DETERMINATION OF ATTERBERG LIMITS USING MOISTURE TENSION METHODS

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This paper presents the results of a laboratory investigation of the relationship between the Atterberg limits and the moisture content as obtained by the moisture tension method. The study was conducted in two basic parts. First, a series of tests was made on 38 soils for the purpose of establishing mathematical models for predicting liquid and plastic limits. The results of these tests showed very good correlation between the standard test results and the moisture tension test results. The soils used had liquid limit values <50 percent and plasticity index <21 percent. Second, the mathematical models were verified by using a total of 144 samples having a wide range of plasticity values. The results showed good correlation for the liquid limit and fair correlation for the plastic limit. The results of the investigation indicate that a linear relationship exists between the consistency limits and the moisture content obtained at various pressure intensities. The results also strongly suggest that the moisture tension test can be used on a routine basis for determining the consistency limits of soils.

•THE Atterberg limits have been extensively used for identifying engineering properties of soils and specifying quality of base courses. Almost all specifications for base course materials set some limits on these constants. To get consistent test results for the liquid and plastic limits and to minimize the time required for such tests, attempts have been made either to modify the standard method for determination of these limits or to correlate the limits obtained by the standard method with those obtained from a completely different method.

The moisture tension method (10, 14, 15, 16, 18) has been studied as an alternate procedure for estimating the liquid and plastic limit. The results obtained by this method show a higher degree of reproducibility (10, 15, 16) than the ASTM standard method. The method also permits testing a large number of soil samples simultaneously.

However, there are some limitations relative to the use of the moisture tension method for determining the consistency limits. Previous studies have utilized textural classification of soils as a basis for determining the relationship between moisture tension and liquid limit. Generally, a specific pressure intensity has been recommended for a given soil textural group (14, 15, 16, 18). The use of this technique for the plastic limit determination and for the identification of nonplastic soils has not been fully explored.

The primary purpose of this study was to investigate the possibility of using a unique pressure intensity in the moisture tension test for establishing the moisture tension-consistency limits relationship for various soil types, regardless of their textural classification, and thus specifying a limit on the moisture content values, as obtained from the moisture tension method utilizing a unique pressure intensity, below which a soil could be classified as nonplastic.

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MATERIALS

This investigation was conducted using 38 soils obtained from the Indiana State Highway Commission. The liquid limit values of these soils ranged from 18 to 50 percent and the plasticity index values were less than 21 percent. Four basic soil types were tested:

1. Inorganic clays of low to medium plasticity, silty clays, lean clays.
2. Inorganic silts and silt clays.
3. Inorganic clays and silts of low plasticity.
4. Nonplastic materials, mostly silty sands.

MOISTURE TENSION METHOD EQUIPMENT

The apparatus used in this investigation essentially consisted of a commercially available ceramic plate extractor capable of holding three ceramic plates. The ceramic plates used were approximately 10¼ in. (26 cm) in diameter and of a design permitting the tests to be run in the 0 to 1 bar (0 to 100 kPa) pressure range. They are commonly designated as "1 bar ceramic plates" (Fig. 1).

Soil samples are placed in rubber rings 2 in. (5.08 cm) in inner diameter and ½ in. (1.27 cm) high on the ceramic plates, which are mounted in the extractor. A maximum of 12 soil samples of this size can be placed on each plate. When the pressure is applied in the extractor, a pressure difference is maintained across each porous plate, the bottoms of which are at atmospheric pressure. Water from the soil is forced out of the extractor through the ceramic plate cells and the outflow tubes until an equilibrium moisture state is reached, and flow then ceases.

TEST PROCEDURES

The liquid and plastic limits were determined in accordance with ASTM D 423-61T and D 424-59 respectively. Four replicated tests were performed by one trained operator on each soil used in this study.

The general procedure for the moisture tension test is as follows. Each soil sample of 50 grams weight (consisting of the fraction passing the No. 40 sieve) was put into a glass jar. A sufficient amount of distilled water was added and carefully mixed with a spatula until the soil mass could be slowly poured out of the jar. Care was taken that the soil was not so wet as to have free water on the surface when standing. The samples were allowed to stand in the capped jars for 2 hours before placing them on the plates.

The ceramic plates were placed in the extractor and saturated with distilled water prior to placing the soil samples on the plate. Twelve rubber rings of 2 in. (5.08 cm) inside diameter and ½ in. (1.27 cm) height were placed on the plate. Each soil sample was placed in the rubber rings on the plate using a spoon. Care was taken to ensure that the mixing and preparation process was consistent to minimize the effects of pore sizes and state of packing on the test results. Although these two factors cannot be precisely controlled by the techniques used in this study, previous studies have shown that good results can be obtained as long as consistency in the method of preparation was maintained (15, 16).

The tubes were next connected and the lid of the extractor was closed and tightened with bolts. The ends of the outflow tubes were kept constantly under approximately 1 in. (2.5 cm) of water in a beaker to ensure outflow into a constant environment as far as humidity was concerned and to check against air leaks (15). Pressure was then applied and adjusted to the required value. The pressure was maintained for 24 hours to ensure reaching an equilibrium state. At the close of a run the outflow tube was pinched to prevent possible backflow of water when the pressure in the extractor was released. The pressure was released and the lid of the extractor was opened. The soil samples were transferred to containers, and the moisture content of these samples was determined in accordance with ASTM D 2216-63T.

This method of preparation was selected and used in this research after a preliminary study was conducted to evaluate the effect of method of preparation of soil samples

on the moisture tension test results (6). Six soils were prepared using five different methods of preparation, three of which had been utilized and tested in previous research (10, 14, 15). A statistical analysis of the results indicated that the method of preparation of the soil samples had no significant effect on the moisture tension test results (at $\alpha = 0.05$). This conclusion, however, should be viewed with some caution because the test results apply only to the relatively limited inference space consituted by the soil test samples and methods of preparation that were used. Also, the statistical analysis indicated significant interaction between the method of preparation and soil type. This suggests that for some soil types the method of preparation may have an effect on the test results and further indicates that a standardized method of preparation of soil samples is important.

The authors believe that consistency in the method of mixing and preparing the soil samples is of essential value in minimizing changes in the pore sizes and packing state of the soil samples that would affect the moisture tension test results, at least to the extent that such changes do not affect its reproducibility.

RESULTS

Prediction of Liquid and Plastic Limits of Soils

Previous studies (15, 16) suggested that the region between the upper and lower flex points in the moisture tension curves could represent the plasticity index of the soil and that this hypothesis is consistent with the mechanism of plasticity as set forth by Grim (7). Furthermore, the interpretation of two pressure intensities, 3 psi (20.7 kPa) and 20 psi (137.9 kPa), relative to the moisture tension curves obtained in a study by Nishio (10) approximately corresponds to the two flexes.

To determine the Atterberg limits-moisture tension relationships, four pressure intensities, 6, 10, 12, and 18 psi (41.4, 68.9, 82.7, and 124.1 kPa), were used. These pressure intensities lie in the range of 3-20 psi (20.7-137.9 kPa) in which the soil samples exhibit plastic behavior, as suggested in previous studies (10, 15, 16).

For each pressure intensity and using the previously described moisture tension test procedure, the moisture content of each soil was determined. For each of the pressure intensities, four replications were made.

Linear regression models were hypothesized to study the relationships between the measured variables (liquid limit and plastic limit) and the independent variable, WC_i (the symbol WC_i will be used to represent the moisture content obtained under "i" psi pressure intensity). A separate model was evaluated for each of four pressure intensities. Nonplastic soils were excluded from this part of the study.

The data for the regression analysis were handled by two different statistical procedures. The first is commonly referred to as "random combination" and the other as "average values".

In the "random combination" scheme, liquid limit values from the four replications on each soil by the standard method were randomly combined with the four moisture content values obtained at a corresponding pressure intensity to form a set of four readings. The data obtained for the 28 soil samples were tested for homogeneity of variance. The assumption of homogeneity of variance for both LL and PL test data was accepted and there was no need of transforming the dependent variables.

In the "average values" scheme, the mean value of the four replicates of the standard liquid and plastic limit tests for each soil was used as the dependent variable. Similarly, the mean WC_i value for each soil was used as the independent variable. Using these average values in the regression analysis eliminates a part of the variation among the replicate measurements, which may make the coefficient of determination R^2 misleadingly high. However, this study indicated that there is very little difference in R^2 due to the use of the two schemes (random combination versus average values). The use of the prediction models obtained by utilizing the random combination scheme could better represent the inference space for this study.

Interpretation of Regression Analysis Results

The models obtained from the regression analysis of the test data were examined

and those providing the best fit of the data were selected. The criterion used to evaluate the best regression equation was the coefficient of determination, R^2, the ratio of the variation explained by the regression equation to the total variation of the data about the mean. Also, the significance of the regression was tested by an F-test at an α level of 0.05. The residuals obtained from the regression analysis were examined to determine if they were correlated. It was observed that the residuals did not show any predominant trend.

The results of the regression analysis using the random combination scheme are summarized in Table 1. An examination of these results indicates that these linear first-order regression models are appropriate for representing the relationship between consistency limits (LL and PL) and the moisture content WC_1. The data show that

1. The prediction models obtained for both the liquid and plastic limits show a high coefficient of determination, R^2. Also, a linear relationship exists between the liquid or plastic limit and the equilibrium moisture content for each of the pressure intensities utilized in this investigation, namely, 6, 10, 12, and 18 psi (41.4, 68.9, 82.7, and 124.1 kPa).
2. The regression models obtained for the prediction of the liquid limit show a higher R^2 value than that obtained for the prediction of the plastic limit values.
3. For the liquid limit prediction models, the R^2 values remain almost the same (0.92-0.95) with changes in the pressure intensity. Conversely, for the plastic limit prediction models, the R^2 values decrease directly with the increase in pressure intensity utilized [the prediction model obtained at 6 psi (41.4 kPa) has an R^2 value of about 0.94, and that at 18 psi (124.1 kPa) has an $R^2 = 0.78$].
4. The deviations of the predicted LL and PL values from the observed values are within the range of those obtained in replicated standard LL and PL test results (6, 9, 10, 15). To make the prediction models less cumbersome and easier to handle, it was decided to simplify the regression coefficients. Because the liquid and plastic limit values are generally determined to the nearest whole percent moisture content, rounding off the regression coefficients in the prediction equations will not affect the results appreciably.

Detection of Nonplastic and Low-Plasticity Soils

Another aspect of the study was concerned with the identification of nonplastic soils by the moisture tension method. [Nonplastic soils are defined as those sandy or noncohesive soils for which it is difficult or impossible to determine the plastic limit.] The moisture contents (WC_1) of the nonplastic soils were obtained by using four different pressure intensities. Study of the moisture content values indicated that WC_1 values of the nonplastic soils had an approximate upper-bound limit depending on the pressure intensity used. Similarly, for the soils exhibiting a plasticity index (PI) less than 3 percent as well as those with PIs between 3 and 6 percent, the moisture content (WC_1) values were within specific ranges. Therefore, it appears that nonplastic and low-plasticity soils can be identified by their limiting WC_1 values. These limiting values for various pressure intensities are given in Table 2.

Figure 2 shows the relationship of the liquid and plastic limits to the moisture content values WC_1 at various pressure intensities (using the simplified regression coefficients). These relationships can be divided into several distinct segments. The lowest segment A indicates the nonplastic region, the region B signifies the range from nonplastic to a PI < 3 percent, and region C approximates the WC_1 values for soils exhibiting PI values between 3 and 6 percent. The region beyond C is for soils exhibiting a PI greater than 6 percent.

Verification of the Proposed Mathematical Models

To verify the proposed relationships, additional soil samples with previously determined consistency limits were obtained from a laboratory outside Indiana. A total of 144 samples representing a large range in soil texture were tested. The liquid limits of these samples ranged between 15 and 80 percent; the highest plasticity index was 60

Figure 1. Setup of equipment showing two extractors.

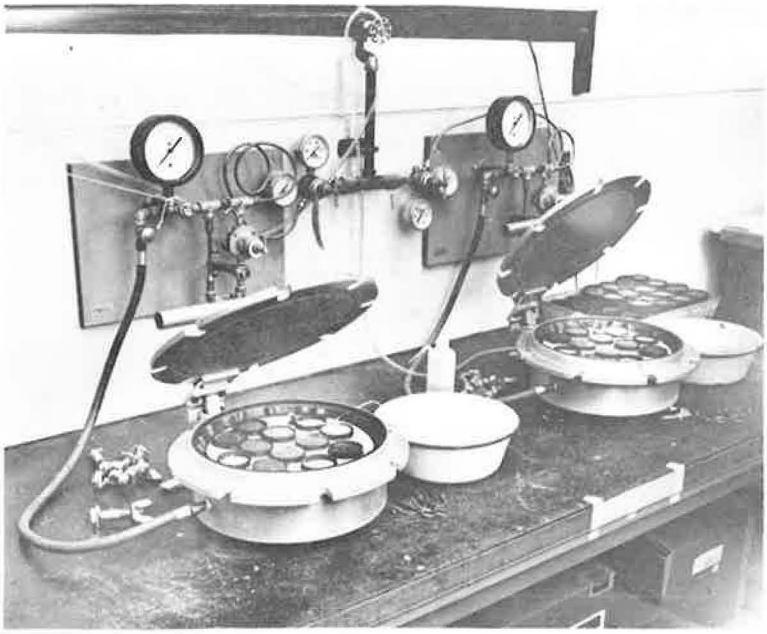


Table 1. Prediction equations for the liquid and plastic limits.

Pressure	Model	R^2	Standard Error	No. of Samples
6 psi (41.4 kPa)	$LL = -3.5863 + 1.3201\ WC_6$	0.93	2.58	112
	$PL = 1.4094 + 0.7097\ WC_6$	0.94	1.22	112
10 psi (68.9 kPa)	$LL = -3.5437 + 1.4867\ WC_{10}$	0.95	2.18	112
	$PL = 1.9906 + 0.7737\ WC_{10}$	0.90	1.59	112
12 psi (82.7 kPa)	$LL = -2.7809 + 1.4892\ WC_{12}$	0.95	2.09	112
	$PL = 2.7699 + 0.7570\ WC_{12}$	0.87	1.85	112
18 psi (124.1 kPa)	$LL = -1.9158 + 1.5029\ WC_{18}$	0.92	2.68	108
	$PL = 3.9766 + 0.7299\ WC_{18}$	0.78	2.41	108

Table 2. WC_i ranges for nonplastic and low-plasticity soils.

Pressure	WC_i Range for Nonplastic Soils[a]	WC_i Range for Soils With PI <3 Percent[a]	WC_i Range for Soils With PI Between 3 and 6 Percent[a]
6 psi (41.4 kPa)	<10	10-15	15-20
10 psi (68.9 kPa)	<9	9-14	14-19
12 psi (82.7 kPa)	<8	8-13	13-18
18 psi (124.1 kPa)	<7	7-12	12-17

[a]Values are in percent moisture content.

Figure 2. Relationship of liquid and plastic limits to moisture content at various pressure intensities.

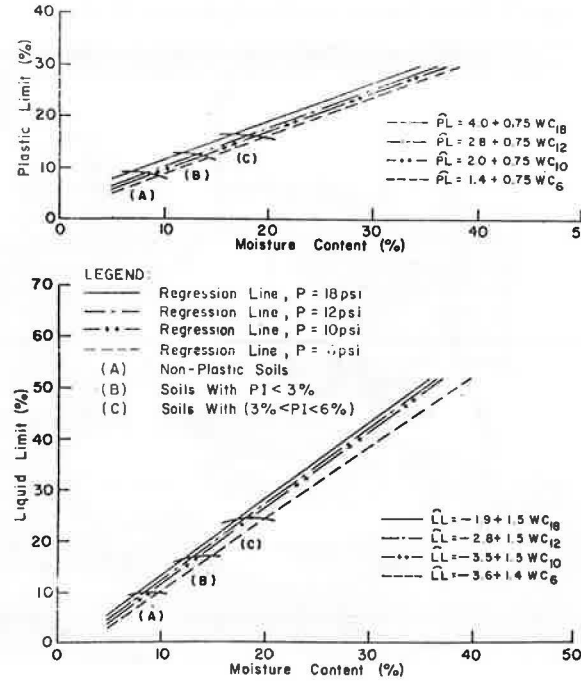
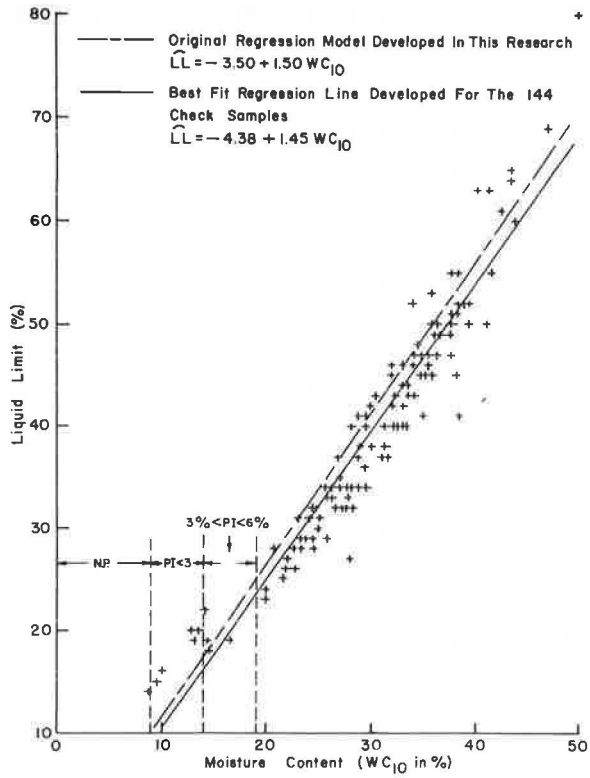


Figure 3. Relationship between liquid limit and moisture content at 10 psi (68.9 kPa) for the check samples (144 data points).



percent. The moisture tension method test was run on these samples at a pressure intensity of 10 psi (68.9 kPa) because a high R^2 value was obtained for both the liquid and plastic limit prediction models for this pressure. Although the models indicate that utilizing a pressure intensity of 6 psi (41.4 kPa) would result in an even higher coefficient of determination R^2, using such a relatively low pressure intensity requires more experimental control and more careful adjustments of the pressure regulators than the higher pressures. The equilibrium moisture content is a function of the pressure intensity applied, i.e., for low pressure, WC_t is higher than that obtained under high pressures. Also, it was observed that transferring the soil samples from the ceramic plates to the containers after releasing the pressure was easier at 10 psi (68.9 kPa) pressure intensity.

Liquid Limit Relationships

The liquid limit prediction model,

$$LL = -3.50 + 1.50\ WC_{10} \tag{1}$$

was applied to the check sample data. The coefficient of determination, R^2, resulting from applying model 1 to the check sample data was 0.89.

To investigate the possibility of a better fitting model for the check samples, a regression analysis of the check sample data was made. The analysis resulted in the following linear model with a coefficient of determination, $R^2 = 0.92$:

$$LL = -4.38 + 1.45\ WC_{10} \tag{2}$$

A plot of standard LL values versus WC_{10} for the check samples together with models 1 and 2 is shown in Figure 3. The deviations of the predicted values from the standard values using both models 1 and 2 are summarized in Table 3.

The next step in this analysis was to compare statistically the original and check sample models. Both models have a general form of the type

$$LL = b_0 + b_1\ WC_{10} \tag{3}$$

It was found that the slope b_1 and the intercept b_0 of the Purdue sample model lie within the 95 percent confidence limits for the regression coefficients β_1 and β_0 respectively of the check sample model. The shift in intercept values could be attributed primarily to operator variability.

These models suggest that a linear model may be the best fit to define the LL versus WC_{10} relationship for any soil. However, for good correlation one might have to adjust the parameters b_0 and b_1 for soils from different geographic areas.

Plastic Limit Relations

A correlation analysis of PL and WC_{10} for the 144 check samples resulted in a simple correlation coefficient, $r = 0.63$. Because of the apparent low correlation when the results of all 144 samples were used, it was decided to restrict the verification of the PL relationship to just those soils having a PI < 21 percent and an LL < 50 percent. This constitutes the inference space of the model developed earlier (Purdue data) and it also covers the majority of soils that an agency would test under normal circumstances.

The data lying inside the prescribed range were included for the analysis (91 data points). The plastic limit prediction model (Purdue data),

$$PL = 2.0 + 0.75\ WC_{10} \tag{4}$$

the best fitting linear regression model (from check samples),

$$PL = 4.77 + 0.54\ WC_{10} \tag{5}$$

Table 3. Summary of deviation of predicted LL values from the standard values.

	Purdue Sample Model[b]		Check Sample Model[c]	
Deviation[a]	No. of Observations	Percent of Observations	No. of Observations	Percent of Observations
1-2	65	45.2	87	60.5
3-4	42	29.2	36	25.0
>4	37	25.6	21	14.5

[a]Standard LL minus predicted LL in percent.
[b]Using the model LL = -3.50 + 1.50 WC_{10}.
[c]Using the model LL = -4.38 + 1.45 WC_{10}.

Figure 4. Relationship between plastic limit and moisture content at 10 psi (68.9 kPa) for the check samples (91 data points).

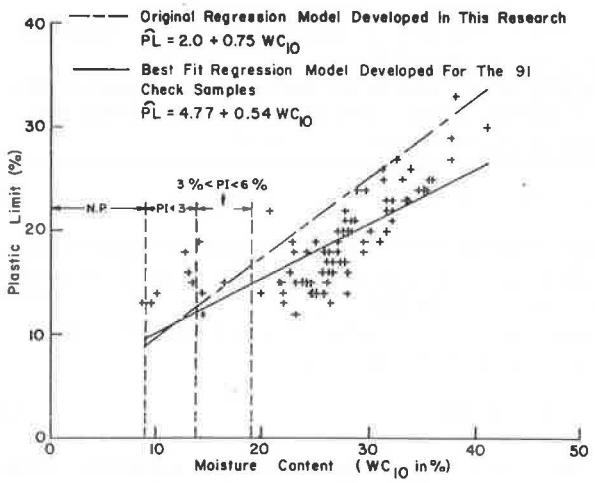


Table 4. Summary of deviation of predicted PL values from the standard values.

	Purdue Sample Model[b]		Check Sample Model[c]	
Deviation[a]	No. of Observations	Percent of Observations	No. of Observations	Percent of Observations
1-2	19	21.0	57	62.5
3-4	27	29.5	29	32.0
>4	45	49.5	5	5.5

[a]Standard PL minus predicted PL in percent.
[b]Using the model PL = 2.0 + 0.75 WC_{10}.
[c]Using the model PL = 4.77 + 0.54 WC_{10}.

and the reduced data (91 data points) are shown in Figure 4. Model 5 resulted in a coefficient of determination $R^2 = 0.60$. The simple correlation coefficient, r, between PL and WC_{10} for the reduced data increased to 0.78.

The deviations of predicted values, using both models 4 and 5, from the standard plastic limits are summarized in Table 4.

Nonplastic and Low-Plasticity Soils

It was observed that the ranges of WC_{10} values postulated for nonplastic and low-plasticity soils are valid for the check sample data. These ranges are indicated in Figures 3 and 4.

CONCLUSIONS

The objective of this study was to investigate the feasibility of using the moisture tension method to determine Atterberg limits. The conclusions are as follows:

1. Linear relationships were developed between the consistency limits (LL and PL) and the moisture content, WC_1, obtained at 6, 10, 12, and 18 psi (41.4, 68.9, 82.7, and 124.1 kPa) pressure intensity. These relationships offer the possibility of using linear models, correlating the consistency limits with the moisture content for predicting liquid and plastic limits.
2. The nonplastic and low-plasticity soils can be identified by their WC_1 values as obtained by the moisture tension method.
3. The results of the verification of the consistency limits-WC_{10} relationships indicated that the liquid limit prediction model showed good agreement with the best-fitting linear regression model for the check sample data. A linear relationship for these parameters explains 92 percent of the variation in the data. The plastic limit model resulted in a relatively poor prediction of the plastic limit values of the check samples. The analysis to determine the best-fitting linear model for the check sample data resulted in an R^2 value of 0.60. This low value can possibly be explained by the fact that forces other than capillarity affect the moisture tension test results, especially in the case of clays. Baver (1) suggested that the water-holding capacity of soils is a function of the clay content, the type of clay minerals, amount of organic matter, and porosity. It is possible that different mineralogical characteristics and origin of the check soils may have caused the differences observed during the verification of these models. Further, some of the difference can be attributed to the variability between different operators. The range of WC_{10} values suggested previously for nonplastic soils as well as those with low plasticity (based on original data) was verified by the check sample data.

ACKNOWLEDGMENTS

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DISCUSSION

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A definite need exists to find alternative methods for determination of Atterberg limits. As the authors have indicated, the conventional methods are time-consuming and, in addition, subject to considerable human error. In any attempt to develop alternative methods, however, the full significance of the results of these tests must be kept in mind. The standard tests appear crude and unscientific to those who are unfamiliar with soil classification, but this is far from the truth. In fact, as far as engineering purposes are concerned no facet of soil classification comes closer to gaining universal acceptance than application of Atterberg limit tests. This is no coincidence. Judicious consideration of both the liquid and plastic limits sometimes in conjunction with other index properties has proved over the years to be a remarkable indicator of soil performance for engineering applications.

In their paper the authors suggest that both the liquid limit and the plastic limit may be obtained from a single test result. This is entirely contrary to the basic meaning and significance of the Atterberg limit tests. The implication for such a proposal is that the liquid limit and plastic limit (and consequently the liquid limit and plasticity index) are uniquely related. This is seen by combining the authors' respective prediction models:

$$LL = -3.50 + 1.50\ WC_{10} \qquad (1)$$

$$PL = 2.0 + 0.75\ WC_{10} \quad (4)$$

Combining (1) and (4) leads to

$$LL = 2.0\ PL - 7.50 \quad (6)$$

and introducing the plasticity index gives

$$PI = 0.5\ LL - 3.75 \quad (7)$$

A further implication of Eq. 7 is that the liquid limit may replace plasticity index as a predictor of soil performance.

Equation 7 may be plotted on the standard plasticity chart. This has been done in Figure 5 together with some typical soils as described by Terzaghi and Peck (19). It becomes obvious from this diagram that the very basis for distinction between soil types is lost in the method proposed by the authors. It is absolutely essential that determination of liquid and plastic limits be made from independent tests. A calibration of the method would be possible within a given soil type, but then one might as well measure liquid limit alone. At any rate, the most frequent use of the Atterberg limits is to define the soil type in the first place.

The moisture tension method appears to be valid as a reliable predictor of liquid limit. However, even for a large number of samples there is some question of feasibility from a time and cost standpoint. This writer is of the opinion that the liquid limit may be most cheaply and reliably predicted for a wide range of fine-grained soils by use of the Swedish fall-cone as discussed by Sherwood and Riley (21).

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AUTHORS' CLOSURE

The authors wish to thank Professor Kay for his review and discussion of our paper. We would like to point out that his discussion is based on extrapolation of our data and prediction models, which would not be appropriate when using a statistical analysis approach.

During the first phase of the study, the liquid and plastic limit prediction models 1 and 4 respectively were developed using soils with a PI < 21 percent and an LL < 50 percent. This constitutes the inference space of the prediction models. In the second phase, which dealt with verifying these prediction models, the liquid limit prediction models gave a good result when used for the check samples, which represent a large range of normal soil texture. At the same time, because of the low correlation between the PL and WC_{10} for the check samples, the verification of the PL relationship using the check samples was restricted to just those soils having a PI < 21 percent and LL < 50 percent, which in turn constitutes the inference space of the models developed using Purdue data.

In other words, the liquid limit prediction models are valid for a wide range of normal soil texture, while the plastic limit prediction models presented were found to be valid only within the range of soils used in the study. It must be kept clearly in mind that the method is primarily recommended for agencies that run hundreds of these tests on soils within the ranges normally encountered, i.e., the ranges that constitute the inference space of the models. The method is not recommended in areas where there are troublesome soils such as clays of very high plasticity. Nor is the method, without a great deal of additional study, applicable to soils that plot far from

Figure 5. Plasticity chart showing implications of proposed method.

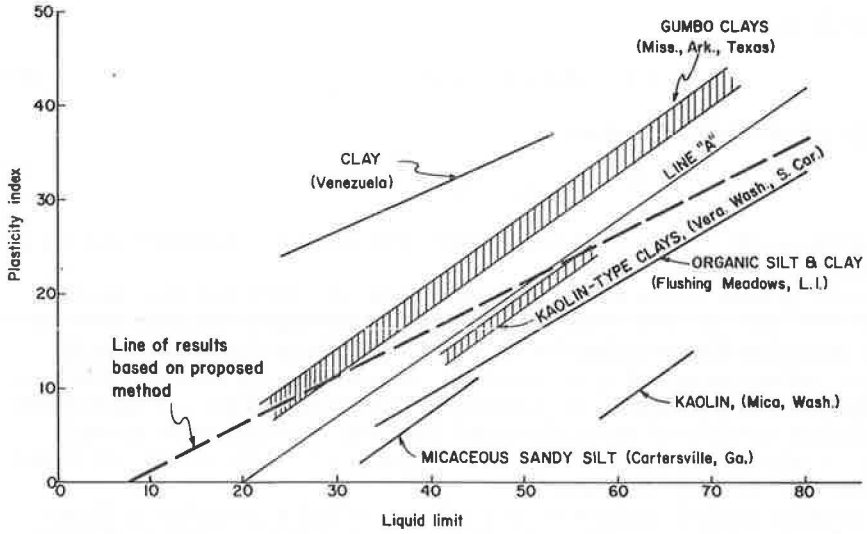
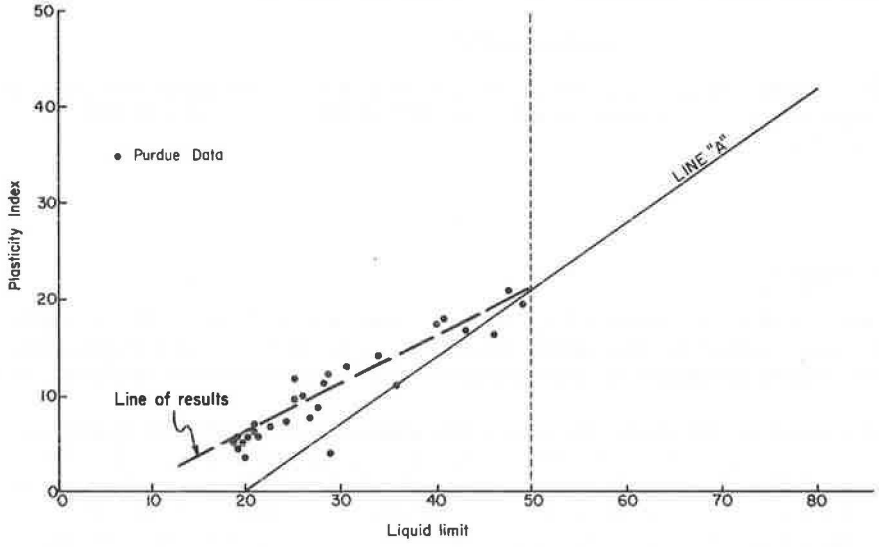


Figure 6. Plasticity chart.



the A line (micaceous soils, highly organic soils, etc.). The authors intend that the method be an engineering tool, which must be used with sound engineering judgment or common sense. Furthermore, the line of results of our study, which is shown in Figures 5 and 6, does not provide a conflict with the basis for distinction between soil types within the inference space of the study. Although we do not place great importance on it, we are pleased that the line of results based on our method is as close to the A line as the figure shows. We feel this is another "proof" of its validity.