Variability of Engineering Properties of Brookston and Crosby Soils

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Engineers have always assumed that soils derived from the same parent material and under the same environmental conditions would have similar engineering properties. To ascertain the extent to which this is true a study was conducted on two soils obtained from Madison and Tipton Counties, Ind., and pedologically classified as Brookston and Crosby.

Twenty borings were obtained from each county—10 from Brookston soils and 10 from Crosby soils. Samples of these soils were subjected to the following tests and the results analyzed statistically: Atterberg limits, Standard AASHO compaction, Hveem stabilometer and swelling pressure, California bearing ratio, grain-size distribution, and unconfined compression.

X-ray diffraction tests were conducted on 8 samples—4 from the rises and 4 from the depressions.

From the statistical analysis, utilizing analysis of variance techniques, it was found that soil variability is a function of the property being measured. The variability of the soils, as defined by the parameters of these tests, was large. The consequences of such variation as it pertains to pavement design were considered.

Diagrams are presented which relate the number of borings required to predict the mean value of a given test parameter to a desired degree of precision.

• WHEN DEALING with relatively large areas, two broad aspects of soil sampling need be investigated: accuracy of soil tests for a given soil type, and determination of the number of soil samples required to define the soil within certain specified limits. The latter pertains to pedological soil classification as well as classification based on landforms.

As an example, a highway crosses a typical glaciated area. By the use of airphotos, agricultural soil maps, and other tools at the disposal of the engineer, the general soil types can be delineated. Next, information on the uniformity of the deposit can be obtained by detailed exploration. The variability among random samples may be great. Clarification of the random variability of soil can be of great value to the soils engineer.

Another phase of the problem is the variability from one soil area to another of the same classification. These data in this regard would be of of great value for setting up "average" soil property values which can be adopted for design.

Data from this last phase can be used by the soils engineer and researcher alike for preliminary pavement design. Correlation studies of pavement performance would also be enchanced if typical strength values were known.

To find the optimum solution to the problems stated above the disciplines of soil mechanics, statistics, airphoto interpretation, and pedology were utilized.

PURPOSE AND SCOPE

The primary purpose of this study was to determine the variation that could be expected in the engineering properties of soils derived from the same parent material and under similar conditions of climate, vegetative cover, age, and topography. Also, the number of samples required to reliably predict these properties was determined.

The areas selected for this study are located in Tipton and Madison Counties, Ind. The parent material is late Wisconsin drift and is illitic in nature. The soils formed from this parent material belong to the Miami-Crosby - Brookston Catena. The Crosby (rise) existing on 0 to 4 percent slopes and the Brookston (depression) existing in depressional areas were used in this study.

Twenty borings were made in each county—10 in elevated positions and 10 in the depressions. The A-, B-, and C-horizons were samples in each boring. However, only moisture content and Atterberg limit determinations were performed on the soil from the A-horizon. The soils from the B-horizon and C-horizon, in addition, were subjected to grain-size analysis, California bearing ratio (CBR) tests, compaction tests (dynamic and kneading), unconfined compression tests, and Hveem stabilometer and swelling tests.

The data from the tests were subjected to statistical analysis to estimate the variance of the soil properties and the number of samples required to define these properties. In regard to the variance of soil properties, two questions were answered:

1. Is there a significant difference between the physical properties of the soil taken from horizons in the same soil series in two counties?
2. Is there a significant difference between the results obtained from the various borings within a given county?

Finally, it was hoped to discover useful relationships among the previously listed properties that would provide information for the preliminary design of structures.

PROCEDURE

Pedologic maps and soil surveys were not available for the counties considered in this study; therefore, it was necessary to make the selection of the boring sites on the basis of airphoto patterns. After studying the airphotos of five Indiana counties, it was decided to use Madison and Tipton Counties because of the similarity of their airphoto patterns. In particular, an area just south of the Union City moraine, in each county, was chosen.

The parent material is Wisconsin drift. However, to negate the effect of the moraine the sampling sites were chosen so that they were equidistant from the moraine (approximately 5 mi).

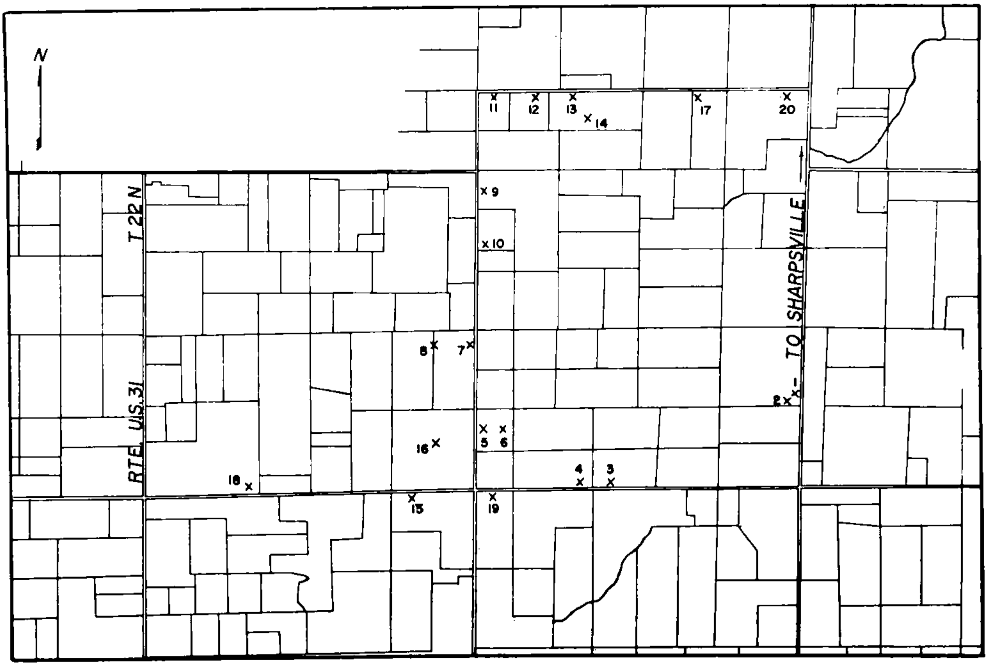


Figure 1. Boring locations, Tipton County.

On the basis of airphoto pattern, the soils of the area were divided into two categories—rises and depressions. Possible boring sites were chosen in the office, after which a field check was made and the final boring locations determined (Figs. 1 and 2). A total of 20 borings was made in each county—10 in the rises and 10 in the depressions (see Fig. 3 for generalized soil profiles based on boring logs).

Samples were obtained by hand augering. Approximately 300 g of soil was taken from the A-horizon of each boring, and values of the Atterberg limits and natural moisture content were determined. Because the A-horizon is often wasted in engineering construction, extensive testing was not warranted.

In addition to samples for the Atterberg limit and natural moisture content tests, approximately 100 lb were taken from both B- and C-horizons of each boring. The latter samples were air dried and quartered into sizes necessary to perform the following tests:

1. Grain-size distribution and specific gravity;
2. Standard AASHO compaction;
3. Hveem stabilometer and swelling pressure;
4. California bearing ratio;
5. Unconfined compression; and
6. X-ray diffraction.

Natural Moisture Content

Moisture content samples were taken from each horizon in each boring, selecting the sample from the same depth below the ground surface —the depth at which these samples were taken depended on whether the boring in question was located in a rise or a depression. No quantitative analysis of these data was attempted. Only one moisture content sample was taken per horizon.

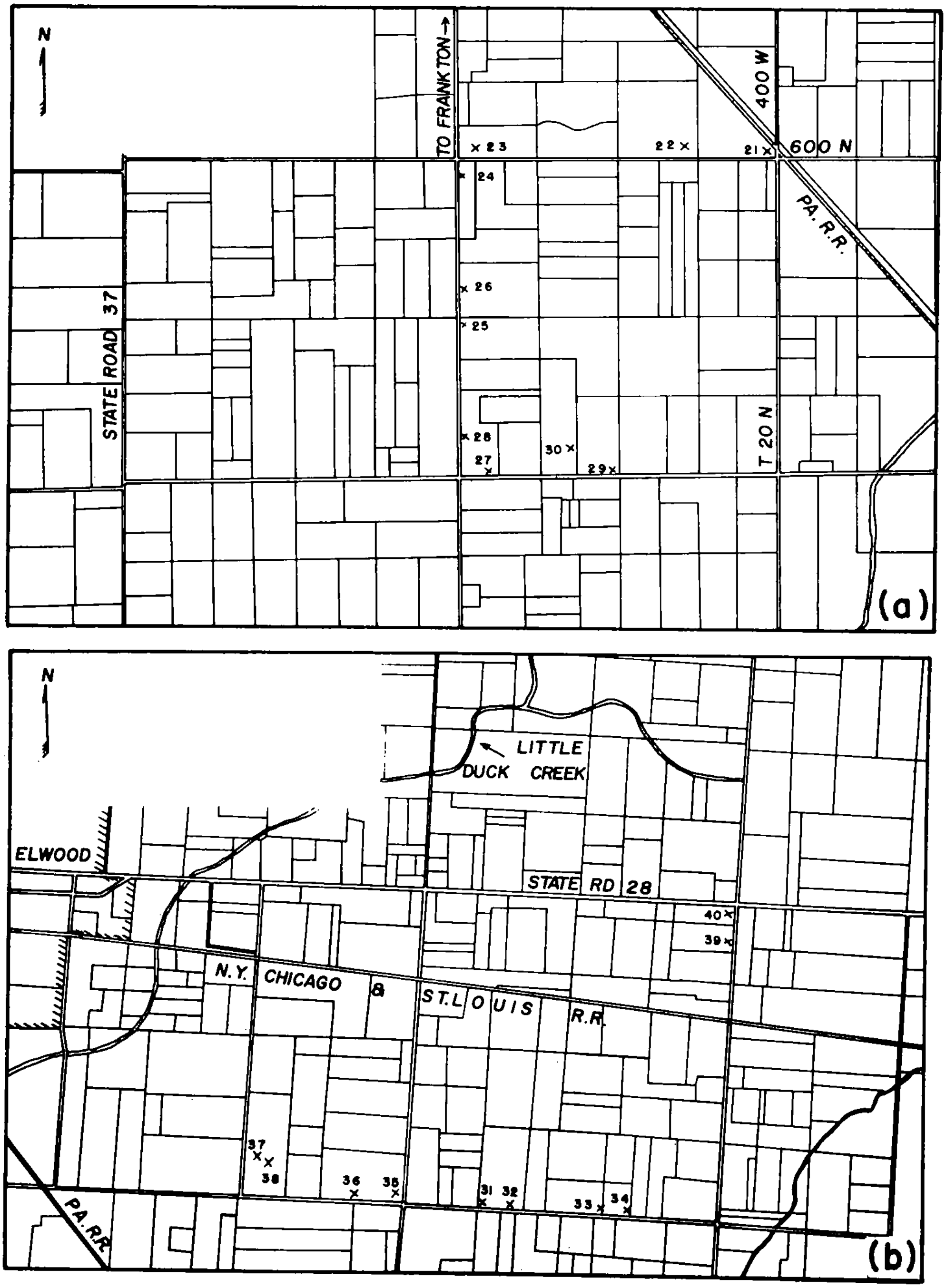


Figure 2. Boring locations, Madison County.

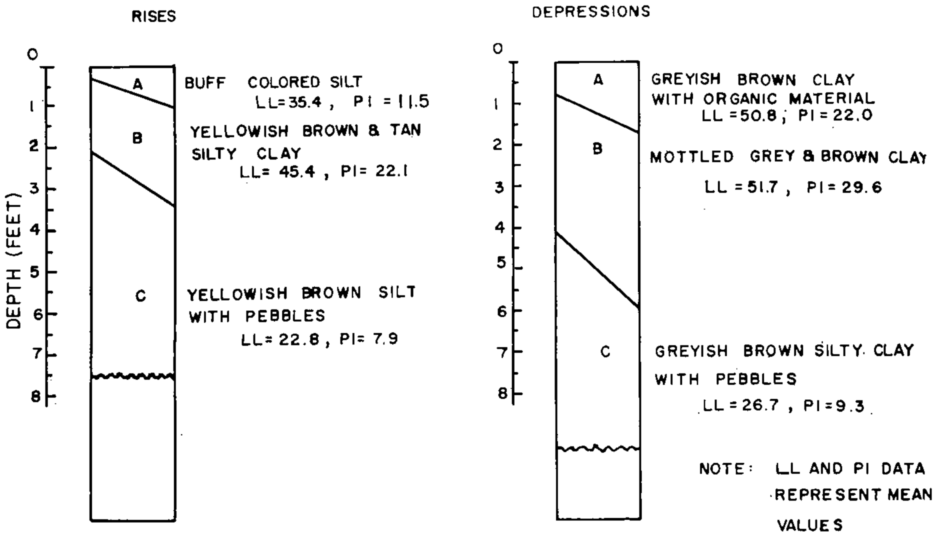


Figure 3. Boring results.

Atterberg Limits

The liquid and plastic limits were determined in accordance with ASTM Designations D423-54T and 424-54T, respectively, with the exception of the method of preparation of the samples. The tests were conducted on samples at their natural moisture content. Such a procedure would best indicate plasticity properties of the in-situ materials. Two determinations were made in each horizon.

Grain-Size Distribution and Specific Gravity

The procedure for determining the specific gravity of the soils is that given in ASTM Designation D854-58. In regard to the grain-size analysis, ASTM Designation D422-54T was employed with the following variations:

1. A constant temperature bath was not used.
2. Two grams of the water conditioner "Calgon," manufactured by the Calgon Company, Pittsburgh, Pa., per 50 g of soil was used as a deflocculating agent.

Compaction Tests

Standard AASHO compaction tests were run according to Method A of ASTM Designation D698-58T.

Hveem Stabilometer and Swelling Pressure Test

Hveem stabilometer and swelling pressure tests were conducted in accordance with test method California 301-B, State of California Division of Highways. Molding moisture content was considered critical and was the controlled variable. This molding moisture content was chosen on the basis of the kneading compaction curves.

The kneading compaction curves were established by the compaction procedure given in test method California 301-B with three variations:

1. All moisture was added to the sample the day before testing.

2. Compaction curves were determined for compaction foot pressures of 350, 250, and 150 psi (see Fig. 8 for typical curves).
3. The compactor foot pressure used to get the soil into the mold was 75 psi instead of 15 psi as prescribed in the test method.

On the basis of the first series of compaction tests, it was determined that the compaction foot pressure that would give densities approximating the standard AASHO results was 150 psi. Thus, the remainder of the tests were run using the 150-psi foot pressure only.

Because it was not feasible to run compaction tests on samples from each horizon, the samples were grouped according to the density obtained from the standard AASHO compaction test. A sample of each group was then subjected to a compaction test using the kneading compactor. The stabilometer specimen from each horizon was then molded at the optimum moisture content (OMC) determined from tests on the sample representative of its density group.

Borings 3, 25, and 12 were used as the standard. For the C-horizon the density groups represented by these samples were more than 120 pcf, 117 to 120 pcf, and less than 117 pcf, respectively. However, in the B-horizon the density range was much narrower and it was necessary, in many instances, to use logic and intuition in assigning a molding moisture content to a given sample. The criteria for determining whether the proper moisture content was assigned were density and the action of the soil under the compaction foot. If a density approximating the standard AASHO was obtained and if there was not significant shoving of the surface during the compaction process, the assigned moisture content was assumed satisfactory.

TABLE 1

OPTIMUM MOISTURE CONTENT

Boring	Horizon	OMC (%)
3	B	16.5
	C	11.0
12	B	18.0
	C	14.2
25	B	17.0
	C	12.0

The moisture contents used for molding the specimens are given in Table 1. The average moisture contents of the samples were controlled to within ±0.5 percent.

CBR Test

CBR tests were conducted in accordance with the U. S. Army Corps of Engineers test procedure given in EM 1110-45-302, Appendix III, 1957, part 5 with the exception that the standard AASHO compactive effort was used. Also, the average molding moisture content was controlled to within ±0.5 percent of the standard AASHO optimum moisture content.

Unconfined Compression Tests

Unconfined compression tests were run on specimens molded with the Harvard miniature compactor. The compactive effort was five layers at 15 blows per layer using a 40-lb spring.

The soils from each horizon were divided into groups according to density and compaction tests conducted on a representative sample of each group to determine the OMC. The same density groups as cited in the discussion of the Hveem tests were utilized. Borings 11, 33, and 24 were taken to represent the high, medium, and low density groups, respectively (based on the density of the C-horizon).

On the basis of these tests, the OMC of the groups are given in Table 2. These average moisture contents were within ±0.5 percent of the desired moisture content.

TABLE 2
OPTIMUM MOISTURE CONTENT

Boring	Horizon	OMC (%)
11	B	16.5
	C	11.6
33	B	18.0
	C	13.0
24	B	17.0
	C	13.0

TABLE 3

County	Boring No.	
	Rise	Depression
Tipton	4, 12	1, 14
Madison	21, 35	24, 28

The rate of strain, used for the unconfirmed compression tests, was 0.07 in. per min. Also, after molding, the samples were wrapped in aluminum foil, placed in a sealed container, stored overnight, and tested the following day.

X-Ray Diffraction Tests

X-ray diffraction tests were run on the B- and C-horizons of 8 borings. Two borings were selected from the rises and 2 from the depressions of each county.

The basis of the selection of the borings to be used was unusual behavior as exemplified by the CBR and Hveem stabilometer data. The samples chosen produced higher CBR and/or stabilometer (R) values for the B-horizon than for the C-horizon. This situation is just the opposite of the normal trend, and it was felt that a knowledge of the clay minerals present might help to explain the reason for this behavior. With this in mind, borings representative of the group of soils in which this event occurred were chosen. Table 3 gives their topographic position and county.

The slides for the X-ray diffraction test were prepared from a portion of the soil quartered for the hydrometer analysis test. Fifty grams of the soil were mixed with approximately 700 cc of water and 2 g of the water softener Calgon. The suspension was then mixed in a mechanical stirrer for 3 min, after which the soil was allowed to settle out of suspension. After a period of time, a sample was taken from the suspension at a depth, based on Stokes' law, where 2-μ particles would be located. This portion of the suspension was placed on a glass slide and allowed to dry.

Statistical Analysis

Following completion of these tests, the data were analyzed using analysis of variance techniques. Table 4 gives the data layout for the analysis of variance studies. With the exception

TABLE 4
DATA LAYOUT FOR ANALYSIS OF VARIANCE

Boring No. / Horizon	Tipton County		Madison County	
	Depressions	Rises	Depressions	Rises
	1 3 6 8....20	2 4 5 7....19	22 24....40	21 23....39
A				
B				
C				

Variables to be analyzed:

Two observations per cell
1. Liquid limit
2. Plastic limit
3. Plasticity index
4. Optimum moisture content
5. Optimum density

One observation per cell
6. CBR values (soaked)
7. Percent passing No. 200 sieve
8. Percent < 0.002 mm
9. Swelling pressure
10. Stabilometer values
11. Unconfined compressive strength

of the Atterberg limits, only the B- and C-horizons are considered.

RESULTS

The analysis of variance model for the test results is

$$Y_{ijklm}=U+C_i+D_j+CD_{ij}+B_{k(ij)}+H_l+HC_{il}+HD_{jl}+HCD_{ijl}+HB_{lk(ij)}+E_{m(ijkl)} \qquad (1)$$

in which

Y_{ijklm}=the value obtained from a given test;
U=the true mean value for the population;
C_i=the between-counties true effect;
D_j=depression vs rise true effect;
$B_{k(ij)}$=between-boring true effect in the C-D cells;
H_l=between-horizons true effect; and
$E_{m(ijkl)}$=error true effect of repeat measurements.

The other terms denote interactions between the main effects listed. As regards the main effects, C, D, and H are fixed while B and E are random. The subscripts may assume values as

$i=1, 2$
$j=1, 2$
$k=1, 2, 3, \ldots\ldots, 10$
$l=1, 2, 3$
$m=1, 2$

The variation in the results of the borings may be represented as

$$\sigma_T^2=\sigma^2+\sigma_B^2+\sigma_{HB}^2 \qquad (2)$$

in which

σ_T^2=the total estimated variance between borings;
σ^2=the variance due to laboratory procedure;
σ_B^2=the variation from boring to boring; and
σ_{HB}^2=the variation in boring results due to differences in the properties of the horizons.

The standard deviation of the mean of the borings can be written

$$\sigma_{\bar{X}}=\sqrt{\frac{\sigma^2+\sigma_B^2+\sigma_{HB}^2}{n}} \qquad (3a)$$

Therefore, if it is desired to predict the mean value of the population to any specified degree of precision, L, then

$$L=t\sigma_{\bar{X}} \qquad (4)$$

in which

L=the limit of accuracy, and
t=the value obtained from the normal distribution and is a function of the α level desired.

The normal t can be used because the estimate of $\sigma_{\bar{X}}$ contains a great many degrees of freedom.

In this study an α level of 0.05 is used, which means that, on the average, 95 percent of the time the true mean values will fall within the limits indicated for the given value of n. Also, for $\alpha=0.05$, $t=1.96$.

The statistical analysis is based on the assumptions that the variance is not significantly affected by a change in operators, there is no significant change in variance with horizon, and there is normality of dependent variables.

In the text and the analysis of variance tables the following abbreviations are used:

DF=degrees of freedom;
MS=mean square; and
EMS=expected mean square.

Atterberg Limits

Liquid Limit.—Table 5 summarizes the results of the analysis of variance. Each main effect and interaction was tested for significance utilizing the F-test for the ratio of two variances (*1*). From these tests it was determined that a significant difference existed between the rises and depressions, between borings

TABLE 5

SUMMARY OF ANALYSIS OF VARIANCE—LIQUID LIMIT

Source of Estimate	DF	Sums of Squares	MS	EMS
Between counties (C_i)	1	$S_i = C_i - C = 57.53$	57.53	$\sigma^2 + 6\sigma_B^2 + 120\sigma_C^2$
Depression vs rise (D_j)	1	$S_j = C_j - C = 4483.36$	4,483.36	$\sigma^2 + 6\sigma_B^2 + 120\sigma_D^2$
CD_{ij}	1	$S_{ij} = C_{ij} - C_i - C_j + C = 23.00$	23.00	$\sigma^2 + 6\sigma_B^2 + 60\sigma_{CD}^2$
Between borings in C-D cell, $B_{k(ij)}$	36	$S_{k(ij)} = C_{ijk} - C_{ij} = 1795.27$	49.87	$\sigma^2 + 6\sigma_B^2$
Horizons H_l	2	$S_l = C_l - C = 25{,}085.67$	12,542.83	$\sigma^2 + 2\sigma_{HB}^2 + 80\sigma_H^2$
HC_{il}	2	$S_{il} = C_{il} - C_i - C_l + C = 85.93$	42.96	$\sigma^2 + 2\sigma_{HB}^2 + 40\sigma_{HC}^2$
HD_{jl}	2	$S_{jl} = C_{jl} - C_j - C_l + C = 1457.52$	728.76	$\sigma^2 + 2\sigma_{HB}^2 + 40\sigma_{HD}^2$
HCD_{ijl}	2	$S_{ijl} = C_{ijl} + C_i + C_j + C_l - C_{ij} - C_{il} - C_{jl} - C = 26.46$	13.23	$\sigma^2 + 2\sigma_{HB}^2 + 20\sigma_{HCD}^2$
$HB_{lk(ij)}$	72	$S_{lk(ij)} = C_{iklj} - C_{ijk} - C_{ijl} + C_{ij} = 3629.75$	50.41	$\sigma^2 + 2\sigma_{HB}^2$
$E_{m(ijkj)}$	120	$S_{m(ijkl)} = \Sigma_{ijklm}\ X^2_{ijklm} - C_{ijkl} = 684.78$	5.71	σ^2
Total	239	$SS = \Sigma_{ijklm}\ X^2_{ijklm} - \frac{T^2}{N} = 37{,}329.27$		

within the different combinations of county and rise vs depression; that is, in the *C-D* cells and between horizons. Also, it was found that the interactions between the horizons and borings in the *C-D* cells tested significant. Significance indicates that the effect being considered makes a major contribution to the variation in the test results.

The analysis of variance and the significance tests also showed that there was no significant difference between counties and that no interaction terms involving counties tested significant. This indicates that the data need not be subdivided on the basis of counties. From Table 5 the following values for the variance estimates can be obtained:

$$\sigma^2 = \frac{685}{120} = 5.71$$

$$\sigma_{HB}^2 = \frac{50.41 - 5.71}{2} = 22.35$$

$$\sigma_B^2 = \frac{49.87 - 5.71}{6} = 7.36$$

therefore,

$$\sigma_T^2 = 5.71 + 22.35 + 7.36 = 35.42.$$

Based on this value of σ_T^2 the number of borings required to predict the LL to a given degree of precision was determined. Figure 4 shows this relationship. Precision (limit of accuracy) is expressed in percentage points of moisture. Thus, for an average of 8 borings, 95 percent confidence limits will be, on the average, ±4 percent. In Figure 4, the ordinates for liquid limit are

$$1.96\sqrt{\frac{35.40}{n}}$$

because 95 percent of a normal curve area is from -1.96 to $+1.96$.

Plastic Limit and Plasticity Index.—To conserve space and aid reading, the analysis of variance tables for the plastic limit, plasticity index and all measured variables subsequently referred to are omitted in this report. If such information is desired, see Hampton (*3*).

The results of analyses of variance of both plastic limit and plasticity index data proved no significant difference between the two counties but all other main effects tested significant; *i.e.*, borings in the C-D cells, horizons and rise vs depression (topography).

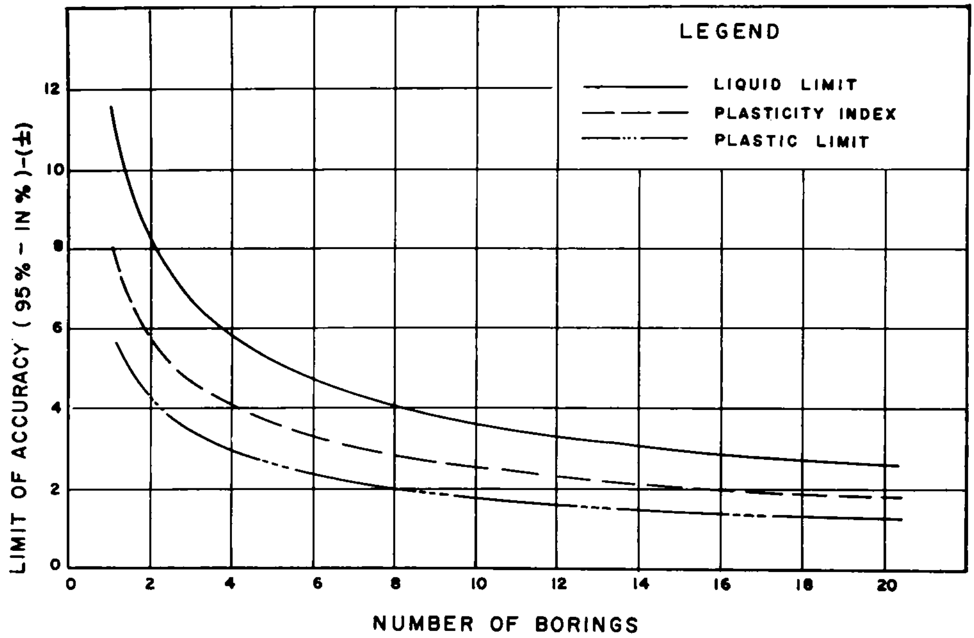


Figure 4. Limit of accuracy *vs* number of borings, Atterberg limits.

As to the plasticity index (PI), all interaction terms tested significant with the exception of county-depression (CD) and horizon-county-depression (HCD) interactions. Considering the plastic limit, only the HCD interaction was not significant.

Considering in the light of Eq. 2 the plasticity index

$$\sigma_T^2 = 5.22 + 3.75 + 7.69 = 16.66.$$

Therefore,

$$\sigma_{\bar{X}} = \sqrt{\frac{16.66}{n}} \qquad (3b)$$

As to the plastic limit,

$$\sigma_T^2 = 1.03 + 6.08 + 2.16 = 9.27$$

and

$$\sigma_{\bar{X}} = \sqrt{\frac{9.27}{n}} \qquad (3c)$$

Based on these values of $\sigma_{\bar{X}}$ the number of borings required to predict the plastic limit and the plasticity index to any desired degree of precision can be computed (see Fig. 4). The limit of accuracy (precision) is in terms of percentage points of moisture.

From Figure 4, considering absolute values, the liquid limit is the most variable and the plastic limit the least. The absolute variability of the plasticity index lies between that of the aforementioned properties.

Figure 5 shows the classification of the soils from the borings used in this study. This plot is based on the Unified Soil Classification System. Some of the points represent more than one boring. Also, the points represent the average of the two determinations for each horizon in a given boring.

The results for a given horizon departmentalize themselves very well. Looking at the over-all picture the A-horizon results lie below the A-line

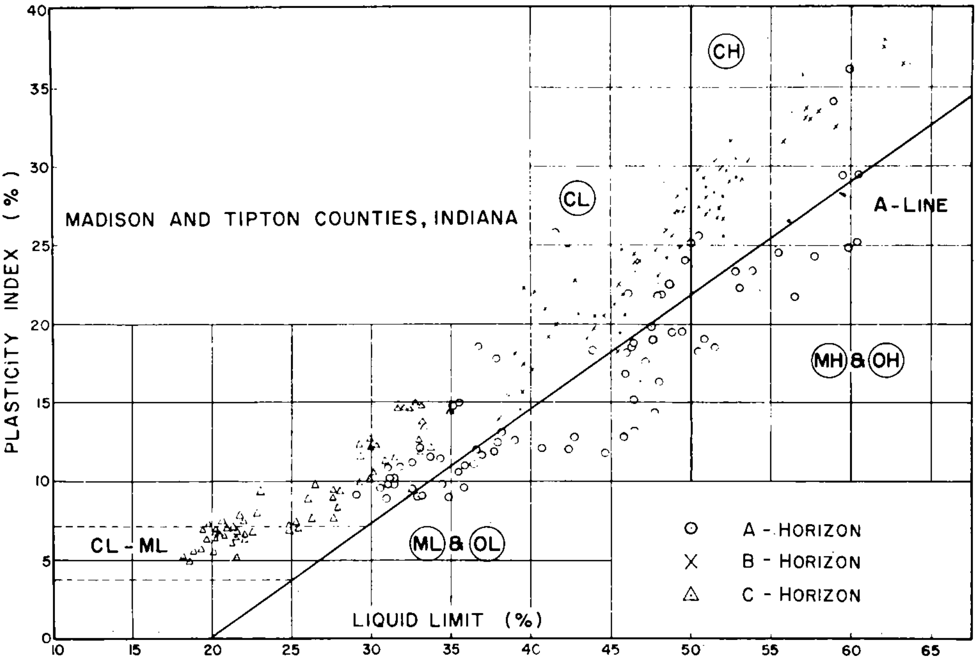


Figure 5. Summary of Atterberg limit data.

in the majority of cases. Furthermore, although it does not show in Figure 5, all the depressional soils had a liquid limit greater than 41 percent though only two samples from the rises had a liquid limit above this value.

For the B-horizon, all the results plotted above the A-line. A slight majority of the samples were classified CL with the remainder CH. Only two of the depressional soils had a liquid limit less than 49 percent though five of the rise soils had liquid limits above this value.

Finally, the C-horizon soils all plotted above the A-line with the majority being classified CL and the remainder CL-ML. A liquid limit of 25 percent appears to be the boundary between the rises and depressions —the latter lying above this value.

The Atterberg limit data were subjected to a linear regression analysis to determine the equation of a line that would represent the data. Considering the B- and C-horizons the regression line representing these data had a slope equal to 0.72, which is approximately equal to the slope of the A-line. However, when considering all three horizons the slope of the regression line is 0.66, which is much less than the slope of the A-line.

Table 6 gives a summary of the Atterberg limit data. It contains the maximum, minimum, and mean values of the liquid limit and plasticity index. This table shows that the mean values of these properties for a given horizon are not greatly different for the two counties.

Compaction Tests (Standard AASHO)

An analysis of variance was conducted on the optimum moisture content (OMC) and the optimum density

TABLE 6
SUMMARY OF ATTERBERG LIMIT DATA

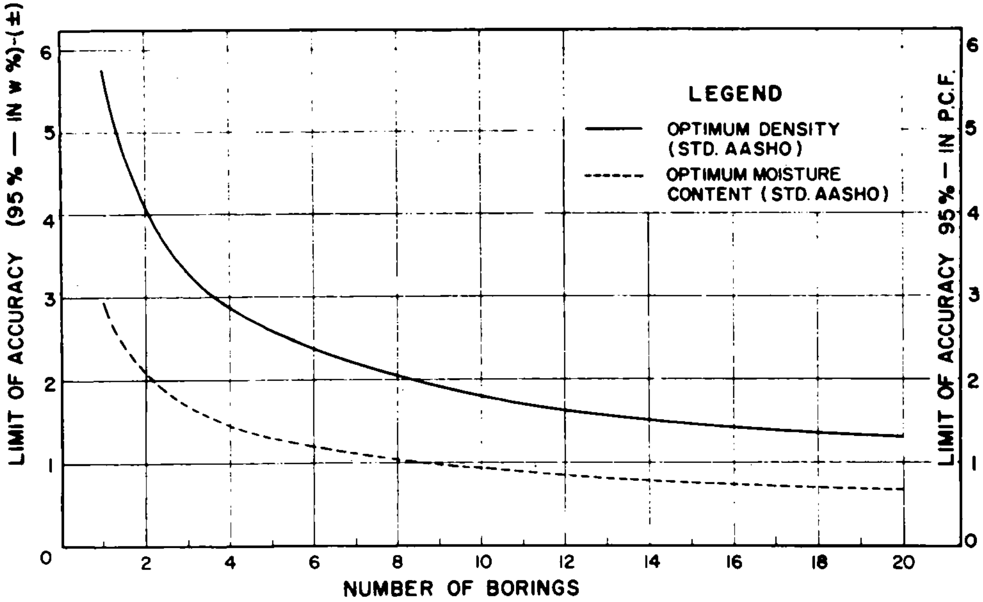
County	Topography	Horizon	Liquid Limit (%)			Plasticity Index (%)		
			Min.	Max.	Mean	Min.	Max.	Mean
Tipton	Rise	A	31.4	44.7	35.5	9.0	18.6	11.7
		B	39.5	53.2	46.7	17.1	29.8	23.8
		C	19.4	33.1	22.8	5.2	14.8	8.2
	Depression	A	43.9	60.4	51.1	12.8	25.2	20.5
		B	49.2	63.2	54.3	27.4	37.9	20.8
		C	14.5	33.7	27.4	NP	14.7	9.6
Madison	Rise	A	29.1	46.5	35.3	8.9	15.2	11.3
		B	38.0	51.9	44.1	13.9	30.3	20.5
		C	18.5	33.2	22.9	5.0	13.5	7.6
	Depression	A	41.6	60.5	50.5	12.8	36.1	23.4
		B	45.7	65.3	51.0	23.9	38.4	28.4
		C	18.1	38.4	26.0	5.2	15.5	9.0

(OD) values using the data from the Standard AASHO compaction tests. Considering the optimum density data, the variance components obtained are $\sigma^2=1.02$, $\sigma_B^2=3.22$, and $\sigma_{HB}^2=4.94$. Therefore, from Eq. 2

$$\sigma_T^2=1.02+3.22+4.94=9.18$$

Using this value of σ_T^2 and Eq. 4 the upper curve of Figure 6 is obtained. The curve represents the relationship between number of borings and limit of accuracy. For example, to predict the mean optimum density of the population within the limit of ±3 pcf it would be necessary to make four borings.

The components of the total variance of the optimum moisture content data are $\sigma^2=0.50$, $\sigma_B^2=0.74$ and $\sigma_{HB}^2=1.01$; therefore, $\sigma_T^2=2.25$. Based on this value of the total variance,



LIMIT OF ACCURACY vs NUMBER OF BORINGS

Figure 6. Limit of accuracy *vs* number of borings.

TABLE 7

SUMMARY OF COMPACTION TEST (AASHO) DATA

County	Topography	Horizon	Opt. Moist. Content (%)			Optimum Density (%)		
			Min.	Max.	Mean	Min.	Max.	Mean
Tipton	Rise	B	17.0	23.0	19.0	99.5	108.2	103.6
		C	10.9	13.7	12.1	117.0	123.0	121.0
	Depression	B	17.2	22.8	19.3	97.7	108.0	103.2
		C	10.1	16.3	13.2	110.0	123.1	117.2
Madison	Rise	B	16.0	20.2	18.2	102.1	108.0	104.3
		C	9.0	15.4	13.2	113.1	125.0	117.5
	Depression	B	16.2	20.4	18.7	102.6	107.3	104.8
		C	10.5	15.1	12.7	114.2	122.7	119.0

σ_T^2, and $t=1.96$—for significance level of 5 percent, $\alpha=0.05$—the lower curve of Figure 6 is obtained.

The factors that tested significant for both the optimum moisture content and density are the horizon and between-boring main effects and the horizon-boring interaction. In addition, the county-topography and the horizon-county-topography interactions tested significant as to the optimum density data. Thus, the absolute variability of the optimum density data is greater than that of the optimum moisture content. This can also be observed from a comparison of the magnitude of the mean squares of the variance estimates, as well as the relative position of the curves of Figure 6.

Table 7 gives a summary of the compaction test data. It contains the maximum, minimum, and mean values of the optimum moisture content and optimum density data. The closeness of the results when horizon is held constant and the wide disparity when it is allowed to vary show why the factors tested significant.

A linear regression analysis was made on the optimum density and plastic limit data. From this analysis it was found that the equation representing the linear relationship between the OD and the PL is

$$\mathrm{OD}=152.6-2.1\ (\mathrm{PL}) \qquad (5)$$

in which

OD=optimum density (lb/ft^3); and
PL=plastic limit (%).

Figure 7 is a graph of Eq. 5. Each point represents the average of the two tests run per sample. No segregation of results based on county and/or topography was observed, but the data did group themselves according to horizon.

Hveem Stabilometer and Swelling Pressure Tests

As described previously, the samples were first grouped according to the optimum density obtained from the Standard AASHO compaction tests. Next a representative sample from each group was subjected to compaction with the kneading compactor to determine the OMC and OD. The samples for the stabilometer and swelling pressure tests were then compacted at the optimum moisture content representative of the group to which it belonged. Figure 8 is typical of the kneading compaction curves from which the optimum moisture content was determined for each group. The 150-psi curves were the basis for this study.

Analyses of variance were conducted on the stabilometer (R-Value) and swelling pressure values. Considering the stabilometer values (R-values), the only factors that may possibly be significant are the between-boring variance (σ_B^2) and the horizon-boring interaction (σ_{HB}^2). As to the swelling pressure, horizons (σ_H^2) and the horizon-topography interaction definitely tested significant,

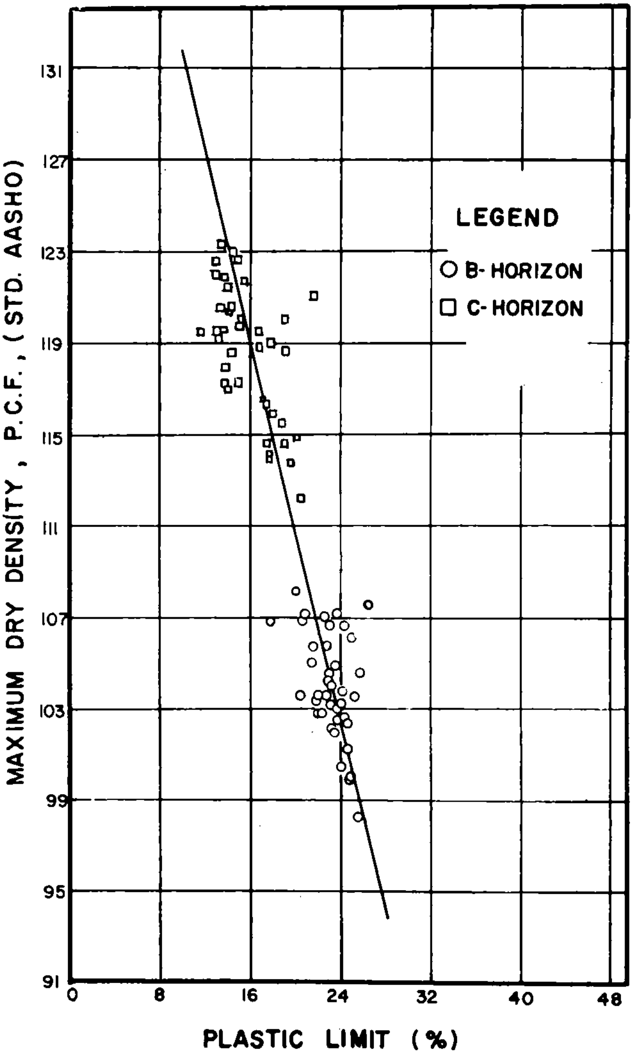


Figure 7. Plastic limit *vs* maximum dry density (Standard AASHO).

and the possibility remains that σ_B^2 and σ_{HB}^2 would test significant.

Inasmuch as there is only one measurement per cell it is impossible to obtain a statistical estimate of the error mean square (σ^2). This makes it impossible to obtain an independent estimate of σ_B^2 or σ_{HB}^2.

Unless independent statistical estimates of the properties in Eq. 2 can be obtained, it is not possible to predict accurately the number of borings required for a given degree of precision. However, to obtain an estimate of the relationship between borings and precision, upper and lower limiting values of σ^2 were assumed. On the basis of experience it is felt that the lower limit should be $\sigma^2=4$ which would give $\sigma_{HB}^2=89.41$ and

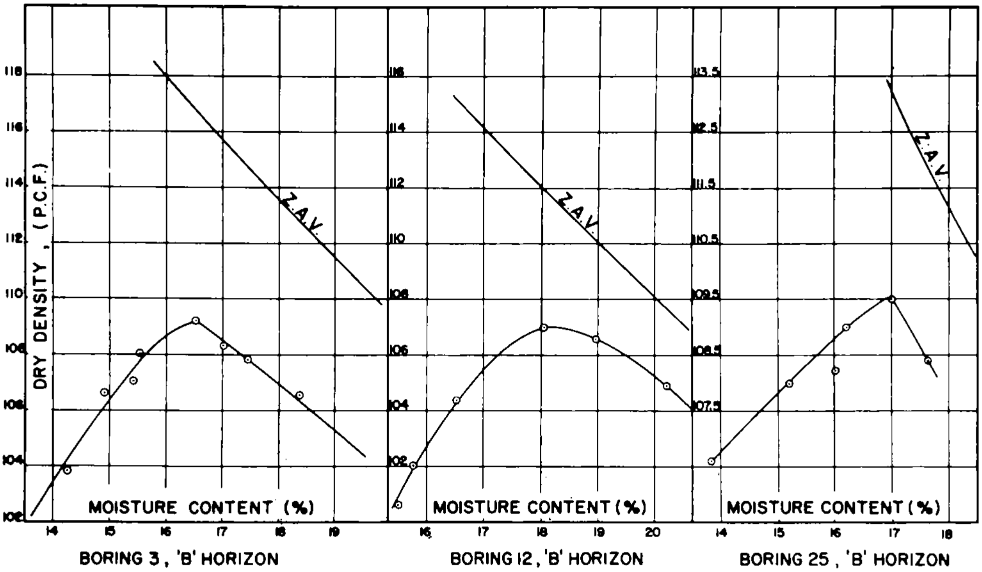


Figure 8. Moisture content *vs* dry density, kneading compaction curves; compactor foot pressure = 150 psi.

$\sigma_B^2 = 51.06$. The upper limit is considered to be $\sigma^2 = 36$, giving $\sigma_{HB}^2 = 57.41$ and $\sigma_B^2 = 70.12$. Thus, for the lower limiting value,

$$\sigma_T^2 = 4 + 89.41 + 51.06 = 144.47$$

and for the upper limiting value of σ^2

$$\sigma_T^2 = 36 + 57.41 + 35.06 = 128.47$$

Based on these values of σ_T^2 the curves of Figure 9 are obtained.

In Figure 9 the limit of accuracy is expressed in terms of both *R*-value and pavement thickness. It is apparent that pavement thickness is relatively insensitive to small changes in *R*-value. Also, it is evident that the variation in σ^2 produces a relatively insignificant change in the number of borings required for a given degree of precision.

Considering the swelling pressure, it was estimated that the maximum value of σ^2 would be 0.50 psi^2 and the minimum value 0.1 psi^2. Thus, the values obtained for the total variance, σ_T^2, are

$$\sigma_T^2 = 0.5 + 1.5 + 1.13 = 3.13$$

and

$$\sigma_T^2 = 0.1 + 1.9 + 1.33 = 3.33$$

It is apparent from Eq. 4 that there will be no significant difference between the number of borings required based upon the limiting values of σ^2. The curve shown in Figure 10 is for $\sigma_T^2 = 3.33$.

The limit of accuracy is expressed in terms of both pounds per square inch and pavement thickness required to prevent swell. It is evident that a small change in swelling pressure causes a large change in the pavement thickness required to prevent swell. For example, if there is an error in the swelling pressure of 0.8 psi, the estimate of the thickness required to prevent swell may be in error by as much as 10.8 in.

CBR Test

Only six samples showed a CBR of more than 12, and the great

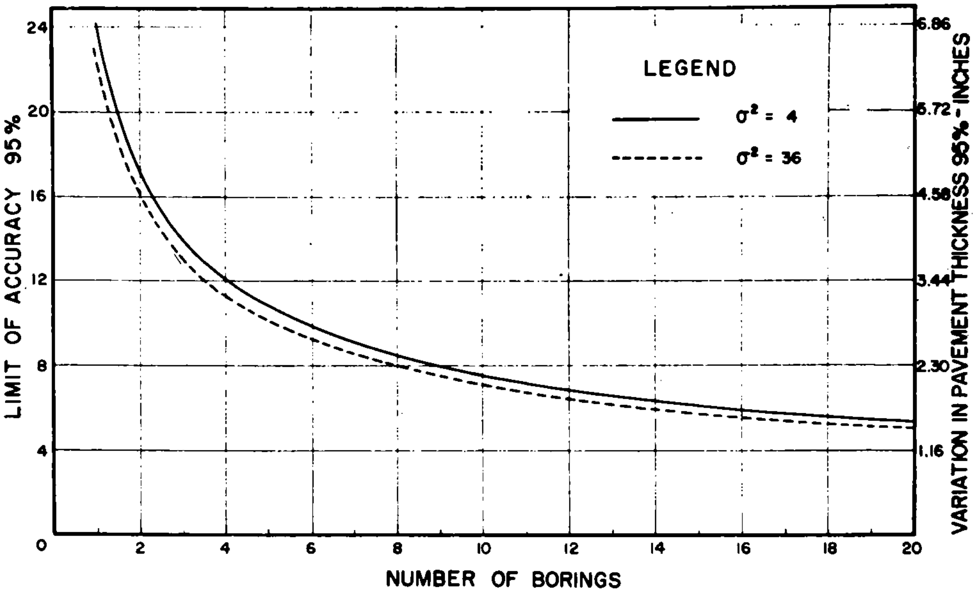


Figure 9. Limit of accuracy *vs* number of borings, *R*-value.

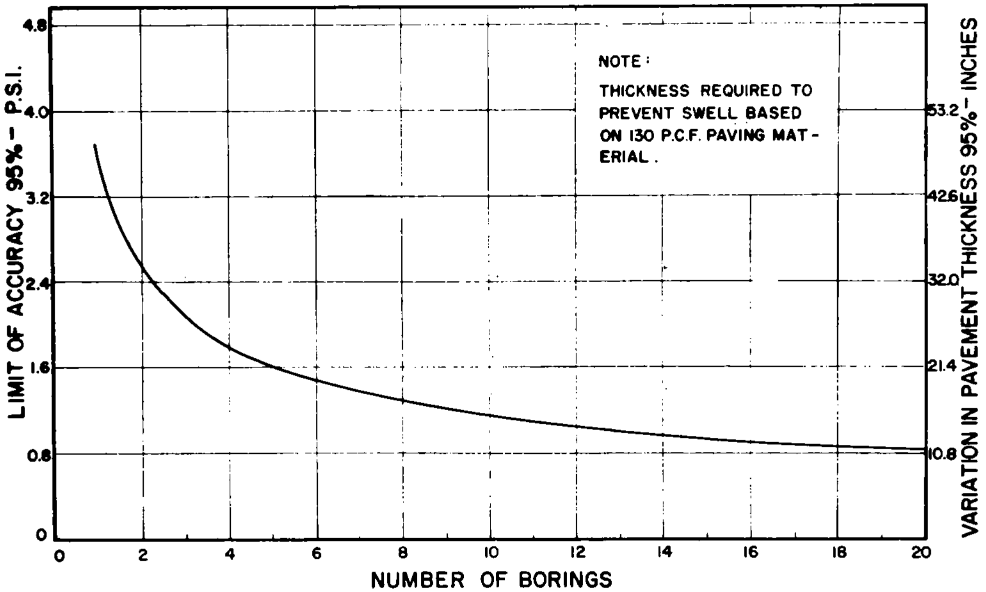


Figure 10. Limit of accuracy *vs* number of borings, swelling pressure.

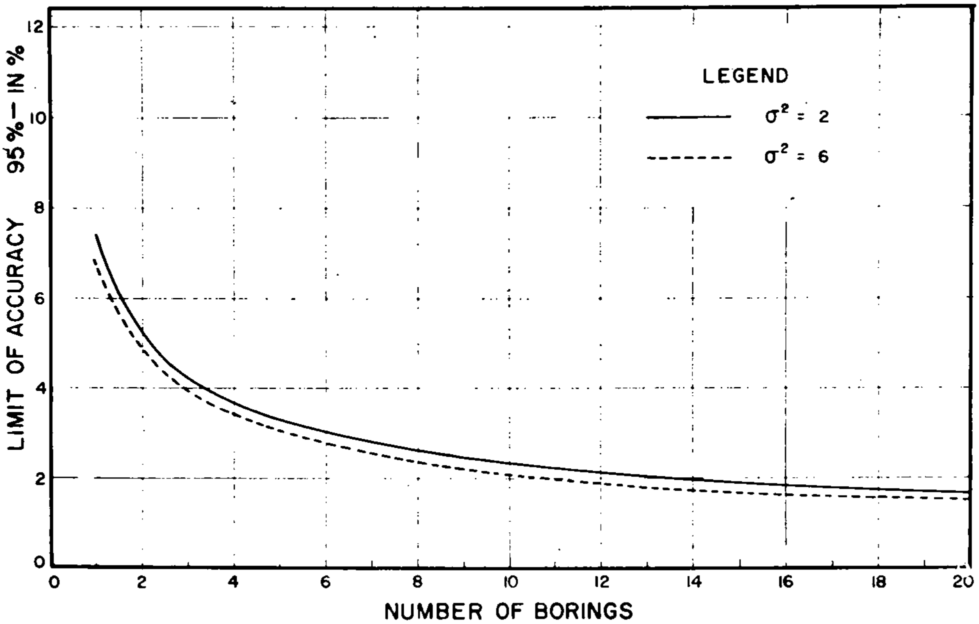


Figure 11. Limit of accuracy *vs* number of borings, CBR.

majority had CBR values less than 10. Of the samples that had CBR values greater than 12, five were from the C-horizon.

In some instances, the CBR value from the B-horizon was greater than that for the C-horizon. This will be explained in the discussion of results.

An analysis of variance was conducted on the results and the relatively small values of the mean squares were noted. This indicated that the variability in the test results was low. Also, only the county-topography interaction tested significant.

Assuming that the maximum value of $\sigma^2=6$ and the minimum value of $\sigma^2=2$, then

$$\sigma_T^2=6+4.32+1.37=11.69$$

and

$$\sigma_T^2=2+8.32+3.37=13.69$$

These values are then used in establishing the curves of Figure 11. It is evident that the magnitude of σ^2 has a nominal effect on the number of borings required for a given degree of precision.

In practically all cases some swell occurred, the magnitude of the swell being greatest for the B-horizon.

Grain-Size Analysis

The data from the grain-size analysis are in two parts: the percent of material finer than 0.074 mm (No. 200 sieve) and the percent of material finer than 0.002 mm. A summary of this information is given in Table 8, which gives the maximum, minimum and mean values of these properties. It is apparent that the soils are fine grained and that the mean values for the measured properties do not vary greatly with county. However, the range (maximum less minimum values) seems to be greater for the rises than the depressions, when comparing counties.

From an analysis of variance on the percent of material finer than

TABLE 8
SUMMARY OF GRAIN-SIZE DISTRIBUTION DATA

County	Topography	Material Finer Than (mm)	Horizon	Percent Passing		
				Min.	Max.	Mean
Tipton	Rise	0.074	B	67.7	95.7	87.1
			C	46.9	75.5	62.8
		0.002	B	25.4	37.5	31.7
			C	16.0	22.5	21.2
	Depression	0.074	B	84.5	97.0	91.8
			C	62.7	87.2	70.9
		0.002	B	26.0	39.4	33.8
			C	13.5	31.0	22.8
Madison	Rise	0.074	B	75.1	96.4	86.8
			C	59.0	94.0	67.3
		0.002	B	23.0	35.0	29.0
			C	11.6	25.5	21.2
	Depression	0.074	B	81.1	96.8	89.9
			C	53.6	80.1	61.6
		0.002	B	28.5	38.0	33.7
			C	17.0	24.0	20.8

0.074 mm it was evident, that the mean square is highly variable due to the magnitude of its values. Also, the factors that tested significant are horizons and the horizon-county-topography interaction. Based on the magnitude of the "Horizon" MS, it was apparent that this effect must be held constant to obtain a reasonable degree of accuracy.

Because there is only one measurement per cell it is not possible to obtain a statistical estimate of the error mean square σ^2. Therefore, to estimate the number of borings required for a given degree of precision it is necessary to assume values of σ^2. To bracket the proper value of σ^2, it was assumed that its maximum would be 25 and its minimum, 4. On this basis, the estimates of the total variance are

$$\sigma_T^2 = 25 + 13.73 + 30.22 = 68.95$$

and

$$\sigma_T^2 = 4 + 34.73 + 40.72 = 79.45$$

These values along with Eq. 4 are used to establish the relationships shown in Figure 12. It is apparent that variations in σ^2 do not have a large effect on the number of borings required for a given degree of precision.

Considering the data for the percent finer than 0.002 mm, the only two effects that tested significant were horizons and topography.

Based on the expected mean square of the between-boring main effect, the maximum possible value of σ^2 is 16.85 for data obtained. However, it is felt that a more realistic maximum value would be 9 and the minimum value 1. On this basis the estimates of the total variance become

$$\sigma_T^2 = 9 + 50.20 + 3.92 = 63.12$$

and

$$\sigma_T^2 = 1 + 58.20 + 7.92 = 67.12$$

Due to the closeness of the square root of these two values, there is a negligible difference between the curves of limit of accuracy vs the number of borings for the two cases considered. Therefore, only the curve for $\sigma_{\mathrm{T}}^2 = 67.12$ was plotted (Fig. 13).

From Figures 12 and 13 the order of variability of the grain-size distribution properties may be determined. The more variable grain-size property is the percent finer than 0.074 mm, followed very closely by the percent finer than 0.002 mm.

Unconfined Compression Test

The soils were divided into three groups, based on Standard AASHO

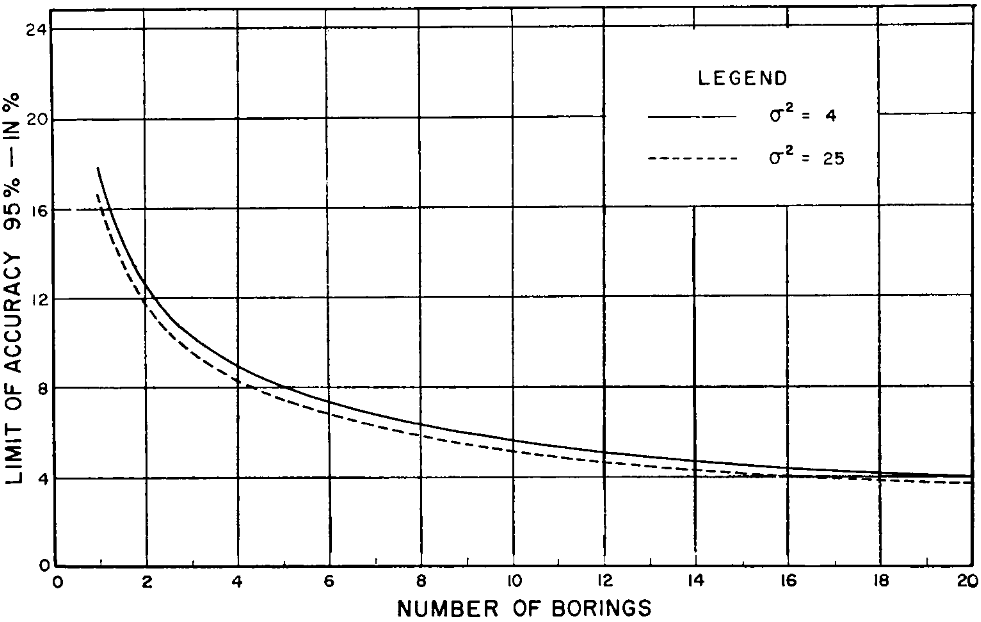


Figure 12. Limit of accuracy *vs* number of borings, percent finer than 0.074 mm.

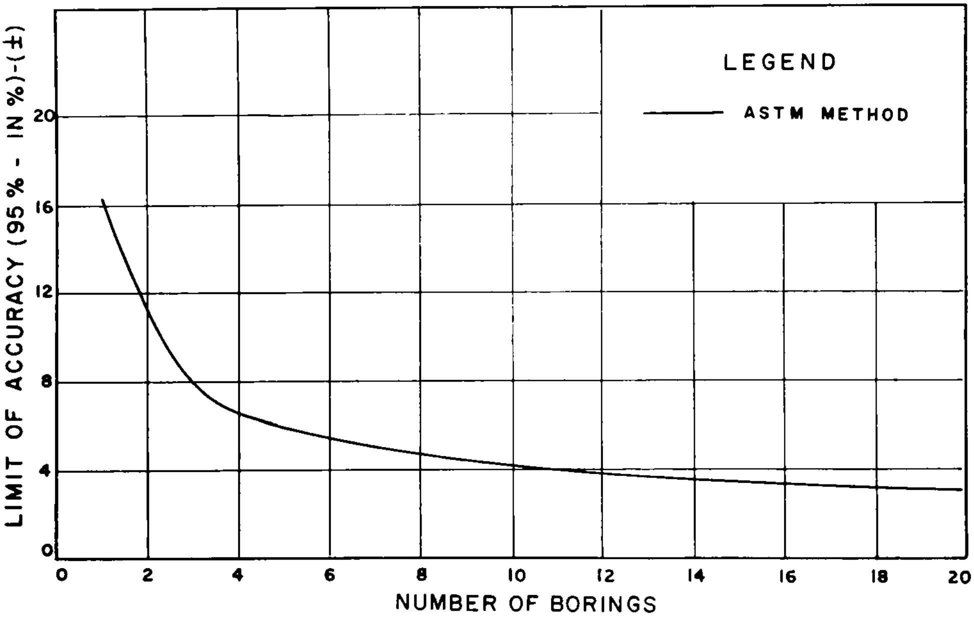


Figure 13. Limit of accuracy *vs* number of borings, percent finer than 0.002 mm.

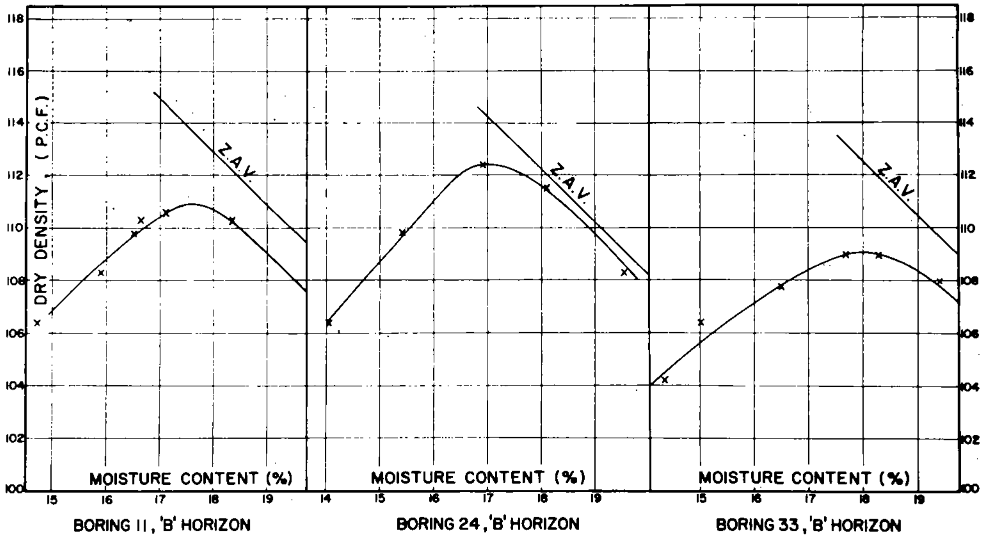


Figure 14. Moisture content *vs* dry density, kneading compaction curves; Harvard miniature compactor, 40-lb spring.

density. A compaction test was conducted on a member of each group to determine the optimum moisture content for that group (see Fig. 14 for typical curves). Subsequently, unconfined compression test specimens were molded at the moisture content representative of the group in which it was a member.

The main effects that tested significant, based on an analysis of variance, were depression vs rise (topography) and horizons. The only interaction term that proved significant was the horizon-county interaction. More factors did not test significant because of the large values for the horizon-boring and between-boring effects.

It was not possible to determine the error variance because only one test was run per sample. Therefore, it was necessary to assume a maximum estimate of the error variance of $\sigma^2=6$ and a minimum value of $\sigma^2=1$. Based on the maximum value, $\sigma_T{}^2=186.90$, and for the minimum value, $\sigma_T{}^2=204.41$. From these estimates of the total variance the relationship between the number of borings and the limit of accuracy was determined (Fig. 15).

The unconfined compressive strength of the B-horizon was greater than that of the C-horizon. Also, in comparing a given horizon, the unconfined compressive strength of the depressions exceeded that of the rises. No definite trend could be established as to the relative strengths of the soils in Madison County vs the soils in Tipton County.

ANALYSIS OF DATA

Atterberg Limits

The mean squares (MS) of the various estimates are indicators of the relative contribution of these effects to the variance. Considering the effects that tested significant, the liquid limit (LL) is much more variable than the plasticity index and the plasticity index is much more variable than the plastic limit (the magnitude of the MS decreasing for a given effect from the former to the

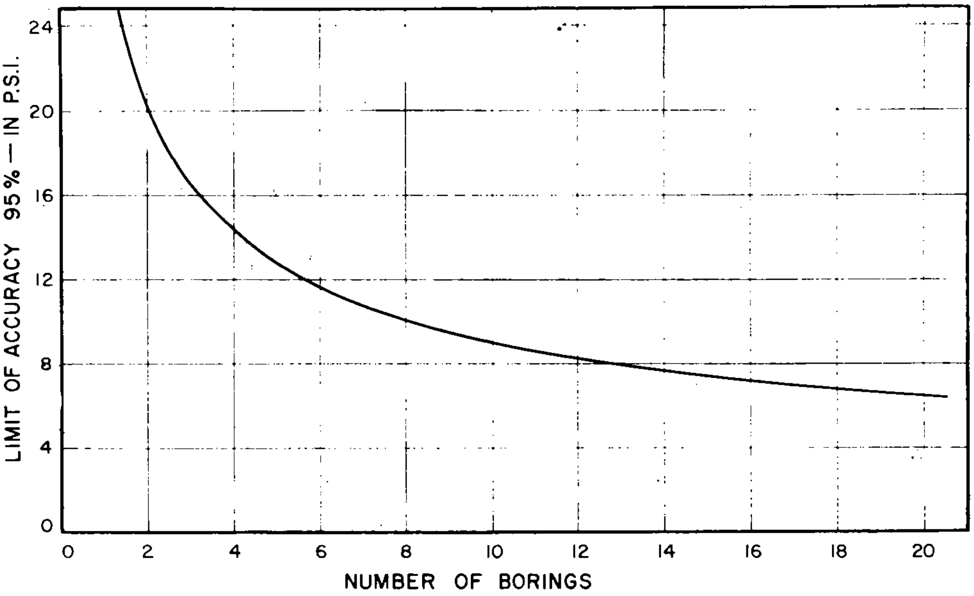


Figure 15. Limit of accuracy *vs* number of borings, unconfined compressive strength.

latter). This indicates that the plastic limit (PL) is relatively constant for the given parent material area even though the values of the LL and PI may vary over a large range. Thus fewer borings would have to be made to determine the PL to a required degree of precision than either of the other two.

As an example, assuming four borings are taken in the areas under consideration, the LL could then be predicted within approximately ±5.8 percentage points of moisture content, the PI within ±4 percentage points and the PL within ±3 percentage points. This difference in the limit of accuracy only decreases slowly with an increase in the number of borings.

The most important factor contributing to the variation in results is horizon. This factor is much more important than any other factor, as is indicated by the extremely large value of the MS.

The second most important contributor to the variation in the results is topographic position; *i.e.*, whether the soil came from a rise or a depression. The third is the interaction variation due to the relationship betwen topographic position and horizon.

There is not much difference between the other two factors that tested significant (between borings in the *C-D* cells and the horizon-boring interaction).

Because only one of the factors that tested significant is used to determine the relationship between the number of borings and the precision (horizon-boring interaction), the other factors should be kept constant in future sampling procedures to predict the mean value of the Atterberg limits. For example, data from the B- and C-horizons should not be used to predict the mean value of the B-horizon. This is to be expected from a knowledge of soil profile development.

On the basis of the analysis of variance for the Atterberg limits, it was observed that the error mean square $E_{m(ijlk)}$, is relatively large for the LL and PL (5.71 and 5.22, respectively. This signifies that an error of as much as ±2.39 percentage points of moisture, in the case of the LL, may be introduced as a result of the test method and operator effect.

At this point, it is necessary to consider the factors, other than boring location, topography, and horizon that contributed to the variance of the Atterberg limit results in this study. Four factors are initial moisture content, operator, depth at which the sample was obtained, and clay mineral content.

Natural Moisture Content.—It has been established that drying a soil sample before testing significantly alters the Atterberg limits. This is particularly true if the drying is allowed to progress below the shrinkage limit. Consequently, the values of the Atterberg limits determined by conducting tests on soil at its natural moisture content may be significantly different from the values obtained from tests conducted on air-dry soil. The amount of the difference depends on the degree of plasticity of the soils; *i.e.*, the greater the degree of plasticity the greater the difference.

The natural moisture contents of the C-horizon were found to be significantly greater than the plastic limit, for the depressions. However, in most instances, the natural moisture content for the rises was approximately equal to or less than the plastic limit. The reason for this is no doubt due to the position of the water table. In the depression borings, water was encountered in practically every hole, though borings in the rises intercepted water in only one instance.

As to the B-horizon, in Tipton County the natural moisture content of the depression soils exceeded the plastic limit, in practically all cases and in Madison County it was less than or equal to the plastic limit. This is directly related to the position of the water table. In Tipton County the water table lies much closer to the surface of the ground than in Madison County. Therefore, considering capillary effects the expected natural moisture content for the B-horizon soils of Tipton County would be greater than for those of Madison County.

The A-horizons of both counties had natural moisture contents, in most cases, less than the plastic limit. This is to be expected because it is in this horizon that ambient temperature changes have their greatest effect. Also, this is the horizon in which the greatest fluctuation in moisture content occurs; as one goes deeper below the surface, the moisture content of the soil becomes more stable.

On the basis of this information, inasmuch as the Atterberg limits were conducted on samples that were not air dried, a portion of the variance was due to the variation in the natural moisture content of the samples.

Operator.—A certain portion of the variance is due to the fact that different operators were used. The number of tests conducted is as follows: Operator 1, 75; Operator 2, 165; total, 240. However, the possibility exists that there is a significant difference between Operators 1 and 2. Such is indicated by the relatively large value of the error mean squares of the LL and the PI, and was shown to be so on the basis of an analysis of variance.

Depth of Sampling.—An attempt was made to obtain each Atterberg limit sample (for a given horizon) at the same depth below the surface of the ground. This control may not have been sufficient because it does not take into consideration the thickness of each horizon. For example, the clay content of the sample, which is one of the major factors in determining the value of the Atterberg limits, is a function of the depth below the surface of the horizon at which the sample is obtained. For example, a sample obtained near the upper surface of the B-horizon will be less plastic than one obtained from the lower boundary of the B-horizon. Consequently, if the thickness of the horizons are not taken into consideration a variability in the results will be introduced. Whether this variation is significant is debatable.

In the C-horizon it was not always possible to take the Atterberg limit samples at the same depth. The interface of the B- and C-horizons was determined by applying hydrochloric acid to the soil as it was removed from the hole. When the acid was placed on material from the C-horizon a noticeable reaction took place. The initial reaction sometimes occurred below the normal sampling depth. Thus, a greater variability of sampling depth was present in the C-horizon.

Compaction Test (Standard AASHO)

Due to the factors that tested significant, for the best results, it is necessary to keep horizon and topography constant, considering the OD. Such a procedure will result in the fewest number of samples being required to predict the population mean value because it eliminates the variability due to the interactions that tested significant.

Considering the optimum moisture content data, the only factor that tested significant and is not considered in the total variance is the horizon effect. Thus, as far as obtaining the total variance, for a given horizon it would not be necessary to discriminate on the basis of topography or counties. In other words, for a given horizon there is no significant difference between the total variance of a rise and that of a depression regardless of county. However, horizons, topography, and counties should be held constant for the maximum degree of accuracy for a given number of borings. It is recognized that the optimum moisture content and optimum density are determined simultaneously for a given soil. Nevertheless, from the standpoint of establishing construction requirements, it minimizes the need for making a large number of compaction tests.

Hveem Stabilometer and Swelling Pressure Tests

Compaction.—Stability numbers (R-values from the Hveem stabilometer) and swelling pressures are a function of the method of compaction, the compacted moisture content, and density. Moisture content was considered one of the most important variables. An attempt was made to compact the samples with ±0.5 percent of the optimum moisture content.

At moisture contents slightly in excess of the optimum, and in some instances at the optimum value, there was appreciable shoving of the surface under the action of the compactor foot (150-psi foot pressure). Whenever this situation occurred, it took place toward the latter phase of the compaction process. Thus, the possibility exists that as the compaction process progressed there were created large positive pore pressures and that, with time, these became sufficient to produce shear failure, under subsequent action of the foot.

This method of compaction may result in a nonhomogeneous sample. This is mainly due to the fact that compaction occurs from the top down. Consequently, one would expect a variation in compacted density with depth. This no doubt affects the strength, compressibility, and swelling characteristics of the compacted soil.

R-*Values.*—Due to the relatively small range of mean squares, no single effect had a dominant roll in determining the R-value. However, due to this relative "uniformity," the total variance estimate is much higher than for any of the other measured properties (with the exception of the unconfined compressive strength). Thus, speaking in absolute terms, the number of borings required for a given degree of precision is much greater (see Fig. 9).

In essence, the stabilometer test is a triaxial test. Consequently, the factors that affect the shearing resistance as determined by triaxial test should affect the R-value (port pressures, mineralogy, density, etc.). Therefore, considering a given parent material group, it appears reasonable to expect the variance estimates to be homogeneous.

Figure 9 shows the relationship between the number of borings, limit of accuracy, and pavement thickness. Though the R-value may vary widely, the resulting change in pavement thickness is relatively small.

According to the Hveem method of pavement design, the thickness of pavement required is determined (*5*) by

$$T=\frac{K'(TI)(90\text{-}R)}{5\sqrt[5]{C}} \qquad (6)$$

in which

$K'=0.095$;
$TI=1.35\ \text{EWL}^{0.11}=8.71$ (assumed), EWL is the total number of equivalent 5,000-lb wheel loads anticipated for the design life;
R=resistance value (R-value); and
C=cohesiometer value=200 (assumed).

Based on Eq. 6,

$$T=0.286\ (90\text{-}R).$$

It is evident that there can be a relatively large variation in R-value with only a nominal change in design thickness. Thus, even though the stabilometer values show large variation from hole to hole, the effect as regards pavement thickness is much less variable due to the fact that traffic is the primary control of pavement thickness. K' and TI are a function of traffic.

The variation in R-value encountered in this study as well as the fact that the R-values for compacted soil from the B-horizon, in some instances, exceeded that of the C-horizon may possibly be due to the effect of pore pressures. Because the swelling pressure test preceded the stabilometer test, the samples were tested at a high degree of saturation. Drainage was not allowed during application of the load, and the shear deformations caused an increase in the pore water pressure.

Those soils whose strength is primarily due to internal friction may have low R-values depending on the rigidity of the soil skeleton and the degree of saturation. If the soil structure deforms little at values of the vertical normal stress less than 160 psi (stress at which the R-value is determined) then the magnitude of the pore pressures will be small and the strength component due to internal friction will be large. Naturally, in the case of a compressible soil skeleton or high degree of saturation the converse is true and one might obtain a low R-value.

For soils whose strength is derived principally from cohesion, the situation may be different. In such cases, the effect of pore pressures can be much less if the strength that results from cohesion is not as greatly dependent on the effective stress on the failure plane at failure as is the strength component due to friction. Depending on the magnitude of the strength contributions from cohesion and internal friction, the degree of saturation, the clay minerals present, and the rigidity of the soil structure, it is quite possible to have the R-value for the B-horizon exceed that for the C-horizon.

Also, the optimum moisture content for each sample was not available. It was assumed that the OMC as determined from a representative sample was appropriate for all the members of the group from which it was selected. The assumption is reasonable, but the degree to which it is valid, in all probability, had an effect on the results.

Swelling Pressure.—Factors that affect the swelling pressure may be listed under two general categories—physiochemical and mechanical. Seed, Mitchell, and Chan (*4*) have shown that the mechanical aspect of the swelling phenomena may at times be of such magnitude that it cannot be neglected. However, because all samples were prepared in the same manner it was assumed that the mechanical aspect of the swelling phenomena could be neglected when considering the variation between samples.

The horizon variance tested significant as did the horizon-topography interaction. Considering the physiochemical aspects of the clay minerals present in these soils, such is to be expected. The quantity of a given type of clay mineral present in a sample depends on the horizon from which the sample was obtained. Also, if the minerals of one horizon have a greater affinity for water than the other, then the greatest amount of swell would be expected in the soil with the higher affinity.

The fact that the horizon-topography interaction tested significant was anticipated. In a rise, the soil is well drained, and in a depression, it is poorly drained. The nonexpanding lattice clays are predominant in the rises, and in the depressions expanding lattice clays are in the majority since they are generated best in environments where there is an abundance of moisture.

The exact quantitative relationship between the quantity of a given clay mineral and the amount of swell was not determined because of the heterogeneity of the amount of clay minerals that may exist at a given point in a given soil mass and the variations in chemical composition and in the weathering stage. Nevertheless, the effect of both quantity and type of clay minerals on the swelling properties of a given soil can be estimated qualitatively.

On the basis of the swelling pressure test it was found that this factor varied greatly with change in moisture content. In some instances, a change in moisture content of 1 percent caused a change in the swelling pressure of as much as 3 psi. Such a change results in a change of flexible pavement thickness required to prevent swell of 40 in. This represents an extreme circumstance, but a difference in thickness of one-tenth this amount is intolerable. Consequently, in those circumstances where the soil may come into equilibrium with free water, it is necessary that its swelling characteristics be adequately defined. Correspondingly, if the soil is to be used as borrow, its compaction moisture content should be specified in such a manner that difficulty from excessive swell will not arise.

The moisture content at which these samples were molded is representative of the OMC of the sample. Compaction of a soil at optimum moisture content and its corresponding density generally yields satisfactory results in regard to swell under prototype pavements.

In addition to satisfying stability requirements, it is necessary to insure that the pavement will not heave when coming in contact with free water. Both requirements are satisfied if the thickness of pavement is adjusted so that thickness by *R*-value is made equal to thickness by expansion pressure. This will usually result at a molding moisture content different from the optimum value. Nevertheless, in most instances the thickness required for stability at the OMC is less than the thickness required to prevent swell. Consequently, the desirable placement moisture content in the field in all probability is greater than the OMC obtained in the laboratory.

The data suggest that, in spite of the small hole-to-hole variation in thickness indicated by the stabilometer test, the combined effects of swelling and *R*-value may result in extreme variation. Figure 10 shows that a small change in swelling pressure means a relatively large change in thickness required to prevent swell.

CBR Data

In many instances, the CBR value for compacted soil from the C-horizon proved to be less than the value for the B-horizon. This is contrary to the normal trend and the difference, although not large, was consistent throughout much of the program.

The most probable causes of the event must lie in the degree of saturation of the upper inch of the sample and/or the difference in quantity and type of clay minerals present in the B- and C-horizons. Although the mineralogy of the soils may have contributed to this effect, a definite relationship could not be established on the basis of available data.

Of the 29 borings in which the CBR value of the C-horizon was found to be less than that of the B-horizon, the moisture content of the upper inch of the sample was much closer to the liquid limit for the C-horizon samples. Because the strength of a soil at the liquid limit is very low (approximately 25 g per sq cm) and is much greater at the plastic limit, the CBR value for the B-horizon is expected to be greater than for the C-horizon.

For CBR values equal to or less than 12 the following equation was used to determine the required thickness of pavement (*2*):

$$t=\sqrt{P\left[\frac{1}{8.1(\mathrm{CBR})}\frac{-1}{p\pi}\right]} \tag{7}$$

in which

t=design thickness of the pavement structure in inches;
P=total wheel or (equivalent wheel) load in pounds; and
p=tire pressure in psi.

However, for CBR values greater than 12, the curve representative of Eq. 7 was extended, as shown in Plate 1 (*2*).

Total wheel load was assumed to be 5,000 lb and the tire pressure 70 psi. Also, the thickness obtained from Eq. 7 is for 5,000 coverages.

To keep the effect of repetition of load on pavement thickness approximately constant for both the stabilometer and CBR tests, it is necessary that the CBR requirement for thickness be adjusted for a number of coverages equivalent to 23.3 million repetitions of a 5,000-lb wheel load.

Table 4.4 (*5*) shows that there are approximately 2.2 trips of a 5,000-lb wheel load required for one coverage. Therefore, the thickness obtained from Eq. 6 should be adjusted for 10.6 million coverages. The adjustment in thickness will be made in accordance with Plate 3 (*2*). Based on an extension of this plate, it is found that 176 percent design is required for 10.6 million coverages. Thus the pavement thickness determined on the basis of 5,000 coverages must be increased by 76 percent.

Comparing the thickness by CBR with the thickness by stabilometer, for the same number of coverages no definite trend could be established for all the data. With the B-horizon, the greater thickness of pavement was obtained in some instances using the CBR method and on about an equal number of occasions using the

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stabilometer. However, with the C-horizon, the CBR method produced the greater thickness in the great majority of cases.

Finally, the total variance of the CBR is relatively small. However, at low values of this parameter a small variation in CBR value produces a large variation in thickness (see Eq. 7).

Unconfined Compression Test

The large variability of the unconfined compressive strength is possibly due to variations in cohesion and moisture content. The former is also a function of the quantity and type of clay minerals present in a given sample.

A certain amount of cohesion is required for stability of unconfined compression samples. This cohesion allows a greater time to reach the failure load and hence a greater strength. There is a greater quantity of clay in the B-horizon than the C-horizon and it was anticipated that the former had the greater strength. The aforementioned factors also tend to explain why the unconfined compressive strengths of the depression soils were greater than the rises. On the basis of this, because the unconfined compressive strength is very sensitive to the amount of cohesion, the variability of the results is expected to be large.

The unconfined compressive strength of a soil varies with its compacted moisture content. Moisture density curves were not established for each sample and therefore this may have introduced a small error.

As a result of the factors that tested significant, it is necessary to hold topography and horizons constant when using this test as a measure of variability. However, due to the large value of the total variance the unconfined compression test is a good measure of variability. At the same time it is too sensitive for practical use. For example, a soil would have to be exceptionally homogeneous before the variation in results would allow a reasonable number of samples to be taken to define adequately this property over a relatively large area.

SUMMARY OF RESULTS AND CONCLUSIONS

The method of selecting boring sites and the number of borings depends on the factors that tested significant in the analyses of variance. For the most precise results, the factors that tested significant and are not included in the determination of σ_T^2 should be held constant:

Property	*Factors To Be Held Constant*
Liquid limit	Topography and horizons
Plasticity index	Topography and horizons
Plastic limit	Topography and horizons
Optimum density	Topography and horizons
Optimum moisture content	Horizons
R-value	None
Swelling pressure	Horizons
CBR	Topography
Percent finer 0.074 mm	Horizons
Percent finer 0.002 mm	Topography and horizons
Unconfined comp. str.	Topography and horizons

County never tested significant for any of these properties. Theoretically this means that one could sample the soils in Tipton County and use the results of tests on these samples to predict the properties of soils in Madison County. However, this is not too safe, because failing to find significance does not prove that there is no difference: there simply was no reliable evidence of any difference. If there is a difference between counties it is likely to be relatively small. Hence, to obtain a more accurate estimate it would be better to base the estimate on samples from both counties. For example, if it is desired to define certain properties of a soil within a specified limit and 10 borings are required, if the areas of interest are far apart it would be better to base estimates on 5 samples from each area rather than 10 samples from one area. The aforementioned is based on the assumption that the soils in the areas are of the same pedologic classification and have similar airphoto patterns.

In using the total variance estimates to determine the number of borings required to define certain properties to within specified limits, one must consider the effect of an error in classification. The total variance estimates contained in this report are based on soils pedologically classified as Brookston (depressions) and Crosby (rises). Consequently, the variance estimates are strictly valid for these soils alone. If the data were applied, by mistake, to soils that did not fit either of these classifications error might result. However, the magnitude of this difference cannot be ascertained without similar research projects on soils of various classifications.

It was assumed that the variance of the measured properties was independent of horizon. This is logical because the B-horizon soils were derived from the C-horizon soils. However, it was not posible to check this assumption because the B- and C-horizon samples were obtained from the same boring. This correlation cannot be taken into consideration statistically.

There are several approaches to the use of information on the variability of soils for design. If the mean value of the design parameter is used, then in general the structure will be overdesigned 50 percent of the time and underdesigned 50 percent of the time. If this situation is not satisfactory it can be altered by using the computed standard deviation of the mean with the proper significance level. The procedure is as follows:

1. Determine the standard error of the mean, as shown in Eq. 2.
2. Based on the significance level chosen, establish the relationship between the number of borings and the limit of accuracy, as shown in Eq. 4.
3. Subtract the limit of accuracy from the mean value obtained from n number of samples.
4. Determine the pavement thickness required on the basis of the value obtained from step 3.

This procedure will insure that the pavement on the average will prove satisfactory $100(1-\alpha)$ percent of the time. In the preceding statement, α is the significance level chosen. In this study, $\alpha=0.05$. Naturally, if in step 3 the limit of accuracy were added instead of subtracted, the resulting design would be unsatisfactory $100(1-\alpha)$ percent of the time. This method assumes normality in the distribution of the measure in question.

Based on the information presented in this report the following conclusions appear justified:

1. To minimize the variation in results due to differences in weathering stage of the clay minerals, all samples should be taken from the same depth below the surface of the horizon under consideration.
2. The low variability of the optimum moisture content data indicates that the number of samples required for construction control would be few.
3. To give a realistic value for the areas under question, a minimum of six samples will normally suffice. Actually, the number of samples required depends on the degree of precision required for the properties of interest. However, with the exception of the highly variable properties, six samples should suffice.
4. The Atterberg limits are affected by the amount of drying to which the samples have been subjected. Consequently, if facilities are not available in which the soils can be maintained at a constant moisture content, it would be best to air dry all samples before conducting the test. This would reduce the variability of the results.

5. Assuming good laboratory technique, the effect of the operator and testing procedure depends on the magnitude of the total variance. For large values of the total variance the effect of large variations in the error mean square on the number of samples required for a given degree of precision is small. However, to increase the accuracy of variability studies it would be best to use just one operator for a given series of tests.

6. Due to the magnitude of the error that may be introduced into the results of Atterberg limit determinations as a function of the test procedure and operator effect, it appears that a one-point method of determining the liquid limit is justified.

7. The Hveem method of flexible pavement design in relation to stability is relatively insensitive to the strength properties of the soil as determined by the R-value. Large variations in R-value can occur with only a relatively small change in pavement thickness required for stability. This is due mainly to design thickness being principally controlled by traffic considerations.

Conversely, the variation in the swelling pressures is relatively small. However, a small change in the swelling pressure results in a large change in the thickness required to prevent swelling. Because both stability and swelling requirements must be satisfied in the Hveem method of design, there may occur large variations in required pavement thickness for a given area.

8. The variance of the CBR values was relatively small. However, they are in the low CBR range with the result that a small change in the CBR value necessitates a large change in pavement thickness.

9. Based on the variability of the reported data, designing on the basis of soil classification or some other simple procedure is justified. This is due to the large variation in design thickness which within a given area will occur because of the variation in the parameter that forms the basis for the design. Also, such variation in results strongly suggests the use of a statistical approach to pavement design.

10. Disparity in variability between the unconfined compression, CBR, and stabilometer tests is probably due to the failure criteria and to the fact that the latter two tests are run on soaked samples.

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