tests made in the field checked very closely the laboratory results for the composite sample These two studies showed that the material in the finished surface was not compacted to its maximum density, probably due to the fact that it had been compacted at 6 5 per cent in excess of its optimum moisture content, that there was no appreciable error in the densities obtained for the finished surface by the sand method, that there was no appreciable error in the densities obtained in the field by the Proctor method, and that the density and optimum moisture content requirements for this project were undoubtedly in error due to the fact that the preliminary sample selected for the control tests did not represent the material on the project

Since gradation is unquestionably an important factor in the density of soils, and especially so with respect to surfaces of this type, mechanical analyses and hydrometer tests were also made in the laboratory on each of the 60 samples mentioned above The average results for these tests indicated that the soil on this project consisted of 74 per cent sand, 15 per cent silt, and 11 per cent clay, or 15 per cent more sand, 9 per cent less silt, and 6 per cent less clay than was present in the preliminary sample selected for job control This difference in gradation and character of the material undoubtedly proves that the sample upon which the job requirements were based was not representative of the soil on this project

CONCLUSIONS

1 Preliminary samples on which the job control data are to be based should not be taken until the grading operations have been completed

2 Extreme care should be exercised in taking the samples on which the job control data are to be based The locations at which the samples are taken should be carefully selected and a sufficient number of samples secured to represent satisfactorily the soil types and variations within these types

3 The equipment for preparing the soil, mixing the cement, distributing and incorporating the water, and compacting the mixture, should be such that the actual time of processing will be reduced to the minimum

4 Comprehensive field tests should be conducted during the progress of the job

EXPERIMENTAL SOIL-CEMENT STABILIZATION AT CHEBOYGAN, MICHIGAN

By W S Housel

Research Consultant, Michigan State Highway Department

During the summer of 1936 the Michigan State Highway Department undertook the experimental soil-cement stabilization of a section of the Shore Line Highway near Cheboygan The Portland Cement Association cooperated in the project by conducting preliminary laboratory tests to supplement those conducted by the Research and Testing Division of the State Highway Department and also assisted in the control and supervision during construction

Construction was started on August 15 Because of frequent rains the first section of 350 ft was not processed until August 25 The last section of 700 ft was processed on October 22 and the project was discontinued on November 6 when it appeared hopeless to attempt further construction in the face of adverse weather conditions Special mention is made of the weather as it constituted the greatest difficulty encountered in the work There were 22 days out of the total 82 days of the construction period on which it rained sufficiently to stop the work During the latter part of the job Sisalkraft paper was used to protect the section under construction While this proved to be of substantial assistance it did not eliminate the difficulty which indicates that the success of this type of soil stabilization by road mix methods depends to a considerable extent upon limiting the construction to a period of less frequent rainfall The adverse weather necessarily affected the quality of the work as well as the speed with which it was conducted This factor must, in fairness, be considered in judging the Michigan project as an example of this type of construction

Some of the details employed on this particular project have been described elsewhere[1] Consequently, this discussion will present information on the design and control of soil-cement mixtures and will make only occasional reference to construction procedure and equipment Some tentative conclusions will be presented with the object of suggesting a basis for designing such mixtures and of outlining procedures to control the construction in the field

PRELIMINARY SOIL SURVEY AND SOIL CLASSIFICATION

The Michigan State Highway Department has for some years included a preliminary soil survey as an essential step in road design A soil survey based upon field surveys and soil classification used by the Soil Survey Division of the U S Bureau of Chemistry and Soils was made of the Cheboygan section of the Shore Line Highway and serves as an excellent illustration of the practical value and adaptability of this type of soil classification to highway design and construction In Figure 1 is shown a strip map giving the different soil types and their boundaries found on the section of road under discussion The characteristics of each soil profile are given in detail in the descriptions furnished with the standard soil maps, and a complete legend of the Michigan area has been prepared for department use The profiles and descriptions of each soil series on the strip map in Figure 1 have been reproduced in Figure 2 There are nine soil series identified on the map and these may be grouped into two classes In one the parent material is sand while in the other the parent material is clay One profile series, Ogemaw, is a special case, being two or three feet of imperfectly drained sand, over clay This series has been included in the clay group because, as will be seen in later discussion, the grading operations brought this clay to the surface and it played an important part in the composition of the subgrade soil The soil series are typical northern podzols with an A_0 horizon of organic debris with a characteristic leached A_1 horizon In general the surface soils were acid as might be expected in podzol soils, a fact which appeared to affect the soil stabilization in one case, which will be discussed later

The grading operations mixed the soils in the original profiles, but a correlation of these two factors can be made by a study of the grading plans, which are shown on the lower part of Figure 1 Three lines are shown which represent the finished grade in plan and also serve as the base line to show cut and fill on the center line and at points 25 ft right and left of the center line The circles on the center line represent balance points for cut and fill and, in general, indicate the disposal of soil from the cuts By comparing the profiles on Figure 2 with the

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[1] (a) "Soil-Cement Road Project-Cheboygan County, Michigan"—J W Kushing Paper for the 29th Annual Mississippi Valley Conference, February 6, 1937

(b) "Principles of Soil Stabilization"—W S Housel, Civil Engineering, May, 1937

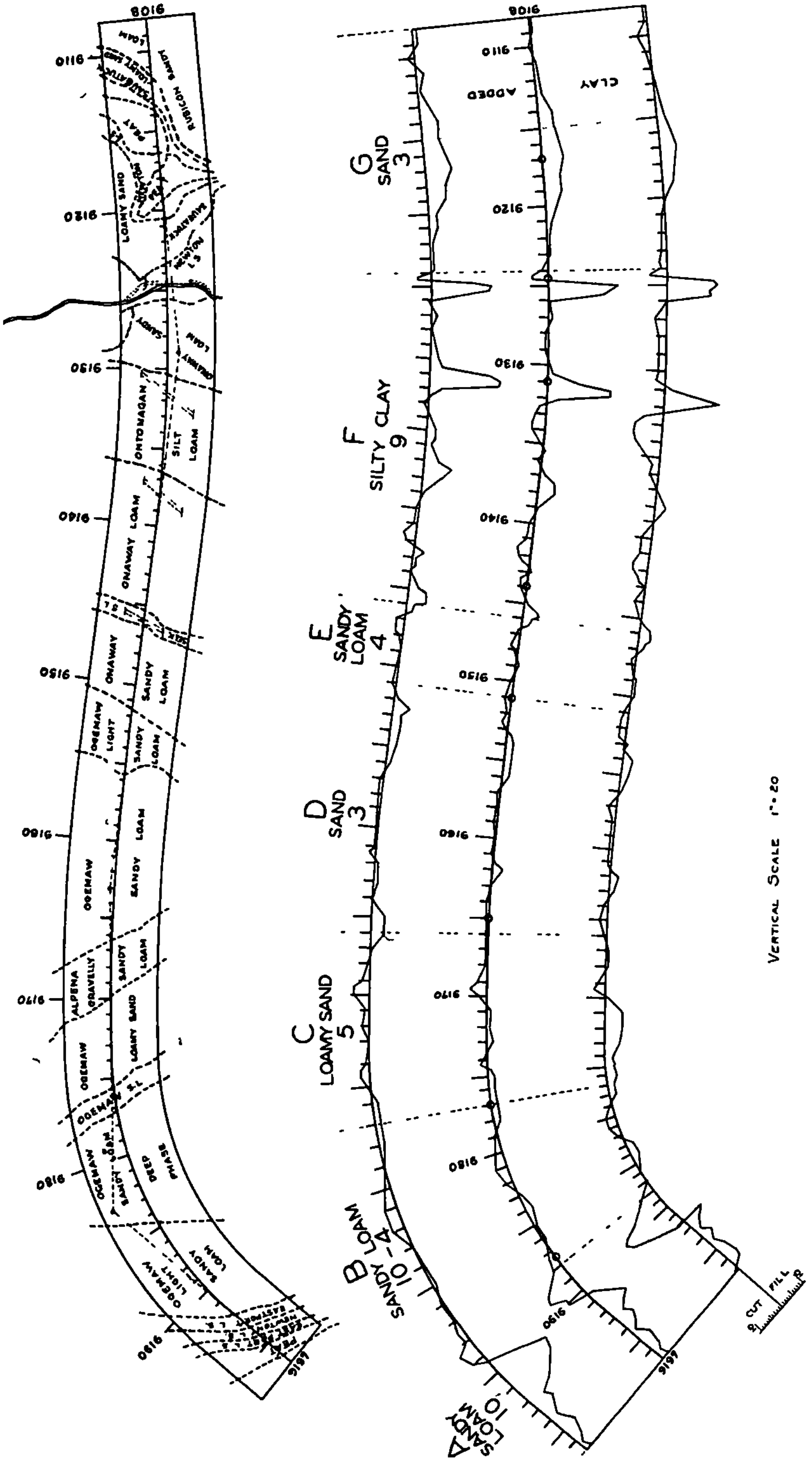
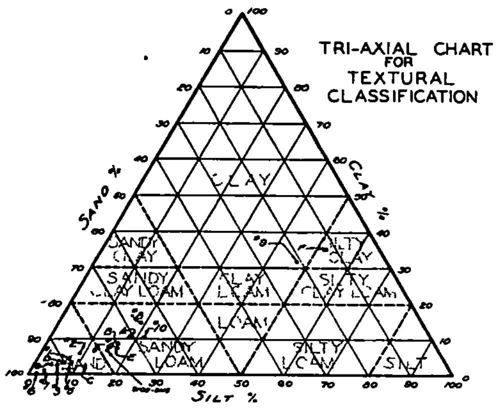


Figure 1. Soil classification from preliminary survey and grading operations



MECHANICAL ANALYSIS - PER CENT

		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Gravel		21 0	13 5	7 0	8 0	19 5	1 0	1 0	17 0	0 0	7 0
Fine Gravel		4 2	2 8	3 4	3 0	3 4	3 0	3 0	10 0	0 1	3 0
Coarse Sand		9 9	7 0	7 4	14 2	23 7	12 2	8 5	6 0	1 2	4 4
Medium Sand		22 3	20 9	22 2	30 0	29 3	40 5	40 5	17 0	2 5	19 6
Fine Sand		28 2	34 8	49 2	21 2	5 6	37 5	38 0	16 0	5 0	22 5
Very Fine Sand		5 2	6 5	3 8	6 1	3 3	4 0	4 7	6 0	11 9	13 5
Silt		5 8	7 5	5 0	11 5	6 5	1 5	3 3	16 0	47 3	20 4
Clay		3 4	5 0	2 0	6 0	2 7	0 3	1 0	12 0	32 0	9 6
Adjusted Soil Mortar Percentage	Sand	88 4	85 2	92 5	81 0	88 5	98 2	95 7	66 2	20 7	67 7
	Silt	7 3	8 9	5 4	12 5	8 1	1 5	3 3	19 3	47 3	22 0
	Clay	4 3	5 9	2 1	6 5	3 4	0 3	1 0	14 5	32 0	10 3

Figure 3

The soil profile is still Ogemaw with one fairly heavy cut of sufficient magnitude to supply from the deeper clay horizon a considerable amount of soil fines for combination with the sand of the upper horizon

In Section C between Sta 9177 and Sta 9166 there is one cut through an Alpena profile in which the parent material is described as coarse sand or gravel, being a beach ridge of an extinct glacial lake This material is scattered over the adjacent Ogemaw profile and the resulting soil in finished grade is classified as loamy sand with a mechanical analysis of 86 per cent sand, 12 per cent silt, and 2 per cent clay which may be compared to Laboratory Sample No 5.

From Sta 9166 to Sta 9151, the grade is laid in the sand horizon of the Ogemaw profile and there is very little cut and fill The soil in the finished grade is described as sand with a mechanical analysis of 90 per cent sand, 6 5 per cent silt, and 3 5 per cent clay, very close to the No 3 sample used in laboratory tests

TABLE 1

Classification of Soil Textures

Section	Station Numbers	Soil Texture (Field)			Laboratory Sample Number	Texture
		Sand	Silt	Clay		
A	9197 to 9188	71 1	17 8	11 1	10	Sandy loam
B	9188 to 9177	76 1	17 3	7 6	10-4	Sandy loam
C	9177 to 9166	86 0	12 0	2 0	5	Loamy sand
D	9166 to 9151	89 9	6 6	3 5	3	Sand
E	9151 to 9146	75 4	17 4	7 2	4	Sandy loam
F	9146 to 9124	11 5	51 5	37 0	9	Clay
G	9124 to 9108	92 6	4 1	3 3	3	Sand
15% Clay Added	9155 to 9108	78 4	14 4	7 2	4	Sandy loam

depth of cut it can be determined reasonably well whether or not any substantial amount of soil from the deeper horizons has been brought up and mixed with surface layers in the finished grade A detailed description of soils in the finished grade will be attempted on this basis

Before discussing the grading operation, however, it appears desirable to present the data in Figure 3 which gives the mechanical analysis of ten preliminary samples taken from the finished grade These ten samples were taken by the project engineer without reference to the original soil survey and represented his attempt to distinguish by visual inspection the different types of soil in the finished grade As later analysis reveals, four types would have been sufficient for preliminary tests, but as a matter of fact complete laboratory tests were made on all ten It is believed that the later analysis also shows that an intelligent correlation of the soil survey and grading operation would have established that four different textural classes were sufficient to establish an adequate design of the soil-cement mixture

In Figure 3 the ten soils have been classified on the basis of the texture of the soil mortar or material passing the No 10 sieve The results are plotted on a triaxial chart with the textural classes used by Eno [2] From this triaxial chart four types of soil may be selected and these will be referred to in subsequent discussion as sand, loamy sand, sandy loam, and clay

The sand includes Samples 3, 6, and 7.

The loamy sand includes Samples 1, 2, 4, and 5.

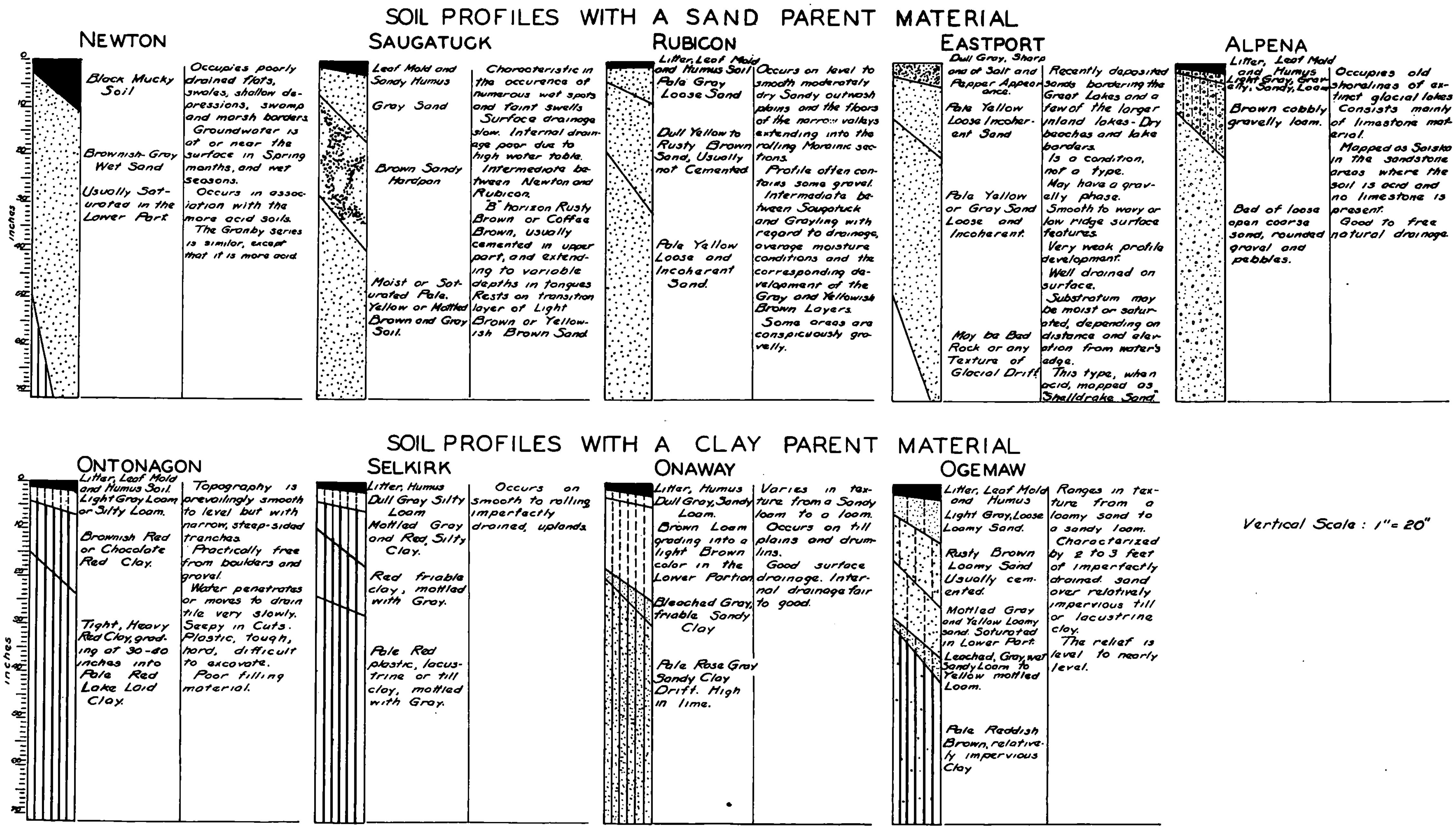
The sandy loam includes Samples 8 and 10

The clay is Sample 9

During construction, check samples were taken of the soil at frequent intervals in each section and sent to the laboratory for mechanical analysis These data are shown in Table 1 which gives the percentage of sand, silt and clay in composite analyses between the stations selected as nearly as possible to coincide with balance points These data have been plotted with the ten original samples shown in Figure 3 and a notation shown in Figure 1 gives the original sample number which is most representative It will be noted that of the original ten samples used in laboratory tests only five were shown in the final classification, namely, 3, 4, 5, 9, and 10 These samples, however, may be represented by the four textures used in the final classification, i e , sand, loamy sand, sandy loam, and clay

As the first step in construction, it is required that the organic material, black muck and leaf mold, be stripped and wasted Starting at the left-hand end of the stabilized section, at Sta 9197 to the balance point near Sta 9188, marked Section A, the soil in the finished grade is described as sandy loam This includes a fairly heavy cut and fill in the Ogemaw profile of two or three feet of loamy sand over clay, the clay containing some sand and gravel The mixture produced a sandy loam with 71 per cent sand, 18 per cent silt and 11 per cent clay, which is fairly well represented by Sample No 10 on Figure 3 with 68 per cent sand, 22 per cent silt, and 10 per cent clay For Section B between balance points at Sta 9188 and Sta 9177 the check samples showed 76 per cent sand, 17 per cent silt and 8 per cent clay, which is a sandy loam and may be compared to Laboratory Sample No 4 with 81 per cent sand, 13 5 per cent silt, and 6 5 per cent clay, although it is more accurately described as intermediate between Laboratory Samples 10 and 4

[2] "Some Effects of Soil, Water, and Climate Upon the Construction, Life and Maintenance of Highways"—Eng Exp Station, Bulletin No 85, Ohio State University



NEWTON: Occupies poorly drained flats, swales, shallow depressions, swamp and marsh borders.

Groundwater is at or near the surface in Spring months, and wet seasons.

Occurs in association with the more acid soils.

The Granby series is similar, except that it is more acid.

SAUGATUCK: Characteristic in the occurence of numerous wet spots and faint swells.

Surface drainage slow. Internal drainage poor due to high water table.

Intermediate between Newton and Rubicon.

"B" horizon Rusty Brown or Coffee Brown, usually cemented in upper part, and extending to variable depths in tongues. Rests on transition layer of Light Brown or Yellowish Brown Sand.

RUBICON: Occurs on level to smooth moderately dry Sandy outwash plains and the floors of the narrow valleys extending into the rolling Morainic sections.

Profile often contains some gravel.

Intermediate between Saugatuck and Grayling with regard to drainage, average moisture conditions and the corresponding development of the Gray and Yellowish Brown Layers.

Some areas are conspicuously gravelly.

EASTPORT: Recently deposited sands bordering the Great Lakes and a few of the larger inland lakes - Dry beaches and lake borders.

Is a condition, not a type.

May have a gravelly phase.

Smooth to wavy or low ridge surface features.

Very weak profile development.

Well drained on surface.

Substratum may be moist or saturated, depending on distance and elevation from water's edge.

This type, when acid, mapped as "Shelldrake Sand."

ALPENA: Occupies old shorelines of extinct glacial lakes. Consists mainly of limestone material.

Mapped as Saisko in the sandstone areas where the soil is acid and no limestone is present.

Good to free natural drainage.

ONTONAGON: Topography is prevailingly smooth to level but with narrow, steep-sided trenches.

Practically free from boulders and gravel.

Water penetrates or moves to drain tile very slowly. Seepy in Cuts. Plastic, tough, hard, difficult to excavate.

Poor filling material.

SELKIRK: Occurs on smooth to rolling imperfectly drained, uplands.

ONAWAY: Varies in texture from a Sandy loam to a loam.

Occurs on till plains and drumlins.

Good surface drainage. Internal drainage fair to good.

OGEMAW: Ranges in texture from a loamy sand to a sandy loam.

Characterized by 2 to 3 feet of imperfectly drained sand over relatively impervious till or lacustrine clay.

The relief is level to nearly level.

Figure 2. Soil series mapped on Cheboygan County Cement Stabilization Project

The short Section E between Sta 9151 and Sta 9146 is in the Onaway profile of a sandy clay parent material The mechanical analysis of the grade sample shows 75 per cent sand, 17 per cent silt, and 7 per cent clay, which is a sandy loam very similar to that in Section B and comparable to Laboratory Sample No 4 This texture is in substantial agreement with the upper horizon of the Onaway profile although the sand appears to be somewhat high

Section F from Sta 9146 to Sta 9124 is the clay section left unstabilized The grading is fairly deep sidehill cut through the Onaway and Ontonagon profiles with clay parent material The mechanical analysis from the check samples shows 12 per cent sand, 52 per cent silt, and 37 per cent clay, classified as silty clay, and is fairly close to Laboratory Sample No 9

Section G from Sta 9124 to Sta 9108 is through several low-lying profiles of Newton, Saugatuck and Rubicon, all of which are from sand parent materials There is considerable waste including peat excavation and, as most of the section is in fill, material has been borrowed from an adjacent Rubicon area to supplement the excavation from roadside ditches The resulting soil is classified as sand and the grade samples are 93 per cent sand, 4 per cent silt, and 3 per cent clay giving a texture very close to Laboratory Sample No 3 Some difficulty was encountered in stabilizing this section and 15 per cent clay by weight was added in the section from Sta 9115 to Sta 9108 This changed the texture to a sandy loam with 78 5 per cent sand, 14 5 per cent silt, and 7 per cent clay which is fairly close to Laboratory Sample No 4 The addition of clay assisted the stabilization process very materially and was adopted as a tentative procedure for future work with sands of the character here encountered

LABORATORY INVESTIGATION

Purpose of Laboratory Tests

It appears from the preceding discussion that the determination of prevailing soil types or series combined with a consideration of grading operations constitutes a practical basis of soil classification for the purpose of designing the stabilized mixture Even though the final classification of these soils into four groups has been made only after a review and correlation of all available data, the same result could have been accomplished by a careful study of the soil series profiles. Although the submission of an excessive number of samples to the laboratory led to some unnecessary duplication of work which should be eliminated in regular construction procedure, this very duplication provided a rather desirable feature for an experimental project

The primary objective of the laboratory tests was to determine the proper proportions of soil, cement, and water to facilitate compaction and produce a durable stabilized mixture The tests indicated that this purpose would have been served by a few representative samples It might also appear that the results of such tests on samples taken at frequent intervals along the grade would serve as the basis for controlling construction procedure

A comparison of results produced in the field operation with the results of laboratory tests on this project, indicate that the laboratory tests are inadequate as control tests except to determine the quantity of cement which would produce durable stabilization While the preliminary tests did serve this purpose and were useful in the soil classification, they did not reflect changes in gradation and void characteristics from station to station with sufficient accuracy to serve as control tests for construction operations After some experience with control tests in the field, laboratory tests were abandoned as a measure of the proper amount of compaction or optimum moisture content It was found that one experienced operator with an occasional helper could run the density-moisture tests for each day's work without holding up the construction and could control the stabilization procedure much more effectively

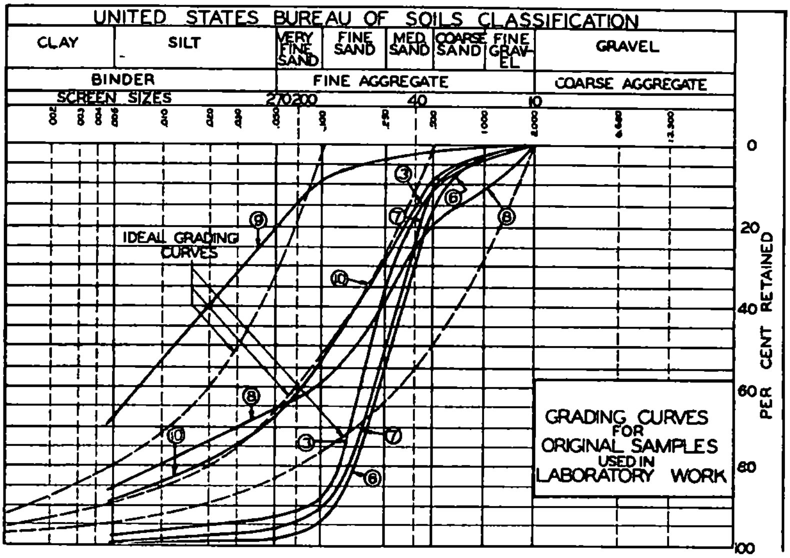


Figure 4

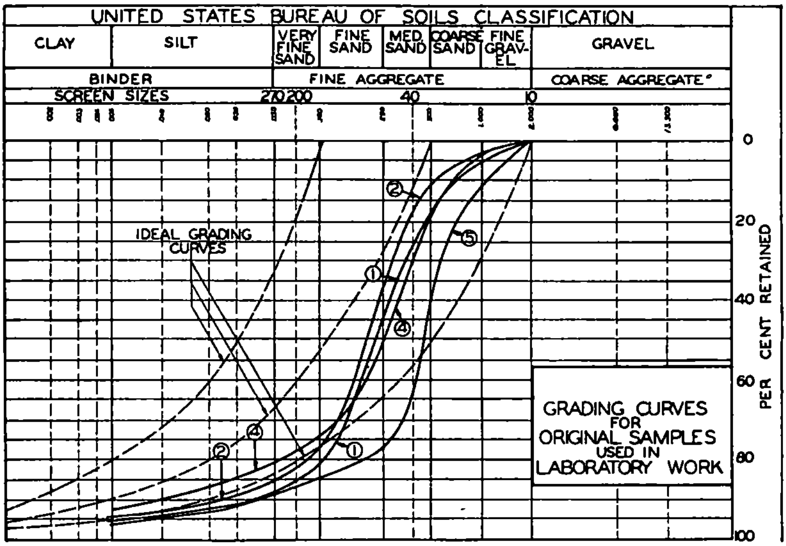


Figure 5

The laboratory investigation was conducted and practically completed before the field work could be undertaken In addition to the tests of the department, the Portland Cement Association conducted a parallel series which were the basis for their recommendations The results of tests in the two laboratories were in substantial agreement, although methods used varied in some respects This discussion will be limited to those tests conducted by the department on the ten laboratory samples previously identified

Gradation and Maximum Density

The mechanical analyses of all samples are shown in Figure 3 The material passing the No 10 sieve, soil mortar, was used in subsequent laboratory tests The gradings of the soil mortar in the various samples are shown on Figures 4 and 5 The distribution of particle size as shown by the conventional method of plotting, shows some characteristics not evident in the textures plotted on the triaxial chart, which show a definite relation to densities obtained in compaction tests The heavy dashed curves in Figures 4 and 5 represent so-called ideal gradings for maximum density for any given maximum size

In Figure 4 are shown gradings for the sand, Samples 3, 6, and 7, the sandy loam, Samples 8 and 10, and the clay, Sample 9 Samples 3, 6, and 7 are the most poorly graded and, as will be seen later, give the lowest compacted densities The clay, Sample 9, is also a poorly graded material, though not so much so as the sands, a fact which is also reflected in a higher compacted density Samples 8 and 10, the sandy loams, are the best graded materials encountered, Sample 10 being particularly close to the ideal curve for a maximum size of 0 5 mm In Figure 5 are shown the gradings of the loamy sands, Samples 1, 2, 4, and 5 Their grading is somewhat better than the sands and poorer than the sandy loams, as might be expected with an intermediate percentage of soil fines, but they do depart substantially from the ideal gradings The addition of soil fines would be a substantial improvement, but all of these materials compacted fairly well and resulted in satisfactory stabilized mixtures

The void characteristics of the ten samples and the grouping into four textures is clearly shown by the compacted densities in Figure 6 The moisture-density relations which show the optimum moisture content and maximum density were obtained by compacting the soil using the procedure developed by the California State Highway Department and described by Proctor The compacted dry densities of the sands vary from 107 2 to 109 lb per cu ft with an average of approximately 108 The loamy sands varied from 115 3 to 116.2

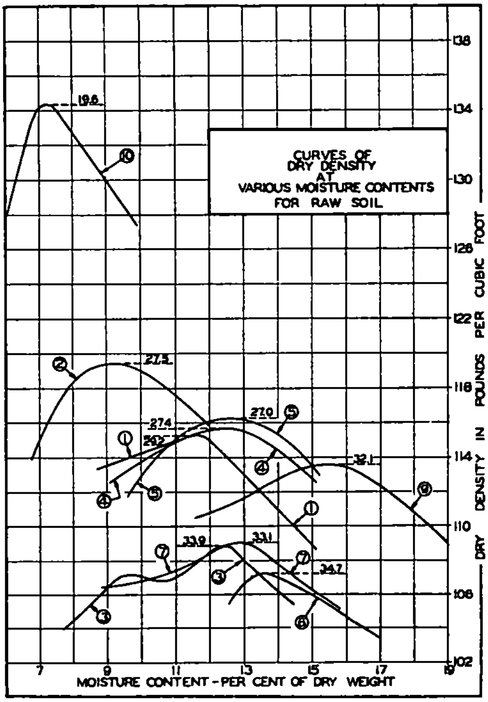


Figure 6

with the exception of Sample 2 which compacted to 119 4 lb per cu ft The sandy loam, Sample 10, gave a dry density of 134 4 lb per cu ft , the highest of any sample No tests were made on Sample 8 which was discarded as a separate classification before the laboratory investigation was started The percentage of total voids in the compacted soil is shown in connection with each curve and will be referred to later

The consistent relation between density and mechanical analysis expressed either in terms of texture or by the grading curves is the most striking feature of the data The variation in density can be predicted from the comparison between the ideal gradings and the actual grading in every case except Sample 2 Sample 2 has a percentage of voids comparable to the other loamy sands but due to a higher specific gravity, 2 64 as compared to 2 55–2 61 for the others of the group, the dry density is higher The optimum moisture content is also lower indicating less absorption which is also consistent with the higher value of specific gravity The consistent relations shown furnish a reliable basis for the grouping of the ten samples into four texture groups previously discussed

It also appears that variation in texture and grading is so accurately reflected in the compacted density that the routine density tests may be the most practical basis of designing the stabilized mixture A further fundamental advantage of the test which measures compacted density is that it directly measures the total voids which later serve as the basis for determining the required cement content

Void Characteristics of Soil-Cement Mixtures

The next step in the laboratory investigation was to compact mixtures of soil and cement using various percentages of cement in order to determine the characteristics of each mixture and to prepare samples for durability tests The mixtures were proportioned by absolute volume, the cement content being expressed as a percentage of the absolute volume of soil plus cement The moisture content was expressed as a percentage of the dry weight of the soil and cement Cement contents of 4, 6, 8, and 10 per cent were used in the preliminary tests The following example illustrates the method of proportioning the trial mixtures

Let s = absolute volume of soil
" c = " " " cement
" v = " " " voids

$$\text{Cement Content} = \frac{c}{s + c}$$

Assume 6% cement content
4000 grams oven dry soil
2 62 specific gravity of soil
3 15 " " " cement

$$s = \frac{4000}{2\ 62} = 1527 \text{ cc} = 94\% \text{ of } s + c$$

$$\frac{1527}{94} = \frac{c}{06}$$

$$c = 97\ 4 \text{ cc}$$

$$97\ 4 \times 3\ 15 = 307 \text{ g cement}$$

Assume 10% water (Per cent dry weight soil and cement)

$$\text{Water} = 10 \times 4307 = 430\ 7 \text{ g of water}$$

$$'' = \frac{430\ 7}{4737\ 7} = 9\ 1\% \text{ (Wet Basis)}$$

Mixtures using the same cement content and various moisture contents were compacted in cylindrical molds 4 in in diameter and 6½ in high The compacted sample was weighed and, knowing the volume of the mold, the dry weight per cubic foot or dry density was computed The percentage of voids in the mixture and the total voids in the compacted soil, excluding the cement, were also computed and are used in later analyses The following example is given for illustration.

Weight of compacted mixture = 2050 g
Moisture 091 × 2050 = 227 5 g

Dry soil and cement = 1822 5 g
Volume of mold 1027 9 cc

$$\text{Dry bulk specific gravity} = \frac{1822\ 5}{1027\ 9} = 1\ 775$$

Density = 1 775 × 62 4 = 110 5 lb per cu ft

The voids in the soil-cement mixture may be computed by finding the specific gravity of combined solids which is the weighted average of the specific gravities of the soil and cement as follows

$2\ 65 \times 94 = 2\ 49$
$3\ 15 \times 06 = \underline{\ 19}$
$2\ 68$ Sp gr combined solids

$$\frac{2\ 68 - 1\ 775}{2\ 68} = 338 \text{ Voids in mixture}$$

$s + c + v = 1$
$s + c = 1 - 338 = 662$ 66 2% solids
$s = 94 \times 662 = 622$ 62 2% soil
$c = 06 \times 662 = 040$ 4 0% cement

The total voids in the compacted soil without cement is the sum of voids in the mixture and the absolute volume of cement If the cement-voids ratio is defined as the ratio of absolute volume of cement to the absolute volume of voids it may be computed as follows

Total voids v = 33 8 + 4 0 = 37 8%

$$\text{Cement-voids ratio } \frac{c}{v} = \frac{4}{37\ 8} = 10\ 6\%$$

The void characteristics of typical compacted mixtures are shown in Figure 7 where the moisture density curves are given for a sand, Sample 3, a loamy sand, Sample 1, and the sandy loam, Sample 10 Sample 9, the silty clay, has been omitted as the clay section was not stabilized and no comparative field results are available. The laboratory density curves for the clay were more erratic than for the other samples, due to greater difficulty in obtaining uniform compaction by hand tamping.

In all cases the total voids in the soil skeleton were increased by the addition of cement but in the case of sands and loamy sands this trend was much less than for the finer grained soils. In other words, the cement helped to fill voids as well as to supply cohesion. In the sandy loam, No. 10, the density decreases as the cement content increases and there is a marked increase in total voids over the raw soil This tendency was also noted in the silty clay, No 9.

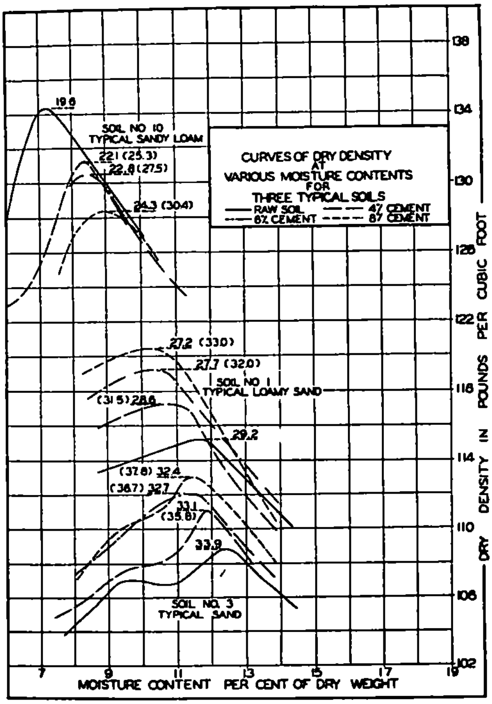


Figure 7

In these finer grained soils the cement apparently forms an expanded structure or results in a bulking effect that produces a decreased density In Figure 7 the percentage of voids in the soil-cement mixtures at maximum density has been indicated and in parentheses the total voids in the mixture, exclusive of the cement, have been shown. The increase in total voids due to bulking action of the cement must be considered in computing the cement-voids ratio and enters into the preliminary design of the mixture

The objective of the analysis of the void characteristics of the soil-cement mixtures is to obtain some practical criterion for design which will accurately reflect the properties of the stabilized mixture, particularly with respect to durability. Throughout the investigation it became increasingly apparent that the behavior of the mixture must be associated in some way with voids and that the efficiency of cement stabilization depends in some way on a relation between voids and cement This is no new idea having been employed as the basis of concrete proportioning theories It may not be too much to say that void characteristics constitute the fundamental conception applicable to any type of mixture and thus offer an obvious line of attack on any such problem

Durability Tests

Two types of durability tests were conducted following the recommendations and general procedure developed by the Portland Cement Association Specimens in the form of 4 by 6½ in cylinders were compacted at optimum moisture content for the various percentages of cement These cylinders were then subjected to cycles of freezing and thawing, and wetting and drying and were brushed and weighed after each cycle

The results are presented graphically in Figures 8 and 9 In each case the loss after 24 cycles has been plotted against the cement-voids ratio The data used in the computation of the cement-voids ratio are given in Table 2 The specimens subjected to durability tests are identified by soil sample number and cement content The specific gravity of the soil was measured by the standard test and the specific gravity of the mixture was computed using the determined value of 3 15 as the specific gravity of the cement The dry density in pounds per cubic foot was determined for each specimen and the total voids in the soil skeleton, the absolute volume of cement per unit volume of compacted mixture, and the cement-voids ratio were all computed as in the example given previously It will be noted that the dry density did not agree exactly with the density at optimum moisture content given in Figure 7 It was impossible to duplicate the maximum density in every specimen, but on the average the agreement is good The results of the durability tests have in every case been correlated with the actual cement-voids ratio of each sample

The comparison between cement-voids ratio and percentage of loss at 24 cycles of freezing and thawing in Figure 8 indicates a definite relationship All but three samples showed a 100 per cent loss or complete failure for a cement-voids ratio of less than 12 per cent All samples with cement-void ratios greater than 12 per cent show a loss of 10 per cent or less with the exception of the specimen containing the No 5 soil with 6 per cent cement, which showed a 50 per cent loss at 24 cycles and failed completely at 28 cycles The various specimens are identified at the bottom of the graph by sample number and cement content

In Figure 9 the results of the wetting and drying cycles have been plotted in exactly the same manner as in Figure 8 The durability of the various specimens also shows a very close relationship between loss and the cement-voids ratio The wetting and drying tests, while not so severe as the freezing and thawing cycles, showed frequent failures for cement-voids ratios less than 12 per cent

It is dangerous to draw sweeping conclusions from only one set of data but until an analysis of a large volume of such information is available it seems proper to discuss tentative conclusions which may serve as temporary criteria To this extent the data indicate that a cement-voids ratio of 15 per cent may produce a mixture as durable as present requirements indicate is essential

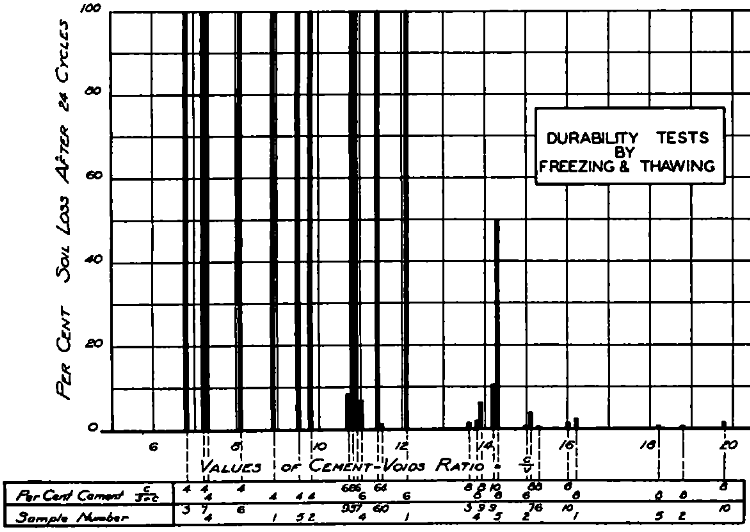


Figure 8

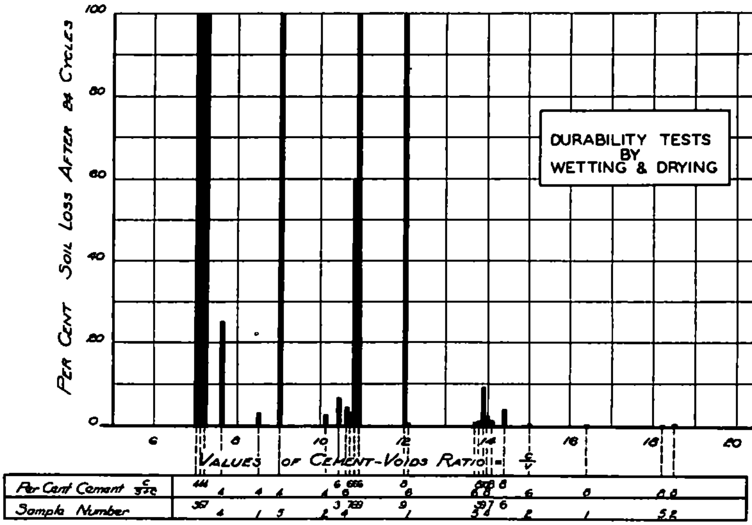


Figure 9

The manner in which the cement acts as a binding medium in a soil-cement mixture with comparatively small cement contents is a matter of speculation The character of the mixture is obviously quite different from mortar in concrete mixtures where the voids in the aggregate are filled with cement paste. The picture which the writer has in mind is a granular soil structure with little more than enough cement paste to join the particles at their points of contact The soil structure is spot-welded, so to speak.

It appears that such a conception is in agreement with the comparatively small cement-voids ratios in which only 15 per cent of the total voids are filled

TABLE 2

CEMENT-VOIDS RATIOS FOR LABORATORY DURABILITY TESTS

Laboratory Sample Number	Cement Content $\frac{s}{s+c}$	Specific Gravity		Freezing and Thawing				Wetting and Drying			
		Soil	Mix	Density of Mix Dry	Absolute Volume Cement c	Absolute Volume Total Voids v	Cement-Voids Ratio $\frac{c}{v}$	Dry Density of Mix	Absolute Volume Cement c	Absolute Volume Total Voids v	Cement-Voids Ratio $\frac{c}{v}$
	per cent			*lb per cu ft*	*per cent*	*per cent*	*per cent*	*lb per cu ft*	*per cent*	*per cent*	*per cent*
	4	2 61	2 63	116 5	2 84	31 8	8 9	114 7	2 80	32 9	8 5
1	6	"	2 64	114 8	4 18	34 5	12 1	114 9	4 18	34 5	12 1
	8	"	2 65	117 1	5 66	34 9	16 2	117 6	5 69	34 6	16 4
	4	2 64	2 66	121 4	2 92	29 8	9 8	122 3	2 95	29 2	10 1
2	6	"	2 67	124 3	4 48	29 9	15 0	124 3	4 48	29 9	15 0
	8	"	2 68	124 3	5 94	31 6	18 0	123 8	5 92	31 9	18 5
	4	2 64	2 66	107 5	2 59	37 9	6 8	109 2	2 63	36 8	7 1
3	6	"	2 67	111 3	4 01	37 2	10 8	110 0	3 96	38 0	10 4
	8	"	2 68	111 0	5 31	38 9	13 6	111 3	5 33	38 7	13 8
	4	2 55	2 57	106 3	2 66	36 3	7 3	107 7	2 69	35 5	7 6
4	6	"	2 59	108 8	4 04	36 7	11 0	107 5	3 99	37 5	10 6
	8	"	2 60	108 3	5 34	38 6	13 8	108 9	5 37	38 3	14 0
	4	2 55	2 57	116 0	2 90	30 5	9 5	114 2	2 85	31 6	9 0
5	6	"	2 59	118 8	4 41	30 9	14 3	117 5	4 36	31 7	13 7
	8	"	2 60	119 2	5 88	32 4	18 2	119 2	5 88	32 4	18 2
	4	2 63	2 65	113 8	2 75	34 0	8 1	108 7	2 63	36 9	7 1
6	6	"	2 66	113 8	4 11	35 6	11 5	111 0	4 01	37 1	10 8
	8	"	2 67	115 4	5 54	36 2	15 3	112 9	5 42	37 6	14 4
	4	2 61	2 63	108 4	2 64	36 6	7 2	108 5	2 64	36 6	7 2
7	6	"	2 64	110 7	4 03	36 9	11 0	110 0	4 01	37 2	10 8
	8	"	2 65	114 2	5 52	36 5	15 1	111 2	5 38	38 1	14 1
	6	2 68	2 71	113 0	4 01	37 1	10 8	113 0	4 01	37 1	10 8
9	8	"	2 72	113 5	5 35	38 5	13 9	107 0	5 05	41 8	12 1
	10	"	2 73	106 0	6 23	43 9	14 2	105 2	6 18	44 4	13 9
	4	2 68	2 70	129 0	3 06	26 6	11 5	128 2	3 04	26 9	11 3
10A	6	"	2 71	128 7	4 57	28 5	16 0	127 7	4 53	29 0	15 7
	8	"	2 72	128 2	6 04	30 5	19 8	127 2	6 00	31 0	19 3

The data presented in Table 2 and Figures 8 and 9 are all taken from the original laboratory tests The comparison of these data with experience in the field and the success of field control is a matter of great practical importance and will be the next subject of discussion While the more exact control in the laboratory may produce a more accurate measure of the characteristics of the soil-cement mixtures, the practical application of the criteria thus developed will depend very largely on the accuracy of field control.

FIELD CONTROL TESTS

After having selected the cement content, the control of the mixing and compaction procedure was the major problem in field control On the Cheboygan project a house trailer was equipped to serve as a field laboratory for control tests The moisture content of the soil was measured before adding the cement and was also determined on the soil-cement mixture at intervals during the mixing operation Moisture was added when required to bring the mix up to the optimum moisture content

The amount of soil in the mix was controlled by loose volume measurements of the scarified soil and by regulating the depth of scarification to produce the required dry weight of soil. The proper proportion of soil for the compacted mix was first determined from the preliminary laboratory tests already described, but it was found that variations in the soil from station to station were sufficient to necessitate compaction tests to determine optimum moisture content and maximum density for each day's work. Representative samples of the raw soil were collected from the section to be processed on the following day and the moisture-density tests run on the mixture of soil and cement The optimum moisture content and maximum density from these tests were substituted for results derived from previous laboratory tests

After the proper depth of soil had been scarified and the required amount of cement and water added and mixed, a compaction test was also made of the final mixture The density obtained was a measure of the accuracy of the proportioning and mixing and the most reliable basis of checking the degree of consolidation by sheep's foot rollers and other compacting equipment After a section had been stabilized, densities in the road were measured by boring holes in the stabilized surface, measuring the depth and volume of the hole, and weighing the material removed Samples of the soil-cement mixture were also collected and sent to the laboratory to determine the actual cement content These data for the various sections are presented in Tables 3, 4, and 5

Table 3 gives the theoretical proportions in the field, assuming that the mixture contained the selected amount of cement The computations are based on the compaction of the final mixture by hand tamping in the standard cylinder which resulted in the dry density in pounds per cubic foot given in column 7. The theoretical cement content is given in column 3 as a percentage of loose volume of cement per cubic foot of compacted mix, assuming the weight of cement as 94 lb per cu ft, loose volume This gives an arbitrary cement content, shown in column 5, amounting to 7 52 or 8 46 lb per cu ft of compacted mix for 8 or 9 per cent of the loose volume of cement, respectively These cement contents have been related to the actual mix in column 4 which gives the cement content as a percentage by weight of the dry mix. The dry weight of soil per cubic foot of compacted mix is given in column 6. The dry weight of soil and cement can be reduced directly to their absolute volumes by dividing by the product of the specific gravity times 62 4, and are given in columns 8 and 9 as a percentage of the unit volume made up of soil, cement, and voids The cement-voids ratio is given in column 9

It may be noted that the cement-voids ratio provided for in the design is less than 15 per cent in all cases, ranging from a low of 11 per cent to a high of 13 per cent In the light of final results of the durability tests there appears to be good reason to question the proportions used as being somewhat lower than desirable It may also be pointed out that the computations are based on the average dry density over a number of stations and, as shown in Table 5, the density range in individual cases may vary approximately 5 lb per cu ft above or below the average. The cement-voids ratio would also show a larger variation than given in Table 3 as the void space in the soil structure is increased or decreased

In Table 4 are shown the actual proportions of the soil-cement mixture computed in the same way as in Table 3 except that the cement contents are determined by laboratory analysis of the mixture Samples of the raw soil and cement were taken at identical stations from which samples of the soil-cement mixture were later obtained The laboratory made a determination of the calcium oxide (CaO) in the mixture and in the soil and cement samples and calculated the cement content from these proportions A comparison of the cement content in percentage of the dry mix in Tables 3 and 4 shows that the actual cement content is considerably higher than the theoretical The theoretical values vary from 6 12 to 7 54 per cent while

TABLE 3

THEORETICAL PROPORTIONS OF FIELD MIXTURE

Section	Station Numbers	Cement Content Per Cent		Field Mixture Compacted in Cylinder					
				Proportions by Dry Weight			Absolute Volume in Per Cent		
		Loose Volume (P C A)	Dry Mix	Lb per Cu Ft			$\frac{s}{s+c+v}$	$\frac{c}{s+c+v}$	$\frac{c}{v}$
				Cement	Soil	Mix			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
A	9197 to 9188	8	6 20	7 52	113 7	121 2	68 9	3 83	12 3
B	9188 to 9177	8	6 15	7 52	114 6	122 1	69 5	3 83	12 6
C	9177 to 9166	8	6 12	7 52	115 3	122 8	70 0	3 83	12 8
D	9166 to 9151	8	6 54	7 52	107 5	115 0	65 2	3 83	11 0
E	9151 to 9146	9	7 12	8 46	110 3	118 8	66 9	4 31	13 0
F	9146 to 9124	—	—	—	—	—	—	—	—
G	9124 to 9108	9	7 54	8 46	103 7	112 2	62 6	4 31	11 5
15% Clay Added	9115 to 9108	8	6 52	7 52	107 6	115 1	65 3	3 83	11 0

Columns 7–8 $s + c + v = 1$ $\frac{s}{s + c + v} = s$ and $\frac{c}{s + c + v} = c$

Column 10 $\frac{c}{v} = \frac{c}{1 - s}$ Theoretical cement-voids ratio actual values vary from 6 42 to 10 53 per cent The actual cement-voids ratios vary from 13 1 to 15 5 as compared to a range of 11 0 to 13 0 in Table 3

While the higher values of cement-voids ratio actually obtained compare more favorably with the 15 per cent apparently required by the durability tests, they also show a failure to obtain a thorough mixture for the full depth supposed to be stabilized It was observed in the field that it was difficult to obtain the full depth of scarification required with the equipment used It was also difficult to mix for the full depth of the loose soil It is entirely probable under these conditions that either the amount of soil stabilized is less than intended or that cement contents are high in the surface and low at the bottom of the stabilized layer In any event, the high cement contents indicate poor control to some extent and a deficiency either in thickness of stabilized base or uniformity of stabilization, both of which are detrimental

TABLE 4

ACTUAL PROPORTIONS OF FIELD MIXTURE

Section	Station Numbers	Cement Content Per Cent	Field Mixture Compacted in Cylinder						
			Proportions Dry Weight in lb per cu ft			Absolute Volumes in Per Cent			
		Dry Mix	Cement	Soil	Mix	Soil $\frac{s}{s+c+v}$	Cement $\frac{c}{s+c+v}$	Total Voids 1-s	$\frac{c}{v}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
A	9197 to 9188	6 42	7 8	113 4	121 2	68 7	3 97	31 3	12 7
B	9188 to 9177	7 90	9 6	112 5	122 1	68 0	4 89	32 0	15 3
C	9177 to 9166	7 80	9 6	113 2	122 8	68 5	4 89	31 5	15 5
D	9166 to 9151	8 02	9 2	106 8	115 0	64 5	4 68	35 5	13 2
E	9151 to 9146	8 20	9 7	109 1	118 8	66 0	4 94	34 0	14 5
F	9146 to 9124	—	—	—	—	—	—	—	—
G	9124 to 9108	10 53	11 8	100 4	112 2	60 7	6 00	39 0	15 3
15% Clay Added	9115 to 9108	8 11	9 3	105 8	115 1	64 0	4 73	36 0	13 1

Columns 7-8 $s + c + v = 1 \quad \frac{s}{s + c + v} = s$ and $\frac{c}{s + c + v} = c$

Column 10 $\frac{c}{v} = \frac{c}{1 - s}$ Actual cement-voids ratio

Table 5 is a comparison of densities of the stabilized mixture measured in three different ways for comparison The first three columns identify the section and type of soil Column 4 gives the actual cement content in per cent of the absolute volume of soil and cement which is the basis of proportioning the laboratory mixes. Column 5 gives dry densities obtained in the laboratory as shown in Figure 7, the values given, however, having been interpolated from these curves for the actual cement content given in column 4 The densities obtained by compacting the final mixture in the standard cylinders are given in columns 6, 7, and 8, being the maximum and minimum values obtained at any station in each section and the average for the whole section Columns 9, 10, and 11 give similar figures for samples taken from the road surface after compaction In the writer's opinion the figures indicate that the preliminary laboratory tests on random samples are not adequate for field control although the comparison is fairly good in some cases The difficulty is, however, in obtaining representative samples rather than in the technique of the control tests or method of design

The samples compacted in the field agree much better with densities in the road and indicate that a rather close control may be obtained in this way. In one case, Section D, the individual maximum and minimum value shows much too wide a range but this was picked up in both the control test and final density in the road This indicates a radical change in soil type which does not fit the classification used for that particular

TABLE 5

DENSITY OF FIELD MIXTURE

Section	Station Numbers	Laboratory Sample Number	Cement Content Per Cent	Dry Density of Field Mixture						
				Laboratory Test*	Lb per cu ft —Compacted					
			$\frac{c}{s+c}$		Compacted in Cylinder			Sample from Road		
					Max	Min	Ave	Max	Min	Ave
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
A	9197 to 9188	10	5 50	130 7	123 5	118 0	121 2	127 7	122 0	123 9
B	to 9177	10-4	6 74	123 7	124 5	118 8	122 1	128 8	110 0	120 6
C	to 9166	5	6 68	121 5	126 2	121 0	122 8	—	—	—
D	to 9151	3	6 80	112 5	118 5	107 0	115 0	123 7	104 0	115 6
E	to 9146	4	6 92	117 9	121 5	116 0	118 8	119 0	119 0	119 0
F	to 9124	9	—	—	—	—	—	—	—	—
G	to 9108	3	9 00	113 6	112 9	111 0	112 2	120 7	105 8	115 3
15% Clay Added	9115 to 9108	4	6 84	117 8	115 5	114 3	115 1	112 9	110 8	111 6

* Interpolated from laboratory curves

section as a whole, again a question of representative sampling

There are several other observations which deserve comment before completing the discussion During construction some difficulty in stabilizing particular sections appeared to be due to high organic content or acidity Values of pH were determined for the soil in the various sections with ordinary indicator solutions According to these determinations the pH varied from 5 6 for some of the sands to 8 8 for the high lime content clay in Section F Most of the soils were slightly acid and the mixing water taken from small streams adjacent to the work was also questionable Tests conducted by the Portland Cement Association indicated a substantial reduction in compressive strength when using this mixing water and for the soil in question Further tests indicated that the addition of clay with a high lime content corrected the sandy soils Whether this improvement was due to supplying additional soil fines which were needed or to correcting the acidity was not clearly determined While the data are inconclusive, there is definite indication that hydrogen ion concentration or acidity is a factor which requires study in connection with soil stabilization in this particular region of highly podzolized soils

Mention should be made of one construction deficiency which, in the writer's opinion, was quite harmful to the finished surface Final rolling was done with an ordinary steam roller It appeared that those wheels which furnished traction caused horizontal displacement on the top inch or so of the mixture resulting immediately in characteristic cracking or in the formation of a plane of weakness which later caused flaking or breaking away of the top surface It appears that compaction of the mixture should be done with dead-weight rolling equipment which does not furnish traction or introduce horizontal shearing forces

Since completion of the project the road has been subjected to one year of weathering with practically no traffic This section of the Shore Line Highway has not been opened and only occasional vehicles going to isolated lake shore points use it Several inspections have been made and observation will be continued The condition of the road is variable, some sections being in satisfactory condition while others show signs of excessive scaling and disintegration. As yet there has been no attempt to correlate these conditions with the analysis given in this report but this will be done on subsequent observations

CONCLUSION

The experience on the Cheboygan cement stabilization project indicates some rather definite relations based on void characteristics of the soil which may be applied to the design of soil-cement mixtures The cement-voids ratio appears to be a controlling factor in producing a durable stabilized mixture There is need for a considerable amount of additional research in order to demonstrate more conclusively the fundamental relations involved and to improve control procedure under actual construction conditions Studies must be made of the physical chemistry of soils to determine the effect of chemical composition including such factors as hydrogen ion concentration

While a thorough investigation of soils to be stabilized should be made preliminary to actual construction, it appears to the writer that the present durability tests can scarcely be considered as feasible on regular construction projects and should be replaced as soon as possible by much shorter routine tests. Durability tests as used on this project should be regarded as research procedures and eliminated as soon as they have served their purpose and other reliable criteria are available The preliminary laboratory study of moisture-density relations requires much less time and might be supplemented by a compression test or something similar as routine procedure. In addition, it appears that the difficulty of representative sampling necessitates control of compaction by field control tests conducted in the field in conjunction with each day's work In this case the preliminary laboratory tests lose much of their value as control media and are useful only in preliminary design

While it is perhaps too early to eliminate the more elaborate laboratory investigations now being attempted, it appears that there is sufficient evidence to outline the following tentative procedure which gives promise of being adequate for field control

Preliminary to Construction

1 Mapping of soil series by preliminary survey
2 Classification of soils by correlation of soil survey and grading operations
3 Mechanical analysis of samples taken from finished grade at frequent intervals to supplement classification made from the soil survey
4 Preliminary determination of void characteristics of representative soils by moisture-density tests
5 Design of the soil-cement mixture by the cement-voids ratio, proportioning soil and cement by absolute volumes
6 Molding of cylinders for compressive strength tests or for durability tests as long as the latter are needed

During Construction

1 Tests on raw soil, measurement of moisture content and loose volume measurement of scarified soil to control depth of scarification
2 Tests on final soil-cement mixture, moisture determinations to control moisture content, compaction test of final mixture to check proportions and mixing, and for a control of compaction in the road Specimens should be preserved for compression test

In connection with the procedure preliminary to construction it may be pointed out that items 4, 5, and 6 may all be performed in the field if the design of the mixture could be standardized, as for example at a cement-voids ratio of 15 per cent Determination of the total voids could be based on the moisture-density relations for the raw soil, a correction made for estimated bulking, and the cement content fully determined When sufficient data are available to establish a relation, perhaps between compressive strength and durability, the field cylinders could be cured in the field and sent to the laboratory for test The control procedure in soil-cement stabilization would then correspond quite closely to the present procedure in controlling operations in concrete construction

SOIL-CEMENT STABILIZATION IN MISSOURI

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The progress report on laboratory work with soil-cement mixtures published in May 1936 by the Portland Cement Association included the results of treating some typical Missouri clay soils These results encouraged the Department to test the practicability of such treatment in certain field test sections which resulted both in demonstrating a place for such a road type and in developing improved construction procedure

Test sections consisted of worn out gravel roads which were programmed for improvement consisting of base construc-