File 672
STATISTICAL ANALYSIS OF
SOIL VARIABILITY

MAY 1961

NO.12

Joint
Highway
Research
Project

BY

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PURDUE UNIVERSITY
LAFAYETTE INDIANA

Final Report

STATISTICAL ANALYSIS OF SOIL SAMPLING

TO: K. B. Woods, Director
Joint Highway Research Project

May 18, 1961

FROM: H. L. Michael, Assistant Director
Joint Highway Research Project

File No: 6-14-1
Project No: C-36-36A

Attached is a final report entitled "Statistical Analysis of Soil Sampling". The report has been authored by Delon Hampton, graduate assistant on our staff, under the direction of Professor E. J. Yoder. Mr. Hampton utilized the report as his Ph.D. thesis.

The report presents the results of a research project which was designed to determine the variability in the engineering properties of soils which were derived from the same parent material under similar environmental conditions. The results clearly indicate that a large variability exists for some properties and the consequences of such variability as it pertains to pavement design are discussed.

The report is presented for the record.

Respectfully submitted,

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Final Report

STATISTICAL ANALYSIS OF SOIL SAMPLING

by

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Joint Highway Research Project
File No: 6-11-2
Project No: C-36-36A

Purdue University
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May 18, 1961

ACKNOWLEDGMENTS

Deep appreciation is expressed to the many people who either participated actively in this project or who were directly instrumental in making the work possible. The following acknowledgments are made to those whose assistance was particularly significant.

The Joint Highway Research Project of Purdue University, Professor K. B. Woods, Director, for providing the funds, materials and equipment for the accomplishment of the project.

Professor E. J. Yoder, Purdue University, for his continuous support, and advice. Professor Yoder, as the author's major professor, deserves special thanks for his thorough review of the drafts of this thesis.

Professor J. L. White, Purdue University, and his staff for their help with the mineralogical studies. Professor I. W. Burr, Purdue University, for his advice on the statistical procedures used.

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ABSTRACT

Hampton, Delon. Ph. D., Purdue University, June 1961. Statistical Analysis of Soil Variability. Major Professor: Eldon J. Yoder.

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. These soils were obtained from Madison and Tipton Counties, Indiana and would be pedologically classified as Brookston and Crosby.

Twenty borings were obtained from each county - ten from Brookston soils and ten from Crosby soils. Samples of these soils were subjected to the following tests and the results analyzed statistically:

1. Atterberg Limits
2. Standard AASHO Compaction Test
3. Hveem Stabilometer and Swelling Pressure Tests
4. California Bearing Ratio Test
5. Grain Size Distribution Test, and
6. Unconfined Compression Test

It should also be noted that x-ray diffraction tests were conducted on eight samples - four from the rises and four 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

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of these test, was very 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.

INTRODUCTION

When dealing with relatively large areas, two broad aspects of soil sampling need be investigated. The first deals with the accuracy of soil tests for a given soil type. Closely allied to this is the problem of determining the number of soil samples required in order to define the soil within certain specified limits. This problem presents itself in regard to pedological soil classification as well as classification based on land forms.

As an example, consider a highway which 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 regarding 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 deals with the variability from one soil area to another of the same classification. The data in this regard would be of great value in connection with setting up "average" soil property values which can be adopted for design.

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

In order to find a solution to the problems stated above the disciplines of soil mechanics, statistics, airphoto interpretation and pedology were utilized in this thesis to study the variability of two glacial soils.

REVIEW OF LITERATURE

Engineers have long assumed that soils derived from the same parent material and under similar conditions of age, topography, climate, and vegetative covering would possess similar engineering properties. As an example, Woods, Belcher, Gregg and Jenkins (24) in 1946 stated, *

....available detailed data for one soil may be applied in general to a second soil that originated and developed under the same conditions as the first. This is the fundamental hypothesis upon which the methods described in this report are based. It holds true for all geological formations, whether they be of bedrock or of transported material moved by wind, water, or ice.

The concept of the "recurring profile", however, dates back prior to the aforementioned work. Its application can be found in the work of Bushnell (3), in 1929 and Stokstad (18), in 1936. Actually, it can be considered to have evolved with the science of pedology and the art of airphoto interpretation because these disciplines make liberal use of it.

The most noteworthy of these early contributions to a better understanding of the relationship between pedology and engineering was the work performed at Purdue University by Woods, Belcher and Gregg (23). To give one a better understanding of the benefits which may accrue from the establishment of such a relationship a quotation from the previous reference is cited:

Probably the most important phase of the development of the relationship between pedology and engineering is the measuring and recording of the engineering characteristics of the many soils and their separate horizons as identified by pedological means. An insight into

* Numbers in parenthesis refer to references listed in Bibliography.

the techniques and procedures employed in soil sampling is essential in such an undertaking for several reasons. In the first place, the accuracy used in soil identification must be checked to determine whether or not the program of study is feasible. Secondly, an understanding of these principles will eliminate the necessity of always having available a soil map of the area in question - particularly in regions where mapping is not complete. The testing of material from the various horizons of the various soils, together with the descriptions of possible pavement problems and corrections, can be done on only a few dozen soils and still cover most of the surface soils of an entire state or even larger areas. If a given soil is mapped in several localities and is found to have practically identical engineering test constants, such information can be used to eliminate a large amount of routine testing that has previously been found necessary when the relationship was not obvious.

In addition to the above authors many others have contributed to a better understanding of the relationship between engineering and pedology. Greenman (7) Hicks (8), McLerran (9), Thornburn and Bissett (20), Belcher (1), Stokstad (19) and many others were instrumental in the progress toward the aforementioned goals.

Today pedologic data is being used on an ever increasing scale by highway departments. Some states, such as Michigan (11), have gone over completely to the design of highways on the basis of a pedologic classification of soils in the state. Others, such as Indiana (23), New Jersey (16), Washington (10), Pennsylvania (15), and Kentucky (5), etc. used the pedologic classification as the basis for making soil maps of their respective areas and to a limited extent for design.

Airphotos

The use of airphotos has gained wide acceptance by civil engineers. Their use was greatly enhanced by the great benefit obtained from them during the last world war. Since then their use has multiplied immensely.

Much literature has been published concerning the use of airphotos in highway engineering. Many highway departments use airphotos in the planning stage. The photos are used in conducting soil surveys and the subsequent

development of soil maps for the location of borrow pits, for highway location studies, for drainage studies in a given area and many other functional uses.

For efficient operation it is best to use both pedology and airphotos in a given area. This allows definition of soil boundaries and the obtaining of soil information, over a large area, very rapidly. The latter statement naturally assumes that one is able to correlate airphoto patterns with pedology and that there is good correspondence between the pedologic classification and engineering properties.

These questions have been answered in part by the publications noted above and those which will be mentioned subsequently. Also, this thesis has as one of its purposes further clarification of these relationships.

Statistics

As was indicated above, the combination of pedology and airphoto interpretation is a vital tool in the planning of an economical soil exploration and testing program. Nevertheless, the human element is still manifest in these procedures and there arises the necessity of reducing this human factor to a minimum. A possible avenue of approach to the attainment of this goal is statistical analysis.

Today the engineer is utilizing statistics to an ever increasing degree in an effort to find solutions to his problems. The properties of soil, due to the very nature of soil formation, can be considered random variables and thus susceptible to statistical analysis.

The most noteworthy use of statistics in an effort to determine soil variability and consequently the number of samples required to define the engineering properties of the soils in a given area was the work of Thornburn

and Larsen (21). This study was based on the soils of DeWitt County, Illinois and indicates the efficiency and economic gain which may accrue from the use of pedologic information and statistics in the planning, design and construction of transportation facilities.

Another important study devoted to the investigation of soil variability is the work of Odell, Thornburn and McKenzie (14) which related the Atterberg limits to various combinations of standard physical and chemical determinations - cation-exchange capacity, percent of organic carbon, percent < 0.002 -mm clay, percent of montmorillonite in the clay separate, and percent of 0.05 to 0.002 -mm silt. Multiple correlation coefficients were determined and thus it was ascertained how knowledge of these variables would allow one to predict the Atterberg limits.

Morse and Thornburn (13) investigated the "Reliability of Soil Map Units" by the use of statistics. The sampling and testing program was conducted on soils of Livingston County, Illinois and included horizons in loess, glacial till and glacial outwash. The properties investigated were the liquid limit (LL), plasticity index (PI) and percent of clay ($< 2\mu$). From this information the number of samples required to adequately characterize an horizon of a Livingston County soil were determined.

Other studies in which statistics was used are those of Deen (5) and the Pennsylvania State University (15). Both projects involved the use of statistics in reducing the number of samples required to define soil boundaries and properties in the construction of engineering soil maps.

PURPOSE AND SCOPE

The primary purpose of this study was to determine the variation which could be expected in the engineering properties of soils derived from the same parent material and under similar conditions of climate, vegetation, age, and topography. Secondly, based on the above, the number of samples required to reliably predict these properties was determined.

The areas selected for this study are located in Tipton County and Madison County, Indiana. 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, according to pedologic soil classification. The Crosby, denoted rise, existing on 0-4% slopes and the Brookston, denoted depressions, existing in depressional areas were utilized in this study.

Twenty borings were made in each county - ten in elevated positions and ten in the depressions. The A, B and C horizons were sampled in each boring. However, only moisture content determinations 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 Boring Ratio (CBR) test, compaction tests (dynamic and kneading), unconfined compression tests and Hveem stabilometer and swelling tests.

The data obtained from the above tests were subjected to statistical analysis in order to estimate the variance of the soil properties and the

number of samples required to define these properties. As regards the former, 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 between the properties listed previously. Such may 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. Consequently, after studying the airphotos of five Indiana counties it was decided to use Madison and Tipton Counties based on 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, in order to negate the effect of the moraine the sampling sites were chosen such that they were equidistant from the moraine (approximately 5 miles).

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. Accessibility was a factor in choosing the final boring sites (Fig. 1 and 2). A total of twenty borings were made in each county (ten in the rises and ten in the depressions). See Fig. 3 for generalized soil profiles.- based on boring logs.

Samples were obtained by hand augering. Approximately 300 grams of soil was taken from the A-horizon of each boring, and values of the Atterberg limits and natural moisture content were determined. Since the A-horizon is many times wasted in engineering construction it was felt that extensive testing was not warranted.

FIG. 3 GRAPHICAL PRESENTATION OF BORING RESULTS

In addition to samples for the Atterberg limit and natural moisture content tests, approximately one-hundred pounds was taken from both the B and C-horizon 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 AASHTO compaction test
3. Hveem stabilometer and swelling pressure test
4. CBR tests
5. Unconfined compression test
6. X-ray diffraction tests

Natural Moisture Content

Moisture content samples were taken from each horizon in each boring. An attempt was made to always select 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 this data was attempted. Only one moisture content sample was taken per horizon.

Atterberg Limits

The Liquid Limits and the 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. It was felt that 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.

As regards the grain-size analysis, ASTM Designation: D422-54T was employed with the following variations.

1. Hydrometer analysis samples were obtained by dry sieving on the No. 200 U. S. Standard sieve and utilizing the portion passing. However, it was realized that this might give an erroneous representation of the grain-size distribution of the fraction passing the No. 200 sieve i.e. a low value of the percent clay. The latter is due to the fact that when the soil is dry the clay particles aggregate. It is debatable whether these will be broken down, during the sieving process, and thus the major portion of the material passing the No. 200 sieve might be silt.

In order to determine the extent to which the above phenomenon was occurring it was decided to conduct the grain-size analysis by the standard ASTM method and compare the results with the dry sieve method.

2. A constant temperature bath was used.
3. Two grams of the water conditioner "Calgon", manufactured by the Calgon Company, Pittsburg, Pennsylvania was used as a deflocculating agent. This amount of Calgon was added per 50 grams of soil.

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 No. 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 No. California 301-B with three variations:

1. All moisture was added to the sample the day prior to testing.
2. Compaction curves were determined for compaction foot pressures of 350 psi, 250 psi and 150 psi. See Figure 8.
3. The compactor foot pressure used to get the soil into the mold was 75 psi instead of 15 psi as prescribed in the aforementioned test method.

On the basis of the first series of compaction tests it was determined that the compaction foot pressure which 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.

Since 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 utilizing the kneading compactor. The stabilometer specimen from each horizon was then molded at the O.M.C., optimum moisture content, 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 the above samples were (a) more than

120 pcf, 117-120 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 as to 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.

The moisture contents used for molding the specimens are as follows:

<u>Boring</u>	<u>Horizon</u>	<u>O.M.C.</u>
3	B	16.5%
	C	11.0%
12	B	18.0%
	C	14.2%
25	B	17.0%
	C	12.0%

The average moisture contents of the samples were controlled to within $\pm 0.5\%$. For the exact moisture content used for samples other than those listed above see Table 17.

California Bearing Ratio 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 $\pm 0.5\%$ 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 fifteen blows per layer using a 40 pound 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 O.M.C. 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 O.M.C. of the groups can be listed as follows:

<u>Boring</u>	<u>Horizon</u>	<u>O.M.C.</u>
11	B	16.5%
	C	11.6%
33	B	18%
	C	13%
24	B	17%
	C	13%

See Table 19 for the exact moisture content assigned to a given sample. These average moisture contents are within a $\pm 0.5\%$ of the desired moisture content.

The rate of strain, used for the unconfined compression tests, was 0.07 in. per min. Also, after molding, the samples were wrapped in aluminum foil, placed in a sealed container and stored overnight. They were 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 two from the depressions of each county.

The basis of the selection of the borings to be utilized 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 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 the above in mind, borings which were representative of the group of soils in which this event occurred were chosen. On the basis of topographic position and county they may be arranged as follows:

	<u>Boring Number</u>	
	<u>Rise</u>	<u>Depression</u>
Tipton County	4, 12	1, 14
Madison County	21, 35	24, 28

The slides for the x-ray diffraction test were prepared from a portion of the soil which was quartered for the hydrometer analysis test. Fifty grams of the soil was mixed with approximately 700 cc of water and 2 grams of the water softener "Calgon". The suspension was then mixed in a mechanical stirrer for three minutes 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 particles of size 2 microns would be located. This portion of the suspension was placed on a glass slide and allowed to dry.

Statistical Analysis

Following completion of the above tests, the data were analyzed, statistically, using analysis of variance techniques. Table 1 shows the data layout for the analysis of variance studies. It should be noted that, with the exception of the Atterberg limits, only the B and C-horizons will be considered.

TABLE 1. DATA LAYOUT FOR ANALYSIS OF VARIANCE

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

Variables to be analyzed2 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 #200 sieve
8. Percent < 0.002mm
9. Swelling pressure
10. Stabilometer value
11. Unconfined compressive strength

RESULTS

The analysis of variance model for the test results is as follows:

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

where, U , is 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

$E_{m(ijkl)}$, error true effect of repeat measurements, and

the other terms denote interactions between the main effects listed above.

As regards the main effects, C, D and H are fixed while B is random. E is also random. The subscripts may assume values as follows:

$$i = 1, 2$$

$$j = 1, 2$$

$$k = 1, 2, 3, \dots, 10$$

$$l = 1, 2, 3$$

$$m = 1, 2$$

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

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

where, 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

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

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

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

where L, the limit of accuracy

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

The normal "t" can be used since 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% 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

1. The variance is not significantly affected by a change in operators,
2. There is no significant change in variance with horizon, and
3. Normality of dependent variables.

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

1. D. F., degrees of freedom,
2. M.S., MS, mean square, and
3. E.M.S., EMS, expected mean square.

The above abbreviations are also used in the text.

Atterberg Limits

Liquid Limit

Table 2 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 (2). From these tests it was determined that a significant difference existed between the rises and depressions, between borings in the C-D cells and between horizons. Also, it was found that the interactions between the horizons and the rise vs depression and the interaction 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 2 the following values for the variance estimates can be obtained:

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

$$\sigma_{HB}^2 = \frac{50.5 - 5.7}{2} = 22.4$$

$$\sigma_B^2 = \frac{49.9 - 5.7}{6} = 7.37$$

TABLE 2. SUMMARY OF ANALYSIS OF VARIANCE - LIQUID LIMIT

Source of Estimate	D.f.	Sums of Squares	MS	EMS
Between Counties (C_1)	1	$S_1 = C_1 - C = 57.53$	57.53	$\sigma^2 + 6\sigma_B^2 + 120\sigma_C^2$
Depression vs Rise (D_1)	1	$S_j = C_j - C = 4483.36$	<u>4483.36</u>	$\sigma^2 + 6\sigma_B^2 + 120\sigma_D^2$
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	$S_k(ij) = C_{ijk} - C_{ij} = 1795.27$	<u>49.80</u>	$\sigma^2 + 6\sigma_B^2$
Horizons H_1	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	$S_{lk}(ij) = C_{ilkl} - C_{ijk} - C_{ijl} + C_{ij}$ $= 3629.75$	<u>50.50</u>	$\sigma^2 + 2\sigma_{HB}^2$
$E_m(ijkl)$	120	$S_m(ijkl) = \sum i j k l m X^2_{ijklm} - C_{ijkl}$ $= 684.78$	5.71	σ^2
Total	239	$SS = \sum i j k l m X^2_{ijklm} - \frac{T^2}{N} = 37,329.10$		

therefore, $\sigma_T^2 = 5.71 + 22.4 + 7.37 = 35.48$.

Based on the above value of σ_T^2 the number of borings required to predict the LL to a given degree of precision was determined. Figure 4 is a graphical representation of this relationship. Precision, denoted limit of accuracy, is expressed in percentage points of moisture.

Plastic Limit and Plasticity Index

The results of analyses of variance of the plastic limit and plasticity index data are shown in Tables 3 and 4. In both instances there was found to be no significant difference between the two counties but all other main effects i.e. borings in the C-D cells, horizons and rise vs depression (topography) tested significant.

As regards 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.

Recall,

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

Then, considering the plasticity index (see Table 3),

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

Therefore,

$$\sigma_{\bar{X}} = \sqrt{\frac{16.66}{n}}$$

TABLE 4. SUMMARY OF ANALYSIS OF VARIANCE - PLASTIC LIMIT

Source of Estimate	D.f.	Sums of Squares	M.S.	EMS
Between Counties (C_i)	1	$S_i = C_i - C = 22.27$	22.27	$\sigma^2 + 6 \sigma_B^2 + 120 \sigma_C^2$
Depression vs Rise (D_j)	1	$S_j = C_j - C = 350.66$	<u>350.66</u>	$\sigma^2 + 6 \sigma_B^2 + 120 \sigma_D^2$
CD_{ij}	1	$S_{ij} = C_{ij} - C_i - C_j + C = 9809.69$	<u>77.86</u>	$\sigma^2 + 6 \sigma_B^2 + 60 \sigma_{CD}^2$
Between Borings in (C-D cell), $B_k(ij)$	36	$S_k(ij) = C_{ijk} - C_{ij} = 495.87$	<u>13.77</u>	$\sigma^2 + 6 \sigma_B^2$
Horizons (H_l)	2	$S_l = C_l - C = 4358.46$	<u>2179.23</u>	$\sigma^2 + 2 \sigma_{HB}^2 + 80 \sigma_H^2$
HC_{il}	2	$S_{il} = C_{il} - C_i - C_l + C = 34.57$	17.28	$\sigma^2 + 2 \sigma_{HB}^2 + 40 \sigma_{HC}^2$
HD_{jl}	2	$S_{jl} = C_{jl} - C_j - C_l + C = 248.52$	<u>124.26</u>	$\sigma^2 + 2 \sigma_{HB}^2 + 40 \sigma_{HD}^2$
HCD_{ijl}	2	$S_{ijl} = C_{ijl} + C_i + C_j + C_l - C_{ij} - C_{jl} - C_{il} + C = 14.01$	7.01	$\sigma^2 + 2 \sigma_{HB}^2 + 20 \sigma_{HCD}^2$
$HB_{lk}(ij)$	72	$S_{lk}(ij) = C_{ijkl} - C_{ijk} - C_{ijl} + C_{ij} = 950.70$	<u>13.26</u>	$\sigma^2 + 2 \sigma_{HB}^2$
$E_m(ijkl)$	120	$S_m(ijkl) = \sum_{ijkl} x^2_{ijklm} - C_{ijkl} = 123.77$	1.03	$\sigma^2 + 2 \sigma_{HB}^2$
Total	239	$SS = \sum_{ijklm} x^2_{ijklm} - \frac{T^2}{N} = 6676.69$		

As regards the plastic limit,

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

and

$$\sigma_{\bar{X}} = \sqrt{\frac{9.27}{n}}.$$

Based on the above 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 Figure 4). Note that 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.

From Figure 5 one can obtain information on 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, it should be noted that 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 overall picture the A-horizon results, in the majority of cases, lie below the A-line. Furthermore, all the depressional soils had a liquid limit greater than 41 percent while only two samples from the rises had a liquid limit above this value.

Considering 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 while 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 which 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 5 shows a summary of the Atterberg limit data. It contains the maximum, minimum and mean values of the liquid limit and plasticity index. From this table it can be seen 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 (O.M.C.) and the optimum density (O.D.) values using the data from the Standard AASHO compaction tests. The results are shown in Tables 6 and 7.

Considering the optimum density data the variance components obtained from Table 6 are $\sigma^2 = 1.02$, $\sigma_B^2 = 3.22$ and $\sigma_{HB}^2 = 4.94$. Therefore, from equation (2) we obtain

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

Utilizing this value of σ_T^2 and equation (4) the upper curve of Figure 6

TABLE 5. SUMMARY OF ATTERBERG LIMIT DATA

County	Topography	Index Property	Horizon	Minimum Value (%)	Maximum Value (%)	Mean Value (%)	Index Property	Minimum Value (%)	Maximum Value (%)	Mean Value (%)
Tipton	Rise	LL	A	31.4	44.7	35.5	PI	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	LL	A	43.9	60.4	51.1	PI	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	LL	A	29.1	46.5	35.3	PI	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	LL	A	41.6	60.5	50.5	PI	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

TABLE 6. SUMMARY OF ANALYSIS OF VARIANCE - OPTIMUM DENSITY

Source of Estimate	D.f.	Sums of Squares	M.S.	EMS
Between Counties (C_i)	1	$S_i = C_i - C = 0.50$	0.50	$\sigma^2 + 4\sigma_B^2 + 80\sigma_C^2$
Depressions vs Rise (D_j)	1	$S_j = C_j - C = 13.10$	13.10	$\sigma^2 + 4\sigma_B^2 + 80\sigma_D^2$
CD_{ij}	1	$S_{ij} = C_{ij} - C_i - C_j + C = 99.78$	<u>99.78</u>	$\sigma^2 + 4\sigma_B^2 + 40\sigma_{CD}^2$
Between Borings in (C-D cell), $B_k(ij)$	36	$S_k(ij) = C_{ijk} - C_{ij} = 501.34$	<u>13.90</u>	$\sigma^2 + 4\sigma_B^2$
Horizons (H_l)	1	$S_l = C_l - C = 8623.03$	<u>8623.03</u>	$\sigma^2 + 2\sigma_{HB}^2 + 80\sigma_H^2$
HC_{il}	1	$S_{il} = C_{il} - C_i - C_l + C = 37.64$	37.64	$\sigma^2 + 2\sigma_{HB}^2 + 40\sigma_{HC}^2$
HD_{jl}	1	$S_{jl} = C_{jl} - C_j - C_l + C = 13.93$	13.93	$\sigma^2 + 2\sigma_{HB}^2 + 40\sigma_{HD}^2$
HCD_{ijl}	1	$S_{ijl} = C_{ijl} + C_i + C_j + C_l - C_{ij} - C_{il} - C_{jl} - C = 46.09$	<u>46.09</u>	$\sigma^2 + 2\sigma_{HB}^2 + 20\sigma_{HCD}^2$
$HB_{lk}(ij)$	36	$S_{lk}(ij) = C_{ijkl} - C_{ijk} - C_{ijl} + C_{ij} = 392.58$	<u>10.91</u>	$\sigma^2 + 2\sigma_{HB}^2$
$E_m(ijkl)$	80	$S_m(ijkl) = \sum_{i,j,k,l} i,j,k,l m X^2_{i,j,k,l m} - C_{ijkl} = 81.70$	1.02	σ^2
Totals	159	$SS = \sum_{i,j,k,l,m} X^2_{i,j,k,l m} - \frac{T^2}{N} = 9809.69$		

TABLE 7. SUMMARY OF ANALYSIS OF VARIANCE - OPTIMUM MOISTURE CONTENT

Source of Estimate	D.f.	Sums of Squares	MS	EMS
Between Counties (C_i)	1	$S_i = C_i - C = 2.19$	2.19	$\sigma^2 + 4 \sigma_B^2 + 80 \sigma_C^2$
Depression vs Rise (D_j)	1	$S_j = C_j - C = 5.01$	5.01	$\sigma^2 + 4 \sigma_B^2 + 80 \sigma_D^2$
CD_{ij}	1	$S_{ij} = C_{ij} - C_i - C_j + C = 4.19$	4.19	$\sigma^2 + 4 \sigma_B^2 + 40 \sigma_{CD}^2$
Between Borings in (C-D cell), $B_k(ij)$	36	$S_{k(ij)} = C_{ijk} - C_{ij} = 125.17$	<u>3.48</u>	$\sigma^2 + 4 \sigma_B^2$
Horizons (H_l)	1	$S_l = C_l - C = 1427.43$	<u>1427.43</u>	$\sigma^2 + 2 \sigma_{HB}^2 + 80 \sigma_H^2$
HC_{il}	1	$S_{il} = C_{il} - C_i - C_l + C = 9.55$	9.55	$\sigma^2 + 2 \sigma_{HB}^2 + 40 \sigma_{HC}^2$
HD_{jl}	1	$S_{jl} = C_{jl} - C_j - C_l + C = 0.06$	0.06	$\sigma^2 + 2 \sigma_{HB}^2 + 40 \sigma_{HD}^2$
HCD_{ijl}	1	$S_{ijl} = C_{ijl} + C_i + C_j + C_l - C_{ij} - C_{il} - C_{jl} - C = 9.46$	9.46	$\sigma^2 + 2 \sigma_{HB}^2 + 20 \sigma_{HCD}^2$
$HB_{lk}(ij)$	36	$S_{lk}(ij) = C_{ijkl} - C_{ijk} - C_{ijl} + C_{ij} = 90.78$	<u>2.52</u>	$\sigma^2 + 2 \sigma_{HB}^2$
E_m	S80	$S_m(ijkl) - \sum ijklm X^2_{ijklm} - C_{ijkl} = 39.70$	0.496	σ^2
Totals	159	$SS = \sum ijklm X^2_{ijklm} - \frac{T^2}{N} = 1713.54$

FIG. 6 LIMIT OF ACCURACY vs NUMBER OF BORINGS

is obtained. The curve represents the relationship between number of borings and limit of accuracy. For example, if one wishes to predict the mean optimum density of the population within the limit of ± 4 pcf it would be necessary to make eight borings.

The total variance of the optimum moisture content data can be determined from Table 7. The components of the total variance 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, σ_T^2 , and $t = 1.96$ - for significance level of 5%, $\alpha = 0.05$ - the lower curve of Figure 6 is obtained.

From Tables 6 and 7, the factors which 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 regards 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 8 shows a summary of the compaction test data. It contains the maximum, minimum and mean values of the optimum moisture content and optimum density data. Noting the closeness of the results when horizon is held constant and the wide disparity when it is allowed to vary discloses why the aforementioned 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 O.D. and the PL is as follows:

TABLE 8. SUMMARY OF COMPACTION TEST (AASHTO) DATA

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

$$O.D. = 152.6 - 2.1(PL) \quad (5)$$

where,

O.D., is the optimum density (lbs/ft³)

and

PL, is the plastic limit (%).

Figure 7 is a graphical presentation of equation (5). Each point represents the average of the two tests run per sample. There was observed to be no segregation of results based upon county and/or topography, 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 O.M.C. and O.D. 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.

Figures 8 and 9 are 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. Tables 17 presents the molding moisture contents for each sample as well as the results of the stabilometer and swelling pressure tests.

On the basis of the information contained in the aforementioned tables, analyses of variance were conducted on the stabilometer (R-value) and

FIG. 7 PLASTIC LIMIT vs MAXIMUM DRY DENSITY (STD. AASHO)

FIG. 8 MOISTURE CONTENT vs DRY DENSITY — KNEADING COMPACTION CURVES
COMPACTOR FOOT PRESSURE = 150 P.S.I.

swelling pressure values. These data are presented in Tables 9 and 10, respectively.

Considering the stabilometer values (R-values), the only factors which may possibly be significant are the between boring variance (σ_B^2) and the horizon-boring interaction (σ_{HB}^2) - see Table 10. As regards the swelling pressure, horizons (σ_H^2) and the horizon-topography interaction definitely tested significant while the possibility remains that σ_B^2 and σ_{HB}^2 would test significant.

Due to the fact that 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 (see Table 9 or 10).

Recall that the total variance σ_T^2 , from which one is able to predict the number of borings required for a given degree of accuracy is determined as follows:

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

Therefore, unless one can obtain independent statistical estimates of these properties it is not possible to accurately predict 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 $\sigma_B^2 = 51.06$. 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

TABLE 9. SUMMARY OF ANALYSIS OF VARIANCE - R-VALUE

Source of Estimate	D.f.	Sum of Squares	MS	RMS
Between Counties (C_i)	1	$S_i = C_i - C =$	7.87	$\sigma^2 + 2\sigma_B^2 + 40\sigma_C^2$
Depression vs Rise (D_j)	1	$S_j = C_j - C =$	39.62	$\sigma^2 + 2\sigma_B^2 + 40\sigma_D^2$
CD_{ij}	1	$S_{ij} = C_{ij} - C_i - C_j + C$	17.39	$\sigma^2 + 2\sigma_B^2 + 20\sigma_{CD}^2$
Between Borings in (C-D Cell) $B_k(ij)$	36	$S_{k(ij)} = C_{ijk} - C_{ij}$	106.12	$\sigma^2 + 2\sigma_B^2$
Horizons (H_l)	1	$S_l = C_l - C =$	93.96	$\sigma^2 + \sigma_{HB}^2 + 40\sigma_H^2$
HC_{il}	1	$S_{il} = C_{il} - C_i - C_l + C$	87.99	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HC}^2$
HD_{jl}	1	$S_{jl} = C_{jl} - C_j - C_l + C$	152.49	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HD}^2$
HCD_{ijl}	1	$S_{ijl} = C_{ijl} + C_i + C_j + C_l - C_{ij} - C_{il} - C_{jl} - C$	99.94	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HD}^2$
$HB_{lk(ij)}$	36	$S_{lk(ij)} = C_{ijkl} - C_{ijk} - C_{ijl} + C_{ij}$	93.41	$\sigma^2 + \sigma_{HB}^2$
Total		$SS = \sum_{ijkl} x_{ijkl}^2 - \frac{T^2}{N}$	7,682.40	

TABLE 10. SUMMARY OF ANALYSIS OF VARIANCE - SWELLING PRESSURE

Source of Estimate	D.f.	Sums of Squares	M.S.	EMS
Between Counties (C _i)	1	$S_1 = C_1 - C = 2.66$	2.66	$\sigma^2 + 2\sigma_B^2 + 40\sigma_C^2$
Depression v _w Rise (D _j)	1	$S_j = C_j - C = 9.43$	9.43	$\sigma^2 + 2\sigma_B^2 + 40\sigma_D^2$
CD _{ij}	1	$S_{ij} = C_{ij} - C_1 - C_j + C = 2.58$	2.58	$\sigma^2 + 2\sigma_B^2 + 20\sigma_{CD}^2$
Between Borings in (C-D cell), B _k (i _j)	36	$S_k(ij) = C_{ijk} - C_{ij} = 99.40$	2.76	$\sigma^2 + 2\sigma_B^2$
Horizons (H _l)	1	$S_l = C_l - C = 61.11$	<u>61.11</u>	$\sigma^2 + \sigma_{HB}^2 + 40\sigma_H^2$
HC _{il}	1	$S_{il} = C_{il} - C_1 - C_l + C = 5.67$	5.67	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HC}^2$
HD _{j1}	1	$S_{j1} = C_{j1} - C_j - C_1 + C = 12.25$	<u>12.25</u>	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HD}^2$
HCD _{ij1}	1	$S_{ij1} = C_{ij1} + C_1 + C_j + C_l - C_{ij} - C_{il} - C_{j1} - C = 2.00$	2.00	$\sigma^2 + \sigma_{HB}^2 + 10\sigma_{HCD}^2$
HB _{1k} (i _j)	36	$S_{1k}(ij) = C_{ijk1} - C_{ijk} - C_{ij1} + C_{ij} = 72.11$	2.00	$\sigma^2 + \sigma_{HB}^2$
Total	79	$SS = \sum_{ijk1} x^2_{ijk1} - \frac{T^2}{N} = 267.21$		

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

and for the upper limiting value of σ^2

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

Based on the above values of σ_T^2 the curves of Figure 10 are obtained.

In Figure 10 the limit of accuracy is expressed both in terms of R-value and pavement thickness. It is apparent that pavement thickness is relatively insensitive to small changes in R-value.

From Figure 10 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. Also, from Table 9, it is evident that the range of the mean squares is relatively narrow, compared to the data discussed in previous sections.

Considering the swelling pressure, Table 10 gives an indication of the variation in test values. It is seen, neglecting the factors which tested significant, that the mean squares vary within narrow limits. Also, compared to the other test values the mean squares are relatively small.

Based upon experience, it was estimated that the maximum value of σ^2 would be 0.50 psi and the minimum value 0.1 psi. Thus, the values obtained for the total variance, σ_T^2 , is

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

and

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

respectively. Recalling that the number of borings required for a given degree of precision may be obtained from the formula

FIG.10 LIMIT OF ACCURACY vs NUMBER OF BORINGS
(R - VALUE)

$$\sigma_{\bar{x}} = \sqrt{\frac{\sigma_T^2}{n}}, \quad (4)$$

it is apparent 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 11 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 this would mean that the estimate of the thickness required to prevent swell may be in error by as much as 10.8 inches.

CBR test

Tables 18 show the CBR values obtained and other pertinent data. From this data insight may be gained into the effect of certain variables on the CBR value.

It should be noted that only six samples showed a CBR of more than 12 and that the great majority had CBR values less than 10. Of the samples which had CBR-values greater than 12, five were from the C-horizon.

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

Table 11 represents a summary of the analysis of variance. The relatively small values of the mean squares should be noted. This indicates that the variability in the test results is low. One should also take cognizance of the fact that only the county topography interaction tested significant.

FIG.11 LIMIT OF ACCURACY vs NUMBER OF BORINGS
SWELLING PRESSURE

TABLE 11. SUMMARY OF ANALYSIS OF VARIANCE - CBR DATA

Source of Estimate	D.f.	Sums of Squares	M.S.	EMS
Between Counties (C_i)	1	$S_i = C_i - C = 3.12$	3.12	$\sigma^2 + 2\sigma_B^2 + 40\sigma_C^2$
Depression vs Rise (D_j)	1	$S_j = C_j - C = 1.25$	1.25	$\sigma^2 + 2\sigma_B^2 + 40\sigma_D^2$
CD _{ij}	1	$S_{ij} = C_{ij} - C_i - C_j + C = 36.18$	<u>36.18</u>	$\sigma^2 + 2\sigma_B^2 + 20\sigma_{CD}^2$
Between Borings in (C-D cell), B _k (ij)	36	$S_{k(ij)} = C_{ijk} - C_{ij} = 314.35$	8.74	$\sigma^2 + 2\sigma_B^2$
Horizons (H_l)	1	$S_l = C_l - C = 14.79$	14.79	$\sigma^2 + \sigma_{HB}^2 + 40\sigma_H^2$
HC _{il}	1	$S_{il} = C_{il} - C_i - C_l + C = 0.84$	0.84	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HC}^2$
HD _{jl}	1	$S_{jl} = C_{jl} - C_j - C_l + C = 1.46$	1.46	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HD}^2$
HCD _{ijl}	1	$S_{ijl} = C_{ijl} + C_i + C_j + C_l - C_{ij} - C_{il} - C_{jl} - C = 41.76$	41.76	$\sigma^2 + \sigma_{HB}^2 + 10\sigma_{HCD}^2$
HB _{lk} (ij)	36	$S_{lk(ij)} = C_{ijkl} - C_{ijk} - C_{ijl} + C_{ij} = 371.87$	10.32	$\sigma^2 + \sigma_{HB}^2$
Total	79	$SS = \sum_{ijkl} x^2_{ijkl} - \frac{T^2}{N} = 785.62$		

Assuming that the maximum value of $\sigma^2 = 6$ and the minimum value of $\sigma^2 = 2$ one obtains

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

and

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

These values are then used in establishing the curves of Figure 12. 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.

It should be noted that 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 will be considered in two parts - the percent of material finer than 0.074mm (No. 200 U. S. Standard Sieve) and the percent of material finer than 0.002mm. A summary of this information is presented in Table 12. This table gives the maximum, minimum and mean values of the aforementioned properties. The values designated "dry" indicate the sample from which the values were determined was obtained by dry sieving on the No. 200 sieve. The values labeled ASTM were obtained by the standard ASTM method of test (see page 15).

By observation of this data certain trends can be noted. 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 the minimum values) seems to be greater for the rises than the depressions, when comparing counties. Also, it should be noted that

FIG.12 LIMIT OF ACCURACY vs NUMBER OF BORINGS
(C B R)

TABLE 12. SUMMARY OF GRAIN SIZE DISTRIBUTION DATA

County	Topography	Property	Horizon	Minimum Value		Mean Value (%)	County	Minimum	Maximum	Mean
				(%)	(%)					
Tipton	Rise	0.074mm	B	67.7	95.7	87.1	Madison	75.1	96.4	86.8
			C	46.9	75.5	62.8		59.0	94.0	67.3
		0.002mm (dry)	B	17.5	29.0	22.6		12.6	28.0	20.1
			C	9.5	23.2	15.2		7.0	18.5	15.2
		0.002mm (ASTM)	B	25.4	37.5	31.7		23.0	35.0	29.0
			C	16.0	22.5	21.2		11.6	25.5	21.2
	Depression	0.074mm	B	84.5	97.0	91.8	Madison	81.1	96.8	89.9
			C	62.7	87.2	70.9		53.6	80.1	61.6
		0.002mm (dry)	B	22.0	34.0	29.1		22.0	32.7	27.3
			C	12.0	23.0	16.8		14.5	18.8	16.5
		0.002mm (ASTM)	B	26.0	39.4	33.8		28.5	38.0	33.7
			C	13.5	31.0	22.8		17.0	24.0	20.8

the ASTM method yields consistently higher values than when the samples are prepared by dry sieving. The difference is greatest for the depressional soils and appears to be slightly greater for Tipton County. These trends will be analyzed statistically, below, and discussed further in the section on "Analysis of Results".

Table 13 summarizes the results of the analysis of variance for the percent of material finer than 0.074mm. Noting the size of the MS values it is evident that this property is highly variable. Also, note that the factors which tested significant are horizons and the horizon-county-topography interaction. Based on the magnitude of the "horizon" MS it is apparent that this effect must be held constant to obtain a reasonable degree of accuracy.

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

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

and

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

respectively. These values along with the fact that

$$\sigma_{\bar{X}} = \sqrt{\frac{\sigma_T}{n}} \quad (4)$$

TABLE 13. SUMMARY OF ANALYSIS OF VARIANCE - % FINER THAN 0.075mm

Source of Estimate	D.f.	Sums of Squares	MS	EMS
Between Counties (C_i)	1	$S_i = C_i - C = 62.12$	62.12	$\sigma^2 + 2\sigma_B^2 + 40\sigma_C^2$
Depression vs Rise (D_j)	1	$S_j = C_j - C = 131.32$	131.32	$\sigma^2 + 2\sigma_B^2 + 40\sigma_D^2$
CD_{ij}	1	$S_{ij} = C_{ij} - C_i - C_j + C = 289.95$	289.95	$\sigma^2 + 2\sigma_B^2 + 20\sigma_{CD}^2$
Between Borings in (C-D cell), $B_k(ij)$	36	$S_{k(ij)} = C_{ijk} - C_{ij} = 2076.15$	85.45	$\sigma^2 + 2\sigma_B^2$
Horizons (H_l)	1	$S_l = C_l - C = 10,818.22$	<u>10,818.22</u>	$\sigma^2 + \sigma_{HB}^2 + 40\sigma_H^2$
HC_{il}	1	$S_{il} = C_{il} - C_i - C_l + C = 8.40$	8.40	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HC}^2$
HD_{jl}	1	$S_{jl} = C_{jl} - C_j - C_l + C = 37.69$	37.69	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HD}^2$
HCD_{ijl}	1	$S_{ijl} = C_{ijl} + C_i + C_j + C_l - C_{ij} - C_{jl} - C_{il} = 181.48$	<u>181.48</u>	$\sigma^2 + \sigma_{HB}^2 + 10\sigma_{HCD}^2$
$HB_{lk}(ij)$	36	$S_{lk}(ij) = C_{ijkl} - C_{ijk} - C_{ijl} + C_{ij} = 1394.12$	38.73	$\sigma^2 + \sigma_{HB}^2$
Total		$SS = C_{ijkl} - \frac{T^2}{N} = 15,999.45$		

are used to establish the relationships shown in Figure 13. 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.

Table 14 represents the analysis of variance data for the percent of material finer than 0.002mm for samples obtained from the soil which passed through the No. 200 sieve in the dry sieving operation. The factors which proved significant were topography, horizons and the horizon-topography interaction. It will be assumed that the maximum value of $\sigma^2 = 6$ and the minimum value is $\sigma^2 = 2$.

Thus the estimates of the total variance becomes

$$\sigma_T^2 = 6 + 4.42 + 3.22 = 13.64$$

and

$$\sigma_T^2 = 2 + 8.42 + 5.22 = 15.64.$$

Utilizing these values one can establish curves which would bound the limit of accuracy for a given degree of precision. However, due to the fact that the curves are a negligible distance apart, only the curve for $\sigma_T^2 = 15.64$ is presented (see Figure 14).

Table 15 represents the data obtained for the percent $< 0.002\text{mm}$, where the test specimen was prepared utilizing the standard procedure recommended by ASTM (see page 15). The only two values which tested significant were horizons and topography. However, the large magnitude of the horizon and horizon-boring interaction should be noted. The latter is over six times as large as in the case of the dry sieving method of sample preparation.

FIG. 13 LIMIT OF ACCURACY vs NUMBER OF BORINGS
(% FINER THAN 0.074 MM.)

TABLE 14. SUMMARY OF ANALYSIS OF VARIANCE - % FINER 0.002mm (dry sieving)

Source of Estimate	D.f.	Sums of Squares	MS	EMS
Between (C_1)	1	$S_1 = C_1 - C$	25.76	$\sigma^2 + 20\sigma_B^2 + 40\sigma_C^2$
Depression vs Rise (D_1)	1	$S_j = C_j - C$	<u>343.37</u>	$\sigma^2 + 20\sigma_B^2 + 40\sigma_D^2$
CD_{ij}	1	$S_{ij} = C_{ij} - C_i - C_j + C$	0.30	$\sigma^2 + 20\sigma_B^2 + 20\sigma_{CD}^2$
Between Borings in (C-D Cell) $B_k(ij)$	36	$S_k(ij) = C_{ijk} - C_{ij}$	12.44	$\sigma^2 + 20\sigma_B^2$
Horizons (H_1)	1	$S_l = C_l - C$	<u>1,568.22</u>	$\sigma^2 + \sigma_{HB}^2 + 40\sigma_H^2$
HC_{il}	1	$S_{il} = C_{il} - C_i - C_l + C$	19.41	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HC}^2$
HD_{jl}	1	$S_{jl} = C_{jl} - C_j - C_l + C$	<u>143.37</u>	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HD}^2$
HCD_{ijl}	1	$S_{ijl} = C_{ijl} + C_i + C_j + C_l - C_{ij} - C_{il} - C_{jl} - C$	1.24	$\sigma^2 + \sigma_{HB}^2 + 10\sigma_{HCD}^2$
$HB_{lk}(ij)$	36	$S_{lk}(ij) = C_{ijkl} - C_{ijk} - C_{ijl} + C_{ij}$	10.42	$\sigma^2 + \sigma_{HB}^2$
Total	79	$SS = \sum_{ijkl} x^2 - \frac{T^2}{N}$

FIG. 14 LIMIT OF ACCURACY vs NUMBER OF BORINGS
(% FINER THAN 0.002 MM.)

TABLE 15. SUMMARY OF ANALYSIS OF VARIANCE - $\% < 2\mu$ (ASTM Method)

Source of Estimate	D.f.	Sums of Squares	MS	EMS
Between Counties (C_i)	1	$S_i = C_i - C = 14.70$	14.70	$\sigma^2 + 2 \sigma_B^2 + 40 \sigma_C^2$
Depression vs Rise (D_j)	1	$S_j = C_j - C = 106.49$	<u>106.49</u>	$\sigma^2 + 2 \sigma_B^2 + 40 \sigma_D^2$
CD $_{ij}$	1	$S_{ij} = C_{ij} - C_i - C_j + C = 0.71$	0.71	$\sigma^2 + 2 \sigma_B^2 + 20 \sigma_{CD}^2$
Between Borings in (C-D cell), B $_{k(ij)}$	36	$S_{k(ij)} = C_{ijk} - C_{ij} = 606.99$	16.85	$\sigma^2 + 2 \sigma_B^2$
Horizons (H_l)	1	$S_l = C_l - C = 2359.86$	<u>2359.87</u>	$\sigma^2 + \sigma_{HB}^2 + 40 \sigma_H^2$
HC $_{il}$	1	$S_{il} = C_{il} - C_i - C_l + C = 5.06$	5.06	$\sigma^2 + \sigma_{HB}^2 + 20 \sigma_{HC}^2$
HD $_{jl}$	1	$S_{jl} = C_{jl} - C_j - C_l + C = 24.31$	24.31	$\sigma^2 + \sigma_{HB}^2 + 20 \sigma_{HD}^2$
HCD $_{ijl}$	1	$S_{ijl} = C_{ijl} + C_i + C_j + C_l - C_{ij} - C_{il} - C_{jl} - C = 43.06$	43.06	$\sigma^2 + \sigma_{HB}^2 + 10 \sigma_{HCD}^2$
HB $_{lk(ij)}$	36	$S_{lk(ij)} = C_{ijkl} - C_{ijk} - C_{ijl} + C_{ij} = 2130.89$	59.2	$\sigma^2 + \sigma_{HB}^2$
Total		$SS = \sum_{ijkl} x_{ijkl}^2 - \frac{T^2}{N} = 5292.08$		

Considering the expected mean square of the between boring main effect it is evident that the maximum possible value of $\sigma^2 = 16.85$. However, it is felt that a more realistic maximum value would be $\sigma^2 = 9$ and the minimum value 1. On this basis the estimates of the total variance becomes

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

and

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

respectively. This information can be utilized in establishing the upper curves of Figure 14. However, due to the closeness of the square root of the above 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 $\sigma_T^2 = 67.12$ was plotted (see upper curve of Figure 14).

From Figures 13 and 14 the order of variability of the grain size distribution properties may be determined. It is evident that the most variable grain size property is the percent finer than 0.074mm, followed very closely by the percent finer than 0.002mm - based on ASTM method of test. The percent finer than 0.002mm based on dry sieve method is much less variable than either of the other two.

Unconfined Compression Test

The soils were divided into three groups, based on Standard AASHO density. A compaction test was conducted on a member of each group to determine the optimum moisture content for that group (see Figures 15 and 16). Subsequently, unconfined compression test specimens were molded

FIG. 15 MOISTURE CONTENT vs DRY DENSITY — KNEADING COMPACTION CURVES
HARVARD MINIATURE COMPACTOR (40 LB. SPRING)

FIG. 16 MOISTURE CONTENT vs DRY DENSITY — KNEADING COMPACTION CURVES
HARVARD MINIATURE COMPACTOR (40 LB. SPRING)

at the moisture content representative of the group in which it was a member. Table 19 summarizes these data.

Table 16 is a summary of the analysis of variance conducted on the unconfined compression test data. The main effects which tested significant were depression vs rise (topography) and horizons. The only interaction term which proved significant was the horizon-county interaction. More factors did not test significant because of the large values of the horizon-boring and between boring effects.

It was not possible to determine the error variance since 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 (Figure 17).

It should be noted that the unconfined compressive strength of the B-horizon was greater than that of the C-horizon. Also, in comparing a given horizon, it was found that the unconfined compressive strength of the depressions exceeded that of the rises. No definite trend could be established as regards the relative strengths of the soils in Madison County versus the soils in Tipton County.

Finally the magnitude of total variance of the unconfined compression test data was much larger than for any of the other measured data.

Soil Mineralogy

Due to the possible differences in the concentrations of the solutions from which the slides were made, it was not possible to make quantitative estimates of the clay minerals present. Therefore, all inferences

TABLE 16. SUMMARY OF ANALYSIS OF VARIANCE - UNCONFINED COMPRESSION TEST

Source of Estimate	D.F.	Sums of Squares	M.S.	EMS
Between Counties (C_i)	1	$S_i = C_i - C = 161.31$	161.31	$\sigma^2 + 2 \sigma_B^2 + 40 \sigma^2$
Depression vs Rise (D_j)	1	$S_j = C_j - C = 1270.42$	<u>1270.42</u>	$\sigma^2 + 2 \sigma_B^2 + 40 \sigma_D^2$
CD_{ij}	1	$S_{ij} = C_{ij} - C_i - C_j + C = 95.05$	95.05	$\sigma^2 + 2 \sigma_B^2 + 20 \sigma_{CD}^2$
Between Borings in (C-D cell), $B_k(ij)$	36	$S_k(ij) - C_{ijk} - C_{ij} = 6087.58$	169.09	$\sigma^2 + 2 \sigma_B^2$
Horizons (H_l)	1	$S_l = C_l - C = 1918.84$	<u>1918.84</u>	$\sigma^2 + 10 \sigma_{HB}^2 + 40 \sigma_H^2$
HC_{il}	1	$S_{il} = C_{il} - C_i - C_l + C = 608.31$	<u>608.31</u>	$\sigma^2 + 10 \sigma_{HB}^2 + 20 \sigma_{HC}^2$
HD_{jl}	1	$S_{jl} = C_{jl} - C_j - C_l + C = 50.24$	50.24	$\sigma^2 + 10 \sigma_{HB}^2 + 20 \sigma_{HD}^2$
HCD_{ijl}	1	$S_{ijl} - C_{ijl} + C_i + C_j + C_l - C_{ij} - C_l - C_{jl} - C = 175.82$	175.82	$\sigma^2 + 10 \sigma_{HB}^2 + 10 \sigma_{HCD}^2$
$HB_{lk}(ij)$	36	$S_{lk}(ij) = C_{ijkl} - C_{ijk} - C_{ijl} + C_{ij} = 4332.98$	120.36	$\sigma^2 + \sigma_{HB}^2$
Total	79	$SS = \sum_{ijkl} x^2_{ijkl} - \frac{T^2}{N} = 14,700.55$

FIG.17 LIMIT OF ACCURACY vs NUMBER OF BORINGS
UNCONFINED COMPRESSIVE STRENGTH

as regards the mineralogy will be qualitative in nature. Nevertheless, it is apparent that samples may differ in the types of clay minerals present and/or the amount of the clay minerals.

Eight borings, four rises and four depressions, were the basis of this mineralogical study. It was found that the same clay minerals were present in all holes except in boring 13, and that the differences occurred in the quantity of clay minerals present and the stage of weathering of the minerals. Boring 13 differed from the others in that it contained very little, if any, illite.

The clay minerals present in all borings and all horizons (except the boring noted above) may be listed as follows:

<u>Mineral</u>	<u>Basal Spacing</u>
	o
Chlorite	14A
	o
Montmorillonite	13A
	o
Illite	10A
	o
Kaolinite	7A

Basal spacing is for untreated samples. Also, it should be noted that vermiculite may be present as a portion of the 13 A material.

The main difference between the B and C-horizons is the quantity of the clay minerals present. The quantity of the clay minerals is greatest in the B-horizon. However, comparing the Crosby (rise) soils with the Brookston (depression) soils it is found that the rise soils show little of the minerals in intermediate weathering stages between illite and montmorillonite while these intermediate stages are very evident in the depressional soils. This indicates that the weathering stage (of the clay

minerals) is further advanced in rises than in depressions.

In both the rises and depressions the expandable minerals i.e. montmorillonite and vermiculite, if the latter is present, manifest themselves at a basal spacing of approximately 13 Å. This indicates that the net residual charge at the surface of the clay minerals is relatively high which is the reason the basal spacing is less than the normal of 14 Å.

There appears to be a significant difference in the stage of weathering of the clay minerals present in the given borings and thus in the quantity of these minerals. This is evident from a plot of the intensity of the reflection received by the X-ray machine, after the x-rays have passed through the sample, versus the angle of incidence of the x-rays with respect to the sample. Each peak of such a curve represents a specific clay mineral or minerals. In some instances the peak representing illite is greater than the montmorillonite peak and vice versa. Since the illite is being weathered to montmorillonite one can use the aforementioned as a measure of the stage of weathering.

As an example, let us consider the depressional soils. Based on the x-ray patterns of the soils from borings 1, 14, 24, and 28 it can be stated that the soil from boring 24 is the least weathered, that from boring 1 is at an intermediate stage of weathering while the soils of borings 14 and 28 are for practical purposes identical and have weathered the most. Such differences affect the quantity of expandable types of clay minerals present. This may be due to differences in the position of the water table.

Another qualitative test for determining the stage of weathering of illite and mica type clay minerals was suggested to the author (22). It is based upon the fact that as the amount of potassium in the interlayer position increases the height of the peak representing the first order

reflection decreases. However, the second order reflection remains essentially the same. Due to the fact that one of the stages of weathering of the aforementioned minerals is the loss of potassium from the interlayer position, such a relationship can be used effectively as a qualitative measure of the degree of weathering of the minerals. The higher the ratio of the height of the first order reflection peak to the second order reflection peak the greater the degree of weathering.

The reason for the above relationship between the intensity of the first order reflection and the potassium content is considered to be that the x-rays when passing through the mineral are scattered by the relatively large potassium ions. Consequently, the reflection which is received by the x-ray machine is reduced in intensity. This substantiated the previous statement on the weathering stages of the soils of borings 1, 14, 24 and 28.

There was more clay in the B-horizon soils than in the C-horizon soils. Also, it should be noted that the types of clay minerals found in the rises were essentially the same as those found in the depressions. The main differences in mineralogy were evidence of the possibility of an interstratified clay mineral in the rises and the greater quantity of clay in the depressions. Also, based on the x-ray pattern it is felt that the rise soils should behave alike with the possible exception of those situations in which illite is absent or present in a negligible amount e.g. boring 13.

The variations in the soil profiles, as indicated above, may be sufficient to significantly affect the engineering properties of soils. When such is the case the exact nature and quantity of the clay minerals must be determined.

ANALYSIS OF DATA

Atterberg Limits

Statistical Analysis

The mean squares (MS) of the various estimates are indicators of the relative contribution of these effects to the variance. Considering the effects which tested significant it is apparent that the liquid limit 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 latter - see Tables 2, 3 and 4). 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 of the above, let us assume four borings are taken in the areas under consideration. We then could predict the LL 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 very slightly 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 between topographic position and horizon.

There is not much difference between the other two factors which tested significant (between borings in the C-D cells and the horizon-boring interaction). This can be seen from the analysis of variance tables.

Since only one of the factors which 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-horizon should not be used to predict the mean value of the B-horizon. This is as one would expect from a knowledge of soil profile development.

On the basis of the analysis of variance table for the Atterberg limits it is 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.

This variance component can be reduced by making repeat measurements i.e. the error mean square can be divided by the number of laboratory tests per horizon. However, due to the fact that the error mean square is small in comparison with the total estimated variance the number of borings required will not be significantly altered by increasing the number of repeat measurements.

Factors Affecting the Atterberg Limit Results

At this point, it is necessary to consider the factors, other than boring location, topography and horizon which contributed to the variance of the Atterberg Limit results, in this study. A list of several factors is as follows:

1. Initial moisture content
2. Operator
3. Depth at which the sample was obtained and clay mineral content.

Natural Moisture Content

It has been established for sometime 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 test 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 upon the degree of plasticity of the soil i.e. the greater the degree of plasticity the greater the difference.

As regards the C-horizon, the natural moisture contents were found to be significantly greater than the plastic limit, for the depressions. However, in the rises the natural moisture content, in most instances, 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 while borings in the rises intercepted water in only one instance.

As regards the B-horizon, in Tipton County the natural moisture content of the depression soils, in practically all cases exceeded the plastic

limit while in Madison County it was less than or equal to the plastic limit. This relationship 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 one would expect that the natural moisture content of the B-horizon soils of Tipton County would be greater than 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 since 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 the above information, it is evident that since the Atterberg Limits were conducted on samples which 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 four operators were used. The number of tests conducted by each is as follows:

<u>Operator</u>	<u>No. of Tests</u>
1	1
2	1
3	73
4	165

240

The effect of operators 1 and 2 is negligible. However, the possibility exists that there is a significant difference between operators 3 and 4. Such appears to be indicated by the relatively large value of the error mean squares of the liquid limit (Table 2) and the plasticity index (Table 3).

Depth of Sampling

In this study 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 or not this variation will be 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-horizon 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.

One Point Determination of the Liquid Limit

The standard method of test for determining the liquid limit of a soil was utilized in this study. This method is preferable over others when one is attempting to determine soil variability or to make correlations between strata in different borings. However, the data suggests that when the purpose of the liquid limit determination is to classify soils, a one-point determination of this property may be valid.

Upon conducting a review of the literature and applying the data contained in this thesis to the available one-point methods for determining the liquid limit, it was found that the method developed by Fang (6) was very reliable. In fact the method agreed with the data well enough that it was deemed unnecessary to develop a new one-point procedure for the data contained in this study.

According to Fang's method the liquid limit may be determined if any one point (N, W_n) on the flow curve is known, when the liquid limit is expressed as:

$$LL = W_n + I_f \log \frac{N}{25} \quad (5)$$

where,

W_n = moisture content at N blows, and

I_f = slope of the flow curve.

The term $I_f \log \frac{N}{25}$ is designated the Moisture Correction Factor and the author presents these values in both tabular and graphical form. Thus if W_n and N are known for a single point on the curve, the LL can be readily determined. Naturally, the closer the moisture content of this single

point to the LL the greater the accuracy of the procedure. Thus it is recommended that N should be within the limits of 17 and 36 blows.

Figure 18 is a plot showing the frequency distribution of the difference between the standard method and Fang's method. It is seen that for approximately 79 percent of the determinations the difference between the two methods was ± 0.5 percentage points of moisture and that over 95 percent of the determinations were within 1 percentage points of moisture of the value obtained from the standard method. On the basis of this work it was felt that an attempt to improve upon this method was not justified. The N value shown in Figure 18 represents the total number of determinations of the liquid limit by the one-point method.

Compaction Test (Standard AASHO)

On the basis of the data in Table 16 it is apparent, due to the factors which tested significant, that for the best results, considering the O.D., it is necessary to keep horizon and topography constant. Such a procedure will result in the least number of samples being required to predict the population mean value because it eliminates the variability due to the interactions which tested significant.

Considering the optimum moisture content data, the only factor which tested significant, and not considered in the total variance is the horizon effect. Thus, as far as obtaining a value of the O.M.C. 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 O.M.C. of a rise and that of a depression. However, for the maximum degree of accuracy for a given number of borings, horizons, topography and counties should be held constant. 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, the above point minimizes the need for making a large number of compaction tests.

On an absolute basis the above trends are apparent from Table 8. For example, considering the O.D., the mean values are greatly different and thus one would expect a large variance component due to the horizon effect. The same situation can be observed by determining the mean values for the other factors.

As regards the O.M.C., the difference between the mean values are much less than for the O.D. Nevertheless, the horizon effect tested significant. However, it is evident that horizon is less important as regards O.M.C. than O.D. - smaller mean square. This is also related to the fact that for a given parent material the absolute value of the possible variation is less for the O.M.C. than the O.D.

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 to be one the most important variables. An attempt was made to compact the samples within ± 0.5 percent of the optimum moisture content. Certain characteristics of the compaction process and the compacted soils should be mentioned.

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 always 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.

Another point to be considered is that this method of compaction may result in a non-homogeneous 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 fact no doubt affects the strength, compressibility and swelling characteristics of the compacted soil.

R-values

Due to the relatively small range of mean squares (Table 9 it can be stated that no single effect had a dominant roll in determining the R-value. However, it should also be recognized that due to this relative "uniformity", the total variance estimate is much higher than for any of the other measured properties. Thus, speaking in absolute terms, the number of borings required for a given degree of precision is much greater (see Figure 10).

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

Figure 10 shows the relationship between the number of borings, limit of accuracy and pavement thickness. It is evident that 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 as follows (25):

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

where,

$$K' = 0.095$$

$$TI = 1.35 \text{ EWL}^{0.11} = 8.71, \text{ EWL is the total number of equivalent 5000 lb wheel loads anticipated for the design life,}$$

$$R = \text{resistance value (R-value) and}$$

$$C = \text{cohesiometer value} = 200 \text{ (assumed).}$$

Based on the above

$$T = 0.2865 (90-R).$$

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. Since 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 which results from cohesion is not as greatly dependent upon the effective stress on the failure plane at failure as is the strength component due to friction. Depending upon 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.

Another point to be considered is that the optimum moisture content for each sample was not available. It was assumed that the O.M.C. 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 which affect the swelling pressure may be listed under two general categories - physio-chemical and mechanical. Seed, Mitchell and Chan (17) have shown that the mechanical aspect of the swelling phenomena may at times be of such magnitude that it cannot be neglected. However, since 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.

It should be noted that the horizon variance tested significant as did the horizon-topography interaction. Considering the physio-chemical 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 one would expect the greatest amount of swell in the soil with the higher affinity.

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

It should be emphasized that the exact quantitative relationship between the quantity of a given clay mineral and the amount of swell was not determined. The main reason for this is the heterogeneity of the amount of clay minerals which may exist at a given point in a given soil mass and the variation in chemical composition as well as variation in the weathering

stage. Nevertheless, qualitatively one can estimate the effect of both quantity and type of clay minerals on the swelling properties of a given soil.

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 inches.

The above 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.

It should be noted that the moisture content at which these samples were molded is representative of the O.M.C. 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.

It should be pointed out that in addition to satisfying stability requirements, it is necessary to insure that the pavement will not heave upon 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 than the optimum value. Nevertheless, it should be noted that in most instances the thickness required for stability, at the O.M.C., 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 O.M.C. obtained in the laboratory.

The data suggests 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. As is shown by Figure 11, a small change in swelling pressure means a relatively large change in thickness required to prevent swell.

CBR Data

It is of interest to note that 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 the data available.

Of the 29 borings in which the CBR-value of the C-horizon was found to be less than that of the B, the moisture content of the upper inch of the sample was much closer to the liquid limit for the C-horizon samples. Recall that the strength of a soil at the liquid limit is very low, approximately 25 gms/cm², and is much greater at the plastic limit. Thus, under the conditions enumerated above, it is to be expected that the CBR-value for the B-horizon might be greater than that for the C-horizon.

For CBR values equal to or less than 12 the following formula was used to determine the required thickness of pavement (4):

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

where

t = design thickness of the pavement structure in inches

P = total wheel (or equivalent wheel) load in pounds

p = tire pressure in pounds per square inch.

However, for CBR values greater than 12 the curve representative of the above was extended as shown in Plate 1 of reference (4).

Total wheel load was assumed to be 5000 pounds and the tire pressure 70 psi. Also, it should be noted that the thickness obtained from equation (7) is for 5000 coverages.

In order 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 5000 pound wheel load (see page 77).

Based on Table 4.4 of reference (25) it is seen that there are approximately 2.2 trips of a 5000 pound wheel load required for one coverage. Therefore, the thickness obtained from equation (6) should be adjusted for 10.6 million coverages. The adjustment in thickness will be made in accordance with Plate 3 of reference (4).

Based on an extension of the aforementioned plate it is found that for 10.6 million coverages 176 percent design is required. Thus the pavement thickness determined on the basis of 5000 coverages must be increased

by 76 percent. Required thickness for both 5000 and 10.6 million coverages are given in Tables 18.

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. Considering the B-horizon in some instances the greater thickness of pavement was obtained utilizing the CBR method and on about equal occasions the stabilometer gave the greater thickness. However, considering the C-horizon, in the great majority of cases the CBR method produced the greater thickness.

Finally, one should note the effect of variation in CBR-value. From Table 11 it is apparent that 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 Equation 7).

Grain Size Distribution

The most significant fact which can be obtained from the grain size distribution data is the large difference in variability between the percent finer than 0.002mm based on the ASTM method and that when the sample was obtained by dry sieving on the No. 200 sieve. The explanation can be found in the method of preparation of the sample.

After a soil has been dried the clay particles agglomerate forming strong bonds. These are very difficult to breakdown into the individual particle sizes. Therefore, even after much manipulation the majority of the clay size particles remained as aggregations. Thus, when the tests were run, since no time was allowed for soaking, the actual quantity of the clay size fraction could not be determined. Those agglomerations of clay particles would be of silt size which would decrease the amount of the clay size fraction as well as the variability of the percent $< 0.002\text{mm}$.

To summarize the above it is sufficient to say that the difference in the method of test is the main reason that the percent finer than 0.002mm, as determined by the two methods, do not reasonably agree.

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 the above, since the unconfined compressive strength is very sensitive to the amount of cohesion, it is to be expected that the variability of the results would 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 which 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 adequately define this property over a relatively large area.

SUMMARY OF RESULTS AND CONCLUSIONS

One of the most important facts obtained from this study is that soil variability is a function of the property being measured. For example, a soil may be highly variable as regards the R-value but its variability might be much less when considering O.M.C. Such must be taken into consideration when attempting to establish the variability of a given deposit.

The properties measured, in this study, and the appropriate absolute value of the total variance, σ_T^2 , are summarized below.

<u>Property</u>	<u>σ_T^2</u>
Optimum moisture content	2.25
Swelling pressure (Hveem)	3.33
Optimum density	9.19
Plastic limit	9.27
CBR	13.69
% < 0.002mm (dry sieving)	15.64
Plasticity index	16.66
Liquid limit	35.48
% < 0.002mm (ASTM method)	67.12
% < No. 200	79.45
R-value	144.47
Unconfined compressive strength	204.41

The above list indicates the order of magnitude of the variability and at

the same time relative values of the absolute variability. However, it should be noted that this arrangement does not clearly present all the factors involved. For example, the $\sigma_T^2 = 3.33$ for swelling pressure has a greater effect in design than the $\sigma_T^2 = 144.47$ for the R-value. The above is due to the much greater effect of a change in swelling pressure on design thickness.

The method of selecting boring sites depends upon the factors which tested significant in the analyses of variance. For the most precise results, the factors which tested significant and are not included in the determination of σ_T^2 should be held constant. With this in mind the following list was compiled.

<u>Property</u>	<u>Factors to be held constant</u>
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
% finer 0.074mm	Horizons
% finer 0.002mm	Topography and horizons
Unconfined compressive strength	Topography and horizons

County never tested significant for any of the properties listed above. 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, to obtain a more accurate estimate it would be better to base same on samples from both counties. For example, if it is desired to define certain properties of a soil within a specified limit and ten borings are required, if the areas of interest are far apart it would be better to base estimates on five samples from each area rather than ten samples from one of the areas. 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 thesis are based on soils pedologically classified as Brookston (depressions) and Crosby (rises). Consequently, the variance estimates are strictly valid for these soils alone. Consequently, if the data were applied, by mistake, to soils which did not fit either of these classifications error would 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 since the B-horizon soils were derived from the C-horizon soils. However, it was not possible 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 this signifies that 50 percent of the time the structure will be over-designed and 50 percent of the time it will be underdesigned. 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 previously shown (equation 2).
2. Based upon the significance level chosen, establish the relationship between the number of borings and the limit of accuracy, as previously indicated (equation 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 operation 3.

The above procedure will insure that on the average the pavement 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.

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

1. In order 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 upon the degree of precision required for the properties of interest. However, with the exception of the highly variable properties the aforementioned number of 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 prior to 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 the one operator for a given series of test.
6. The ASTM method for determining the percent finer than 0.002mm is more accurate than the dry sieving method outlined previously. The latter procedure, even though the results are much less variable, underestimates the quantity of the clay size fraction present in a given soil. For the soils used in this study the error could be as much as 30 percent.
7. Due to the magnitude of the error which 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.

8. The Hveem method of flexible pavement design, as regards 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 the fact that design thickness is 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. Due to the fact that 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.

9. 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.
10. Based on the variability of the data presented in this thesis, it appears that 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 will occur within a given area due to the variation in the parameter which forms the basis for the design. Also, such variation in results strongly suggests the use of a statistical approach to pavement design.
11. Disparity in variability between the unconfined compression, CBR and stabilometer tests is probably due to the failure criteria, and the fact that the latter two tests are run on soaked samples. (See Appendix B.) In essence, all three tests are triaxial in nature.

PROPOSED RESEARCH

In light of the information previously presented it is recommended that future research, in this area, take the following form:

1. Determination of soil variability, for other parent material areas and,
2. Clarification of the effect of quantity and type of clay minerals on soil variability, as measured by standard engineering tests.

The aim of the first proposal is to determine if the variability, as determined by a given test is independent of parent material type. If not, to determine that portion of the variability which is due to parent material.

The second study is quite similar in approach. Its purpose would be to ascertain the effect of the type and quantity of clay minerals present on soil variability. Also, it would be of interest to determine the effect of the variation of the aforementioned factors on the magnitude of the property being measured. For example, much difficulty was obtained in obtaining a density comparable to the standard AASHO test when using kneading compaction (150 psi foot pressure) for sample 13C. It happens that this sample contains an insignificant quantity of illite.

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APPENDIX A

Summary of Unconfined Compression Test,
Hveem Tests and California Bearing Test Data

NOTATION

The symbols used in the tables in this section and not previously defined have the following meaning:

E , strain at failure

M.C., w_i , molding moisture content

Q_u , unconfined compressive strength

T_E , thickness of flexible pavement required to prevent swell

T_R , thickness of flexible pavement required for stability -
based on Hveem Stabilometer Test

t_1 , thickness of flexible pavement, based on the CBR method of
design, required for 5000 coverages of a 5000 pound wheel
load

t_2 , the thickness t_1 adjusted for 10.6 million coverages

γ_o , γ_k , as compacted dry density

γ_a , dry density obtained from the Standard AASHTO compaction
test

TABLE 17a. SUMMARY OF HVEEM TEST DATA - DEPRESSIONS
(Tipton County)

Sample No.	w _i (%)	Y _k (pcf)	Y _k /Y _a (%)	Swelling pressure (psi)	R-value	T _E (inches)	T _R (inches)
1B	16.5	107.0	100.3	7.5	16.7	99.8	16.7
3B	16.6	110.1	102.8	4.0	25.0	53.6	18.6
6B	17.8	99.6	101.4	10.0	8.0	132.9	23.5
8B	17.9	107.0	103.4	4.8	19.0	63.5	20.4
10B	18.4	107.4	102.2	3.8	16.8	51.0	21.0
12B	18.2	107.0	105.1	3.9	20.8	52.5	19.8
14B	17.7	108.1	107.8	4.6	19.1	61.0	20.3
16B	17.6	109.5	106.6	3.4	24.1	44.9	18.9
18B	17.6	109.9	105.1	3.9	22.3	51.5	19.4
20B	18.1	101.2	99.5	4.1	17.2	53.9	21.8
1C	14.1	106.0	92.2	6.7	5.1	89.4	24.3
3C	10.8	120.4	99.2	0.2	53.5	2.7	10.5
6C	11.8	119.4	99.9	1.3	21.0	17.7	19.8
8C	12.3	119.1	99.7	10.0	33.0	13.2	16.2
10C	13.7	117.9	103.0	2.1	20.2	27.4	20.0
14C	11.5	114.1	98.0	4.2	9.9	55.5	23.0
16C	14.3	111.7	99.7	2.4	17.6	32.3	17.6
18C	11.2	121.3	99.0	2.0	19.9	26.2	20.1
20C	11.0	124.5	105.0	0.7	23.8	9.3	18.9

TABLE 17b. SUMMARY OF HVEEM TEST DATA - RISES
(Tipton County)

Sample No.	w _i (%)	γ_k (pcf)	γ_k/γ_a (%)	Swelling pressure (psi)	R-value	T _E (inches)	T _R (inches)
2B	17.2	110.5	103.3	2.4	24.9	31.5	18.6
4B	17.9	103.5	102.1	4.7	10.5	63.0	22.5
5B	17.8	104.0	104.3	4.3	18.5	56.7	20.5
7B	16.6	105.0	100.2	2.8	20.0	37.8	18.9
9B	17.7	105.2	102.0	3.1	21.2	40.7	19.7
11B	17.0	107.6	100.8	3.4	23.0	45.7	19.2
13B	17.5	104.0	101.6	3.6	27.0	48.2	18.1
15B	16.7	110.2	101.8	2.2	25.0	29.0	18.6
17B	18.2	103.6	103.9	4.6	11.0	60.9	22.6
19B	17.5	104.5	100.5	3.8	18.5	49.8	20.5
2C	10.6	123.1	100.4	1.0	23.0	13.0	19.2
4C	11.1	116.0	97.5	3.8	8.5	49.8	23.4
5C	11.1	119.0	98.7	1.5	23.0	19.6	19.2
7C	11.5	120.0	101.3	2.3	14.2	30.4	21.7
9C	11.0	124.5	102.0	0.7	23.8	9.3	19.0
11C	11.1	125.2	102.3	0.8	21.4	10.9	19.7
13C	12.7	109.0	88.2	3.4	9.5	45.5	23.1
15C	11.0	122.1	100.5	1.5	37.0	19.3	15.2
17C	11.2	122.2	101.4	1.1	26.0	14.9	18.4
19C	11.0	121.0	101.2	0.7	50.0	9.0	11.5

TABLE 17c. SUMMARY OF HVEEM TEST DATA - DEPRESSIONS
(Madison County)

Sample No.	w _i (%)	Y _k (pcf)	Y _k /Y _a (%)	Swelling pressure (psi)	R-value	T _E (inches)	T _R (inches)
22B	16.5	106.9	99.7	9.6	12.9	127.0	22.1
24B	17.6	109.6	104.9	3.0	17.5	39.2	20.8
26B	16.2	110.8	103.9	3.7	19.0	48.6	20.4
28B	17.5	110.8	104.9	3.4	20.7	44.6	19.9
30B	17.6	107.1	104.5	3.9	12.7	51.7	22.2
32B	17.8	109.6	106.0	3.3	21.8	44.5	19.5
34B	18.0	106.8	100.3	4.2	18.3	56.4	20.6
36B	17.9	109.9	106.9	1.7	25.5	22.1	18.5
38B	18.4	107.4	103.0	2.4	19.1	31.4	20.4
40B	18.0	106.8	103.1	5.6	17.4	73.8	20.8
22C	12.2	121.0	101.0	1.5	20.7	19.7	19.9
24C	11.6	115.1	100.8	3.2	14.0	42.9	21.8
26C	11.7	122.0	102.1	1.5	29.2	19.4	17.4
28C	12.3	117.7	101.1	3.3	13.8	43.2	21.8
30C	11.7	121.8	101.4	1.7	34.0	23.2	16.1
32C	11.8	122.0	101.8	1.7	23.8	23.0	19.0
34C	11.0	122.5	100.6	1.3	20.8	17.8	19.8
36C	11.0	124.5	101.5	1.1	30.2	15.1	17.1
38C	14.2	116.0	100.4	1.2	29.1	16.2	17.4
40C	12.1	123.7	103.0	0.9	19.9	11.4	20.1

TABLE 17d. SUMMARY OF HVEEM TEST DATA - RISES
(Madison County)

Sample No.	w _i (%)	γ_k (pcf)	γ_k/γ_a (%)	Swelling pressure (psi)	R-value	T _E (inches)	T _R (inches)
21B	18.2	105.8	103.1	5.6	15.5	74.6	21.4
23B	17.6	105.7	102.1	3.9	22.4	52.1	19.4
25B	17.3	108.4	100.7	1.6	25.0	21.2	18.6
27B	16.5	108.3	101.6	1.6	23.8	20.7	19.0
29B	18.2	107.8	102.1	2.2	27.2	28.9	18.0
31B	17.6	105.3	101.9	2.7	33.0	36.8	16.3
33B	18.5	106.4	103.4	2.4	31.6	31.5	16.7
35B	17.2	107.1	103.4	2.0	30.7	26.7	17.0
37B	17.0	108.7	104.1	2.4	19.4	32.3	19.4
39B	18.4	103.4	101.0	2.0	29.6	25.9	17.3
21C	12.4	115.8	101.0	4.2	9.9	56.4	23.0
23C	41.6	113.2	99.5	0.6	42.9	7.8	13.5
25C	12.2	120.0	101.2	2.1	14.0	27.2	21.5
27C	12.1	120.3	102.5	3.8	20.5	50.0	19.9
29C	11.6	114.5	95.9	2.6	9.2	34.4	23.0
31C	11.8	116.6	99.7	3.9	7.0	52.5	23.8
33C	11.6	117.0	99.4	3.5	6.3	46.5	26.8
35C	11.2	122.4	99.4	2.0	16.0	26.2	21.2
37C	11.6	120.2	102.4	2.2	23.2	29.7	19.1
39C	12.2	115.4	99.6	0.3	60.0	3.4	8.6

TABLE 18a. SUMMARY OF CBR TEST DATA - DEPRESSIONS
(Tipton County)

Sample No.	M.C. (%)	γ_o (pcf)	γ_o/γ_a (%)	Swell (%)	CBR (%)	M.C. Top 1" (%)	t_1 (in.)	t_2 (in.)
1B	17.6	101.7	95.4	1.11	8.5	22.6	12.7	22.8
3B	17.7	105.9	98.4	1.13	7.3	25.2	14.2	25.6
6B	22.3	99.0	101.0	1.49	6.6	30.3	15.2	27.4
8B	19.4	102.2	99.0	.73	7.5	26.2	13.9	25.0
10B	19.0	104.0	99.0	1.00	7.6	25.0	13.8	24.8
12B	19.4	102.0	100.1	1.13	5.7	28.0	16.6	29.8
14B	19.1	100.2	99.8	1.16	7.5	28.8	13.9	25.0
16B	19.0	103.6	101.0	.42	7.4	22.7	14.1	25.4
18B	19.5	104.2	99.8	.84	8.5	23.4	12.7	23.0
20B	20.5	99.2	97.6	.45	6.9	22.4	14.6	26.2
1C	15.0	111.6	97.2	.40	7.5	19.3	13.9	25.0
3C	10.7	119.3	99.0	.25	17.6	13.2	3.4	6.12
6C	14.0	114.2	95.6	.62	2.0	16.1	30.4	54.7
8C	12.9	118.3	99.0	.16	14.0	16.6	4.64	8.36
10C	14.4	115.8	101.0	.00	4.2	18.2	20.0	36.0
12C	14.4	116.0	102.0	.29	7.4	19.7	14.1	25.4
14C	12.6	117.8	101.0	.56	13.6	16.3	4.56	8.22
16C	15.4	111.7	99.5	.27	5.0	21.1	18.1	32.6
18C	11.4	122.5	100.8	.47	6.3	14.9	15.6	28.1
20C	12.8	120.2	101.5	.20	6.5	13.7	15.3	27.6

TABLE 18b. SUMMARY OF CBR TEST DATA - RISES
(Tipton County)

Sample No.	M.C. (%)	γ_o (pcf)	γ_o/γ_a (%)	Swell (%)	CBR (%)	M.C. Top 1" (%)	t ₁ (in.)	t ₂ (in.)
2B	16.8	107.0	100.0	.76	6.4	24.0	15.4	27.7
4B	20.7	100.0	98.8	.91	9.9	25.1	11.4	20.5
5B	20.3	97.8	98.1	.33	5.6	28.8	16.9	30.4
7B	18.3	100.7	96.2	.62	9.2	25.8	11.9	21.4
9B	19.7	103.0	99.6	.48	7.7	26.0	13.7	24.6
11B	18.4	102.8	96.3	.42	6.7	22.9	15.0	27.0
13B	19.3	100.0	97.5	.76	6.2	28.3	15.7	28.2
15B	17.1	109.7	101.2	.13	12.5	N/A	5.1	9.1
17B	20.9	102.0	102.2	.49	9.0	26.0	12.2	22.0
19B	17.8	102.0	98.3	.91	6.5	27.1	15.3	27.6
2C	11.5	123.2	100.5	.22	4.1	13.4	20.4	36.7
4C	13.2	114.8	96.4	.58	8.7	19.5	12.4	22.3
5C	12.5	120.2	99.9	.00	9.4	13.2	11.8	21.2
7C	13.3	119.0	100.6	.02	3.8	16.1	21.3	38.4
9C	11.7	122.3	100.4	.62	5.4	17.5	17.2	31.0
11C	11.4	123.7	100.8	.02	4.2	13.5	20.0	36.0
13C	12.0	121.3	99.4	.31	4.1	14.6	20.4	36.8
15C	12.2	123.0	101.3	2.09	2.0	15.2	30.5	55.0
17C	11.4	122.0	101.4	.20	6.0	17.3	16.1	29.0
19C	12.5	121.0	101.2	-.24	8.3	13.8	13.0	23.4

TABLE 18c. SUMMARY OF CBR TEST DATA - DEPRESSIONS
(Madison County)

Sample No.	M.C. (%)	γ_o (pcf)	γ/γ_a (%)	Swell (%)	CBR (%)	M.C. Top 1" (%)	t_1 (in.)	t_2 (in.)
22B	18.4	103.0	96.1	1.09	6.0	25.8	16.1	29.0
24B	18.1	105.6	101.0	1.09	9.3	23.0	11.9	21.4
26B	18.7	105.3	98.8	.75	7.8	23.3	13.5	24.3
28B	19.6	104.8	99.2	.44	6.0	22.4	16.1	29.0
30B	18.9	106.0	102.2	1.11	6.7	26.7	15.0	27.0
32B	20.0	103.8	100.1	2.5	7.0	22.5	14.5	26.1
34B	17.5	107.0	100.5	.78	8.0	24.5	13.3	23.9
36B	20.0	102.8	100.0	.40	6.1	24.9	15.9	28.6
38B	17.9	101.4	97.0	1.05	8.7	22.8	12.5	22.5
40B	19.8	103.1	99.5	1.27	7.0	26.4	14.5	26.2
22C	13.4	116.1	97.3	.38	3.4	19.9	22.7	40.8
24C	14.8	113.5	99.0	.11	5.4	16.2	17.2	31.0
26C	12.2	120.0	100.0	.18	4.4	15.3	19.6	35.2
28C	13.5	116.0	100.0	.27	5.8	16.8	16.5	29.7
30C	12.4	120.0	100.0	.29	9.7	15.8	11.5	20.6
32C	11.8	120.7	100.8	.22	3.8	17.2	21.4	38.5
34C	11.5	124.2	102.2	-0.18	5.1	12.7	17.8	32.0
36C	11.4	123.4	100.8	1.53	3.8	14.2	21.4	28.5
38C	14.1	115.3	100.0	2.02	4.9	20.4	18.3	33.0
40C	11.5	115.2	96.4	1.15	3.9	18.5	21.0	37.0

TABLE 18d. SUMMARY OF CBR TEST DATA - RISES
(Madison County)

Sample No.	M.C. (%)	Y _o (pcf)	Y _o /Y _a (%)	Swell (%)	CBR (%)	M.C. Top 1" (%)	t ₁ (in.)	t ₂ (in.)
21B	19.6	101.5	99.0	1.20	8.4	25.7	12.9	23.2
23B	19.4	101.7	98.4	1.15	6.5	27.7	15.3	27.5
25B	16.7	106.1	98.8	.58	4.4	21.8	10.8	19.4
27B	17.2	106.0	99.5	.69	8.9	22.4	12.3	22.1
29B	17.5	103.3	98.0	.87	6.4	23.5	15.4	27.8
31B	18.8	103.8	100.2	.53	9.2	24.3	11.9	21.4
33B	18.3	99.7	96.9	1.40	3.7	27.7	21.6	38.9
35B	18.4	103.6	99.9	1.11	5.8	26.0	16.5	29.7
37B	19.7	104.0	99.5	.00	5.7	25.3	16.6	29.8
39B	18.7	101.4	99.0	.84	7.8	27.0	13.5	24.3
21C	15.0	114.5	10.0	.49	5.9	19.5	16.2	29.2
23C	14.1	112.0	98.5	.67	18.6	17.5	6.2	11.1
25C	13.1	119.7	101.2	.29	5.5	17.2	17.0	30.6
27C	12.1	117.5	100.0	.69	4.6	19.4	19.0	34.2
29C	12.6	118.1	99.3	.60	10.6	16.6	10.7	19.3
31C	13.4	114.2	97.6	.80	4.3	20.4	19.9	35.8
33C	13.3	117.0	99.3	.64	3.6	19.4	22.0	39.6
35C	10.5	111.3	90.5	.49	2.7	17.6	25.9	46.6
37C	12.9	117.8	100.2	.22	7.7	19.1	13.7	24.6
39C	12.9	114.0	98.6	.42	14.4	17.5	4.3	7.8

TABLE 19a. SUMMARY OF UNCONFINED COMPRESSION TEST DATA
DEPRESSIONS (Tipton County)

Sample No.	M.C. (%)	γ_o (pcf)	γ_o/γ_a (%)	Q_u (psi)	E (%)
1B	18.1	110.0	103.6	68.7	9.1
3B	17.8	110.9	103.4	65.5	10.0
6B	18.0	104.2	106.0	94.0	4.3
8B	18.3	108.5	105.0	69.5	7.5
10B	16.6	112.9	107.4	85.0	4.8
12B	18.3	108.3	106.6	77.0	8.9
14B	18.2	108.3	107.9	77.3	9.8
16B	18.1	105.6	102.8	57.0	13.5
18B	16.7	111.9	107.0	81.5	8.9
20B	18.2	104.2	102.3	56.5	3.6
1C	13.4	110.0	95.7	51.5	2.6
3C	11.2	120.0	99.6	54.1	2.8
6C	13.5	119.6	100.0	52.0	4.3
8C	13.0	120.7	101.0	49.3	4.8
10C	13.0	108.0	94.3	62.0	3.7
12C	13.5	118.5	104.2	60.0	5.3
14C	12.5	116.0	99.5	64.5	3.4
16C	13.1	106.5	95.0	73.6	2.5
18C	12.0	124.0	102.0	69.0	6.9
20C	12.5	122.0	103.0	56.7	9.0

TABLE 19b. SUMMARY OF UNCONFINED COMPRESSION TEST DATA - RISES
(Tipton County)

Sample No.	M.C. (%)	γ_o (pcf)	γ_o/γ_a (%)	Q_u (psi)	E (%)
2B	17.2	112.1	104.8	63.6	8.8
4B	18.2	105.2	104.0	90.0	4.7
5B	17.8	107.5	108.0	62.7	5.0
7B	16.5	105.5	100.8	69.1	2.8
9B	17.6	106.9	103.5	62.5	3.9
11B	16.9	109.5	102.8	93.5	5.2
13B	17.7	108.9	106.2	64.6	6.2
15B	17.7	111.8	103.2	37.6	19.0
17B	17.7	107.9	108.0	75.8	6.4
19B	16.9	108.2	104.2	68.5	4.8
2C	11.2	123.8	101.0	54.1	4.4
4C	13.3	122.9	103.5	54.0	11.6
5C	11.8	117.2	97.3	49.5	2.8
7C	13.5	121.8	102.7	58.5	6.4
9C	11.6	123.9	101.4	62.5	6.4
11C	11.8	122.8	100.0	53.2	5.1
13C	11.3	121.7	98.8	55.0	3.8
15C	11.9	121.2	99.8	43.0	3.5
17C	11.7	121.0	100.2	60.0	4.4
19C	13.0	121.0	101.3	31.2	7.5

TABLE 19c. SUMMARY OF UNCONFINED COMPRESSION TEST DATA -
DEPRESSIONS (Madison County)

Sample No.	M.C. (%)	γ_o (pcf)	γ_o/γ_a (%)	Q_u (psi)	E (%)
22B	17.8	111.0	103.4	76.0	8.7
24B	16.6	109.5	104.8	77.0	4.8
26B	16.5	113.7	105.6	64.1	9.8
28B	17.1	111.2	105.2	73.0	10.3
30B	17.5	108.4	105.0	83.5	8.7
32B	18.3	110.5	106.9	60.0	10.5
34B	17.6	111.2	104.6	66.0	10.5
36B	18.2	110.4	107.5	66.1	10.3
38B	17.0	113.1	108.2	52.5	12.5
40B	17.7	109.3	105.8	81.7	8.8
22C	12.6	121.7	101.5	63.2	6.0
24C	11.3	109.5	95.9	60.1	1.9
26C	13.2	121.5	101.6	63.4	8.0
28C	13.1	116.6	100.1	68.1	3.1
30C	11.9	116.9	97.4	57.3	3.0
32C	11.8	118.9	99.0	65.6	3.1
34C	11.8	125.5	103.0	57.7	8.9
36C	12.1	124.4	101.5	55.6	8.5
38C	12.8	114.2	99.2	59.0	2.9
40C	11.3	113.8	95.0	61.6	2.0

TABLE 19d. SUMMARY OF UNCONFINED COMPRESSION TEST DATA - RISES
(Madison County)

Sample No.	M.C. (%)	γ_o (pcf)	γ_o/γ_a (%)	Q_u (psi)	E (%)
21B	18.2	108.6	105.9	74.0	9.8
23B	18.3	108.4	105.1	54.5	6.9
25B	17.4	112.9	104.9	64.3	7.6
27B	18.0	108.8	102.1	36.5	14.8
29B	18.1	111.4	105.5	43.9	15.7
31B	16.6	106.2	102.7	45.5	3.3
33B	18.4	106.1	103.0	66.2	5.5
35B	17.9	108.0	104.3	49.0	8.5
37B	16.8	110.0	105.0	68.5	5.5
39B	18.4	105.0	102.5	50.5	4.8
21C	12.7	116.0	101.2	7.5	2.6
23C	13.2	113.1	99.4	31.7	2.8
25C	13.2	120.3	101.5	66.9	5.9
27C	12.8	121.9	104.0	64.2	6.7
29C	13.6	121.0	101.5	54.1	6.4
31C	13.3	121.0	103.2	64.5	5.4
33C	13.0	121.1	102.8	69.0	7.7
35C	11.4	117.7	95.3	57.5	3.5
37C	12.6	122.5	104.3	59.0	7.1
39C	13.2	115.9	100.0	13.7	2.8

APPENDIX B

Discussion of the Effect of Failure Criteria on the
Variability of the Unconfined Compression Test Results

APPENDIX B

DISCUSSION OF THE EFFECT OF FAILURE CRITERIA ON THE
VARIABILITY OF THE UNCONFINED COMPRESSION TEST RESULTS

It was felt that the large magnitude of the unconfined compression test variance, $\sigma_T^2 = 204.41$, was due to the fact that it was not computed on the basis of a limiting strain criterion. Also, due to the fact that large strains are not tolerable under most engineering structures, it was considered necessary to investigate the variability of the results at some arbitrarily low value of strain.

The maximum value of strain that could be utilized was 2.5 percent. A higher value would not have permitted use of information from all available borings.

Table 20 is the result of an analysis of variance conducted on stress values at 2.5 percent strain. Comparing Table 20 with Table 16 it is evident that the unconfined compression test data are more variable when based upon the limiting strain criterion. For example the total sums of squares is much greater for the case of limiting strain (21,160.34 vs 14,700.55).

Assuming $\sigma^2 = 1$, one obtains $\sigma_{HB}^2 = 245.10$ and $\sigma_B^2 = 130.65$; therefore, σ_T^2 for the criterion of maximum stress is 204.41. Thus, by using the concept of limiting strain, the magnitude of the total variance is increased by approximately 85 percent.

Consequently, for the data presented in this thesis, the variability of the unconfined compression test results is much greater when the limiting

TABLE 20. SUMMARY OF ANALYSIS OF VARIANCE - UNCONFINED COMPRESSION TEST
(Limiting Strain Criterion)

Source of Estimate	D.f.	Sums of Squares	M.S.	EMS
Between Counties (C_i)	1	$S_i = C_i - C = 469.96$	469.96	$\sigma^2 + 2\sigma_B^2 + 40\sigma_C^2$
Depression vs Rise (D_j)	1	$S_j = C_j - C = 830.11$	830.11	$\sigma^2 + 2\sigma_B^2 + 40\sigma_D^2$
CD_{ij}	1	$S_{ij} = C_{ij} - C_i - C_j + C = 6.11$	6.11	$\sigma^2 + 2\sigma_B^2 + 20\sigma_{CD}^2$
Between Borings in (C-D cell), $B_k(ij)$	36	$S_{k(ij)} = C_{ijk} - C_{ij} = 9441.60$	262.30	$\sigma^2 + 2\sigma_B^2$
Horizons (H_l)	1	$S_l = C_l - C = 263.17$	263.17	$\sigma^2 + \sigma_{HB}^2 + 40\sigma_H^2$
HC_{il}	1	$S_{il} = C_{il} - C_i - C_l + C = 1189.66$	<u>1189.66</u>	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HC}^2$
HD_{jl}	1	$S_{jl} = C_{jl} - C_j - C_l + C = 15.58$	15.58	$\sigma^2 + \sigma_{HB}^2 + 20\sigma_{HD}^2$
HCD_{ijl}	1	$S_{ijl} = C_{ijl} + C_i + C_j + C_l - C_{ij} - C_{il} - C_{jl} - C = 84.66$	84.66	$\sigma^2 + \sigma_{HB}^2 + 10\sigma_{HCD}^2$
$HB_{lk}(ij)$	36	$S_{lk}(ij) = C_{ijkl} - C_{ijk} - C_{ijl} + C_{ij} = 8859.49$	246.10	$\sigma^2 + \sigma_{HB}^2$
Total	79	$SS = \sum_{ijkl} x^2_{ijkl} - \frac{T^2}{N} = 21,160.34$		

strain is used. However, this will not be true in all cases. When the initial slopes of the stress strain curves are not greatly different the magnitude of the total variance, based on a limiting strain, may be less than for a maximum stress criterion.

VITA

VITA

Delon Hampton was born in Chicago, Illinois on August 23, 1933. He received his primary and secondary education in the Chicago Public School System, graduating from Englewood High School in 1950.

Mr. Hampton received the BSCE degree from the University of Illinois in 1954. At this time he accepted the position of instructor, in Civil Engineering, at Prairie View A and M College, Prairie View, Texas.

After one semester at Prairie View A and M College, he entered the United States Army in January, 1955. His tour of duty was two years.

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His publications are:

Hampton, Delon and Yoder, E. J., "Effect of Rate of Strain on the Strength of Compacted Soil," Water Tensions; Swelling Mechanisms; Strength of Compacted Soil, Bulletin 245, Highway Research Board, 1960.

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