COMPUTATION OF SHRINKAGE LIMIT USING THE SLOPE OF FALL CONE FLOW CURVE

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ABSTRACT

This paper presents a model that uses a slope British cone flow curve or plasticity index of soil to compute the shrinkage limit of the soil. The model was developed based on the analysis of 186 Atterberg limits test results collected from the literature. It has been demonstrated that all Atterberg limits, namely liquid limit, plastic limit, and shrinkage limit, can be determined using a British fall cone in a single testing operation.

INTRODUCTION

The Atterberg limit measures the critical water content of fine-grained soil at which the soil changes from one state to another. These limits are liquid, plastic, and shrinkage limit. These limits are carried out using different testing methods. The liquid limit is determined using the Casagrande percussion method (AASHTO T89-94) or the fall cone method (BS 1377). The plastic limit is determined using the rolling thread method (BS 1377-Part 2:1990, AASHTO T90-94), and the shrinkage limit is determined using the mercury method(BS 1377:Part 2:1990, AASHTO T92-88, ASTM D427-98). The alternative method to ASTM D427-98 is ASTM D4943-02 which uses wax instead of mercury, but both methods are operator-dependent and error-prone. Mercury is a hazardous material that can affect the operator if not handled correctly. Several alternative methods have been proposed to determine the shrinkage limit to improve test results' repeatability and avoid using hazardous (mercury) material, such as sand replacement, wax method, and reverse extrusion. [Cerato (2006), Prakash and Sridharan (2011), Prakash and Sridharan (2012), Kayabali (2015)].

The shrinkage limit of the soil is defined as the water content at which no further volume decrease occurs, but where the degree of saturation is still essentially 100%, i.e., is the water content at which the soil changes from semi-solid state to solid state. Contrary to the expansivity of soil potential, the shrinkage limit decreases as the plasticity index of the soil increases.

It has been reported that the shrinkage limit of the soil does not depend on the plasticity of the soil; the main factor affecting the shrinkage limit is the grain size distribution and fabric. The main force responsible for initiating the shrinkage is the capillary forces, which are related to pore size within the soil particles, which is a function of the grain-size distribution [Sridhran & Rao (1971), Sridhran & Prakash (2000), Kayabali &Yaldiz (2015)].

Casagrande proposed a simple method of estimating the shrinkage limit based on the plasticity chart utilizing the U-line and A-line, suggesting that the shrinkage limit is a plasticity property of soil. This method was reported to be yield results which are close to the determined values of the shrinkage limit [Holtz and Kovacs (1981), cited by Kayabali(2012)].

This paper presents a method of computing the shrinkage limits of soil using the slope of the British fall cone flow or plasticity index, suggesting that the shrinkage limit is a plasticity characteristic of the soil. The proposed models were developed based on an analysis of 186 shrinkage limit test results collected from the literature. The proposed models were found to agree reasonably well with the determined value of the shrinkage limit.

THE BRITISH FALL CONE MOISTURE-PENETRATION FLOW CURVE

The fall cone flow curve within the penetration range of 20±5 mm is linearly modeled to determine the liquid limit (BS 1377). However, the slope of the fall cone flow curve continuously decreases as the moisture content decreases. The slope of the fall cone flow curve becomes stable when the fall cone slope is calculated using a penetration value of 5 mm or lower than 5 mm and its corresponding moisture content. Equation 1 was proposed for the computation of the slope of the fall cone flow curve slope (Maregesi, 2022).

Based on an analysis of 60 soil plasticity data, Maregesi(2022) established that the soil plasticity index is highly correlated to the slope of the fall cone flow curve. Based on this correlation, equation 2 was proposed to be used to compute the plasticity index (R^2=0.9926).

$$S = \frac{w_{25} - w_5}{25 - 5} = \frac{w_{25} - w_5}{20} \dots \dots (1)$$

where

W_{25} and W_5 are water contents corresponding to 25 mm and 5 mm penetration values.

$$I_P = 24.94(S + 0.03541)^{-1.044} \dots \dots (2)$$

Manipulation of equation 2 and making the fall cone slope as a subject result in equation 3.

$$S = \frac{21.7783}{I_p^{0.9579}} - 0.0354 \dots \dots (3)$$

ANALYSIS OF SHRINKAGE LIMIT DATA FROM LITERATURE

The liquid limit is the largest of Atterberg's limits. In most cases, the shrinkage limit is regarded as the lowest limit. However, it has been reported that for some soil, the shrinkage limit is higher than the plastic limit suggesting that the soil at the plastic limit is not necessarily fully saturated [Nitterberg (1982), Nagaraj and Srinvasamurthy(1986)].

Atterberg limits data published by several authors were collected and analyzed [Cerrato & Lutenegger (2006), Prakash & Sridharan (2011, Prakash & Sridharan (2012), Kayabali (2012), Kaybali (2013), Prakash *et al* (2015) and Vincent *et al* (2021). During data analysis, it was assumed that the liquid limit was determined using the British fall cone; thus, the slope of the fall cone curve was computed using equation 3. It was established that the shrinkage index of the soil, which is defined as the arithmetic difference between the liquid limit and the shrinkage limit, is highly correlated with the slope of the fall cone flow curve, as shown in Figure 1(R^2=0.99) fitted using a two-terms power function. Based on this data analysis, the shrinkage index can be calculated using equation 4.

$$S_i = LL - SL = \frac{79.9}{S^{0.5858}} - \frac{45.95}{S^{0.2649}} \dots \dots (4)$$

Where
S_i is the shrinkage index, LL is the liquid limit, SL is the shrinkage limit, and S is the slope of the fall cone flow curve.

Replacing S in equation 4 with equation 3, the shrinkage index can be directly computed using the plasticity index as shown in equation 5.

$$S_i = \frac{79.9}{\left(\frac{21.7783}{I_p^{0.9579}} - 0.0354\right)^{0.5858}} - \frac{45.95}{\left(\frac{21.7783}{I_p^{0.9579}} - 0.0354\right)^{0.2649}} \dots (5)$$

The capability of computing the shrinkage limit using the plasticity index of soil indicates that the shrinkage limit is the plasticity property of the soil.

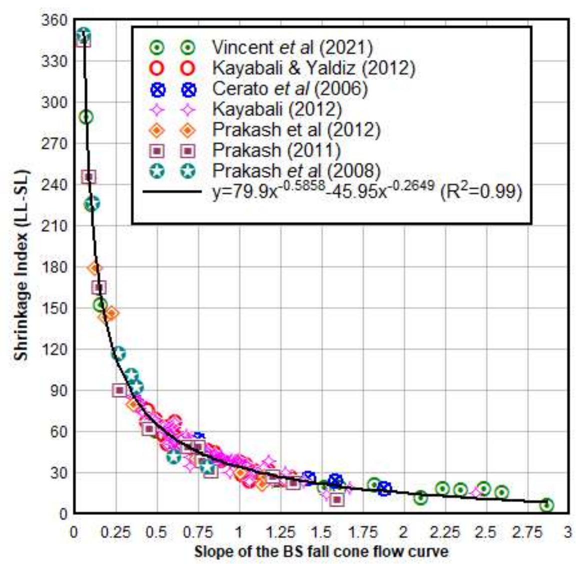

Figure 1: Relationship between the fall cone slope and shrinkage index

DISCUSSION OF THE RESULTS

Figure 2 shows the equation plot for computing the plasticity index (Equation 2) and shrinkage index (equation 4). It can be seen that the change in plasticity index and change in the shrinkage index follows the same pattern echoing the earlier suggestion that the shrinkage limit is a plasticity property of the soil. At a low plasticity index of about 20, the plastic limit and the shrinkage limit are relatively closer to each other, suggesting that the shrinkage limit may be higher than the plastic limit for soils with a low plasticity index, i.e., of less than 20.

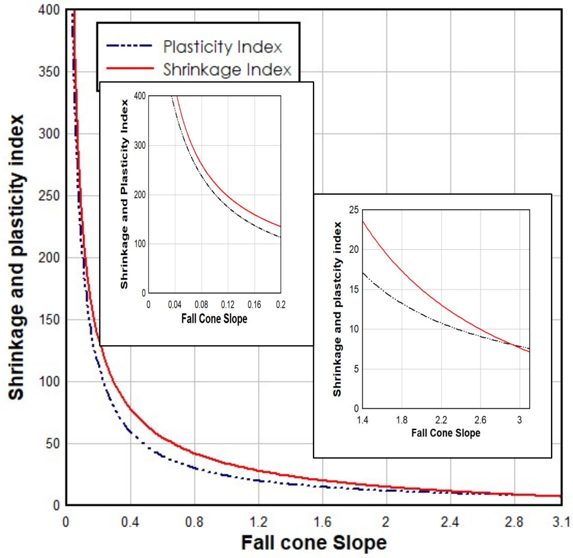

Figure 2: comparison between the plasticity index and shrinkage index

Figure 3 shows the residual of the shrinkage limit data fitted using equation 4. It can be seen that despite the fact that the model was developed based on the computation of the slope of the fall cone flow curve using plasticity data collected from literature and also that some of the data used, its liquid limit was determined using the Casagrande cup, the model still fits the shrinkage limit data reasonably well. Figure 4 shows the residual histogram, which indicates that more than 80% of the results are within the accuracy range of SL±4%.

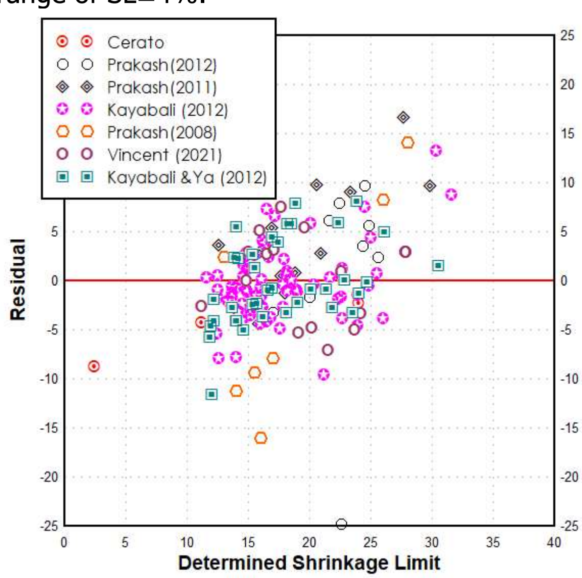

Figure 3: Residual analysis of fitted data

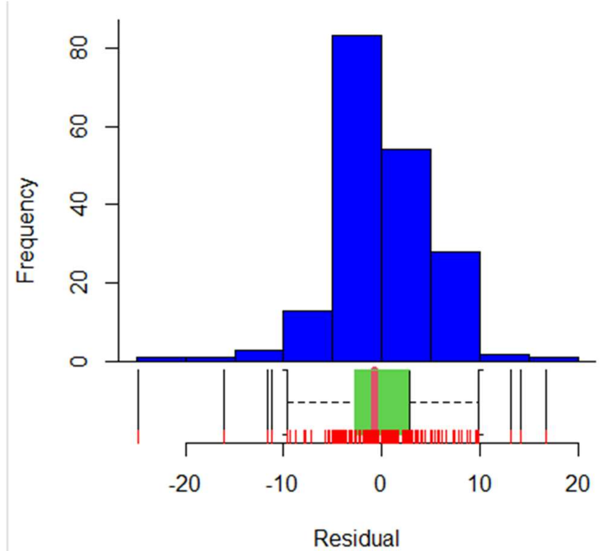

Figure 4: Residual histogram of the fitted shrinkage limit data

SUMMARY AND CONCLUSION

The determination of the shrinkage limit using the mercury method is time-consuming and error-prone. The proposed method of computing the shrinkage limit using the flow curve parameter is a simple, quick, easier, and more convenient method. This study indicates that the fall cone can be used for the determination of all Atterberg limits, namely liquid limit, plastic limit, and shrinkage limit. The analysis of the shrinkage limit test result suggests that the shrinkage limit is a plasticity property of the soil.

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