THE PLASTICITY INDEX OF INORGANIC CLAY

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ABSTRACT

This paper presents a model that can be used to compute the plasticity index of inorganic soil using the correlation between the liquid limit and the plasticity index. The model was developed using British fall cone Atterberg limit test results using 120 inorganic soils of widely varying plasticity, including commercial bentonite, and validated using 136 Atterberg limits test results from the literature.

Analysis of the Atterberg limits data of widely varying plasticity characteristics and geological origin indicates that the plasticity index of most inorganic soil follows a well-defined trajectory in the space of liquid limit and plasticity index, which can be modeled mathematically, suggesting that each liquid limit is associated with a unique value of the plasticity index.

INTRODUCTION

The plasticity index of most inorganic soil is highly correlated to the liquid limit. Therefore, the liquid limit can be used as the sole variable for predicting the plasticity index of inorganic soil. The soil's liquid limit and plasticity index vary depending on the type of clay minerals and clay content within the soil matrix. Therefore, including a variable that relates the liquid limit and plasticity index of the inorganic soil to its mineralogical composition in the model is important to ensure that the model accurately computes the plasticity index of inorganic soil.

Maregesi (2023) reported that the average slope of the British fall cone curve could be used for classifying the type of clay minerals, namely kaolinite, illite, and montmorillonite, within the soil matrix. The average slope, defined as 20/LL (liquid limit), is the parameter that describes the rate of change of shear strength of the soil as the moisture varies and can be used to classify the type of clay minerals within the soil; at the same time, it can be used to predict the plasticity index of the inorganic soil.

This paper presents a model that can be used to predict the plasticity index of the inorganic soil using the liquid limit determined using the British fall cone curve (BS 1377:Part 2:1990). The model was developed using 120 Atterberg test results, which included natural soils, kaolinite, and commercial bentonite. The model was validated using 136 Atterberg limits test results collected from the literature.

THE CORRELATION BETWEEN BRITISH FALL CONE SLOPE AND PLASTICITY INDEX

The slope of the fall cone curve is correlated to the plasticity index of the inorganic soil. Maregesi (2022) reported that the slope of the fall cone flow curve progressively decreases as the moisture content decreases. The slope tends to quasi-stabilize at a penetration value of about 5 mm. Based on this gradual change of slope as the penetration value decreases, Maregesi (2022) proposed to compute the slope of the fall cone curve using Equation 1, whereby the slope of the fall cone curve is calculated using penetration values of 25 mm and 5 mm and their corresponding moisture contents respectively. Maregesi (2023) proposed that the average fall cone slope computed from penetration of 20 mm and its corresponding moisture content, which is the liquid limit, and the original (0,0), is invariant and measures the rate of change of shear strength of the inorganic soil as moisture content varies. The fall cone average slope can be computed using Equation 2.

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

$$S = \frac{20-0}{LL-0} = \frac{20}{LL} \ldots \ldots (2)$$

Where

'S' is the slope of the fall cone curve, 'LL' is the liquid limit, and 'W_{25}' and 'W_5' are the water content corresponding to 25 mm and 5 mm fall cone penetration, respectively.

The Atterberg limits of 120 soil samples of widely varying plasticity, including commercial bentonite, were analyzed during this study. The natural soil samples were taken from the Songea area in northern Tanzania, and kaolin samples were taken from Kisarawe in Tanzania. The summary of the Atterberg limits test results analyzed during this study is shown in Figure 1. The liquid limit varied from 16 to 330, the plastic limit ranged from 10 to 57, and the plasticity index varied from 2 to 242.

Analysis of the data indicates that the average slope of the fall cone flow curve (20/LL) is highly correlated to the plasticity index of soil, as evidenced by the coefficient of Determination (R^2) of 0.9982 when fitted using the power function shown in Equation 1, which can be simplified to Equation 2. The fitted data are shown in Figure 2.

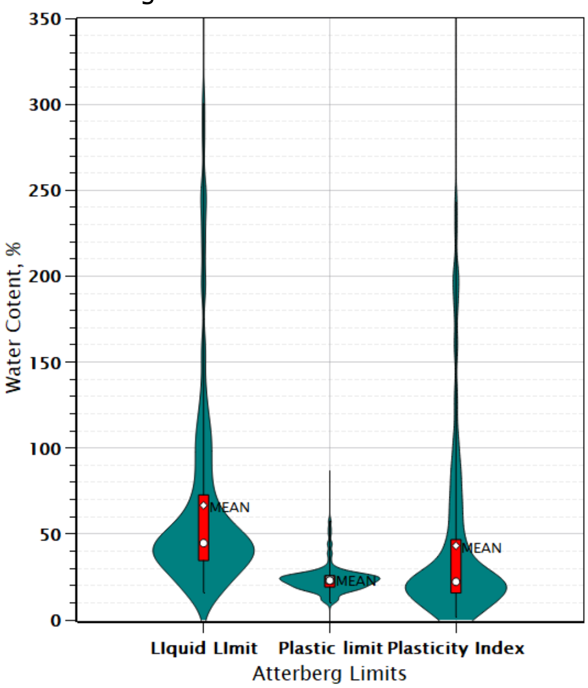

Figure 1: Summary of Atterberg limits data used for developing the model

From Figure 2, it can be seen that the relationship between the average slope (20/LL) and the plasticity index smoothly traverses through the montmorillonite clay band (the montmorillonite clay has an average slope of less than 0.16), as well as the kaolinite band (the kaolinite clay has an average fall cone slope of more 0.6), suggesting that the proposed model can be used to predict the plasticity index of montmorillonite, binary mixture of kaolinite and montmorillonite or illite and kaolinite clay (Maregesi, 2023).

Equation 2 suggests that the plasticity index of inorganic soil is a function of liquid limit such that there is only one value of liquid limit for each value of the plasticity index. Therefore, the liquid limit of the inorganic soil can be used as the sole predictor of computing the plasticity index of the inorganic soil.

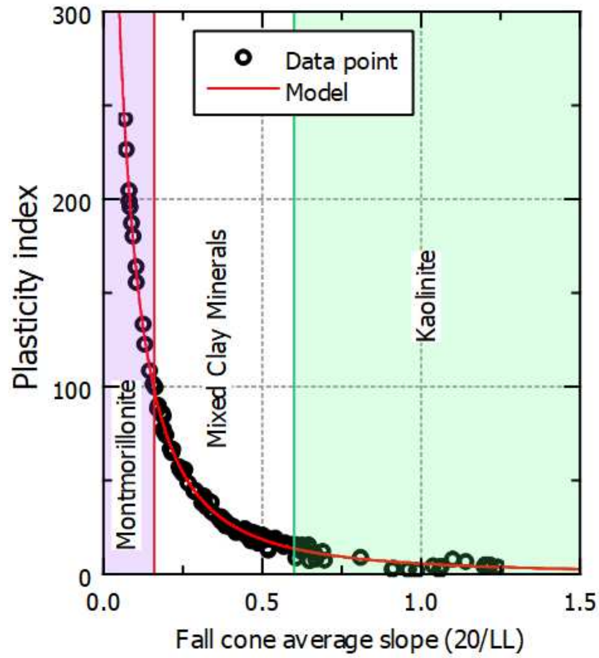

Figure 2: The relationship between average slope (20/LL) and plasticity index (R^2=0.9982)

$$PI = 680.64\left(1+\frac{10.51(20)}{LL}\right)^{-1.97} \quad \ldots..(1)$$

$$PI = 680.64\left(1+\frac{210.312}{LL}\right)^{-1.97} \quad \ldots..(2)$$

COMPUTATION OF THE PLASTICITY INDEX USING THE MODEL

The plasticity index of the 120 soil samples tested during this study was computed using Equation 2. The residual plot showing the difference between the determined plasticity index and the computed plasticity index is shown in Figure 3, from which it can be seen that the model predicted the plasticity index with an accuracy of ±5. Figure 4 shows the comparison of the determined and computed plasticity index, from which it can be seen that the computed and the determined plasticity index correlate quite well, as evidenced by the coefficient of determination (R^2=0.998).

Figure 5 shows equation 2 and the Atterberg limits data used for model development, from which it can be seen that the model fits the data reasonably well. Figure 6 shows the histogram of the residual, from which it can be seen that 87%

of the test results are within the accuracy of ±3. Figure 7 shows the Q-Q plot of the residuals, which shows that the residual is normally distributed.

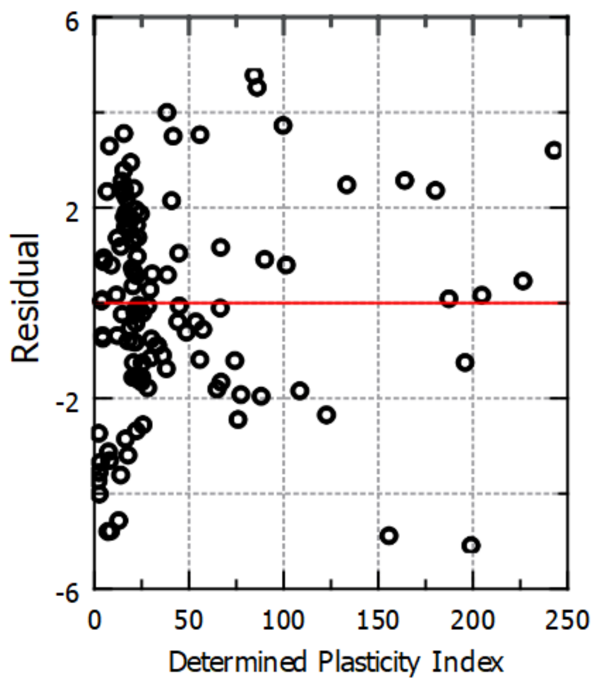

Figure 3: The residual plot showing the difference between the determined and the computed plasticity index

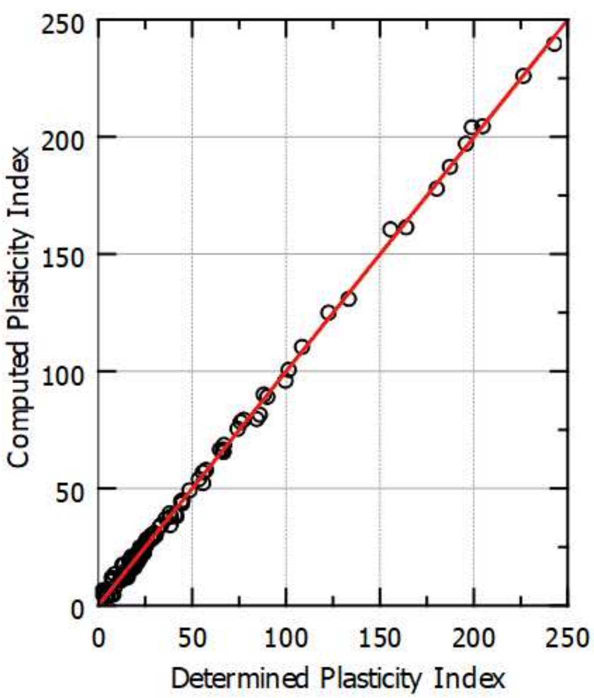

Figure 4: The correlation between the determined and the computed plasticity index (R^2=0.998)

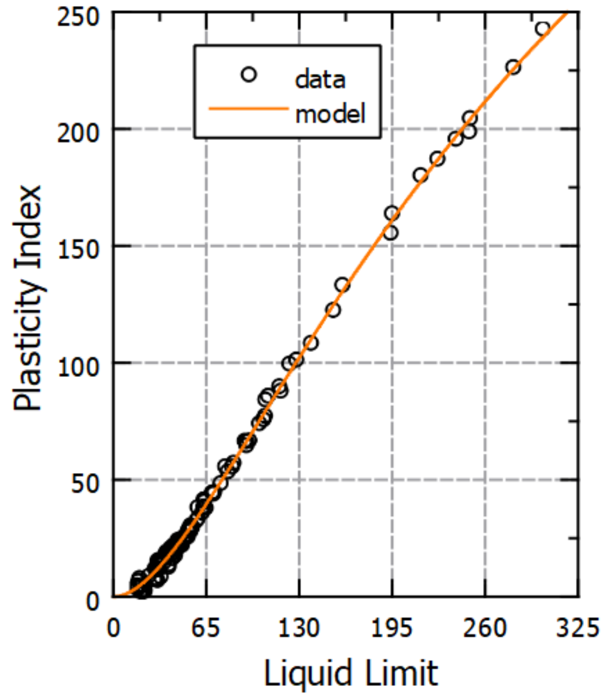

Figure 5: The liquid limit and plasticity index with a best-fit line using Equation 2

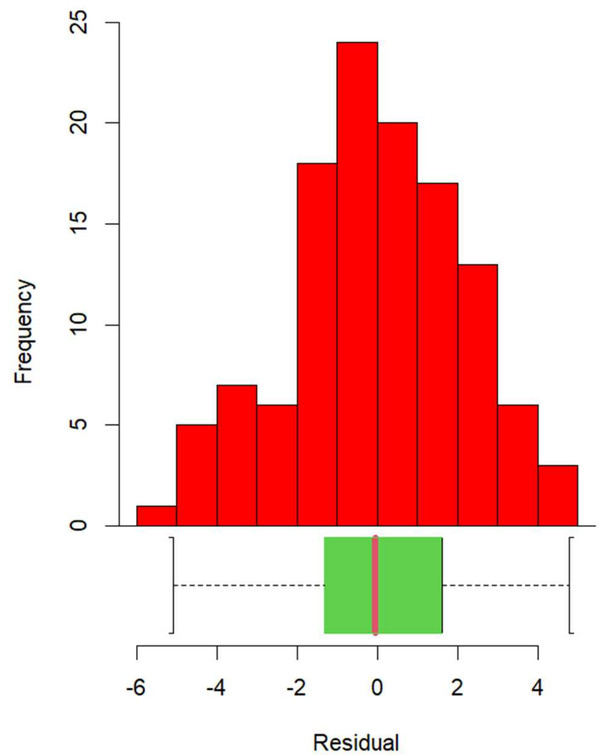

Figure 6: Residual histogram and box plot

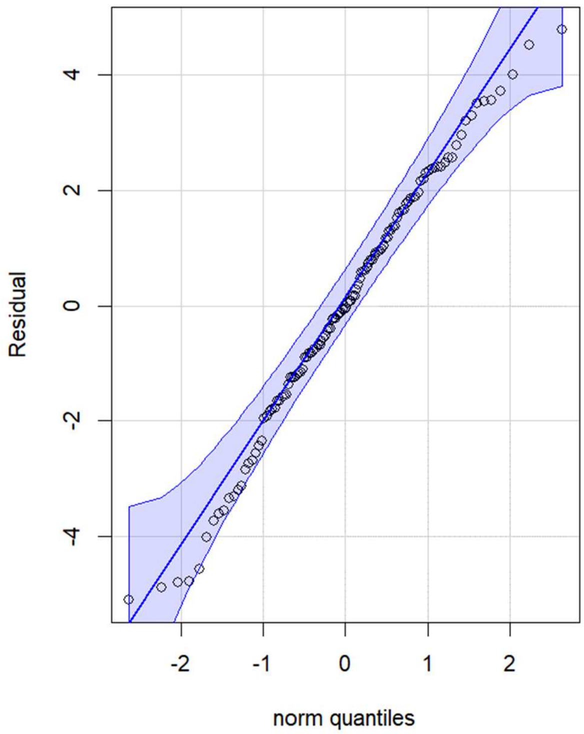

Figure 7: Q-Q plot of the residual

VALIDATION OF THE MODEL

The proposed model given in equation 2 was validated using 136 Atterberg limit data collected from the literature (Kayabali et al., 2016- 60 test results; Niaz et al., 2019- 65 test results; Landris et al.,2009 -11 test results). The summary of the Atterberg limits test results used for the validation of the model is shown in Figure 8. The residual plot is shown in Figure 9, from which it can be seen that the proposed model computes the plasticity index of the inorganic soil with an accuracy of ±9. The data presented by Kayabali et al. was found to be very consistent, with an accuracy of ±3. The Atterberg limit data published by Niaz et al. has an accuracy of ±8.7, and that of Landris et al. is fitted within the accuracy of ±5. Figure 10 shows the histogram plot from which it can be seen that 87% of the test results are within the accuracy of ±3. Figure 11 shows the Q-Q plot from which it can seen that the residual is normally distributed. Figure 12 shows the fitted data in the space of the liquid limit and plasticity index, from which it can be seen that the model fits the data reasonably well.

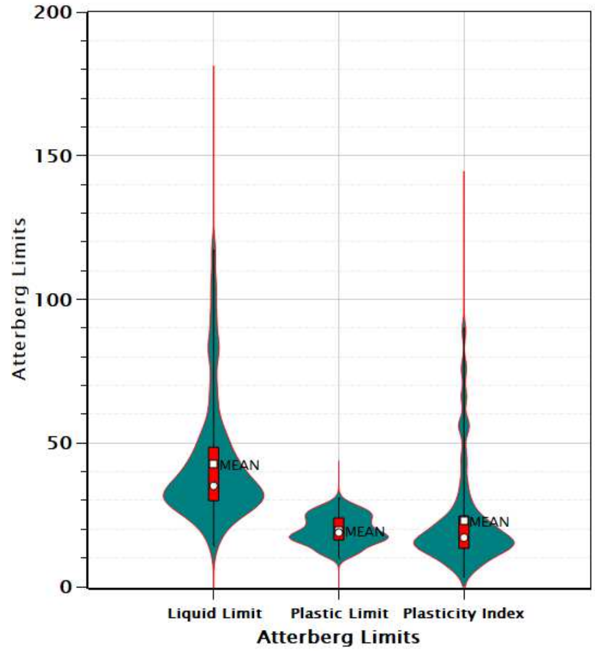

Figure 8: Summary of the Atterberg limits data used for validating the model

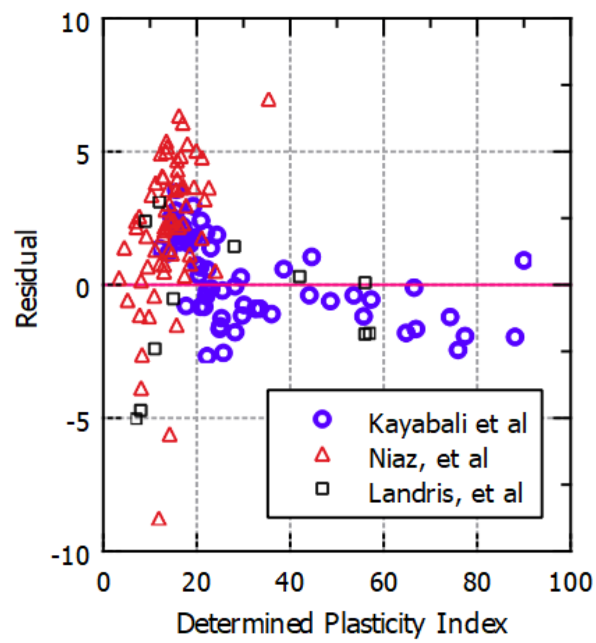

Figure 9: Residual plot showing the difference between the determined and the computed plasticity index

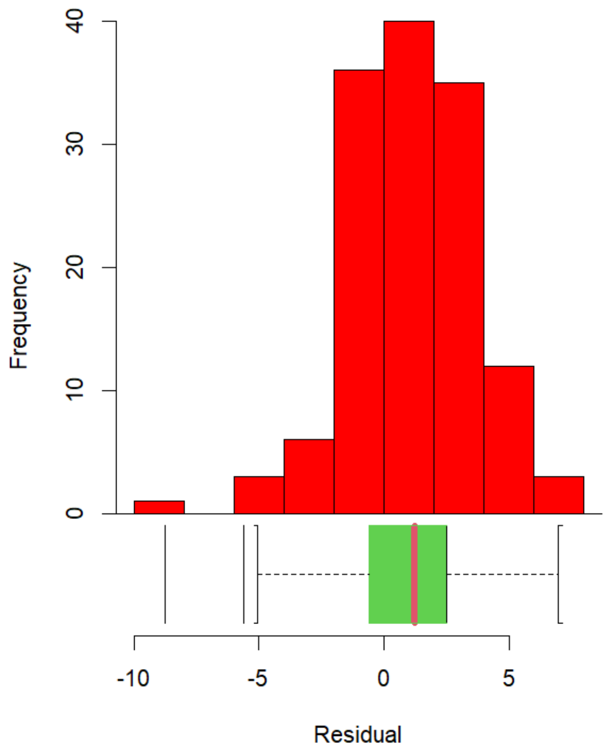

Figure 10: Residual histogram and box plot

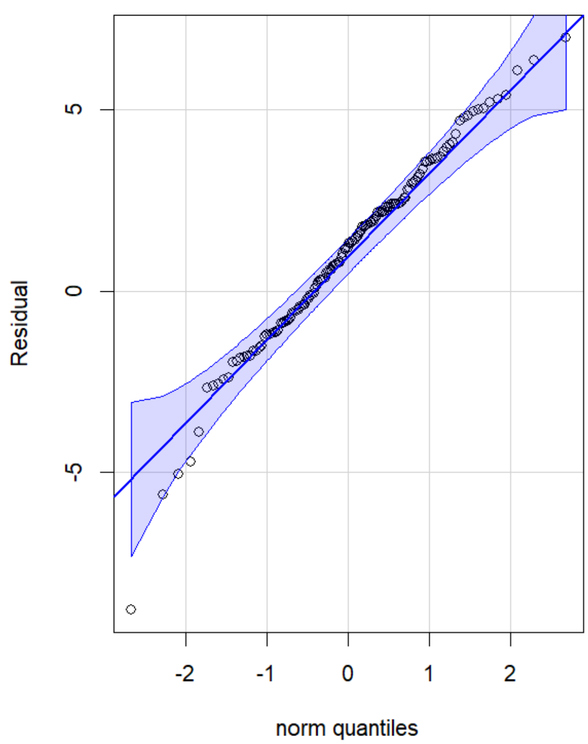

Figure 11: Q-Q plot of the residual

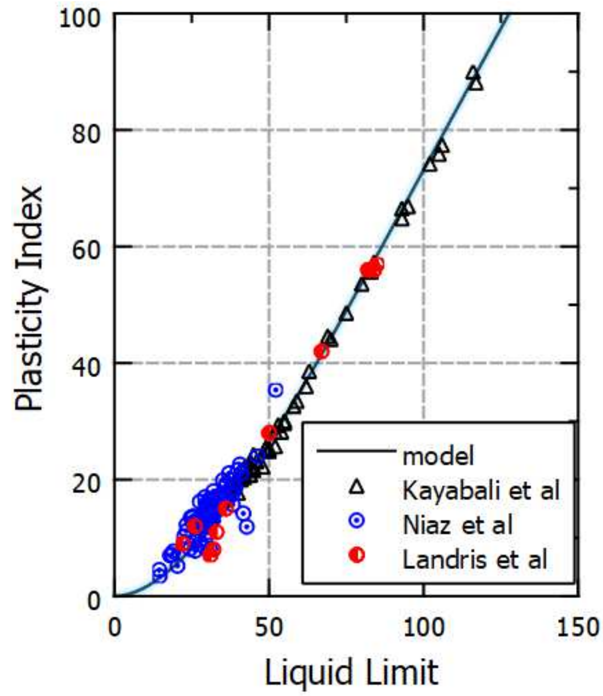

Figure 12: The liquid limit and plasticity index with a best-fit line using Equation 2

DISCUSSION OF THE RESULTS

The analysis of the 120 Atterberg limit test results carried out during this study, and 136 data from the literature suggest that the plasticity index of the inorganic soil is a function of a liquid limit such that there is a unique plasticity index value for every liquid limit and that the relationships between liquid limit and plasticity index can be defined using a mathematical model shown in equation 2. Thus, the Atterberg limit test results of the inorganic soil are supposed to follow the trajectory defined by equation 2. However, due to testing variability, particularly the plastic limit and the fact that in most cases, the in-situ soil is a mixture of both organic and inorganic soil, in some cases, the departure of the Atterberg limit data from equation 2 trajectory is noted. In accordance with AASHTO T90, the reproducibility of the plasticity index is 18%; therefore, the Atterberg limit of inorganic soil is supposed to plot within the envelope defined by equation 2±18%. The reproducibility envelope is shown in Figure 13. The proposed reproducibility envelope was validated using 122 Atterberg limit data from the literature (Sridharan et al. – 41 results; Feng, 2001 -30 results; Feng, 2004-21 results and Karakan, 2022 – 30 results). It can be seen that most of the Atterberg limit test results are plotting within the reproducibility envelope, particularly when the liquid limit is more than 100. However, at a liquid limit of less than 100, some of the Atterberg limits plots outside the reproducibility envelope of ±18%. This is because the reproducibility envelope is narrow at liquid limit of less than 70. O'Kelly et al, 2018 using soil of intermediate to high plasticity soil with a liquid limit within the range of 36-77, reported reproducibility of plastic limit to be 8. Therefore, for liquid limit of less than 70, the reproducibility envelope was modified to form two segments piece-wise envelope composed of ±8 up to 70 liquid limit values. For liquid limit of more than 70, the reproducibility envelope of ±18% was maintained. The modified reproducibility envelope is shown in Figure 14. It can be seen that after modification of the reproducibility envelope, only 15 results out of 122 (12%) plotted outside the modified reproducibility envelope.

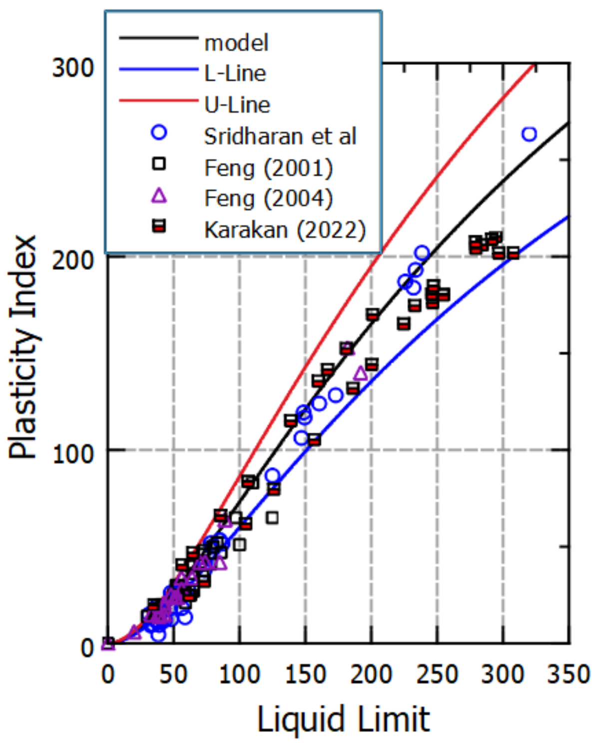

Figure 13: The boundary of which all inorganic clay is supposed to plot

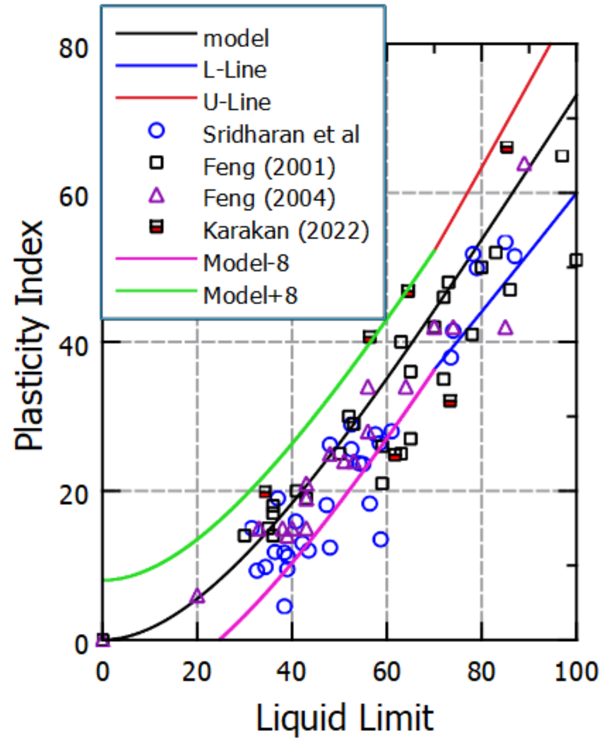

Figure 14: The boundary of which all inorganic clay is supposed to plot

SUMMARY AND CONCLUSION

Based on the analysis of the test results presented in this study, it is postulated that the liquid and plasticity index follow a well-defined trajectory for inorganic clay containing active water, such as montmorillonite, illite, and kaolinite clay, suggesting that a liquid limit of the inorganic soil is associated with unique value of plasticity index. The relationship between the liquid limit and the plasticity index is defined by Equation 2. For soils that contain dormant water that does not contribute to the plasticity of the soil, such as allophane, halloysite, chlorite, diatomaceous, and organic soil plots below the L-line. Therefore, any soil plotting below the L-line contains some percentage of inactive clay minerals with dormant water content or organic clay or silt.

Based on the test results analyzed during this study, it can be concluded as follows:

1. Inorganic soil liquid limit is associated with unique plasticity index values and follows a well-defined trajectory, which is defined mathematically using equation 2.
2. The new U-line is defined based on the inherent variation of the test results, particularly the plastic limit, which is based on the reproducibility of the plasticity index of 18% reported in AASHTO T90 for soil with a

liquid limit of more than 70, and for liquid limit of less than 70, the U-line is established following the reproducibility of 8.

3. The new proposed envelope can be used as a method of classifying inorganic clay from organic clay, i.e., the soil that contains organic clay plots below the L-line and also can be used as basis of classifying active and inactive clay, active clay plots within the reproducibility envelope while the inactive clay plots below the L-line.
4. Considering the fact that the fall cone and Casagrande cup yields different liquid limit values, the proposed model shown in Equation 2, new U-line, and L-line are only valid for the British fall cone Atterberg limit test results.

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