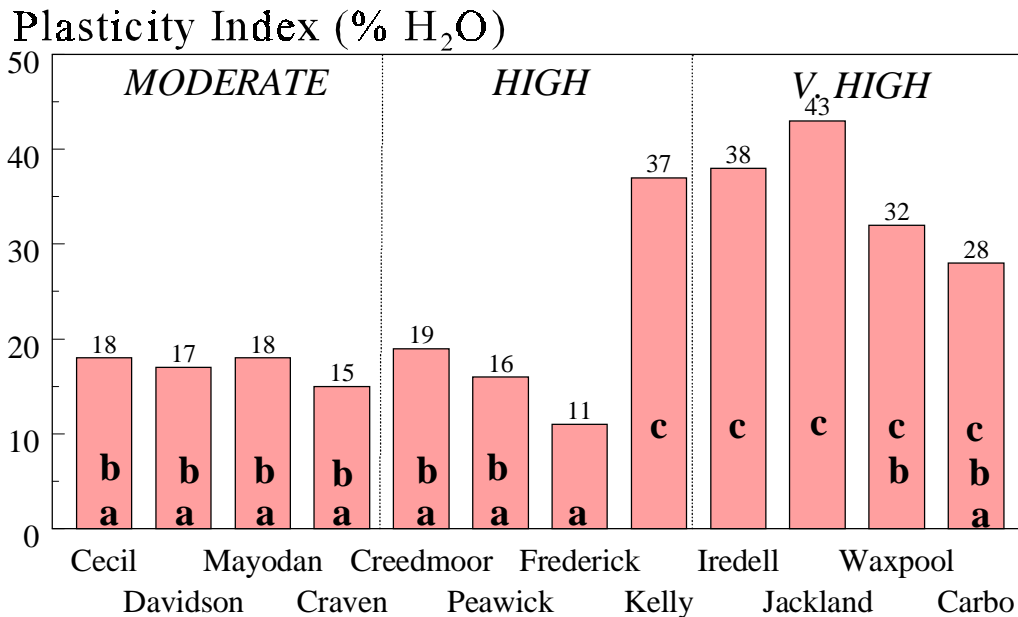
swell soils if using only CEC is used to estimate shrink-swell potential. Likewise, Mayodan and Craven, which occur in the moderate to high shrink-swell zone, had significantly higher CEC compared with Creedmoor, Peawick, Kelly, and Iredell in the high and very high classes.

Liquid limit is the highest in the very high shrink-swell class, intermediate in the high class, and lowest in the moderate class (Figure 3.3). Liquid limit demonstrated good correlation with expected shrink-swell class, however, differentiating the moderate from the high shrink-swell class and the high from the very high class was difficult.



**Figure 3.3. Relationship between liquid limit and estimated shrink-swell class. Means (above bars) followed by the same letter are not significantly different at the 0.05 level.**

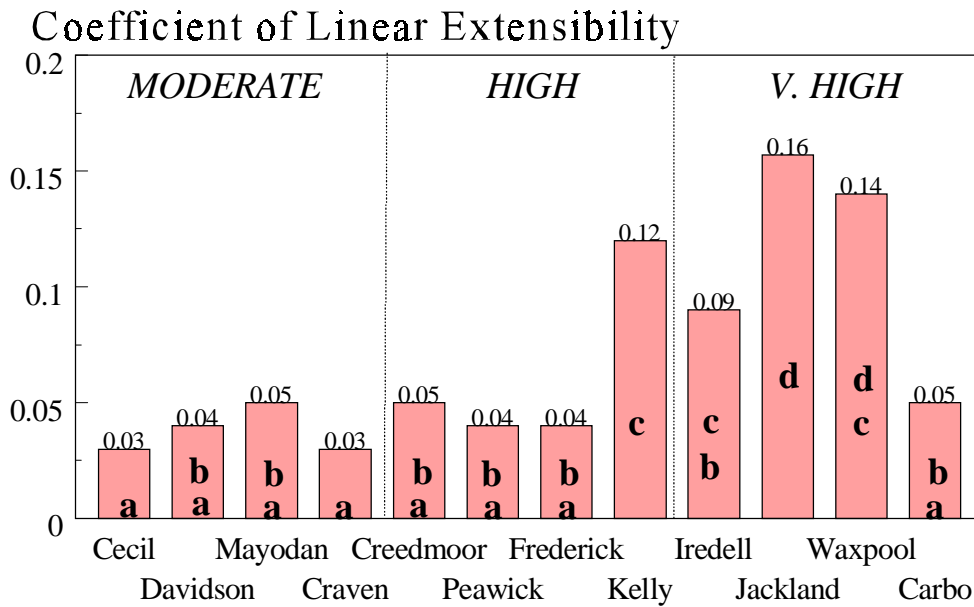
Plasticity index (PI), used widely by the geotechnical community to assess shrink-swell potential, showed little correlation with expected shrink-swell class (Figure 3.4). However, two distinct groups, which overlap the predefined classes, were indicated. Kelly, Iredell, Jackland, Waxpool, and Carbo had much higher PI's than the remainder of the soils.



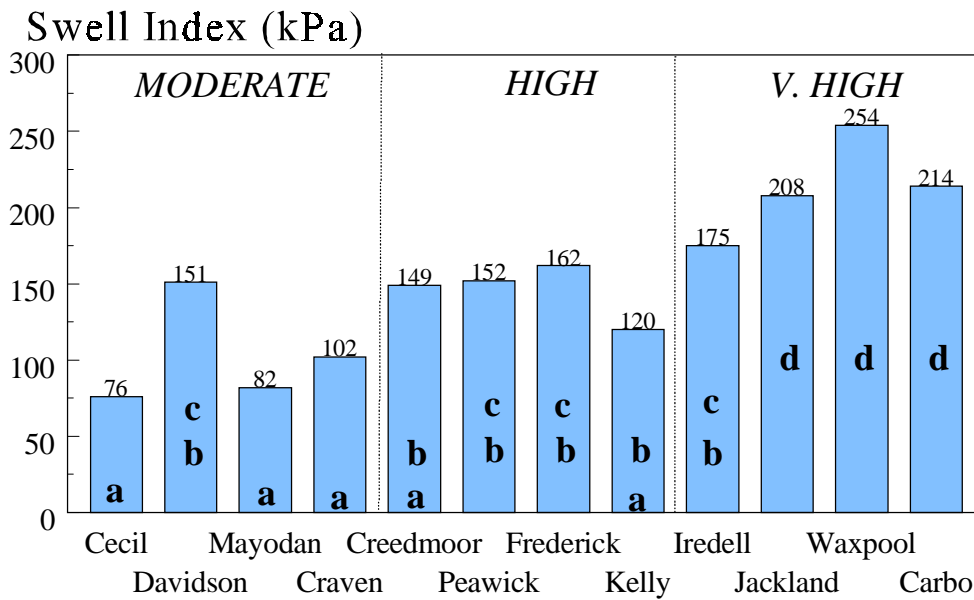
**Figure 3.4. Relationship between plasticity index and estimated shrink-swell class. Means (above bars) followed by the same letter are not significantly different at the 0.05 level.**

COLE and swell index are direct measurements of shrink-swell potential (Figures 3.5 and 3.6). No discernable relationship was observed between estimated shrink-swell class and COLE for the 12 soils (Figure 3.5). However, as with plasticity index, two distinct groups separating soils into moderate/high and high/very high were observed. The other direct indicator of shrink-swell potential, swell index, showed a high correlation with estimated shrink-swell class (Figure 3.6). Three of the four moderate classes had moderate swell indices. Cecil had measured shrink-swell potential of low although it borders the moderate class. All four very high soils had swell indices that placed the soils in the very high shrink-swell class.

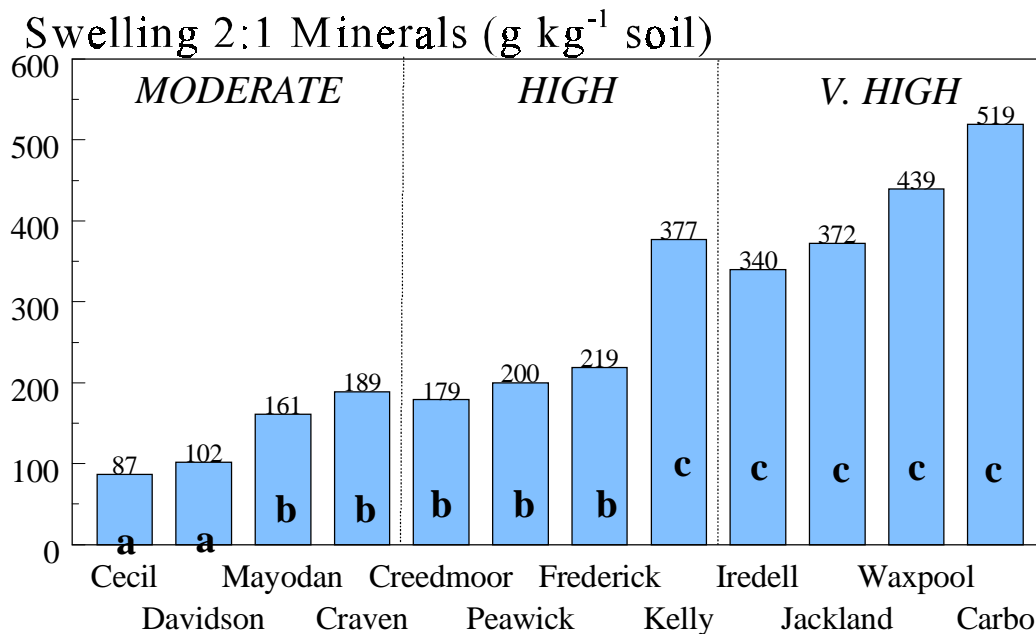
Swelling 2:1's (smectite, vermiculite) had the highest correlation with shrink-swell class, as expected (Figure 3.7). Smectitic Waxpool, Jackland, and Iredell had high smectite contents as does the mixed mineralogy Carbo. The kaolinitic Cecil and Davidson soils had the lowest smectite contents, whereas soils with mixed mineralogy, in both the moderate and high classes, had intermediate smectite contents. The Creedmoor soil averaged 350 g kg<sup>-1</sup> clay but had similar smectite



**Figure 3.5. Relationship between COLE and estimated shrink-swell class. Means (above bars) followed by the same letter are not significantly different at the 0.05 level.**



**Figure 3.6. Relationship between swell index and estimated shrink-swell class. Means (above bars) followed by the same letter are not significantly different at the 0.05 level.**



**Figure 3.7. Relationship between swelling 2:1 mineral content and estimated shrink-swell class. Means (above bars) followed by the same letter are not significantly different at the 0.05 level.**

content, on a whole-soil basis, to the high clay (78%) Frederick. Both had similar swell indices of about 120 kPa, further supporting the use of whole-soil smectite content rather than clay content when estimating shrink-swell behavior.

### **3.4.2. Correlation of Shrink-Swell Properties**

All shrink-swell indices measured were positively correlated with each other. Swelling 2:1's, CEC, and liquid limit (indirect measures of shrink-swell potential) were significantly and positively correlated with swell index, a direct measurement of shrink-swell potential (Table 2). COLE and PI were not significantly correlated to shrink-swell properties, although other studies have indicated as such (Anderson et al., 1973; Franzmeier and Ross, 1968; McCormack and Wilding, 1975; Schafer and Singer, 1976). The lack of correlation of COLE and PI in this study may be due to aluminum interlayering or high Fe-oxide coating of the clays inhibiting swelling.

**Table 3.2. Correlation coefficients for soil properties.**

	Clay	CEC	Swelling 2:1's	Plasticity Index	Liquid Limit	Swell Index
CEC	<b>0.16†</b>					
Swelling 2:1's	0.52	<b>0.78</b>				
Plasticity Index	0.49	0.60	0.53			
Liquid Limit	0.57	0.68	<b>0.72</b>	<b>0.79</b>		
Swell Index	0.54	<b>0.78</b>	<b>0.99</b>	0.51	<b>0.71</b>	
COLE	0.39	0.62	0.61	<b>0.89</b>	0.65	0.59

†Significant correlations ( $p\text{-level} = 0.05$ ) indicated in **boldface**.

### 3.4.3. Expansive Soil Index

The absolute values of the four soil indices most correlated with predicted shrink-swell potential in this study were swelling 2:1's, CEC, swell index, and liquid limit. Thus, these soil indices were summed into an Expansive Soil Index (*ESI*) given by the following equation:

$$ESI = \text{swelling 2:1's} + \text{swell index} + \text{liquid limit} + \text{CEC}$$

*ESI* ratings greater than 500 indicate high and very high shrink-swell potential (Table 3.3) and would require special design of foundations, such as adding reinforcing bars to footings and/or installing moisture barriers, to decrease potential expansive soil damage. An *ESI* less than 500 describes soils with moderate to high shrink-swell potential. Special design features are suggested to reduce shrink-swell risk although the design of such features may not be as extensive as required for foundations constructed on higher shrink-swell potential soils.

Identifying and quantifying swelling 2:1 minerals is a difficult, time-consuming, and expensive property to routinely measure. Only a few laboratories are equipped to make these types of quantifications. Table 2 showed that high values of swell index, liquid limit, and CEC corresponded to high amounts of swelling 2:1 clay minerals. Thus, an alternative *ESI*, termed *ESI-2*, was proposed which used only the absolute values of swell index, liquid limit, and CEC. *ESI* and *ESI-2* were highly

correlated ( $R^2 = 0.92$ ) and gave similar shrink-swell risk separations of the soils (Table 3.3). However, separations were not as distinct as when swelling 2:1's are in the equation. However, an *ESI-2* of about 250 appeared to separate soils of high risk from soils of very high risk. Demarcation of moderate risk soils from high risk was not as distinct. Thus, conservative estimates of shrink-swell potential are recommended. Although swell index is an easy parameter to measure, there is little swell index (PVC) data in soil survey databases. However, extensive data on liquid limits and CEC are contained in many soil characterization databases. Thus, a third expansive soil index, *ESI-3*, can be formulated using only liquid limit and CEC as shrink-swell predictors. Fewer categories of estimated shrink-swell risk would be entailed when using this index.

**Table 3.3. Expansive soil indices (ESI).**

<b>Soil Series</b>	<b>ESI†</b>	<b>ESI-2‡</b>	<b>ESI-3§</b>	<b>Shrink-Swell Risk</b>
Cecil	201	143	67	<b>MODERATE</b>
Davidson	283	215	64	<b>MODERATELY HIGH</b>
Mayodan	296	155	73	
Craven	314	167	65	
Creedmoor	388	227	78	<b>HIGH</b>
Peawick	412	225	73	
Frederick	417	230	68	
Kelly	422	198	78	
Iredell	586	263	88	<b>VERY HIGH</b>
Jackland	668	313	105	
Carbo	753	320	106	
Waxpool	773	350	96	

†swelling 2:1's + swell index + liquid limit + CEC

‡swell index + liquid limit + CEC

§liquid limit + CEC



We now have developed three ESI's each requiring a different level of data input and applying a different level of shrink-swell predictability. What *ESI* rating should be employed for various intensities of site assessment? We suggest the following guidelines:

- *ESI-3 -- liquid limit and CEC*; employed when general information is needed, such as performing feasibility studies for a proposed subdivision or highway *ESI-3* would be sufficient to screen suitable areas from unsuitable areas; liquid limit and CEC are indirect indicators of shrink-swell potential
- *ESI-2 -- swell index, liquid limit, and CEC*; used when site-specific information is needed, such as suitability of a sites for home foundations or on-site wastewater disposal; swell index is a direct measure of swelling pressure;
- *ESI — swelling 2:1's, swell index, liquid limit, and CEC*; used when data is needed in litigation court cases or when additional information is required for foundations or other structures designed to reduce potential damage from shrink-swell soils.

#### **3.4.4. Parent Material Correlation with Shrink-Swell Indices**

Many other soils are formed from the same or similar parent materials as the soils described in this study. Thus, it is possible to extrapolate these data and *ESI* ratings for similar soils based upon parent material. Soils with restricted drainage formed from mafic rocks and metamorphic shales, and shallow soils formed from carbonate parent material are at high risk for expansive soil behavior (Table 3.4). Moderate risk was assumed in soils formed from Triassic sandstone and shales, deep soils formed from carbonate rocks, and Coastal Plain clayey fluvial and marine sediments. Lower risk can be correlated with soils formed from well drained felsic and mafic parent materials.

### **3.5. CONCLUSIONS**

Expansive soils cause billions of dollars of damage to homes and property in the U.S. each year. Damage can be avoided or mitigated if the propensity of a soil to shrink and swell is known before construction. Predicting shrink-swell potential accurately requires both the knowledge of which soil properties influence shrinking and swelling and the magnitude of these parameters. Recognizing the need for quantitative soil information, we developed an expansive soil rating system to assess shrink-swell potential of twelve clayey soils formed from major parents materials that occur throughout Virginia. The *Expansive Soil Indices (ESI)* are obtained by summing the absolute values

of swelling 2:1 minerals, swell index, liquid limit, and CEC. Three levels of precision are available with highest precision obtained with all four properties. Intermediate precision is available by using swell index, liquid limit, and CEC and lower precision, but rapid assessment, can be achieved by using only liquid limit and CEC. The *ESI* system has the flexibility of allowing for the classification of other soils formed from similar parent materials can be classified into the *ESI* rating system allowing for rapid, quantitative assessment of shrink-swell potential of a soil.

**Table 3.4. Shrink-swell potential risk of soils as related to parent material.**

Shrink-Swell Risk	Parent Material	Soil Series
<b>HIGH</b>	<i>Mafic rocks, poorly drained to moderately well drained</i>	Jackland Waxpool Iredell
	<i>Carbonate rocks, shallow to rock</i>	Carbo
	<i>Triassic rocks, thermally altered shales</i>	Kelly
<b>MODERATE</b>	<i>Carbonate rocks, deep to rock</i>	Frederick
	<i>Triassic rocks, shales and sandstones</i>	Mayodan Creedmoor
	<i>Coastal Plain sediments, clayey fluvial/marine</i>	Craven Peawick
<b>LOW</b>	<i>Mafic rocks, well drained</i>	Davidson
	<i>Felsic rocks, well drained</i>	Cecil

### 3.6. REFERENCES

- American Society for Testing and Materials. 1993. Annual book of ASTM standards. Construction. Section 4. Soil and rock; dimension stone; geosynthesis. Vol. 04.08. ASTM, Philadelphia, PA.
- Anderson, J.U., Kamal Elfadil Fadul, and G.A. O'Connor. 1973. Factors affecting the coefficient of linear extensibility in Vertisols. *Soil Sci. Soc. Am. Proc.* 37:298-299.
- Carstea, D.D., M.E. Harward, and E.G. Knox. 1970. Comparison of iron and aluminum hydroxy interlayers in montmorillonite and vermiculite. I. Formation. *Soil Sci. Soc. Am. Proc.* 34:517-521.
- Davidson, S.E. and J.B. Page. 1956. Factors influencing swelling and shrinking in soils. *Soil Sci. Soc. Am. Proc.* 20:320-324.
- Franzmeier, D.P. and S.J. Ross, Jr. 1968. Soil swelling: Laboratory measurement and relation to other soil properties. *Soil Sci. Soc. Am. Proc.* 32:573-577.
- Gill, W.R. and C.A. Reaves. 1957. Relationships of Atterberg limits and cation-exchange capacity to some physical properties of soil. *Soil Sci. Soc. Am. Proc.* 21:491-494.
- Holtz, Wesley G. and Harold J. Gibbs. 1956. Engineering properties of expansive clays. *Trans. ASCE* 121:641-677.
- Jackson, M.L., L.D. Whittig, and R.P. Pennington. 1950. Segregation procedure for the mineralogical analysis of soils. *Soil Sci. Soc. Am. Proc.* 14:77-81.
- Karathanasis, A.D. and B.F. Hajek. 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 soils. *Fed. Housing Admin. Rpt.* 701.
- McCormack, D.E. and L.P. Wilding. 1975. Soil properties influencing swelling in Canfield and Geeburg soils. *Soil Sci. Soc. Am. Proc.* 39:496-502.
- Mehra, O.P. and M.L. Jackson. 1960. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. *Clays Clay Min.* 7:317-327.
- Rich, C.I. 1968. Hydroxy interlayers in expansible layer silicates. *Clays Clay Min.* 16:15-30.

- Rich, C.I. 1969. Suction apparatus for mounting clay specimens on ceramic tile for x-ray diffraction. *Soil Sci. Soc. Am. Proc.* 33:815-816.
- Ross, G.J. 1978. Relationships of specific surface area and clay content to shrink-swell potential of soils having different clay mineralogical compositions. *Can. J. Soil Sci.* 58:159-166.
- Schafer, William M. and Michael J. Singer. 1976. Influence of physical and mineralogical properties on swelling of soils in Yolo County, California. *Soil Sci. Soc. Am. J.* 40:557-562.
- Soil Survey Staff. 1993. Soil survey manual. USDA-SCS Agric.Handb. 18. U.S. Gov. Print. Office, Washington, D.C.
- Soil Survey Staff. 1994. Keys to Soil Taxonomy. 6<sup>th</sup> ed. Pocahontas Press, Blacksburg, VA.
- Soil Survey Staff. 1996. Soil survey laboratory methods manual. Soil Survey Investigations Rpt. 42, Ver. 3. National Soil Survey Center, Lincoln, NB.
- Soil Survey Staff. 1997. Map unit interpretation records database. [www.statlab.iastat.edu/soils/muir/](http://www.statlab.iastat.edu/soils/muir/).
- Whittig, L.D. and W.R. Allardice. 1986. X-ray diffraction techniques. *In* A. Klute (ed.) *Methods of soil analysis*. Part 1. Physical and mineralogical methods. 2<sup>nd</sup> ed. *Agronomy* 9:331-362.

# CHAPTER 4

# Distribution of Swelling Soils in Virginia as Influenced by Parent Material and Shrink-Swell Potential

## 4.1. ABSTRACT

Smectite has been identified as the major property controlling shrink-swell potential of soils. We identified and quantified 11 clayey soils, encompassing several parent materials, to evaluate smectite distribution within soil profiles. Smectite contents in four mineralogy classes selected for study are estimated to range from 5 to more than 50%. The *mineralogy classes*, soil series, and (parent materials) examined include *smectitic* -- Jackland and Waxpool (diabase); *vermiculitic* -- Kelly (thermal shale); *kaolinitic* -- Cecil (granite gneiss) and Davidson (diabase); and *mixed* -- Carbo and Frederick (limestone), Craven and Peawick (Coastal Plain sediments), and Mayodan and Creedmoor (Triassic sandstones and shales). Three sites in each of the 12 soil series were described and major horizons sampled for mineralogical analysis. Sand and clay mineralogical composition was determined by x-ray diffraction and thermal methods after iron removal.

Smectite distributions within the 11 soil profiles can be differentiated by parent material. Smectite concentration in the clay fraction increased with depth in soils formed from the mafic rocks, diabase, and the thermally altered shale possibly indicating transformation of smectite by alteration of primary minerals from the parent materials. Smectite weathers to kaolinite and hydroxy-interlayered vermiculite, and/or hydroxy-interlayered smectite with increasing proximity to the soil surface thus accounting for the observed decrease in smectite towards the soil surface.

The highest amount of smectite from the granite gneiss, limestone, sandstones and shales, and Coastal Plain sediments was in the Bt2 horizon. This could indicate neof ormation of smectite by dissolution of primary and secondary minerals and precipitation as neogenetic smectite. Smectite contents decreased both with depth and towards the soil surface from the maximum in the Bt2 horizon indicating unfavorable conditions for smectite formation in these layers.

Smectite was highest in the smectitic soils. Highly weathered kaolinitic soils, Cecil and Davidson, have the lowest smectite content. The vermiculitic Kelly soil also had contains low smectite. The mixed mineralogy soils had a wide range in smectite ranging from 100 g kg<sup>-1</sup> in Frederick to 500 g kg<sup>-1</sup> in the Creedmoor.

## 4.2. INTRODUCTION

Smectite has been identified as the major soil property controlling shrink-swell potential of soils (Borchardt, 1989). Smectite dominates the clay fraction of Vertisols, the most severe of the shrink-swell soils, but most high shrink-swell soils in the humid southeastern U.S. are Alfisols or Ultisols in which smectite comprises a significant portion of the clay mineral fraction, but may or may not be the dominant mineral species. Smectite coexists with minerals considered to be diagnostic for highly weathered soils, kaolinite and HIV.

Depotassication of mica can lead to the formation of smectites (Crawford et al., 1983). Smectites that form from the weathering of mica are termed transformation smectites (Robert, 1973). Vermiculite may transform from mica initially but is considered an unstable intermediate especially with trioctahedral members such as biotite (Kittrick, 1973). Dioctahedral micas and vermiculites may be stable at surface temperatures and pressures (Robert, 1973).

Environmental conditions that favor mica transformation to smectite are 1) temperatures and pressures low enough to destabilize the tetrahedral Al in micas (Jackson, 1963), 2) low  $K^+$  concentration, 3) high Si concentrations, and 4) low Al concentrations. At pH's greater than 6 or 7, these conditions exist and soils are likely to contain smectite. At pH values less than 6, mica weathers to vermiculite and then kaolinite (Ismail, 1970) or directly to kaolinite (Harris et al., 1985). Two Aqualfs in Ohio exhibited a weathering sequence involving the transformation of clay mica to vermiculite to a low charge vermiculite/high charge smectite (Ransom et al., 1988).

Low and high charge smectites have been reported in acidic Ultisols and Alfisols in Mississippi (Nash, 1979), Alabama (Karathanasis and Hajek, 1983) and Texas (Senkayi et al., 1985), in Mollisols in Iowa (Laird et al., 1988), and in Aridisols in California (Reid et al., 1996). High-charged smectites, identified as beidellite, were present in surface horizons and proposed to be developed from the weathering of mica. Conversely, the low-charge smectites, identified as montmorillonite, occurred only at depth and were theorized to be inherited from montmorillonites in the parent material (Nash, 1979; Reid et al., 1996; Senkayi et al., 1985).

Smectites that precipitate from soil solutions are called neogenetic smectites. Neogenetic smectites tend to form in soils from deep in the profile towards the soil surface, i.e., from the bottom up, whereas other clay minerals form in the upper horizons where soil weathering is most intense.

Under restricted drainage, smectite may form from soil solution in any parent material that contains the necessary components. Montmorillonite will form in restricted drainage environments with high Mg, such as in mafic rocks. As a soil becomes more leached, smectite exists only in microenvironments surrounding individual grains containing Mg (Borchardt, 1989). In well drained environments, smectites tend not to precipitate because intense leaching removes Mg from solution (Eswaran, 1979). Smectites will persist in environments with pH's as low as 3.6 but only if Si and Mg solution concentrations are high in restricted leaching conditions (Karathanasis and Hajek, 1984).

In highly leached soils low in organic matter and moderately acidic (pH  $\approx$  5), smectites are transformed into pedogenic chlorites or hydroxy-interlayered vermiculite or hydroxy-interlayered smectite (Barnhisel and Bertsch, 1989; Rich, 1968). In very intense weathering conditions, evidence exists for the direct transformation of montmorillonite to kaolinite (Altschuler et al., 1963; Karathanasis and Hajek, 1983; Wilson and Cradwick, 1972). Hydroxy-Al interlayers in montmorillonites have been reported to be more stable than in vermiculites (Carstea et al., 1970).

The objectives of this study are: 1) identify and quantify distribution of smectite in profiles of 11 benchmark expansive soils and 2) infer genesis of smectite in the soil profiles.

### **4.3. MATERIALS AND METHODS**

#### **4.3.1. Study Design**

We selected 11 clayey soils, encompassing several parent materials and estimated shrink-swell potential classes, to evaluate smectite distribution within soil profiles (Table 4.1). Smectite contents in four mineralogy classes selected for study were estimated to range from 5 to more than 50%. Smectitic and vermiculitic soils are specified if the clay fraction has more smectite or vermiculite, respectively, than any other single clay mineral. Kaolinitic classes are applied if the clay fraction contains more than 50% kaolinite. Mixed mineralogy classes are designated if no one clay species dominates. The *mineralogy classes*, soil series, and (parent materials) examined include *smectitic* -- Jackland and Waxpool (diabase); *vermiculitic* -- Kelly (thermal shale); *kaolinitic* -- Cecil (granite gneiss) and Davidson (diabase); and *mixed* -- Carbo and Frederick (limestone), Craven and Peawick (Coastal Plain sediments), and Mayodan and Creedmoor (Triassic sandstones). Three sites in each of the 11 soil series were described and major horizons sampled for laboratory analysis.



**Table 4.1. Classification and estimated shrink-swell potential of soil series.**

Physiographic Province	Parent Material	Soil Series	Classification <sup>†</sup>	Shrink-Swell Potential <sup>‡</sup>
Ridge and Valley	limestone	Frederick	mixed, Typic Paleudult	high
		Carbo	mixed, Typic Hapludalf	very high
Piedmont	granite gneiss	Cecil	kaolinitic, Typic Kanhapludult	moderate
Triassic Basins	diabase (diorite)	Jackland	smectitic, Aquic Hapludalf	very high
		Waxpool	smectitic, Aeric Ochraqualf	very high
		Davidson	kaolinitic, Rhodic Kandiudult	moderate
	thermal shale	Kelly	vermiculitic, Aquic Hapludalf	high
	sandstone/shale	Creedmoor	mixed, Aquic Hapludult	high
Mayodan		mixed, Typic Hapludult	high	
Coastal Plain	fluvial/marine	Craven	mixed, Aquic Hapludult	moderate
		Peawick	mixed, Aquic Hapludult	high

<sup>†</sup>All soils are in the fine family particle-size class (350 to 600 g kg<sup>-1</sup> clay).

<sup>‡</sup>Soil Survey Staff. 1997. Map unit interpretation records database.

#### 4.3.2. Laboratory Analysis

Samples were air-dried, ground, and sieved to remove coarse fragments greater than 2 mm. Laboratory analysis include particle size distribution, CEC, Atterberg limits, potential volume change (PVC) and are presented Chapter 3. Mineralogical composition of the clay fraction (< 2 µm) was determined by x-ray diffraction and thermal methods. Free Fe oxides were removed with dithionate-citrate-bicarbonate (Mehra and Jackson, 1960). Sand was removed by sieving, and the clay fraction was separated from silts by centrifugation (Jackson et al., 1950). Oriented mounts of the clay fraction were prepared by the method of Rich (1969) and saturated with KCl and MgCl<sub>2</sub>-glycerol (Whittig and Allardice, 1986). Random powder mounts of the sand and silt fractions were also prepared for mineralogical analysis. Minerals were identified with a Scintag XDS 2000 x-ray diffractometer with Cu-K $\alpha$  radiation. Thermal analysis of clay fraction was accomplished with a Dupont 990 Differential Scanning Calorimeter. Quantitative estimates of kaolinite and gibbsite were obtained by measuring endothermic peak areas. Quantitative estimates of other clay fractions were determined by

proportioning integrated peak areas of x-ray diffractograms, using kaolinite as an internal standard. Swelling 2:1 minerals were estimated by summing the smectite content and ½ of the vermiculite content.

#### 4.4. RESULTS AND DISCUSSION

Smectite distributions within the 11 soil profiles can be differentiated by parent material. Smectite concentration in the clay fraction increased with depth in soils formed from mafic rocks (diabase) and thermally altered shale (Table 4.2). This could indicate transformation of smectite by alteration of primary minerals (mica, chlorite, and hornblende) in the parent materials. Smectite weathers to kaolinite and hydroxy-interlayered vermiculite, and/or hydroxy-interlayered smectite with increasing proximity to the soil surface (Table 4.2) thus accounting for the observed decrease in smectite towards the soil surface.

The highest amount of smectite from the granite gneiss, limestone, sandstones and shales, and Coastal Plain sediments was in the Bt2 horizon where maximum expression of the argillic horizon occurs. This indicated neof ormation of smectite by dissolution of primary and secondary minerals and precipitation as neogenetic smectite. Aluminum, Fe, Mg, and Si from weathering of quartz and phyllosilicates in the surface accumulate in the Bt2 horizons, providing an environment favorable for smectite formation. Smectite contents decreased away from the maximum in the Bt2 horizon indicating unfavorable conditions for smectite stability in upper and lower horizons.

Smectite was highest in the smectitic soils, as would be expected, ranging from 350 to 600 g kg<sup>-1</sup> of clay (Table 4.2). Of the two smectitic soils, Waxpool had the highest amount of smectite, followed by Jackland. Leaching is inhibited in the poorly drained Waxpool soil whereas significant removal of clay mineral constituents occurs in the better drained Jackland soils. Highly weathered kaolinitic soils, Cecil and Davidson, had the lowest smectite content averaging 50 g kg<sup>-1</sup> clay. The vermiculitic Kelly also was typified by a low smectite content with a maximum of 150 g kg<sup>-1</sup>. The mixed mineralogy soils had a wide range in smectite ranging from 100 g kg<sup>-1</sup> in Frederick to 500 g kg<sup>-1</sup> in the Creedmoor.

Mica was present in the sand fraction of all parent materials (Table 4.3). Mica, a weathering precursor of smectite, either increased with depth or remains the same in all soils with the exception of Jackland where mica attained a maximum the middle of the profile. This could indicate the

**Table 4.2. Identification and quantification of clay mineral suites (<2 µm).**

Soil Series	Horizon	KAO†	SME	INT	VER	HIV/ HIS	MIC	GIB
----- <i>g kg<sup>-1</sup> clay</i> -----								
--								
<b>mafic rocks (diabase)</b>								
Jackland	Btss	100	200	650	--	--	50	--
	BCt	150	500	150	50	50	100	--
	C	50	550	350	--	50	tr	--
-----								
Waxpool	Bt1	50	20	500	150	50	50	--
	Bt2	100	600	100	50	100	50	--
	C	50	650	150	50	50	50	--
-----								
Davidson	Bt1	550	50	50	100	200	50	tr
	Bt2	600	50	-	200	50	100	tr
	Bt3	450	100	50	200	50	150	--
-----								
<b>thermal shale</b>								
Kelly	Bt1	350	--	150	300	150	50	--
	Bt2	200	50	200	400	50	100	--
	Bt3	100	150	200	550	--	100	--
-----								
<b>felsic rocks (granite gneiss)</b>								
Cecil	Bt1	600	50	100	100	100	50	tr
	Bt2	500	50	250	150	50	--	--
	BC	500	50	150	200	50	50	--
-----								
<b>Coastal Plain sediments</b>								
Craven	Bt1	400	400	--	100	50	50	--
	Bt2	350	200	150	200	50	50	--
	C	350	150	150	100	50	200	--
-----								

<b>Soil Series</b>	<b>Horizon</b>	<b>KAO<sup>†</sup></b>	<b>SME</b>	<b>INT</b>	<b>VER</b>	<b>HIV/HIS</b>	<b>MIC</b>	<b>GIB</b>
<b>Coastal Plain sediments</b>								
Peawick	Bt1	450	300	100	50	50	50	--
	Bt2	400	350	100	50	--	100	--
	BCg	250	300	50	100	--	300	--
<b>Triassic sandstones and shales</b>								
Creedmoor	Bt1	300	350	--	200	100	50	--
	Bt2	250	500	--	100	50	100	--
	BC	200	400	150	150	--	100	--
Mayodan	Bt1	300	300	100	50	200	50	--
	Bt2	400	300	260	150	50	100	--
	BC	250	250	--	20	60	20	--
<b>carbonate rocks (limestone)</b>								
Frederick	Bt1	350	50	150	50	50	350	tr
	Bt2	500	100	50	50	50	250	--
	BCt	450	100	100	50	--	300	--
	C	400	50	200	50	--	300	--
Carbo	Bt1	100	200	200	150	150	200	--
	Bt2	100	450	50	50	--	350	--
	Ct1	50	150	200	200	100	300	--
	Ct2	50	100	150	150	150	400	--

<sup>†</sup>KAO=kaolinite; SME=smectite; INT=interstratified 2:1's; VER=vermiculite; HIV/HIS=hydroxy-interlayered vermiculite/hydroxy interlayered smectite; MIC=mica; GIB=gibbsite; tr=trace.

**Table 4.3. Identification of sand mineral suites (0.05 - 2 mm).**

<b>Soil Series</b>	<b>Horizon</b>	<b>QTZ†</b>	<b>FLD</b>	<b>MUS</b>	<b>BIO</b>	<b>MAF</b>	<b>VER</b>	<b>MISC</b>
<b>mafic rocks (diabase)</b>								
Jackland	Btss	3‡	2	2	--	1	2	1
	BCt	2	2	2	1	2	1	2
	C	2	2	1	1	3	1	2
Waxpool	Bt1	2	3	1	--	2	1	1
	Bt2	2	2	2	--	2	1	1
	C	2	2	2	1	3	1	1
Davidson	Bt1	4	2	1	--	--	2	1
	Bt2	4	2	2	--	--	1	1
	Bt3	3	3	2	--	--	1	1
<b>thermal shale</b>								
Kelly	Bt1	2	2	1	--	--	--	2
	Bt2	2	2	1	--	--	--	2
	Bt3	1	3	1	--	--	--	2
<b>felsic rocks (granite gneiss)</b>								
Cecil	Bt1	5	1	3	--	--	1	1
	Bt2	5	1	3	--	--	1	1
	BC	5	2	2	--	--	1	1
<b>Coastal Plain sediments</b>								
Craven	Bt1	5	2	2	--	--	1	1
	Bt2	5	2	1	--	--	1	1
	C	4	2	1	--	--	1	--

Soil Series	Horizon	QTZ <sup>†</sup>	FLD	MUS	BIO	MAF	VER	MISC
<b>Coastal Plain sediments</b>								
Peawick	Bt1	5	2	2	--	--	1	--
	Bt2	4	3	3	--	--	1	--
	BCg	4	3	3	--	--	1	--
<b>Triassic sandstones and shales</b>								
Creedmoor	Bt1	5	2	3	--	--	1	1
	Bt2	5	2	2	--	--	1	1
	BC	5	2	2	--	--	1	--
Mayodan	Bt1	5	1	2	--	--	1	1
	Bt2	5	1	2	--	--	1	1
	BC	5	1	2	--	--	1	--
<b>carbonate rocks (limestone)</b>								
Frederick	Bt1	5	1	1	--	--	--	1
	Bt2	5	1	1	--	--	--	1
	BCt	5	2	1	--	--	--	1
	C	4	2	1	--	--	--	1
Carbo	Bt1	5	2	2	--	--	--	2
	Bt2	4	2	2	--	--	--	1
	Ct1	4	3	3	--	--	--	1
	Ct2	4	3	3	--	--	--	1

<sup>†</sup>QTZ=quartz; FLD=K feldspar; MUS=muscovite mica; BIO=biotite mica; MAF=mafic minerals (hornblende, olivine, pyroxene); MISC=other minerals (opaques, heavy minerals).

presence of colluvial parent materials in the upper Jackland profile. Only a trace amount of mica was detected in the diabase saprolite. If mica weathers to smectite, a negative correlation between mica content and smectite content should be observed. Frederick and Carbo soils showed this relationship

where high mica contents ( $> 250 \text{ g kg}^{-1}$  clay) corresponded to low smectite contents ( $< 200 \text{ g kg}^{-1}$  clay). The exception was the Bt1 horizon of the Carbo where mica and smectite contents were both high ( $> 350 \text{ g kg}^{-1}$  clay). Conversely, low mica contents ( $< 100 \text{ g kg}^{-1}$  clay) in the Jackland, Waxpool, Creedmoor, and Mayodan soils corresponded to high smectite contents ( $> 300 \text{ g kg}^{-1}$  clay) in the same soils. The highly weathered Cecil and Davidson soils exhibited both low clay mica contents and low smectite contents as both clay mineral components are weathered to kaolinite and hydroxy-interlayered vermiculite/smectite (Table 4.2).

#### 4.5. CONCLUSIONS

- Smectite concentration in the clay fraction increases with depth in soils formed from mafic rocks (diabase) and thermally altered shale. This could indicate transformation of smectite by alteration of primary minerals (mica, chlorite, and hornblende) in the parent materials. Smectite weathers to kaolinite and hydroxy-interlayered vermiculite, and/or hydroxy-interlayered smectite with increasing proximity to the soil surface thus accounting for the observed decrease in smectite towards the soil surface.
- The highest amount of smectite from the granite gneiss, limestone, sandstones and shales, and Coastal Plain sediments is in the Bt2 horizon where maximum expression of the argillic horizon occurs. This indicates neof ormation of smectite by dissolution of primary and secondary minerals and precipitation as neogenetic smectite. Smectite contents decrease both with depth and towards the soil surface from the maximum in the Bt2 horizon indicating unfavorable conditions for smectite stability in upper and lower horizons.
- Smectite is highest in the smectitic soils and lowest in the highly weathered kaolinitic soils, Cecil and Davidson. The vermiculitic Kelly also has a low smectite content but has a high vermiculite content, presumably inherited from the parent material. The mixed mineralogy soils have a varying amounts of smectite.
- Mica, a weathering precursor of smectite, is present in the sand fraction of all parent materials. Frederick and Carbo soils show a relationship where high mica contents correspond to low smectite contents. However, the Bt1 horizon of the Carbo has high mica and smectite contents. Conversely, low mica contents in the Jackland, Waxpool, Creedmoor, and Mayodan soils correspond to high smectite contents. The highly weathered Cecil and Davidson soils

exhibit both low clay mica contents and low smectite contents as both clay mineral components are weathered to kaolinite and hydroxy-interlayered vermiculite/smectite.



#### 4.6. REFERENCES

- Altschuler, Z.S., E.J. Dwornik, and H. Kramer. 1963. Transformation of montmorillonite to kaolinite during weathering. *Science* 141:148-152.
- Barnhisel, R.I. and P.M. Bertsch. 1989. Chlorites and hydroxy-interlayered vermiculite and smectite. p. 729-788. *In* J.B. Dixon and S.B. Weed (ed.) *Minerals in soil environments*. 2<sup>nd</sup> ed. Soil Sci. Soc. Am. Book Ser. No. 1. Madison, WI.
- Borchardt, G. 1989. Smectites. p. 675-727. *In* J.B. Dixon and S.B. Weed (ed.) *Minerals in soil environments*. 2<sup>nd</sup> edition. Soil Sci. Soc. Am. Book Ser. No. 1, Madison, WI.
- Carstea, D.D., M.E. Harward, and E.G. Knox. 1970. Comparison of iron and aluminum hydroxy interlayers in montmorillonite and vermiculite. I. Formation. *Soil Sci. Soc. Am. Proc.* 34:517-521.
- Crawford, T.W., Jr., L.D. Whittig, E.L. Begg, and G.L. Huntington. 1983. Eolian influence on development and weathering of some soils of Point Reyes Peninsula, California. *Soil Sci. Soc. Am. J.* 47:1179-1185.
- Eswaran, H. 1979. The alteration of plagioclases and augites under differing pedo-environmental conditions. *J. Soil Sci.* 30:547-555.
- Harris, W.G., L.W. Zelazny, J.C. Baker, and D.C. Martens. 1985. Biotite kaolinization in Virginia Piedmont soils: I. Extent, profile trends, and grain morphological effects. *Soil Sci. Soc. Am. J.* 49:1290-1297.
- Ismail, F.T. 1970. Biotite weathering and clay formation in arid and humid regions, California. *Soil Sci.* 109:257-261.
- Jackson, M.L., L.D. Whittig, and R.P. Pennington. 1950. Segregation procedure for the mineralogical analysis of soils. *Soil Sci. Soc. Am. Proc.* 14:77-81.
- Karathanasis, A.D. and B.F. Hajek. 1983. Transformation of smectite to kaolinite in naturally acid soil systems: Structure and thermodynamic considerations. *Soil Sci. Soc. Am. J.* 47:158-163.
- Karathanasis, A.D. and B.F. Hajek. 1984. Evaluation of aluminum-smectite stability equilibria in naturally acid soils. *Soil Sci. Soc. Am. J.* 48:413-417.
- Kittrick, J.A. 1973. Mica-derived vermiculites as unstable intermediates. *Clays Clay Min.* 21:479-488.

- Laird, D.A., T.E. Fenton, and A.D. Scott. 1988. Layer charge of smectites in an Argialboll-Argiaquoll sequence. *Soil Sci. Soc. Am. Proc.* 52:463-467.
- Mehra, O.P. and M.L. Jackson. 1960. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. *Clays Clay Min.* 7:317-327.83:531-546.
- Nash, V.E. 1979. Mineralogy of soils developed on Pliocene-Pleistocene terraces of the Tombigbee River in Mississippi. *Soil Sci. Soc. Am. J.* 43:616-623.
- Ransom, M.D., J.M. Bigham, N.E. Smeck, and W.F. Jaynes. 1988. Transitional vermiculite-smectite phases in Aqualfs of southwestern Ohio. *Soil Sci. Soc. Am. J.* 52:873-880.
- Reid, D.A., R.C. Graham, L.A. Douglas, and C. Amrhein. 1996. Smectite mineralogy and charge characteristics along an arid geomorphic transect. *Soil Sci. Soc. Am. J.* 60:1602-1611.
- Rich, C.I. 1968. Hydroxy interlayers in expansible layer silicates. *Clays Clay Min.* 16:15-30.
- Rich, C.I. 1969. Suction apparatus for mounting clay specimens on ceramic tile for x-ray diffraction. *Soil Sci. Soc. Am. Proc.* 33:815-816.
- Robert, M. 1973. The experimental transformation of mica toward smectite: Relative importance of total charge and tetrahedral substitution. *Clays Clay Min.* 21:167-174.
- Senkayi, A.L., J.B. Dixon, L.R. Hossner, and L.A. Kippenberger. 1985. Layer charge evaluation of expandable soil clays by an alkylammonium method. *Soil Sci. Soc. Am. J.* 49:1054-1060.
- Soil Survey Staff. 1993. Soil survey manual. USDA-SCS Agric.Handb. 18. U.S. Gov. Print. Office, Washington, D.C.
- Soil Survey Staff. 1994. Keys to Soil Taxonomy. 6<sup>th</sup> ed. Pocahontas Press, Blacksburg, VA.
- Soil Survey Staff. 1996. Soil survey laboratory methods manual. Soil Survey Investigations Rpt. 42, Ver. 3. National Soil Survey Center, Lincoln, NB.
- Soil Survey Staff. 1997. Map unit interpretation records database. [www.statlab.iastat.edu/soils/muir/](http://www.statlab.iastat.edu/soils/muir/).
- Whittig, L.D. and W.R. Allardice. 1986. X-ray diffraction techniques. *In* A. Klute (ed.) *Methods of soil analysis. Part 1. Physical and mineralogical methods.* 2<sup>nd</sup> ed. *Agronomy* 9:331-362.
- Wilson, M.J. and P.W. Cradwick. 1972. Occurrence of interstratified kaolinite-montmorillonite in some Scottish soils. *Clay Min.* 9:435-437.

# **CHAPTER 5**

# **Quantifying the Relationship between Shrink-Swell Indices and Soil Properties of Expansive Soil Map Units**

## **5.1. ABSTRACT**

A study was conducted in the Culpeper Basin in northern Virginia to quantify soil shrink-swell indices. Two to five delineations each of five map units were selected for study. Three profiles were sampled within each delineation to complete a nested sampling scheme. Three map units of smectitic, high shrink-swell soils with series names of Haymarket, Jackland, and Waxpool were selected. Also selected was a vermiculitic, high shrink-swell soil map unit named Kelly and a kaolinitic, a low shrink-swell soil map unit named Davidson. The Bt horizons of Haymarket, Jackland, Waxpool, and Kelly are clayey and have high CEC's, liquid limits, and plasticity indices. The soils in the Davidson map unit also have high clay contents but have lower swell indices, liquid limits, plasticity indices, and CEC's than the other four map units.

Shrink-swell indices and related soil properties exhibited high variability. However, the variability is partitioned within the delineations of each map unit. Each delineation within an individual map unit consists of the same variability. Shrink-swell potentials in all five map units are correlated with liquid limit, clay content, and CEC. However, individual map units exhibit differing relationships. Liquid limit and clay content are the best predictors of swell index in the Haymarket, Jackland, and Waxpool map units whereas clay content is the best predictor in the Kelly and Davidson map units. CEC is weakly correlated with shrink-swell potential in all five map units.

## **5.2. INTRODUCTION**

Changes in land use in rapidly urbanizing areas, such as the northern Virginia counties adjacent to Washington, D.C., continues at a rapid pace increasing the competition for remaining undeveloped land areas. Much of the land has already been converted from rural farmsteads and woodlands to subdivisions or has been designated as prime agricultural land thus protecting it from further development. This leaves the marginally adequate lands (soils) for further use. These soils are marginal for development because of soil properties, such as slow percolation rates for on-site wastewater disposal, or because they have significant amounts of clays that are conducive to shrink-swell tendencies. To complicate matters, soil map units identified in soil survey reports are composed

of more than one kind of soil, the proportions of which are variable due to natural complexity of soil parent materials. Nonetheless, such soils are being converted to non-agricultural uses as sewer and water services are extended into once rural areas. Expansive soils, or soils with high shrink-swell potential, comprise extensive acreage in several counties in the Culpeper Basin in northern Virginia.

Identification and location of soils for site assessment is best accomplished by consulting a detailed soil map. Further detailed evaluations are a logical strategy for the specific siting of facilities such as houses, foundations, roads, or septic adsorption fields. During the updating process of the Fauquier County (Virginia) Soil Survey, individual soil map units were examined extensively, with specific studies designed to identify variability and appropriately partition the variability into pedons, delineations, or map units. In addition to variability assessments, soil properties have been quantified during the update process by map unit. Some of these properties lead to shrink-swell behavior.

Soil variability compounds interpretation of a map unit for a specific use. Identification and quantification of spatial variability of soil properties in map units are needed to make accurate soil and land use interpretations. Map unit variability can be evaluated by several statistical methods including analysis of variance, geostatistics, and coefficients of variability. No one procedure is recommended over another; study design depends on time constraints, efficiencies, needs, and objectives of the user and investigators. Analysis of variance can be used to evaluate map unit composition and variability in a typical second-order soil survey as it allows the study of the spatial aspect of variability with reduced numbers of samples (Wilding and Drees, 1983). Nested ANOVA has been employed in several map unit studies (Wilding et al., 1965; Edmonds et al., 1985; Thomas et al., 1989). These studies allowed for the partitioning of variability into map units, delineations within map units, pedons within delineations, and profiles within pedons. Studies evaluating variability of crop yields and soil properties in map units have found variability to be as great within map units as between map units (Edmonds et al., 1985; Thomas et al., 1989; Karlen, et al., 1990). Variability within map unit delineations is often greater among (between) delineations of the same map unit (Wilding et al., 1965). However, variability within delineations has been observed to be greater than variability between delineations (McCormack and Wilding, 1969) possibly due to complex parent materials, landscape variability, aspect, or other factors that cannot be delineated at the mapping scale.

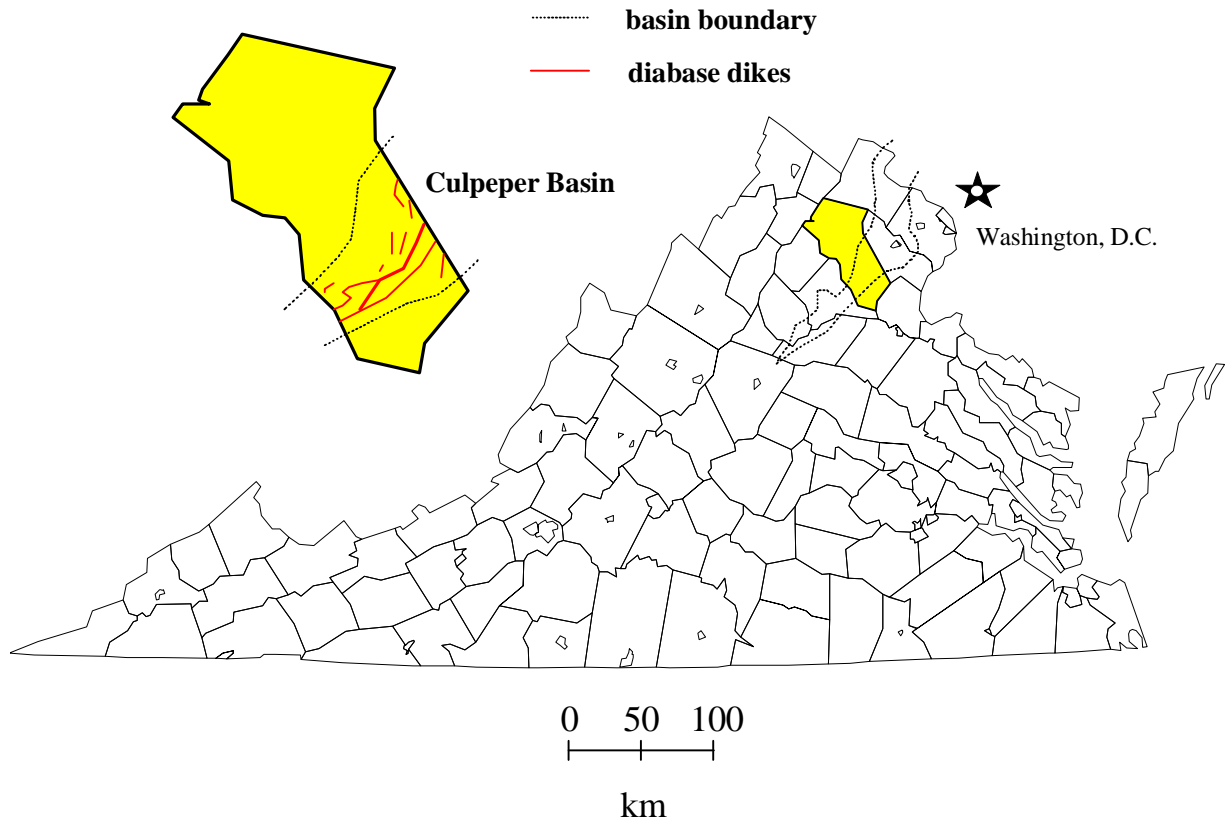
Volume change in shrink-swell soils is related to the properties of the clay fraction. Studies to estimate clay fraction properties such as plasticity index, clay content, specific surface area, and clay mineralogy have identified these properties as the most common indicators (predictors) of potential volume change (see Chapter 3). In soils dominated by illite, clay content is as reliable in predicting swelling potential as are the Atterberg limits (McCormack and Wilding, 1975). In a study of 12 southern soils with a variety of clay mineralogical suites from montmorillonite, to mixed systems, to soils dominated by kaolinite, CEC was the soil property most correlated with mechanical strength and shrinkage of clods (Gill and Reaves, 1957). Clay content and specific surface area were highly correlated to coefficient of linear extensibility in micaceous and kaolinitic soils in Ontario, Canada and less correlated to montmorillonitic soils (Ross, 1978). In a study of montmorillonitic soils in Alabama, Karathanasis and Hajek (1985) found that smectite content was the only consistent soil property that significantly correlated with laboratory-measured shrink-swell potential.

The objectives of this study are 1) make quantitative estimates of shrink-swell indices and soil properties, 2) partition variability into map unit components, i.e., among map units, between delineations within a map unit, between profiles within a delineation, and 3) determine best predictors or indicators of shrink-swell potential.

### **5.3. MATERIALS AND METHODS**

#### **5.3.1. Geology**

The study area is within the Culpeper Basin region of southern Fauquier County, Virginia (Figure 5.1). The Culpeper Basin was formed in the late Triassic period (200 million years ago) when the paleocontinent, Pangea, began splitting apart. This rifting formed basins from present-day Canada to South Carolina. Sediments filled the Triassic Basins upwards to thousands of meters thick. The sediments lithified into brown and maroon sandstones and shales. During the Jurassic, volcanic activity occurred and extensive intrusions of igneous dikes were thrust upward through the sedimentary rocks. Much of this igneous material cooled into diabase, a medium-grained basalt. These dikes formed low ridges in the otherwise subdued basin landscape that are generally oriented



**Figure 5.1. Study area in Culpeper Basin, Fauquier County, VA. Thermally altered shales surround diabase dikes.**

in the present-day southwest to northeast direction. The heat from the igneous intrusions ‘baked’ surrounding sediments forming thermally altered shales that surround the diabase dikes (Froelich and Gottfried, 1988). Soils formed on these two parent materials have high clay contents and appreciable amounts of smectite (montmorillonite) and vermiculite.

### **5.3.2. Study Area**

The Culpeper Basin soils are forming on the diabase and thermally altered shale residual parent materials. These soils have high and very high shrink-swell potential with appreciable amounts of smectite and vermiculite and high clay contents. The soils selected for study from the diabase residuum are well-drained Davidson (clayey, kaolinitic, thermic Rhodic Kandudults) and Haymarket (fine, smectitic, mesic Typic Hapludalfs), moderately well drained Jackland (fine, smectitic, mesic Aquic Hapludalfs), and somewhat poorly to poorly drained Waxpool (fine, smectitic, mesic Aeric

Ochraqualfs). Thermally altered shale residual material was represented by the Kelly series (fine, vermiculitic, mesic Aquic Hapludalfs). Haymarket, Jackland, Waxpool, and Kelly are rated as having high or very high shrink-swell potential (Soil Survey Staff, 1997). The Davidson soil has low shrink-swell potential.

### **5.3.3. Study Design**

The soil survey of Fauquier County (USDA-SCS, 1956) is currently being updated. Five delineations in each of the five map units were randomly selected from Fauquier County soil survey maps. Three sites within each delineation were randomly located in a two-level nested sampling scheme. Morphological descriptions were made and series named at each site to assess map unit composition and variability. The control section of the argillic (Bt) horizon was bulk sampled for physical, chemical, and mineralogical analysis. The argillic horizon occurs at the depth which foundations are typically installed (45 to 90 cm).

### **5.3.4. Laboratory Analysis**

Samples were air-dried, ground, and sieved to remove coarse fragments greater than 2 mm. Laboratory analyses include particle size distribution, CEC, Atterberg limits, potential volume change (PVC), and clay mineralogy. Particle size distribution by pipette and CEC were done in accordance with National Cooperative Soil Survey laboratory methods (Soil Survey Staff, 1996). Atterberg limits (liquid limit, plasticity index) were measured by ASTM method D4318 (American Society for Testing and Materials, 1993). Potential volume change was determined by the method of Lambe (1960). Shrink-swell potential was determined on each sample based on PVC data. Shrink-swell potential classes are low (<81 kPa), moderate (81-153 kPa), high (153-225 kPa), and very high (>225 kPa) (Soil Survey Staff, 1993). Mineralogical analysis was performed on control sections from one typifying pedon from each map unit. Free Fe oxides were removed with dithionate-citrate-bicarbonate (Mehra and Jackson, 1960). Sand was removed by sieving, and the clay fraction was separated from silts by centrifugation (Jackson et al., 1950). Oriented mounts of the clay fraction were prepared by the method of Rich (1969) and saturated with KCl and MgCl<sub>2</sub>-glycerol (Whittig and Allardice, 1986). Clay minerals were determined with a Scintag XDS 2000® x-ray diffractometer with Cu-K $\alpha$  radiation and quantified by estimating peak areas.



### 5.3.5. Statistical Analysis

Descriptive statistics of mean, minimum and maximum values, and coefficient of variability were estimated by the UNIVARIATE procedure (SAS Institute, 1985a).

Observations ( $Y_{ijk}$ ), e.g., clay percentage, CEC, liquid limit, etc., in the map units were described by the linear model

$$Y_{ijk} = \mu + M_i + D_{ij} + \epsilon_{ijk}$$

where  $\mu$  represents overall mean,  $M_i$  represents the effect due to a particular map unit,  $D_{ij}$  represents the effect due to a particular delineation, and  $\epsilon_{ijk}$  represents variation among the profiles within a given delineation and errors in sampling and laboratory procedures.

The SAS analysis of variance procedure (SAS Institute Inc., 1985b) was used to evaluate statistical differences between delineations and among map units for the measured soil properties. Percent of the total variance contributed by each component in the sampling scheme was estimated by dividing variance contributed by the individual components by total variance.

Stepwise regression techniques of SAS STEPWISE (SAS Institute, 1985b) were used to isolate the soil properties significantly correlated with swell index.

## 5.4. RESULTS AND DISCUSSION

### 5.4.1. Variability of Shrink-Swell Indices

The Bt horizons of the soils in the Haymarket, Jackland, Waxpool, and Kelly map units were, on average, clayey with high or very high swell indices, and had moderate to high CEC, liquid limits, and plasticity indices (Table 5.1). The soils in the Davidson map unit, although having similar clay content, had significantly lower swell indices, liquid limits, plasticity indices, and CEC compared with the other four map units.

Average clay contents were higher in the less well drained Jackland, Waxpool, and Kelly soils as compared with the well-drained Davidson and Haymarket map units (Table 4.1). Less well-drained soils in a catena typically had more clay. The range in clay content was greater in the Davidson and Haymarket map units as reflected by the high coefficient of variability. Family particle-size class, as defined by *Soil Taxonomy* (Soil Survey Staff, 1994) for the soils in the map units straddled the fine and very fine classes, averaging about 60% clay. Davidson, Haymarket, and Kelly map units contained inclusions of fine-loamy soils (Kelly - 7%, Haymarket - 22%, Davidson - 33%), thus, based

on family particle-size class, these three map units contained dissimilar soils.

**Table 5.1. Average, minimum, and maximum values and coefficient of variability of map units for selected shrink-swell indices.**

Property†	Statistic	Map Unit				
		Davidson	Haymarket	Jackland	Waxpool	Kelly
Clay	Average	472a‡	478a	610a	557a	560a
	Minimum	244	283	348	398	318
	Maximum	691	652	742	714	703
	CV	34	28	20	17	20
CEC	Average	16a	30b	38c	29b	28b
	Minimum	12	17	24	19	16
	Maximum	20	51	49	44	49
	CV	15	39	17	21	32
Liquid Limit	Average	49a	60ab	78c	66bc	63bc
	Minimum	30	47	28	43	39
	Maximum	68	73	99	84	75
	CV	26	29	29	16	18
Plasticity Index	Average	17a	29ac	46b	37bc	34c
	Minimum	10	15	21	14	16
	Maximum	31	40	64	57	43
	CV	41	50	27	30	26
Swell Index	Average	113a	211b	337c	229b	210b
	Minimum	43	76	115	95	62
	Maximum	211	400	585	336	439
	CV	45	70	46	26	36

†Clay in g kg<sup>-1</sup>; CEC in cmol<sub>c</sub> kg<sup>-1</sup> of soil; liquid limit and plasticity index in percent H<sub>2</sub>O by weight; swell index in kPa; CV=coefficient of variability.

‡Means in a row followed by the same letter are not significantly different at the 0.05 level.

Average CEC for the smectitic Haymarket, Jackland, and Waxpool map units and the vermiculitic Kelly was significantly higher compared with the Davidson CEC (Table 5.1). Jackland had the highest CEC, a reflection of the high clay content, coupled with large amounts of smectite. Variability of this property was less than variability of other measured soil properties. Given a correlation between clay content and dominant clay mineral species, CEC may be estimated in the field.

Atterberg limits are measurements of plasticity of a soil at specified moisture contents. Liquid limit is the moisture content at which a soil changes from a plastic body to a viscous liquid and can begin to flow. Plastic limit is the lowest moisture content at which a soil can be deformed and maintain its shape without cracking. The difference between liquid limit and plastic limit is the plasticity index (PI) or a measure of a soil's potential plasticity and is widely used in the geotechnical community to assess shrink-swell potential. Soils with high PI's are considered to have the capacity for expansive behavior. Liquid limit was highest in the Jackland map unit, followed by Waxpool, Kelly, Haymarket, and Davidson (Table 5.1). The high liquid limits were partially a reflection of the higher clay contents, but were best explained by expanding 2:1 minerals. Typically, the greater the specific surface area, the greater the total amount of water required to satisfy the conditions at liquid limit. Given that water adsorption is the same for all surfaces, expanding 2:1's, with more internal surface layers, adsorb more water and thus have higher liquid limits (Mitchell, 1993). Plasticity index followed the same trend as liquid limits for the map units. Plasticity index was significantly higher in Jackland, Waxpool, and Kelly as compared with Davidson and Haymarket. Soils with high layer charges (2:1 clays) can retain plasticity at lower moisture contents. Variability in both liquid limit and PI was large in all map units thus the dissimilar inclusions of low liquid limit and low PI soils will affect site suitability.

Swell index was not significantly different between the smectitic Waxpool and Haymarket soils and the vermiculitic Kelly soils (Table 5.1). The Davidson soils had significantly lower swell indices compared with the other four map units. The swell index for the Jackland map unit was significantly higher compared with the other map units, but exhibited the greatest variation in swell index ranging from a low of 115 kPa (2300 lbs ft<sup>-2</sup>) to almost 600 kPa (12,500 lbs ft<sup>-2</sup>). The Jackland and Waxpool soils had average measured shrink-swell potential of very high and the Kelly,

Haymarket, and Davidson soils had high shrink-swell potential. Each map unit had potential ratings ranging from moderate to very high (Table 5.1). Again, variability of this direct shrink-swell estimator was great within each map unit as reflected in both minimum and maximum values and in the coefficient of variability.

Shrink-swell indices and postulated behavior were similar when comparing averages among the five map units, but pedons within the map units were dissimilar based on variability. This wide difference in all shrink-swell indices emphasizes the need for reliable estimates of map unit composition and variability to accurately predict the probability of encountering expansive soils.

#### **5.4.2. Map Unit Composition**

All profiles in each of the five map units were classified in the field based on morphological descriptions. Criteria employed in delineating taxonomic units in the map units were depth to bedrock, family particle size class, matrix color, drainage class, and estimated shrink-swell potential. All map units, except Davidson, were dominated by soils other than the named series but the inclusions have similar use and management interpretations. Davidson was the purest map unit in terms of named series with half the profiles classifying as Davidson (Table 5.2.) Haymarket and Waxpool map units contained the greatest percentage of dissimilar inclusions. Dissimilar inclusions in the high shrink-swell Haymarket, Jackland, Waxpool, and Kelly map units would consist of soils with more favorable shrink-swell properties. For other use and management decisions, such as row crop production, inclusions of better soils would not be a detriment. However, for siting a home, contrasting soils could be as detrimental to a foundation as a high shrink-swell soil.

#### **5.4.3. Map Unit Variability**

The percentage of total variation contributed by map units, delineations, and profiles in the sampling design is given for swell index and the properties correlated with swell index in Table 5.3. Large values for profile variance indicate significant short-range variability. Large values for map unit and delineation variance indicate variability within the delineation.

**Table 5.2. Composition of soil map units, Fauquier County.**

Map Unit	Named Series	Similar Inclusions†	Dissimilar Inclusions‡
----- % of map unit -----			
Haymarket	22	34	44
Jackland	20	67	13
Waxpool	20	47	33
Kelly	27	73	0
Davidson	50	33	17

†Soils that have alike properties; differences do not affect use and management.

‡Soils that differ in one or more properties from named series; affect use and management.

**Table 5.3. Probability and percent total variation contributed by map units, delineations, and profiles of shrink-swell indices.**

Property	Level†				
	Map Unit		Delineation		Profile‡
	%	<i>p</i> §	%	<i>p</i>	%
Swell Index	22	0.0126	2	0.3950	76
CEC	--	--	39	0.0031	61
Liquid Limit	17	0.0459	15	0.0882	67
Plasticity Index	24	0.0222	18	0.0502	58
Clay	8	0.1812	28	0.0153	64
% passing 200 sieve	27	0.0207	15	.0703	58

† Levels of comparison are: map unit = between map units; delineation = between delineations within a map unit; profile = between profiles within a delineation.

‡ Includes error variance.

§ Probability (*p*) of rejecting the null hypothesis of equal group means.

Although individual map units showed extreme variability within delineations for shrink-swell indices (Table 5.1), the variability was consistent from delineation to delineation. The field soil scientists did a good job of partitioning the variability within the delineations. Each delineation within an individual map unit consisted of the same variability.

On the average, Jackland, Waxpool, and Kelly soils would be rated as having high shrink-swell soils but are commonly mapped with areas of low to moderate shrink-swell potential. This is critical in siting a home. We do not want one corner of the house on low shrink-swell material and another corner on high shrink-swell soils. Differential shrinking and swelling of the two contrasting materials could potentially cause as much or more damage than siting a home on a uniform high shrink-swell soil unless special engineering designs for each site are employed. Such examples are specially designed reinforced foundations, grading, guttering, and landscaping that moves water away from the foundation. Thus, a detailed on-site investigation seems prudent for any map unit containing high shrink-swell soils.

#### **5.4.4. Prediction of Swell Index**

Given statistically significant variability in the shrink-swell indices, is there a relationship between the more easily measured soil properties that can be used to estimate shrink-swell potential? Regression is a useful statistical technique for modeling and predicting the relationship between variables. In this study, multiple linear regression was used to isolate soil properties significantly correlated to swell index.

Liquid limit, clay content, and CEC were the best predictors of shrink-swell potential when all five map units were examined as one population (Table 5.4). However, when evaluating individual map units, CEC was weakly correlated with swell index in the Kelly and Haymarket map units and uncorrelated in the Jackland, Waxpool, and Davidson map units (Table 5.4). Liquid limit and clay content both correlated with swell index in all five map units but at different magnitudes. Liquid limit was the best predictor for the Bt horizons in the Haymarket, Jackland, and Waxpool map units. These three soils comprised a catena with diabase saprolite parent material and were dominated by smectite in the clay fraction. Swell index in the Davidson and Kelly map units was best explained by clay content. Smectite comprised a small portion of the clay fraction relative to the amounts of kaolinite in the Davidson and vermiculite in the Kelly (see Chapter 4).

**Table 5.4. Correlations (R) between soil properties and swell index for map units.**

Soil Property	R				
	Jackland	Waxpool	Kelly	Davidson	Haymarket
Liquid Limit	0.69	0.66	0.58	0.88	0.85
Plasticity Index	0.68	0.62	0.44	0.93	0.82
Clay	0.64	0.72	0.79	0.96	0.73
CEC	0.17	0.35	0.64	0.20	0.57

### 5.5. CONCLUSIONS

- The Bt horizons of the soils in the high and very high shrink-swell Haymarket, Jackland, Waxpool, and Kelly map units were clayey and had high CEC's, liquid limits, and plasticity indices. The soils in the lower shrink-swell potential Davidson map unit, although with similar clay content, had significantly lower swell indices, liquid limits, plasticity indices, and CEC than the other four map units.
- Variability of the shrink-swell indices and related properties was high in all map units. Variability of the soil properties translates into variability of series in the map units. Named series in the high/very high shrink-swell map units comprised less than 1/4 of the map unit. Similar series, or inclusions, comprised the majority of these map units. Dissimilar inclusions could adversely impact foundations if a home is sited on both low/moderate and high/very high shrink-swell soils.
- Although there was extreme variability in the map units, the variability occurred within the delineations of each map unit. Each delineation within an individual map unit consisted of the same variability.
- Liquid limit, clay, and CEC were the best predictors of shrink-swell potential when all 5 map units are examined as one population. However, when evaluating individual map units, CEC was only weakly correlated with swell index in the Kelly and Haymarket map units and uncorrelated in the Jackland, Waxpool, and Davidson map units. Liquid limit and clay were the best predictors of swell index in the Haymarket, Jackland, and Waxpool map units. Clay

content was the best predictor in the Davidson and Kelly map units. Differences in soil property correlations in the map units was proposed to be related to clay mineralogy where high smectite contents had a great influence on liquid limit in the diabase-derived map units.



## 5.6. REFERENCES

- American Society for Testing and Materials. 1993. Annual book of ASTM standards. Construction. Section 4. Soil and rock; dimension stone; geosynthesis. Vol. 04.08. ASTM, Philadelphia, PA.
- Edmonds, W.J., J.C. Baker, and T.W. Simpson. 1985. Variance and scale influences on classifying and interpreting soil map units. *Soil Sci. Soc. Am. J.* 49:957-961.
- Froelich, A.J. and D. Gottfried. 1988. An overview of early Mesozoic intrusive rocks in the Culpeper Basin, Virginia and Maryland. *In Studies of the early Mesozoic basins of the eastern U.S.* U.S. Geol. Surv. Bull. 1976. U.S. Gov. Print. Office, Washington, D.C.
- Gill, W.R. and C.A. Reaves. 1957. Relationships of Atterberg limits and cation-exchange capacity to some physical properties of soil. *Soil Sci. Soc. Am. Proc.* 21:491-494.
- Jackson, M.L., L.D. Whittig, and R.P. Pennington. 1950. Segregation procedure for the mineralogical analysis of soils. *Soil Sci. Soc. Am. Proc.* 14:77-81.
- Karathanasis, A.D. and B.F. Hajek. 1985. Shrink-swell potential of montmorillonitic soils in udic moisture regimes. *Soil Sci. Soc. Am. J.* 49:159-166.
- Karlen, D.L., E.J. Sadler, and W.J. Busscher. 1990. Crop yield variation associated with Coastal Plain soil map units. *Soil Sci. Soc. Am. J.* 54:859-865.
- Lambe, T.W. 1960. The character and identification of expansive soils. Fed. Housing Admin. Rpt. 701.
- McCormack, D.E. and L.P. Wilding. 1969. Variation of soil properties within mapping units. *Soil Sci. Soc. Am. Proc.* 33:587-593.
- McCormack, D.E. and L.P. Wilding. 1975. Soil properties influencing swelling in Canfield and Geeburg soils. *Soil Sci. Soc. Am. Proc.* 39:496-502.
- Mehra, O.P. and M.L. Jackson. 1960. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. *Clays Clay Min.* 7:317-327.
- Mitchell, J.K. 1993. Fundamentals of soil behavior. 2<sup>nd</sup> ed. John Wiley and Sons, New York.
- Rich, C.I. 1969. Suction apparatus for mounting clay specimens on ceramic tile for x-ray diffraction. *Soil Sci. Soc. Am. Proc.* 33:815-816.

- Ross, G.J. 1978. Relationships of specific surface area and clay content to shrink-swell potential of soils having different clay mineralogical compositions. *Can. J. Soil Sci.* 58:159-166.
- SAS Institute. 1985a. SAS user's guide: Basics. Version 5. SAS Inst., Cary, NC.
- SAS Institute. 1985b. SAS user's guide: Statistics. Version 5. SAS Inst., Cary, NC.
- Soil Survey Staff. 1993. Soil survey manual. USDA-SCS Agric.Handb. 18. U.S. Gov. Print. Office, Washington, D.C.
- Soil Survey Staff. 1994. Keys to Soil Taxonomy. 6<sup>th</sup> ed. Pocahontas Press, Blacksburg, VA.
- Soil Survey Staff. 1996. Soil survey laboratory methods manual. Soil Survey Investigations Rpt. 42, Ver. 3. National Soil Survey Center, Lincoln, NB.
- Soil Survey Staff. 1997. Map unit interpretation records database. [www.statlab.iastat.edu/soils/muir/](http://www.statlab.iastat.edu/soils/muir/).
- Thomas, P.J., J.C. Baker, and T.W. Simpson. 1989. Variability of the Cecil map unit in Appomattox County, Virginia. *Soil Sci. Soc. Am. J.* 53:1470-1474.
- USDA-SCS. 1956. Soil survey of Fauquier County, Virginia. U.S. Gov. Print. Office. Washington, D.C.
- Whittig, L.D. and W.R. Allardice. 1986. X-ray diffraction techniques. *In* A. Klute (ed.) *Methods of soil analysis. Part 1. Physical and mineralogical methods.* 2<sup>nd</sup> ed. *Agronomy* 9:331-362.
- Wilding, L.P. and L.R. Drees. 1983. Spatial variability and pedology. p. 83-116. *In* L.P. Wilding, N.E. Smeck, and G.F. Hall (ed.) *Pedogenesis and soil taxonomy. I. Concepts and interactions.* Elsevier Sci. Publ. B.V. Amsterdam, The Netherlands.
- Wilding, L.P., R.B. Jones, and George M. Schafer. 1965. Variation of soil morphological properties within Miami, Celina, and Crosby mapping units in west-central Ohio. *Soil Sci. Soc. Am. Proc.* 29: 711-717.

# CHAPTER 6

## CONCLUSIONS

This research focused on identifying and quantifying the soil properties correlated with shrink-swell potential for 12 major benchmark soils in four physiographic provinces in Virginia. The *mineralogy classes*, soil series, and (physiographic provinces, parent materials) examined include *smectitic* -- Jackland and Waxpool (Culpeper Triassic diabase); *vermiculitic* -- Kelly (Triassic thermal shale); *kaolinitic* -- Cecil (Piedmont, granite gneiss) and Davidson (Triassic, diabase); and *mixed* -- Carbo and Frederick (Valley and Ridge, limestone), Craven and Peawick (Coastal Plain, fluvial and marine sediments), and Mayodan and Creedmoor (Richmond and Farmville Triassic sandstones). Three sites in each of the 12 soil series were described and major horizons sampled for laboratory analysis. The overall objectives of this study were:

- 1) Quantify properties and shrink-swell indices of 12 expansive soils in four major physiographic provinces in Virginia; correlate shrink-swell potential with soil properties and shrink-swell indices; develop an expansive soil rating system using soil properties correlated with shrink-swell potential; and develop shrink-swell risk categories for soils within different parent materials;
- 2) Identify and quantify distribution of swelling clay minerals within soil profiles in 12 expansive soils; and
- 3) Obtain quantitative estimates of shrink-swell indices and soil properties of five expansive soils in the Culpeper Basin; partition variability into map unit components, i.e., among map units, between delineations within a map unit, between profiles within a delineation; and determine best predictors or indicators of shrink-swell potential.

Conclusions from each of the three objectives are:

### *Objective 1*

- Soils with estimated high or very high shrink-swell potential were clayey, with clay contents exceeding 60%. These expansive soils also exhibited high CEC ( $>15 \text{ cmol}_c \text{ kg}^{-1} \text{ soil}$ ), high liquid limits ( $>70$ ), and appreciable swelling 2:1 mineral content ( $> 15\%$  montmorillonite +  $\frac{1}{2}$  vermiculite on a whole soil basis).
- An expansive soil rating system, termed the *Expansive Soil Index (ESI)*, was developed using the soil properties most correlated with shrink-swell potential. The sum of swelling 2:1

minerals, swell index, liquid limit, and CEC gave expansive soil potential ratings (ESI) for each soil series. The higher the ESI, the greater shrink-swell potential. Where less detailed information is required, such as for initial feasibility studies, an ESI consisting of liquid limit and CEC was recommended.

- The soils were grouped into risk categories based on parent material to allow for classification of similar soils into the ESI rating system. Soils with restricted drainage formed from mafic rocks, soils formed from carbonate parent material, and metamorphic shales were at high risk for expansive soil behavior.

#### *Objective 2*

- Smectite concentration in the clay fraction increased with depth in soils formed from mafic rocks (diabase) and thermally altered shale. This indicated transformation of smectite by alteration of primary minerals (mica, chlorite, and hornblende) in the parent materials. Smectite weathers to kaolinite and hydroxy-interlayered vermiculite, and/or hydroxy-interlayered smectite with increasing proximity to the soil surface thus accounting for the observed decrease in smectite toward the soil surface.
- The highest amount of smectite in soils weathered from the granite gneiss, limestone, sandstones and shales, and Coastal Plain sediments was in the Bt2 horizon where maximum expression of the argillic horizon occurs. This indicated neoformation of smectite by dissolution of primary and secondary minerals and precipitation as neogenetic smectite. Smectite contents decreased both with depth and toward the soil surface from the maximum in the Bt2 horizon indicating unfavorable conditions for smectite stability in upper and lower horizons.
- Smectite was highest in the smectitic soils and lowest in the highly weathered kaolinitic soils, Cecil and Davidson. The vermiculitic Kelly also had a low smectite content but had a high vermiculite content, presumably inherited from the parent material. The mixed mineralogy soils had varying amounts of smectite.
- Mica, a weathering precursor of smectite, was present in the sand fraction of all parent materials. Frederick and Carbo soils showed a relationship where high mica contents corresponded to low smectite contents. However, the Bt1 horizon of the Carbo had high

mica and smectite contents. Conversely, low mica contents in the Jackland, Waxpool, Creedmoor, and Mayodan soils corresponded to high smectite contents. The highly weathered Cecil and Davidson soils exhibited both low clay mica contents and low smectite contents as both clay mineral components were weathered to kaolinite and hydroxy-interlayered vermiculite/smectite.

- Vermiculite, typically an intermediate weathering product in soils, is not a dominant mineral in any of the soils, with the exception of Kelly.

### *Objective 3*

- The Bt horizons of the soils in the high and very high shrink-swell Haymarket, Jackland, Waxpool, and Kelly map units were clayey and have high CEC's, liquid limits, and plasticity indices. The soils in the lower shrink-swell potential Davidson map unit, although with similar clay content, had lower swell indices, liquid limits, plasticity indices, and CEC than the other four map units.
- Variability of the shrink-swell indices and related properties were high in all map units. Variability of the soil properties translated into variability of series in the map units. Named series in the high/very high shrink-swell map units comprised less than 1/4<sup>th</sup> of the map unit. Similar series, or inclusions, comprised most of these map units. Dissimilar inclusions could adversely affect foundations if a home is sited on both low/moderate and high/very high shrink-swell soils.
- Although there was extreme variability in the map units, the variability occurred within the delineations of each map unit. Each delineation within an individual map unit consisted of the same variability.
- Liquid limit, clay, and CEC were the best predictors of shrink-swell potential when all five map units are examined as one population. However, when evaluating individual map units, CEC was only weakly correlated with swell index in the Kelly and Haymarket map units and uncorrelated in the Jackland, Waxpool, and Davidson map units. Liquid limit and clay were the best predictors of swell index in the Haymarket, Jackland, and Waxpool map units. Clay content was the best predictor in the Davidson and Kelly map units. Differences in soil property correlations in the map units was proposed to be related to clay mineralogy where

high smectite contents had a great influence on liquid limit in the diabase-derived map units.

# CHAPTER 7



## SUMMARY

Water is responsible for considerable property damage in the Commonwealth of Virginia, with floods and hurricanes inflicting millions of dollars of damage each year. Although not as sudden or dramatic as floods and hurricanes, expansive soils can cause considerable more damage to structures and highways than other natural disasters combined. Damage ranges from minor cracking in exterior walls to major displacement of the structure.

Soils exhibiting expansive behavior are common throughout Virginia. Soils with estimated high shrink-swell potential range from the well-drained, red Frederick soils of the limestone valley in western Virginia to the poorly drained, gray Waxpool soils in northern Virginia. What properties do these disparate soils have in common that predisposes them to shrink-swell behavior? Our research focused on this fundamental question. We found that several soil properties were correlated with predicted shrink-swell potential -- swelling 2:1 minerals (smectite and vermiculite), swell index, liquid limit, and CEC. Using absolute values of these four soil properties we developed an *Expansive Soil Index (ESI)* that assesses soils for shrink-swell risk. High *ESI* values indicate high shrink-swell soils. We anticipate classifying shrink-swell risk of additional soils with the *Expansive Soil Index*. *ESI* will give soil scientists, geologists, engineers, planners, realtors, builders, code enforcement officials, and other clientele an accurate method of assessing shrink-swell potential for most soils in Virginia.