Shrinkage of Clays

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Abstract

In many parts of the world the shrink-swell characteristics of fine-grained material is of considerable importance and of potential economic significance. Expansive soils cause significant damage to structures and roadways by cyclically shrinking and swelling within the active zone, which is defined as the depth in a soil to which periodic changes of moisture occurs. In the U.S., expansive soils cover large parts of Texas, Oklahoma and the upper Missouri Valley, and are typically montmorillonitic in nature. Traditionally there are two ways to identify the shrink-swell potential of the clay deposit: measure the shrinkage characteristics or measure the swelling characteristics. This paper discusses the shrinkage characteristics of fine-grained soils.

Four natural and pure clays were tested to determine shrinkage characteristics and the respective shrinkage curves are presented and discussed. The direct measurement of the limit of shrinkage from the shrinkage curves of the Linear Shrinkage and Shrinkage Limit tests are discussed and compared to the calculated Shrinkage Limit from the ASTM D-427 Shrinkage Limit test. It is shown that the Linear Shrinkage and the Shrinkage Limit tests produce similar shrinkage curves and a consistent Limit of Shrinkage. The calculated Shrinkage Limit from the Shrinkage Limit test underpredicts the limit of shrinkage for the soils tested and is extremely operator dependent.

Introduction

Measuring the shrinkage characteristics of a soil can help to delineate clay mineralogy (montmorillinitic-illitic-kaolinitic) and shrink/swell potential of a geologic deposit. Two laboratory test methods of measuring the shrinkage properties of fine-grained soil are the Shrinkage Limit (Transport and Road Research Laboratory Method (TRRL), Head (1994) and ASTM D-427:04) and the Linear Shrinkage (BS-1377:90). The Shrinkage Limit test calculates the volumetric shrinkage and the Linear Shrinkage test is used to calculate one-dimensional shrinkage, although the volumetric shrinkage may be calculated. The linear shrinkage is a measure of the average oven dry length of the sample after shrinkage to the original length which occurs at an initial water content at or above the Liquid Limit. The Shrinkage Limit of a soil is defined as the water content at which no further volume decrease occurs, but where the degree of saturation is still essentially 100 % (Holtz and Kovacs 1981) (Figure 1). This curve can be reproduced in the laboratory by weighing and measuring the sample as it dries slowly over several days (TRRL Method, Head 1994). The distinct break in the curve where water content continues to decrease but volume remains constant is a direct, and the truest, measure of the limit of shrinkage. This direct measurement of the limit of shrinkage was performed in this study to have a basis to compare to the calculated Shrinkage Limit test results.

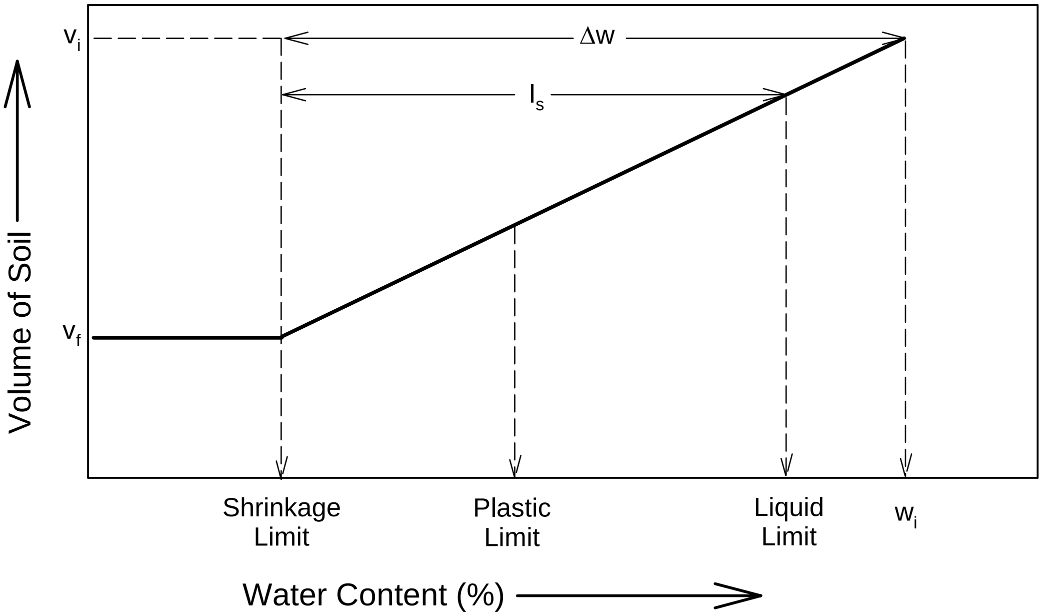

Figure 1. Definition of Shrinkage Limit.

In most cases, the shrinkage curve shown in Figure 1 is not actually determined and the Shrinkage Limit is obtained by calculation per ASTM D-427 which provides a simple point observation.

Four natural and pure clays will be tested to determine shrinkage characteristics. The direct measurement of the limit of shrinkage from the shrinkage curves of the Linear Shrinkage and Shrinkage Limit tests are discussed and compared to the calculated limit of shrinkage from the Shrinkage Limit test. It is shown that the Linear Shrinkage and the Shrinkage Limit tests produce similar shrinkage curves and that the Linear Shrinkage test, because of its ease and reproducibility is an acceptable substitute for the operator dependent and somewhat material intensive (use of Mercury) Shrinkage Limit test.

Investigation

Three general approaches have been used to determine limits of shrinkage in clays; (1) The measurement of volumetric shrinkage of clays using mercury performed in general accordance with the British Standard (BS-1377:1990 Test 6.3) using the TRRL Method (a multi-point method that determines the shrinkage limit by measuring volumetric shrinkage using mercury while slowly drying the sample over several days to create a shrinkage curve), (2) the measurement of volumetric shrinkage of clays using mercury performed in general accordance with American Society for Testing and Materials (ASTM) D 427-04 Standard Test Method for *Shrinkage Factors of Soils by the Mercury Method* (ASTM 2005), and (3) the measurement of linear shrinkage of clays performed in general accordance with the British Standard (BS 1377:1990, Test 5). The Linear Shrinkage Test may be an attractive alternative to the Shrinkage Limit Test (ASTM D 427) which requires the use of mercury in determining the final volume of the soil pat after oven drying. The test only describes the change in length of the sample even though three-dimensional shrinkage occurs. The three dimensional shrinkage can be calculated by assuming that shrinkage is uniform in all directions.

In this study, both a direct measurement of the limit of shrinkage, which is the true measure, and a calculated shrinkage limit were determined. The direct measurement of the limit of shrinkage was determined from shrinkage curves, which were created by allowing soil in both tests to dry slowly in room temperature conditions over several days while taking frequent readings of water content and length/diameter changes. Measuring the length/diameter changes over time eliminates the need for mercury to measure the volumetric shrinkage over time, as proposed in the TRRL Method. The limit of shrinkage was determined at the water content below which there was no further decrease in volume. This direct measurement of the limit of shrinkage was compared to the calculated shrinkage limit which was determined by ASTM D-427 using the volumetric displacement of mercury.

Calculated Shrinkage Limit

An aluminum shrinkage dish was coated with petroleum jelly to prevent the soil from sticking to the dish and forming cracks when drying. The dish was filled in three layers by placing approximately one-third of the amount of wet soil to fill the dish and tapping the dish on a firm base until no apparent air bubbles remained. This step was repeated with the second and third layers and the soil was smoothed across the top of the dish with a spatula. The mass of the soil and dish was recorded. The dish and soil were air dried for a few hours until the soil turned a lighter color and then oven dry the soil at 110° C to constant mass. The dried dish was removed from the oven and weighed.

The volume of the shrinkage dish was found by filling the dish to slightly overflowing with mercury and pressing the glass plate down on the mercury surface to remove the excess. The mass of the dish and the mercury was obtained and the volume of the "wet soil" pat was computed by divided the mass of the mercury by the unit weight of mercury, which is 13.55 g/cm^3. The volume of the "dry soil" pat was found by filling a glass cup with mercury, using the glass plate with three prongs to remove any excess. The glass cup was placed in an evaporating dish of known mass and the dried soil from the shrinkage dish was removed and placed on the mercury surface (it floats). Using the glass plate with the three prongs, the soil pat was immersed in the mercury until the glass plate rested firmly on the glass cup with no air trapped between the mercury and the plate. The dispersed mercury was measured and the volume of the dry pat was recorded. The shrinkage limit was determined by the following equation:

$$SL = w - \left(\frac{V - V_0}{M_0} \rho_w \right) \times 100 \qquad [1]$$

where:

w = Initial water content of the soil as a percentage of the dry mass (%)

$$w = \left[\frac{(M - M_0)}{M_0} \right] \times 100 \qquad [2]$$

where:

M = initial wet soil mass (g)
M_0 = dry soil mass (g)
ρ_w = approximate density of water equal to 1.0 g/cm^3
V = volume of the wet soil pat or mercury in shrinkage dish (cm^3)
V_0 = volume of the dry soil pat (cm^3)

Linear Shrinkage

The Linear Shrinkage Test appears to have been first introduced by the Texas Highway Department in 1932 (Heidema 1957) and is currently described as a standard test procedure in British Standard BS 1377:1990. The bar linear shrinkage test was found to be the most reliable calcrete soil constant in road construction (Netterberg 1978) and most significant indicator of plasticity/cohesion for a gravel wearing course material (Paige-Green 1989). Haupt (1980) and Emery (1985) performed studies to determine subgrade moisture prediction models and indicated that the inclusion of the bar linear shrinkage produced as good, if not better, prediction models than the inclusion of any of the other Atterberg Limit results. Paige-Green and Ventura (1999) conclude from their evaluations of various bar linear shrinkage tests performed that the bar linear shrinkage test is a more effective test to indicate material performance than the more traditional Atterberg limits.

The Linear Shrinkage Limit test was performed with one hundred and fifty grams of soil mixed with tap water until reaching a consistency of 15 blows in the Casagrande cup. A third of the soil was placed in a greased brass mold approximately 140 mm long and 25 mm in diameter. The soil was placed in the mold in three layers and tapped against a flat surface in between the layering to remove air bubbles from the soil. The sample was allowed to air dry for four hours. Then the soil sample was placed in an oven at 105˚C for 18 hours.

After the soil was dry, the mold was removed from the oven and allowed to cool. The length of the soil sample was measured three times with digital calipers and the average was used to calculate linear shrinkage using the equation:

$$LS = \left(1 - \frac{L_{avg}}{L_o}\right) \times 100 \qquad [3]$$

where:

LS = Linear Shrinkage (%)
L_{avg} = Average Length (mm)
L_o = Original Length of Brass mold (mm)

The Linear Shrinkage test potentially has a number of advantages over other tests, including:

1. The test is simple to perform
2. The test is essentially independent of operator and therefore may be subject to less variability.
3. The equipment is simple and inexpensive.
4. The test does not require use of toxic materials.
5. The test can be used for soils of low plasticity, such as silts, as well as for clays.
6. The test directly measures the desired behavior; i.e., shrinkage.

To calculate the volumetric shrinkage from a linear shrinkage test, uniform 3-D shrinkage is assumed and the volumetric shrinkage is calculated as:

$$VS = 1 - \frac{V_f}{V_o} \times 100\% \,. \qquad [4]$$

where:

VS = Volumetric Shrinkage (%)
$V_f = 0.5 L_f \pi r_f^2$ = final volume (mm^3) [5]

where:

L_f = final measured length (mm)
π = constant = 3.14
r_f = final calculated radius assuming constant 3D shrinkage (mm)

$V_o = 0.5 L_o \pi r_o^2$ = initial volume (mm^3) [6]

where:

L_0 = original measured inside length of mold (mm)
r_0 = initial measured inside radius of mold (mm)

This volumetric shrinkage calculation may be related to the shrinkage index, I_s, which is the difference between LL and SL.

Tests were performed on one pure clay and three natural clays from different geologic regions: 1. Kaolinite – Georgia, 2. Residual Deposit – White Marsh, Maryland, 3. Loess Deposit – Nebraska, 4. Iowa Clay Paleosol – Highly weathered glacial till, ABE 9-7. In addition to the Shrinkage Limits and Linear Shrinkage tests, other laboratory characterization tests included Atterberg LL and PL, total specific surface area (SSA), Cation Exchange Capacity (CEC), and hydrometer analysis to determine the clay fraction (CF) (< 0.002 mm).

Results

Table 1 provides the data from the tests performed.

	Total SSA (m^2/g)	CF (%)	CEC (meq/100 g)	LL %	PL %	Calculated SL %	Direct Measure SL %	I_s	LS %
Georgia White Dirt	13	29.3	2.0	42.7	30.0	24.0	28.0	18.8	7.1
White Marsh, MD	54	33.0	7.6	35.9	20.8	11.2	18.0	24.7	10.3
Nebraska Loess	115	19.5	18.7	42.0	25.1	16.0	21.0	26.1	11.8
Clay Paleosol	298	52.2	27.0	56.5	24.1	2.4	9.0	54.1	18.9

The soils tested are arranged in order of increasing total surface area, from kaolinite to a natural soil containing montmorillonite (SSA = 13 to 298 m^2/g).

Shrinkage Curves from Shrinkage Limit Dish and Linear Shrinkage Mold

The shrinkage curves for the four soils from both the Linear Shrinkage and Shrinkage Limit Tests are presented in Figure 2 through Figure 9. The limit of shrinkage is determined at the point at which there is no further change in specimen dimensions. It can be seen that the shrinkage curves from the two tests are very similar and show the same limit of shrinkage value. The calculated Shrinkage Limit values from the mercury method are shown on the figures and are 2.5 to 6.8 % lower than the limit of shrinkage determined from the shrinkage curves, depending on the soil tested. Figure 2 presents typical data from both procedures for Georgia White

Dirt and Figure 3 presents the same data normalized by the respective original length or diameters to show that the shrinkage curves are almost identical from both tests.

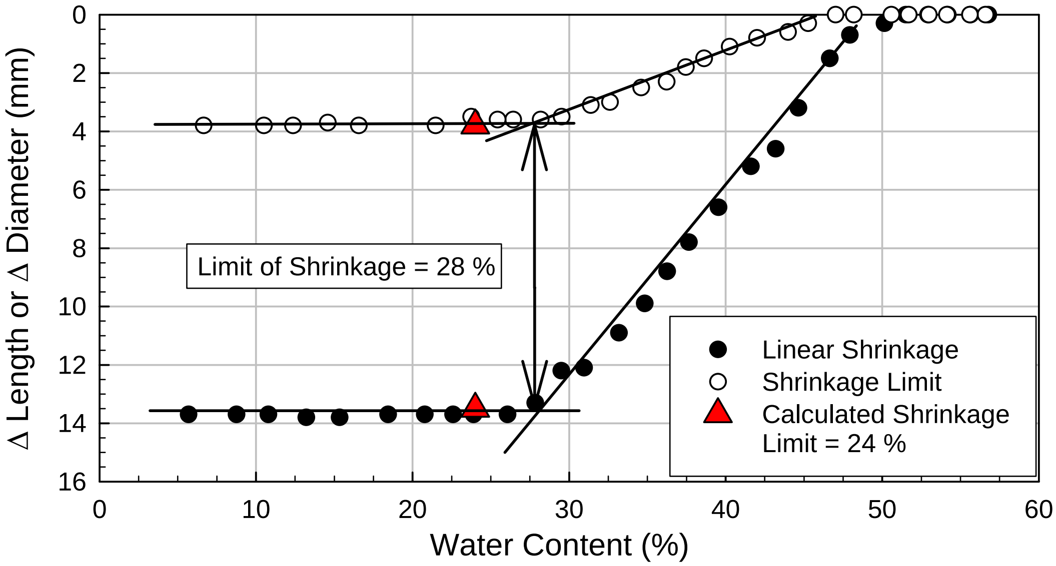

Figure 2. Georgia White Dirt Kaolinite Shrinkage Curves from Linear Shrinkage and Shrinkage Limit Tests.

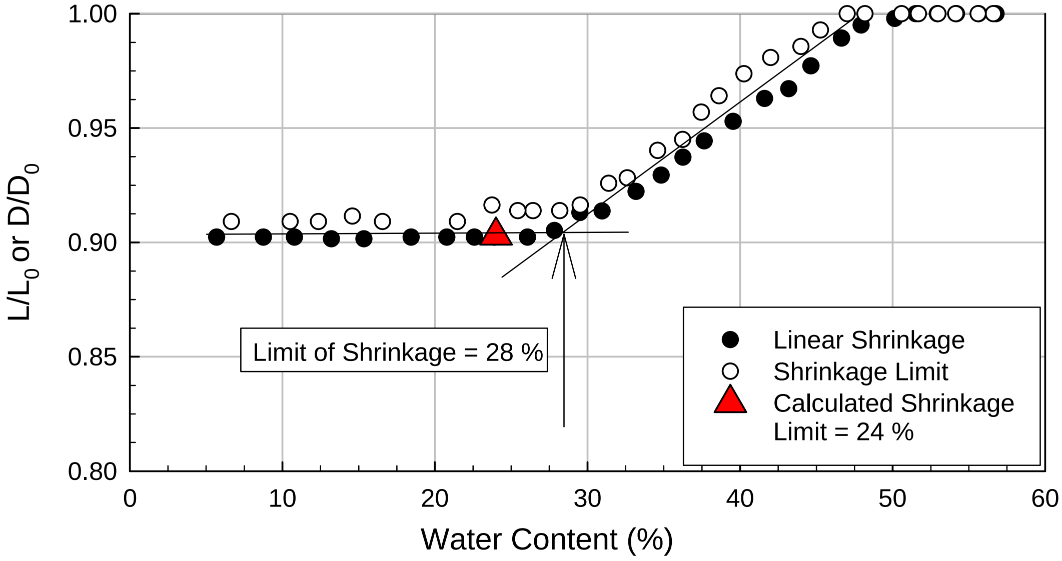

Figure 3. Georgia White Dirt Kaolinite Normalized Shrinkage Curves from Linear Shrinkage and Shrinkage Limit Tests.

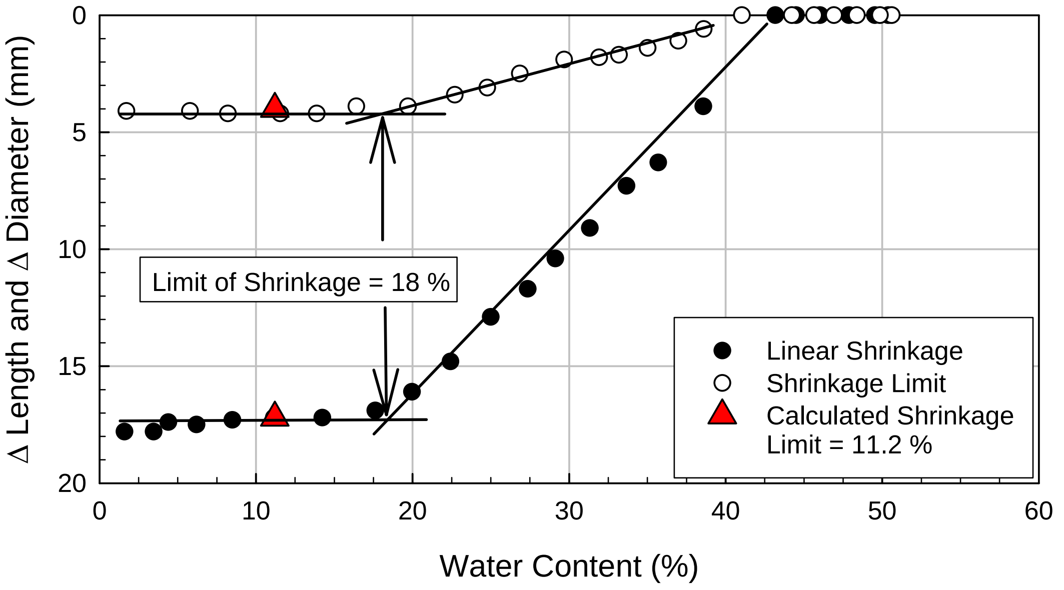

Figure 4. White Marsh Residual Soil Shrinkage Curves from Linear Shrinkage and Shrinkage Limit Tests.

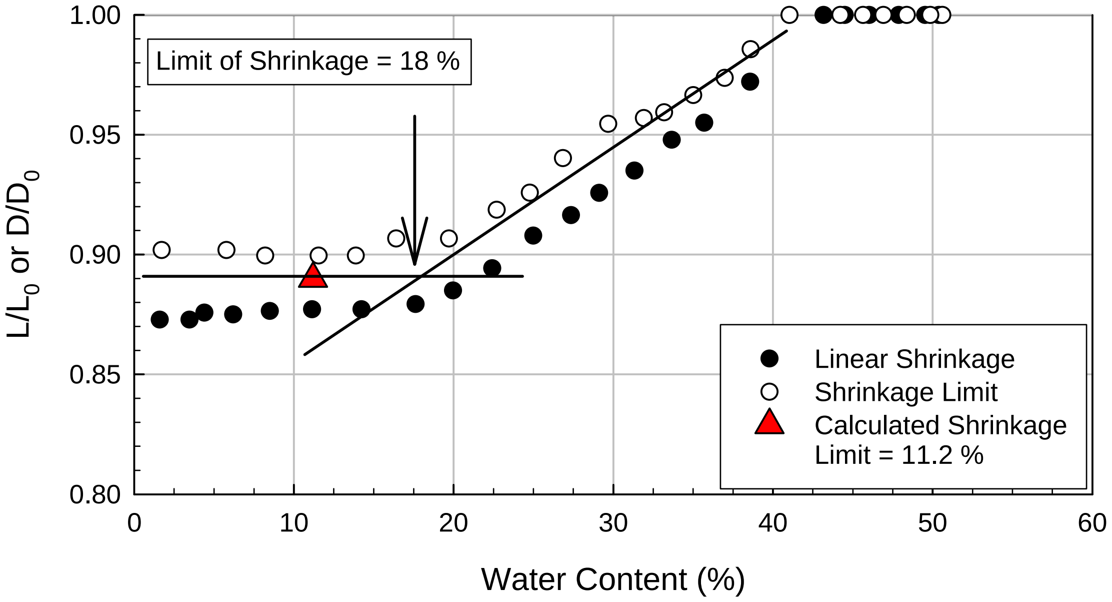

Figure 5. White Marsh Residual Soil Normalized Shrinkage Curves from Linear Shrinkage and Shrinkage Limit Tests.

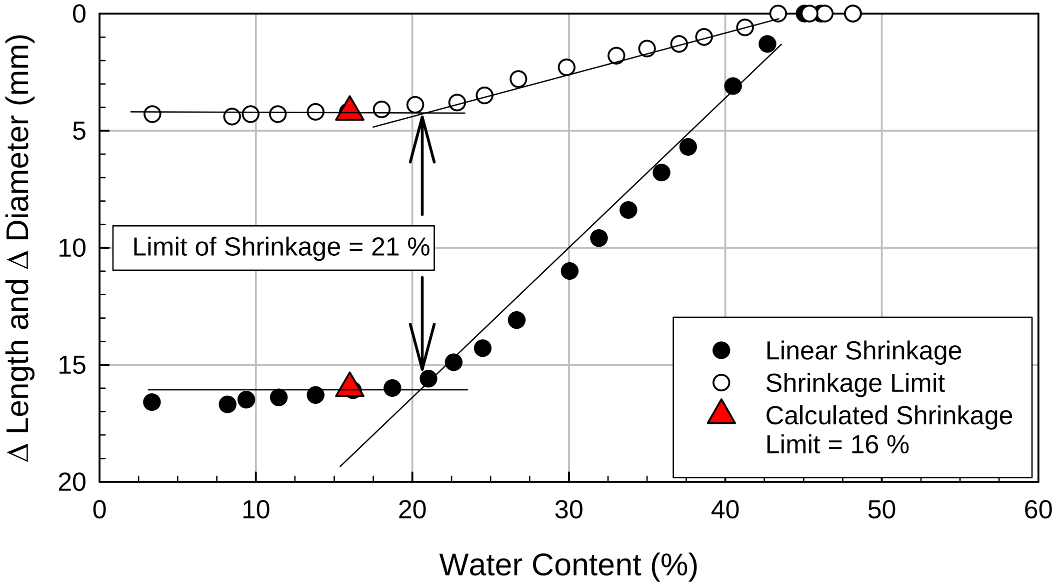

Figure 6. Nebraska Loess Shrinkage Curves from Linear Shrinkage and Shrinkage Limit Tests.

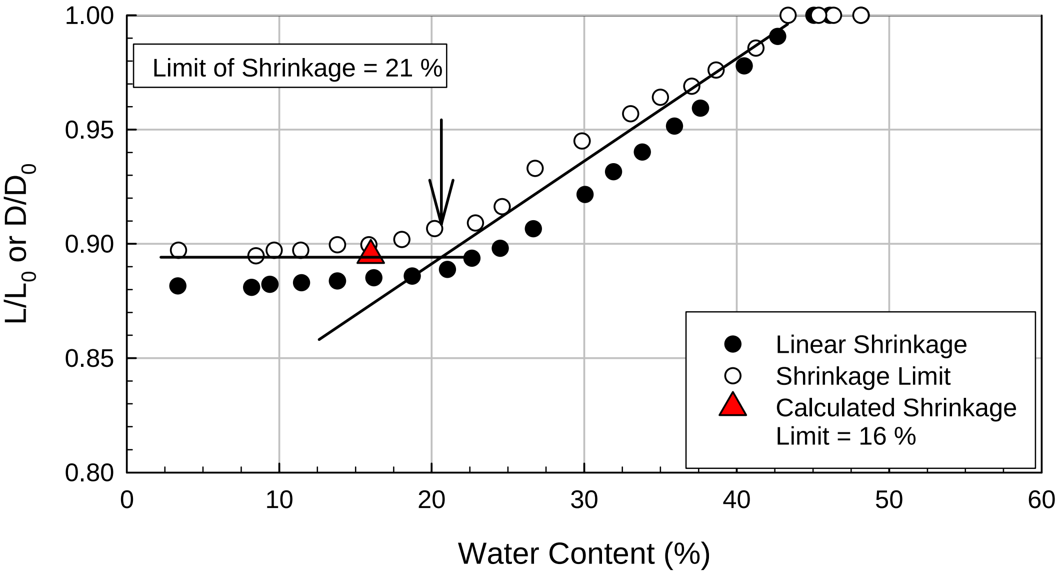

Figure 7. Nebraska Loess Shrinkage Curves from Linear Shrinkage and Shrinkage Limit Tests.

Discussion

The shrinkage limit curves, produced by measuring both the weight and length or diameter as the soil slowly dried, show a linear drying portion between length and diameter change and water content and then a distinct break at which water content keeps decreasing but no more volume change occurs. This point is called the limit of shrinkage and occurs at the same water content for the shrinkage curves from both the shrinkage limit and linear shrinkage tests. It is the true measure of the limit of shrinkage. However, the calculated shrinkage limit using ASTM D-427 is lower than the direct measurement of the limit of shrinkage for all four soils; in one case by almost 8%. Directly measuring the limit of shrinkage by creating a shrinkage curve is the most accurate method. However, it is time consuming (> 1 week for highly expansive soils) and requires multiple measurements and care so that the soil does not dry too quickly. Therefore, although the direct measurement of the limit of shrinkage is the most accurate method, it would be preferable to obtain the shrinkage limit of a soil by making one measurement as in ASTM D-427 or BS 1377:1990.

However, performing a shrinkage limit test following the ASTM D 427-04 standard using the mercury method is extremely operator dependent, as is the newer ASTM D4943-02 Standard Test Method for Shrinkage Factors of Soil by the Wax Method, although the latter does not use a toxic material to measure shrinkage. Mercury is extremely dense and therefore, one extra or one missing drop of mercury in the displacement calculation or a crack or chip in the soil pat can change the shrinkage limit result by a few percent. Even repeat experimental tests performed by the same operator with the same soil pat can result in slightly different shrinkage limit results.

The linear shrinkage test, while easier and less operator dependent also has a few problems with repeatability, such as cracking and bowing, variations in drying, lubrication of the troughs and filling the troughs, as identified in Sampson et al. 1992. For highly expansive clays, the soil tends to bow upward during drying, therefore making a "linear" measurement extremely difficult. The use of a slot rather than a trough in order to eliminate or at least reduce bowing was first described by Wall (1959) and subsequently evaluated by Newill (1961) and Sampson et al. (1992). This slot allows material being tested to dry from two sides and makes the drying process more even. However, even with the aforementioned problems, the linear shrinkage test has been found to be repeatable to better than 1% (Wall 1959) and less than 2 % (Heidema 1957), which is considerably better than the results of the LL, PL and PI results which have been shown to be operator dependent and have large variability (Shook and Fang 1961).

It is recommended when possible, the limit of shrinkage be obtained from a shrinkage curve because that method produces the most accurate limit of shrinkage. However, when time does not permit, we recommend using the Linear Shrinkage test in lieu of the ASTM D-427 mercury method because it is very repeatable and not influenced by operator experience. If the SL is desired, the volumetric shrinkage should be calculated from the linear shrinkage test as described in Equation 4 and be related to the shrinkage ratio, I_s, which is the difference between the LL and the SL as shown in Figure 1. The volumetric shrinkage calculated from the linear shrinkage test may be higher than the I_s value because the calculated volumetric shrinkage is taken from the initial water content, which is usually higher than the LL, to the oven-dry weight, where I_s is the difference between LL and SL.

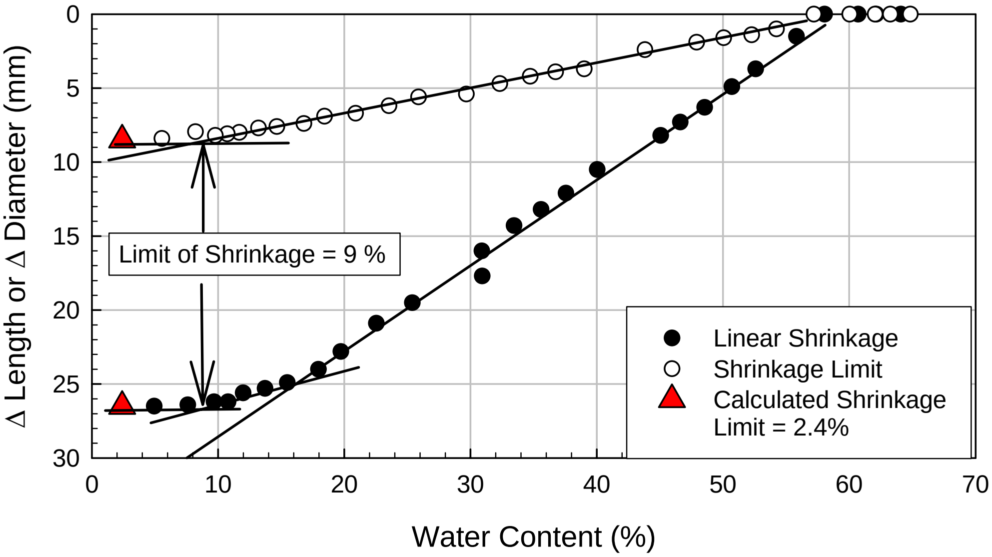

Figure 8. Iowa Paleosol Shrinkage Curves from Linear Shrinkage and Shrinkage Limit Tests.

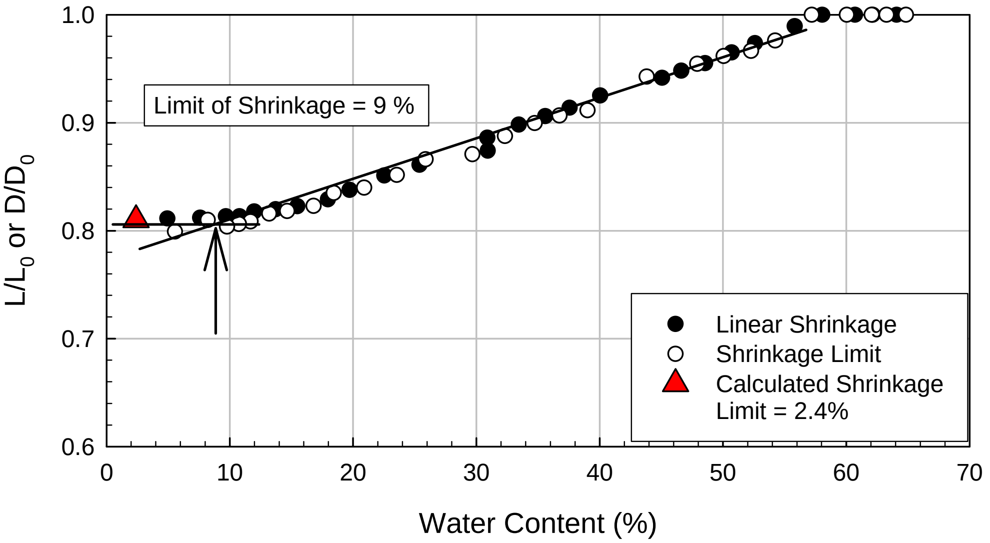

Figure 9. Iowa Paleosol Normalized Shrinkage Curves from Linear Shrinkage and Shrinkage Limit Tests.

Conclusions

After comparing the results of the calculated Shrinkage Limit test to the direct measurement of the limit of shrinkage using a shrinkage curve, it was found that the calculated Shrinkage Limit value from ASTM D-427 consistently underpredicted the limit of shrinkage directly determined from the shrinkage curve and was difficult to obtain repeatable results. Therefore, we recommend determining the limit of shrinkage by creating a partial shrinkage curve using either the Shrinkage Limit or Linear Shrinkage test procedure for sample preparation and measuring the change in length or diameter over time. The length of time to construct a shrinkage curve may be reduced to one to two days if a few points were measured initially to construct the linear drying portion of the shrinkage curve, and then the sample was oven dried to get the final point on the horizontal line where no additional volume change takes place. The intersection of these two lines will be the limit of shrinkage. This procedure produces the most repeatable and accurate method of determining the limit of shrinkage of a soil.

References

Emery, S.J. (1985). Prediction of moisture content for use in pavement design. Ph.D. Thesis, University of Witwatersrand, Johannesburg.

Haupt, F.J. (1980). Moisture conditions associated with pavements in Southern Africa. MSc Thesis, University of Witwatersrand, Johannesburg.

Head, K.H. (1994). Manual of Soil Laboratory Testing. Soil Classification and Compaction Tests. 2nd Edition. Vol 2. pp. 99-104.

Heidema, P.B. (1957). The Bar-Shrinkage Test and the Practical Importance of Bar-Linear Shrinkage as an Identifier of Soils. Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, pp. 44-48.

Holtz, R.D. and Kovacs, W.D. (1981). An Introduction to Geotechnical Engineering. Prentice-Hall. Ed. Newmark, N.M. and Hall, W.J.

Paige-Green, P. (1989). The influence of geotechnical properties on the performance of gravel wearing course materials. Ph.D. Thesis, University of Pretoria, Pretoria.

Paige-Green, P. and Ventura, D. (1999). The bar linear shrinkage test – More useful than we think!. 12th Regional Conference of the Geotechnics for Developing Africa. Ed. Blight and Fourie, Vol. 12, pp. 379-387.

Netterberg, F. (1978). Calcrete wearing courses for unpaved roads. The Civil Engineer in South Africa, Vol. 20, No. 6, pp. 129-138.

Newill, D. (1961). An investigation of the linear shrinkage test applied to tropical soils and its relation to the plasticity index. Crowthorne: Road Research Laboratory, Research Note RN/4106/DN.

Sampson, L.R., Ventura, D.F.C. and Kalombo, D.K. (1992). The linear shrinkage test: justification for its reintroduction as a standard South African test method. Pretoria: South African Roads Board. Research Report 91/189.

Shook, J.F. and Fang, H.Y. (1961). A Study of Operator Variability in the Determination of Liquid and Plastic Limits of Soil. HRB Highway Research Abstracts, Vol. 31, No. 9, pp. 26-28.

Wall, G.D. (1959). Observations of the use of lineal shrinkage from the liquid limit as an aid to control in the field. Proceedings of the 2nd Regional Conference for Africa on Soil Mechanics and Foundation Engineering. pp. 175-180.