PAVEMENT PERFORMANCE RELATED TO SOIL TEXTURE AND COMPACTION

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SYNOPSIS

This paper reports one of the researches conducted by the Highway Research Laboratories of Purdue University cooperating with the State Highway Commission of Indiana. The correlation of pavement performance with soil texture is shown by performance surveys, and the need for increased use of semi-granular and granular materials for embankments, subgrades, and base courses is indicated. The importance of obtaining compaction is emphasized, particularly where semi-granular materials are employed.

Performance surveys of flexible pavements made during adverse weather conditions indicate wide variation in performance which can be directly attributed to the variations in soil textures and differential pavement thicknesses. Many miles of secondary pavements with a total thickness of 6 in. or even less and located on semi-granular soils were found to be in excellent condition. In contrast, many miles of pavement 12 in. or more thick were found inadequate when located on silty-clay soil.

Subsequent performance surveys revealed many rigid pavements 20 yr. or more old, many of which were of thicknesses less than the conventional 9-7-9 in., all performing relatively well when located on granular or semi-granular soils. In contrast, there are relatively new pavements less than 10 yr. old and of conventional thicknesses performing unsatisfactorily when located on plastic, silty-clay soils.

These observations stress the importance of more extensive use of granular materials for embankments, subgrades, and bases. Further abstract analyses are used to illustrate the importance of adequate compaction, and to suggest the possibility that the fine portion of soil-aggregate combinations may be critical unless compaction is far in excess of that normally obtained in modern construction.

The ultimate objective of all analyses of soils and other materials relative to highway engineering is the application of ensuing data to the highways themselves. Thus, studies of highway performance are logical means for evaluating the results of these analyses—both theoretical and applied—and their incorporation in practice. Aside from the large number of variables which cannot be isolated nor distinctly correlated, the field serves as a good proving ground and as an indicator of factors which should be the object of further research. It is with this viewpoint that the Joint Highway Research Project has made extensive performance surveys of Indiana highways during the past few years, one of the results being a prominent indication of relationships between pavement performance and soil texture.

In any study of these relationships, due regard must be given to the differences in rigid and flexible pavements, the main factors affecting the performance of each, and the conditions favoring correlation with a minimum of observations. For rigid pavements there are four such conditions as follows:

1. Extreme variations in soil texture within relatively short distances.
2. Some adverse climatic conditions, particularly high precipitation.
3. Traffic loads as great as or in excess of those for which the pavement was designed.
4. Reasonable differences in the ages of the pavements being observed.

Contrary to appearances, these requirements do not vitiate results obtained from surveys of many miles of pavement where conditions are not variable or extreme; they merely emphasize the fact that without these conditions the influencing variables cannot be consistently evaluated with any degree of certainty.

Because flexible pavements have some characteristics unlike those of rigid surfaces, the factors conducive to profitable results from surveys of non-rigid surfaces are not the same as those listed—particularly with reference to traffic and age. Here the pavements are more susceptible to damage by climatic influences, e.g., the spring break-up, even under light loads and at early ages. Hence, the influence of soil texture on pavement performance can be determined on the basis of observations of hundreds or even thousands of miles of pavements and at the same time the wide extremes in total base and surface thickness existing in these roads, on a state system such as exists in Indiana, become an asset, in place of another cumbersome variable: In the end, moderately accurate standards of total pavement and base thickness can be established for each soil area. With these considerations in mind it can be seen that the most favorable period for obtaining soil texture-performance information on flexible pavements is one in which a relatively high percentage of the total mileage is in a failing or near failing condition—a period when accelerated destruction predominates, as it were. It is generally known that such a period exists, particularly in the north-central states, in the spring of the year; recent observations indicate that the severity of the spring break-up varies from year to year, the most damaging one following a fall or early winter with precipitation possibly above normal followed by a winter with temperatures below normal. Such a season in Indiana was encountered in the spring of 1943. The flexible pavement data used in this presentation were obtained from the surveys made during this period.

Surveys of both classes of pavements in Indiana were made by car, but the techniques of obtaining and compiling information were slightly dissimilar. Most of the data concerning paving materials, thicknesses, dates of construction, subgrade treatments, and like features for rigid pavements were obtained from construction records so that only the actual performance characteristics were determined in the field. On the other hand, information from records of construction of flexible pavements was supplemented by some determinations of base thicknesses in failed and unfailed sections on the highways. In both cases the major soil areas were outlined in accordance with a previous state-wide soil survey (1)[1] thereby making verification in the field necessary only in locations where the soil textures were doubtful.

The interpretation of data from the several sources may be diverse depending upon the relationships being investigated. As a result of the abundant information obtained directly or indirectly from the Indiana surveys, several relationships have been established and reported (2) (4) (5) in various forms.

To correlate performance with soil texture, the soils of the State were tentatively separated into seven general groups since conditions limited the correlation to that of major features rather than specific differences such as soils of the depressions as opposed to those on gently sloping ground. The soil groups and their corresponding predominant textures were:

1. Granular materials in depth—sands and gravels of the terraces, kames, eskers, outwash plains, dunes, beaches, etc.
2. Sands of shallow depth underlain by till—sands on silty clays (predominantly).
3. Loess—windblown silt and fine sand.
4. Wisconsin till—heterogenous silts and clays with pebbles in the parent material.
5. Illinois drift—silty materials in the upper horizons underlain by parent material similar to that of the Wisconsin till.
6. Residual soils—mainly silts and clays derived from limestones, shales, and sandstones.
7. Lacustrine soils—silts and clays.

Subsequent and more detailed analysis of these factors, if such prove to be desirable, will logically require further division of these groups.

Indiana contains rather extensive deposits of sands and considerable data were compiled covering the performance of flexible pavements on these and other granular materials. A list of pavements, located on sand subgrades, and representing approximately 60 miles of roads, was compiled, all of which showed excellent performance. This list was by no means complete, but those roads included in the tabulation were representative of flexible pavements on sand, the thickness of which possibly did not average over 8 in.

[1] Numbers in parentheses refer to the list of references at the end of the paper.

A similar tabulation of flexible pavements located on gravel and gravel-like materials was compiled. The total length of these roads did not exceed 50 miles, yet this figure in combination with the 60 miles previously mentioned represents a total of 110 miles of relatively thin flexible pavements located on granular or semi-granular material, all showing excellent performance. Figure 1 illustrates the condition of a flexible pavement on a granular soil during the 1943 spring break-up.

Figure 1. A flexible pavement on granular soil undamaged during the 1943 spring break-up.

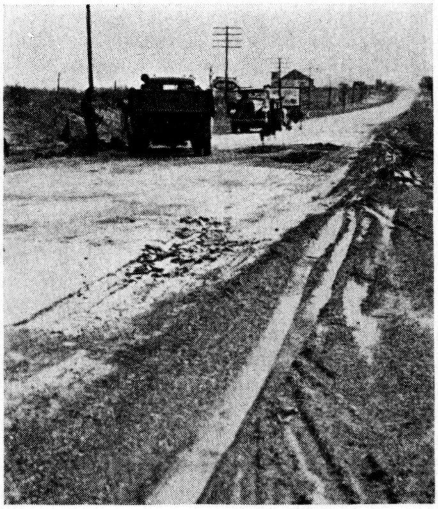

Figure 2. A damaged rigid pavement in a cut section where the subgrade was sand underlain by till at a shallow depth.

The importance of shallow sands on till and their relation to the performance of both flexible and rigid pavements had not been properly evaluated previous to the 1943 survey. These soils, found extensively within the glacial boundary in the United States and Canada, exist in parts of eight Indiana counties surrounding extinct Lake Kankakee as transition zones between the old lakebed sands in depth and the outlying silty-clay till. Despite the fact that granular materials prevail to a depth of 1 to 3 ft.—in effect a large-scale insulation course without drainage—secondary roads of this area as well as most primary roads were in distress. The significance of this combination of circumstances cannot be overemphasized. Figure 2 shows the extreme distress commonly found on both flexible and rigid pavements in areas of shallow sand on till.

The extent of windblown silts in Indiana is not great, nor are there many pavements in this region to serve as objects of performance surveys. Nevertheless, observations indicated that neither flexible nor rigid pavements on this soil were severely damaged. It would appear from the data obtained and from other experiences that windblown silts are problem soils only in respect to erosion, and construction operations under adverse moisture conditions.

It was necessary to subdivide the Wisconsin till soils into those of rolling topography in contrast to the situations of relatively flat areas. The performance of pavements in the rolling areas was, on a percentage basis, exceptionally good, the distress being localized such that failures occurred predominantely in cut sections. The Wisconsin till is relatively young and its profile has not developed to any great depth; adverse water conditions are encountered in almost any degree of cut. Figure 3 shows a flexible pavement in distress in one such cut section. The Wisconsin till of flat topography is by far the most extensive soil area in the state. Consequently, this extent must be considered in evaluating the fact that over 300 miles of pavements on these silty clays were in distress during the break-up in the spring of 1943. Figure 4 is a typical example of the type of failure which occurred on these soils. Of special significance is the fact that pavements in cuts only a few inches in depth were particularly susceptible to failure.

As in the case of the Wisconsin till, the Illinoian drift was divided into areas of rolling and flat topography. This drift is much older than the Wisconsin and the resulting soil profile, of course, is weathered much more deeply. This weathering process developed a profile which is exceedingly silty in the surface horizons but often having a relatively impervious clay-pan-like development subjacent. The soils on level topography, of course, have the deeper profiles. The importance of this profile development is indicated in the number of pavements found distressed in shallow cuts and the contrasting good performance of pavements in deep cuts or in locations where no cuts were made. Here the presence of the impervious horizon was strikingly apparent. Excepting the many short sections of break-up in shallow cuts, the performance of pavements in the rolling Illinoian drift was satisfactory. In contrast, approximately 70 miles of secondary pavements were in a state of failure, in level Illinoian drift soil areas. Figure 5 is an example of a failure on a road underlain by this soil.

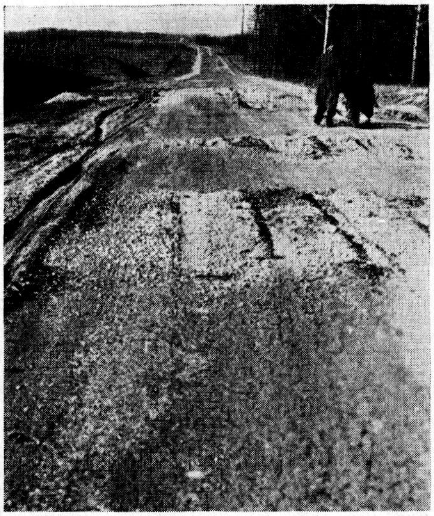

Figure 3. View showing serious break-up of a flexible pavement in a cut through Wisconsin drift.

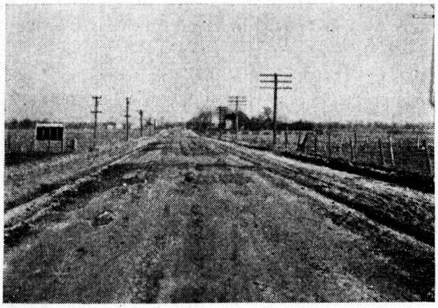

Figure 4. Extreme distress of a flexible pavement on level Wisconsin till

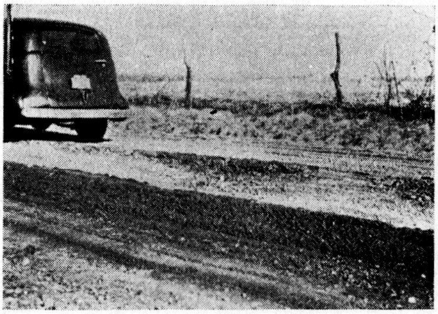

Figure 5. Failed pavement on Illinoian drift—flat topography

Figure 6. A localized failure typical of those occurring on flexible pavements in the residual soil areas.

The performance of flexible pavements on residual soil is somewhat difficult to evaluate in Indiana for a number of reasons. These soils are found in the southern section of the state; the area is not large nor is it densely populated. It follows that traffic would be less here than in the more populous sections. Also, the bedrocks of the area vary within relatively short distances so that evaluation on a large area basis is difficult. With these qualifications it is appropriate to point out that relatively few roads and only short sections of these roads were in distress during the spring break-up of 1943. The highway pictured in Figure 6 illustrates the "spotty" failures of a flexible pavement located on a residual soil.

Lacustrine soils in Indiana occur mainly in two rather distinct locations in the northern part of the State. These locations mark the beds of extinct glacial lakes once extensions of present Lakes Michigan and Erie. Neither is extensive, but both are important in that population and industry are concentrated nearby resulting in highway traffic which is heavy in volume and weight. This is particularly true of the situation near Chicago. Because of these factors the highways are almost wholly primary, and the scarcity of secondary roads precludes reliable analyses of pavements of this class. On the other hand, the Chicago region with its many miles of rigid pavements having various ages and construction features in combination with severe climatic and traffic influences is nearly ideal for the study of performance—particularly in those areas where lake-bed soils alternate in relatively short distances with beach sands and dunes.

United States highways 12, 20, 6, 30 and 41 are among those available for study in this region. With few exceptions, all pavements on these roads performed entirely satisfactorily when located on granular materials, the exceptions being localized failures where the pavement was placed on sand over till at shallow depths and some short sections constructed with unsatisfactory aggregates. In contrast, a majority of the pavements on these roads constructed in areas of plastic silty clays, whether of lacustrine or drift origin, performed poorly to unsatisfactorily.

One excellent illustration of the differential in performance is U. S. 30. Between U. S. 41 and the Illinois state line, U. S. 30 is a four-lane pavement of 10-in. uniform thickness, constructed in 1923. This 1-mi. section is located on sand, and with the exception of some design defects, is, as shown in Figure 7, in excellent condition today. A few miles to the east is a section of U. S. 30 constructed in 1937 and having a 9–7–9-in. section but located on a plastic silty clay. Here the performance was especially poor. See Figure 8 The superior qualities of granular subgrades

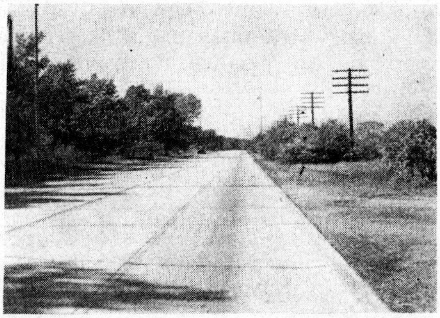

Figure 7. View of U. S. Highway No. 30 located on sand. This pavement of ten inch uniform thickness was constructed in 1923.

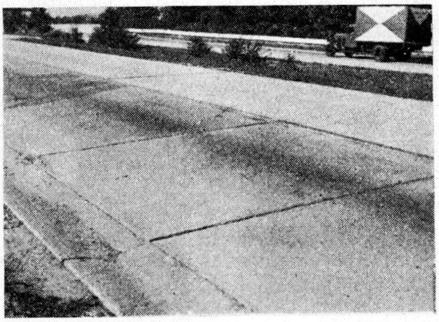

Figure 8. Slab settlements on pavement constructed in 1937 and located on plastic Wisconsin till.

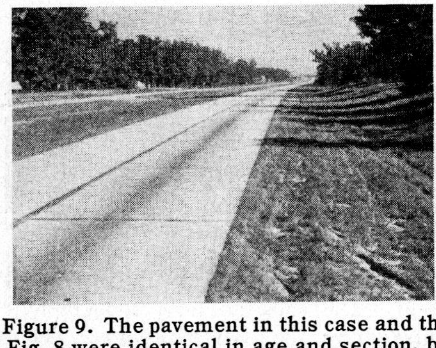

Figure 9. The pavement in this case and that of Fig. 8 were identical in age and section, but different in that this pavement had a sand insulation course.

are illustrated by comparison of Figure 8 and Figure 9, the latter showing a location on the same road where sand insulation was placed beneath the pavement and above the plastic soil.

Observations of U. S. 41 confirmed those obtained on U. S. 30. One section of the former road was built in 1927 with a 9–7–9-in. section and is located in an area of level sand. See Figure 10. In contrast, the performance of another part of this road built under the same contract but involving moderately deep cuts through silty clays is represented by conditions shown in Figure 11. Probably the latter section will be rebuilt in the near future, while the former section will without doubt be satisfactory for many years to come. Similarly, a four-lane pavement (U. S. 20) constructed in 1924 has performed with excellence, while the same highway has been severely distressed in adjacent moraines of silty clay Wisconsin till. Another section of the same road built in 1931 and underlain by lacustrine and morainic soils, has been reconstructed because of the excessive pumping that resulted from heavy traffic.

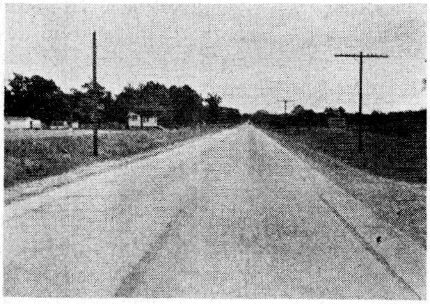

Figure 10. A section of U. S. Highway No. 41 located on sand (constructed in 1927).

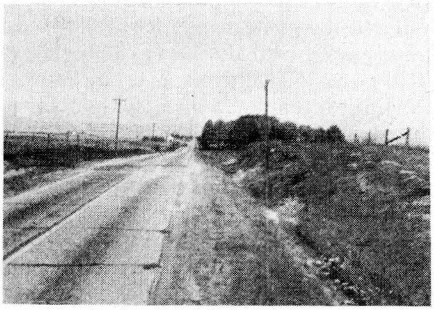

Figure 11. A section of U. S. Highway No. 41 located on silty clay (age and design the same as those of the pavement shown in Fig. 10).

To determine further the performance of pavements on sands as opposed to adjacent sections on plastic lacustrine soils, U. S. 12 and U. S. 6 in Porter and Lake Counties served as excellent sources of information. The former road was constructed in 1923 with a 7–8–7-in. section; yet, regardless of uniformity in pavement thickness and age, the conditions of the pavement on sand (Fig. 12) and in the lacustrine area (Fig. 13) are clearly different. Similar observations were made on U. S. 24 in northeastern Indiana where the subgrade varied from lacustrine clays to sand of the beaches formed by the lake during its existence.

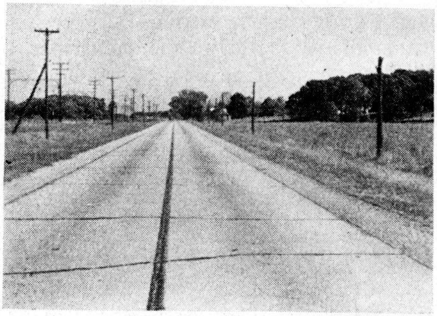

Figure 12. View showing the performance of U. S. Highway No. 12 constructed on sand in 1923.

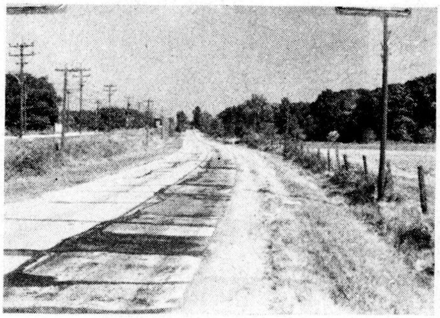

Figure 13. This pavement on U. S. Highway No. 12 is located on lacustrine soil but has the same age and design features as the pavement in Fig. 12.

Previous examples have been directed toward situations where the traffic was exceptionally severe. As a matter of course, there were several pavements traversing the different soil areas considered but not subjected to heavy traffic, and in these cases performance was almost invariably good. Such a case, typified by S. R. 53 constructed in 1930 and having a 9–7–9-in. section, is illustrated by Figure 14.

The information obtained from these surveys in some cases merely verifies reasonable estimates of the relative importance of some soils and their effects on pavement performance. Still, other findings contrary to preconceived notions are outstanding and warrant serious consideration in future design. Soil maps prepared for various purposes serve as valuable aids (1) (3) in such analyses.

The data concerning rigid pavements show that about 85 per cent of the total mileage—most of which is located on silty clay soils but with only moderate amounts of heavy traffic—was performing satisfactorily. Approximately 10 per cent of the total mileage was showing some signs of distress for causes other than excessive traffic and poor soils. Five per cent of the total mileage was in serious distress as a result of the combination of heavily loaded vehicles on pavements located on plastic silty clay soils. Sections of pavements adjacent to failing areas were frequently found to be performing entirely satisfactorily when located on granular materials. This was true despite the fact that some good pavements were more than 20 yr. old, while adjacent failed pavements located in poor soil areas were frequently less than 10 yr. of age. These data show strikingly that the variations in age and pavement design for rigid pavements were less important than soil texture for those roads located in soil areas of varying texture and subjected to a large number of heavy loads.

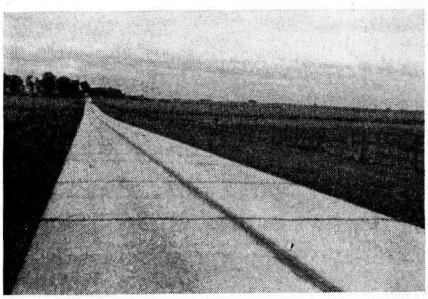

Figure 14. View of S. R. 53 in northwestern Indiana

With regard to flexible pavements, the observations pertaining to thickness; the fact that underlying granular soils are not invariable guarantees of good performance, e.g. shallow sand on till; and the prevalence of excessive amounts of free water in the bases of pavements that failed are results the significance of which cannot be denied. The last of these three observations indicates that adequate compaction and selection of materials is correlative with the importance of texture of the soils in subgrades and bases.

During the past several years much work has been devoted to compaction with marked success, and the reports of data from tests and field applications have been numerous to the extent of becoming repetitive. Fortunately for the researcher, the essence of these developments is now in the process of publication as a wartime road problems bulletin by the Highway Research Board Committee on the Compaction of Embankments and Subgrades (6) and as a Road Paper by the Institution of Civil Engineers (7) in England. Notwithstanding these copious data, some phenomena pertaining to the subject have remained unexplained, which in lieu of research and concrete solutions can be analyzed only in the abstract.

For example, little attention has been given to the possible distribution of moisture in soil-aggregate combinations and the influence of this moisture on the cohesive portion of the mix. The data in Table 1 illustrate conditions theoretically existant in saturated materials having various proportions of granular and cohesive[2] constituents. Results of laboratory tests for compaction (Proctor), grain size distribution, and limits of consistency are the averages of those actually determined for several samples having proportions of soil and aggregate within the ranges cited, while the condition of saturation, the percentage of absorption (5 per cent) for the aggregates, and the distribution of moisture with respect to the two portions of the material are assumed. Also, for the purpose of computation, an average value of 2.67 has been chosen as representative of the specific gravity of the solid matter in all cases.

Significant among these figures is the relationship between the computed moisture con-

[2] Defined here as soil passing the No. 40 sieve (0.42 mm.) because of the practice of determining limits of consistency for that fraction of a sample (8) (9).

tent of the soil in each instance and the actual moisture contents representing the liquid limit and plastic limit of that soil. Values for this comparison, demonstrated by the material having 20 per cent passing the No. 40 sieve, are obtained as follows:

Unit Wt. (Dry) at "100 per cent of maximum compaction" = 130.0 lb. per cu. ft.

All calculations based on 1 cu. ft. of compacted material

Total Material

$$\text{Volume of solid matter} = \frac{130.0}{2.67 \times 62.4} = 0.787 \text{ cu. ft.}$$

$$\text{Volume of voids} = \frac{0.213}{1.000}$$

$$\text{Moisture content (saturated)} = \frac{0.213 \times 62.4}{130.0} \times 100 = 10.2 \text{ per cent}$$

Aggregate

$$\text{Water absorbed} = 0.05\,(130.0 \times 0.80) = 5.2 \text{ lb.}$$

Soil

$$\text{Moisture content} = \frac{(0.213 \times 62.4) - 5.2}{(130.0 \times 0.20)} \times 100 = 31.1 \text{ per cent}$$

LL = 18.0 per cent P.L. = 12.0 per cent

By this manner of comparison, the tabulated figures show that even when compaction is 105 per cent of "maximum," in no case is the moisture content of the soil lower than its plastic limit, and in one instance the saturated moisture content of the soil is greater than the liquid limit despite the high degree of compaction.

The comparative results of these determinations are considerably different from those obtained by comparison between the saturated moisture content of the total soil-aggregate material and the limits of consistency of the soil. Both accentuate the importance of intensive compaction, but the latter may be inadequate through its failure to denote the possibility of critical moisture contents in the soil despite tendencies to mini-

TABLE 1

SUMMARY OF DATA ILLUSTRATING THEORETICAL MOISTURE CONDITIONS IN SATURATED SOIL-AGGREGATE MIXES

Total Material (Soil-Aggregate)						Agg.-Ret. on No. 40 Sieve		Soil—Passing No. 40 Sieve				
Composition		Percentage of Max. Compaction (Proctor)[a]	Unit Wt. (Dry) lb. per cu.ft.	Saturated		Dry Wt. per cu.ft. of Total Material (lb.)	Wt. of Water Absorbed[b] (lb.)	Dry Wt. per cu.ft. of Total Material (lb.)	Wt. of Water Not Absorbed (lb.)	M.C. %	L.L.	P.L.
Ret. No. 40 Sieve	Pass. No. 40 Sieve			Wt. of Water per cu.ft. of Material (lb.)	M.C. %							
%	%											
20	80	80	76.0	33.8	44.5	15.2	0.8	.60.8	33.0	54.3	44	26
		90	85.5	30.2	35.3	17.1	0.9	68.4	29.3	42.9		
		100	95.0	26.6	28.0	19.0	1.0	76.0	25.6	33.7		
		105	99.8	24.8	24.9	19.9	1.0	79.9	23.8	29.8		
40	60	80	92.0	27.7	30.1	36.8	1.8	55.2	25.9	47.0	28	17
		90	103.5	23.3	22.5	41.4	2.1	62.1	21.2	34.2		
		100	115.0	19.0	16.5	46.0	2.3	69.0	16.7	24.2		
		105	120.8	16.9	14.0	48.3	2.4	72.5	14.5	20.0		
50	50	80	96.0	26.2	27.3	48.0	2.4	48.0	23.8	49.7	26	15
		90	108.0	21.6	20.0	54.0	2.7	54.0	18.9	35.0		
		100	120.0	17.1	14.3	60.0	3.0	60.0	14.1	23.5		
		105	126.0	14.9	11.8	63.0	3.2	63.0	11.7	18.6		
60	40	80	100.0	24.6	24.6	60.0	3.0	40.0	21.6	54.0	21	14
		90	112.5	20.0	17.8	67.5	3.4	45.0	16.6	36.9		
		100	125.0	15.2	12.2	75.0	3.8	50.0	11.4	22.8		
		105	131.2	12.9	9.8	78.7	3.9	52.5	9.0	17.1		
80	20	80	104.0	23.1	22.2	83.2	4.2	20.8	18.9	90.8	18	12
		90	117.0	18.2	15.5	93.6	4.7	23.4	13.5	57.7		
		100	130.0	13.3	10.2	104.0	5.2	26.0	8.1	31.1		
		105	136.5	10.9	8.0	109.2	5.5	27.3	5.4	19.8		

[a] Does not necessarily represent maximum field compaction because material retained on No. 4 sieve eliminated in laboratory compaction test.

[b] Assumed absorption of 5 per cent.

mize the percentage of fine material and to increase the degree of compaction.

Laboratory tests for the stability of soils and soil-aggregate combinations often appear to be discrepant in that the results of tests under different moisture conditions are not consistent with those reasonably anticipated. As expected, the granular mix has the better strength characteristics—stress and deformation—when the materials are tested under conditions of optimum moisture and density as determined by respective compaction tests. Again as expected, the cohesion of the fine soil predominates if these same materials are permitted to dry previous to testing for

Figure 15. A flexible pavement on a soil-aggregate base damaged during the 1943 spring break-up.

strength, and the soil has the greater strength. But, if both are saturated previous to the strength tests, the characteristics of the granular mix are no better than and are often inferior to those of the soil—a material always considered particularly vulnerable to reduction in strength with increasing moisture content. To those who have been puzzled by laboratory results of this nature, the information in Table 1 may be particularly gratifying.

Unconditional application of these concepts to field problems would, of course, be fallacious. Even granting that the distribution of moisture in a soil-aggregate mix is in accordance with the assumption, laboratory methods (10) and good judgment show that in the majority of situations the granular mixes are too permeable to retain water in quantities sufficient for saturation unless the supply of water is continuous. Yet, one questions the adequacy of drainage in locations where the granular subgrade is of "trench construction," or in any situation where thawing during the spring occurs from the surface downward while frozen soil adjacent to the thawing subgrade prevents the escape of water in any direction. Here the conditions conducive to break-up may be momentary, but the damage, as in the case illustrated by Figure 15, is permanent. Numerous observations in performance surveys tend to substantiate this interpretation where almost instantaneous destruction of pavements has occurred.

While abstract analyses of problems of this nature cannot be conclusive, they offer fruitful opportunities for research, serious thinking, and profitable discussion. Thus this hypothesis is offered with the possibility that it will receive all three from those who are concerned with pavements and the factors influencing their performance.

BIBLIOGRAPHY

1. Belcher, D. J., Gregg, L. E., and Woods, K. B., "The Formation, Distribution, and Engineering Characteristics of Soils," Purdue University Engineering Experiment Station Bulletin No. 87, January (1943).
2. Woods, K. B. and Shelburne, T. E., "Pumping of Rigid Pavements in Indiana," *Proceedings*, Highway Research Board, Vol. 23, p. 301 (1943).
3. Janda, H. F., "Longitudinal Cracking of Concrete Pavements on State Highway 13 in Clark and Taylor Counties, Wisconsin," *Proceedings*, Highway Research Board, Vol. 15, p. 157 (1935).
4. Shelburne, T. E. and Woods, K. B., "1943 Survey of Secondary Roads (Spring Break-Up)," Report to the Advisory Board of the Joint Highway Research Project, Purdue University, April, 1943 (Unpublished).
5. Shelburne, T. E. and Woods, K. B., "A Reconnaissance of Portland Cement Concrete Pavements in Indiana," Report to the Advisory Board of the Joint Highway Research Project, Purdue University, October, 1944 (Unpublished).
6. Highway Research Board, "War Time Road Problems Bulletin on Compaction of Subgrades and Embankments," 1945.

7. Marwick, A. H. D., "The Basic Principles of Soil Compaction and Their Application," The institution of Civil Engineers, Road Engineering Division, Road Paper No. 16, London (1945).
8. American Society for Testing Materials, "Standard Method of Test for Plastic Limit and Plasticity Index of Soils," A.S.T.M. Designation D 424–39, Adopted, 1909.
9. American Association of State Highway Officials," Standard Methods of Determining the Liquid Limit of Soils," A.A.S.H.O. Designation: T89–42, and "Standard Methods of Determining the Plastic Limit of Soils," A.A.S.H.O. Designation: T90–42.
10. Gregg, L. E., "Suggested Method for Obtaining Saturated Samples of Cohesive Soil for Strength Tests," A.S.T.M. Procedures for Testing Soils, Part III, Suggested Methods, September, 1944.

DISCUSSION

MR. JEAN E. HITTLE, *Joint Highway Research Project, Purdue University*. After reading this paper on Pavement Performance Related to Soil Texture and Compaction, the writer feels than an extension of Table 1 of that paper might possibly further emphasize some of the objectionable moisture conditions that prevail in certain soil-aggregate combinations. For this purpose the two charts which follow were constructed to show the density and moisture relationships as well as volumetric quantities and other pertinent information.

Figure A, "Soil-Aggregate Relationships, considers soil-aggregate combinations of a totally saturated material having a specific gravity of 2.65. Here again, it was assumed that the aggregate or material retained on the No. 40 sieve absorbed only 5 per cent moisture. Figure B, "Soil Relationships," considers the more general relationships of a material having a specific gravity of 2.65. One of the unique features of these charts is the fact that all of the several relationships to be considered are clearly shown by means of a series of straight lines; moreover this graphic presentation gives a quick and complete conception of the interrelationship that exists among the variables of density, moisture, and composition.

In connection with the values shown on the charts, consider for instance a soil-aggregate combination having a dry density of 120 lb. per cu. ft. and 20 per cent finer than the No. 40 sieve. A quick reference to the chart shows the saturated moisture content of total material to be approximately 14 per cent. However, the moisture content of the material passing the No. 40 sieve is shown to be approximately 53 per cent. Then, momentarily consider the fine fraction of this soil-aggregate combination as an independent volume. Referring to Figure B the dry density shown for 53 per cent moisture and 100-per cent saturation is about 79 lb. per cu. ft. as compared with the dry density for the total material of 120 lb. per cu. ft.

This example further illustrates the high moisture contents that can exist in the fine fraction of a soil-aggregate combination; and as the authors have pointed out, this moisture content may in many instances be considerably in excess of the plastic limit or even the liquid limit of the soil fraction. To some this might possibly be construed as meaning that the limits of consistency indicate the lower limiting value of moisture content that can be tolerated in the material passing the No. 40 sieve. Actually, this is not the case; and in view of the authors' experience and the information contained in the bibliography which they have appended to their paper, they obviously did not intend to imply that there was a relation between the liquid and plastic limits and the tolerance of material finer than the No. 40, since such a procedure would not conform with conditions encountered in the field. Thus, the actual test data of the consistency limits serves largely as a basis of comparison with the saturated-moisture contents which are possible to exist in the soil fraction of a soil-aggregate combination.

In discussing the high moisture contents of the soil fraction in saturated soil-aggregate combinations the authors make the following statement: "Unconditional application of these concepts to field problems would, of course, be fallacious." One might pursue this thought further and consider some of the relations shown on Figure A with respect to practice encountered in the field and laboratory. As the authors have pointed out and as this chart also shows, the important variables that are involved are: (1) the moisture content of the material passing the No. 40 sieve; (2) the percentage of material finer than the No. 40 sieve; and (3) the dry density of the total material. A brief study of the interrelationship of these three variables as shown on the chart brings forth the following generalizations:

1. For a given dry density (above a saturation moisture content of 5 per cent) increases in the percentage finer than the No. 40 causes corresponding decreases in the saturation moisture content of that fraction.

2. For a given percentage finer than the No. 40, increases in the dry density of the total material causes corresponding decreases in the saturation moisture content of the fine fraction.

3. For a given saturation moisture content of the material finer than the No. 40, increases in the percentage finer than the No. 40 causes corresponding increases in the dry density of the total material.

If these three generalizations are studied collectively it becomes apparent that there are some implications which are contradictory to our past knowledge and practice. For instance, the first generalization tacitly implies that the higher percentages of fine material are desirable since the saturation moisture content of that material is lowered. This is theoretically true insofar as the saturation moisture contents of the soil fraction is concerned, however, if one pursues this implication further it is apparent that such a proposition is in direct contradiction with conditions encountered in both laboratory and field studies. The fallacy of the implication lies in the fact that a higher percentage of the fine material can only result in a lower dry density. This has been demonstrated repeatedly by laboratory and field methods and is also confirmed by the test data supplied

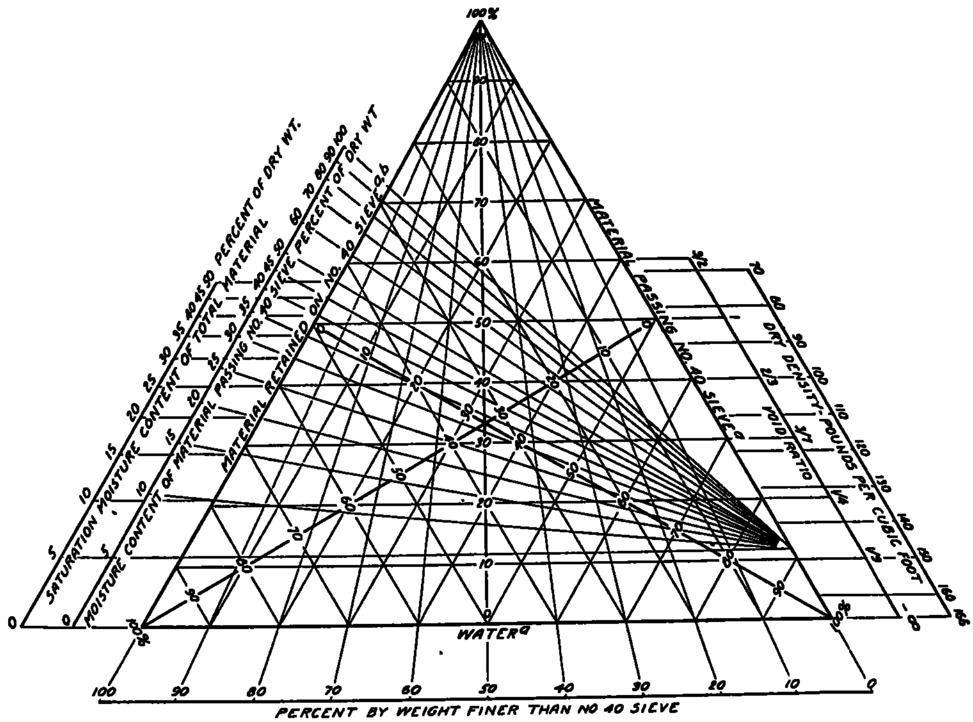

Figure A. Soil-Aggregate Relationships for 100 per cent Saturation, Specific Gravity = 2.65
[a] **Expressed as percentage of the total volume.**
[b] **Assumed absorption of 5 per cent.**

by the authors in Table 1 of their paper. Therefore, the first generalization is of little or no practical value to those concerned with soil-aggregate combinations.

The second generalization taken from the chart is in complete agreement with our present knowledge of soil-aggregate combinations since it is a special case of one of the fundamental concepts of compaction. Inasmuch as these concepts are universally accepted by engineers, a further discussion of them would only be repetitious. For these reasons this particular generalization is not a significant contribution within itself to the subject at hand; however, it does reemphasize the importance of density as a means of lowering the saturation moisture content of the soil fraction.

Of the three generalizations that have been considered, the third and last one is doubtless the most significant since it clearly indicates, qualitatively at least, some of the detrimental effects of the soil fraction in soil-aggregate combinations. In one sense, the second and third generalizations complement each other in that they both involve the all-important variable of density. In the second, the increase in density decreased the saturation moisture content of the soil fraction when a given composition was considered; in the third, increases of the soil fraction decreased the dry density when a given saturation moisture content of the soil-fraction was considered. Thus, on the basis of a maximum of dry density and a minimum of moisture in the soil fraction at saturation these two gen-

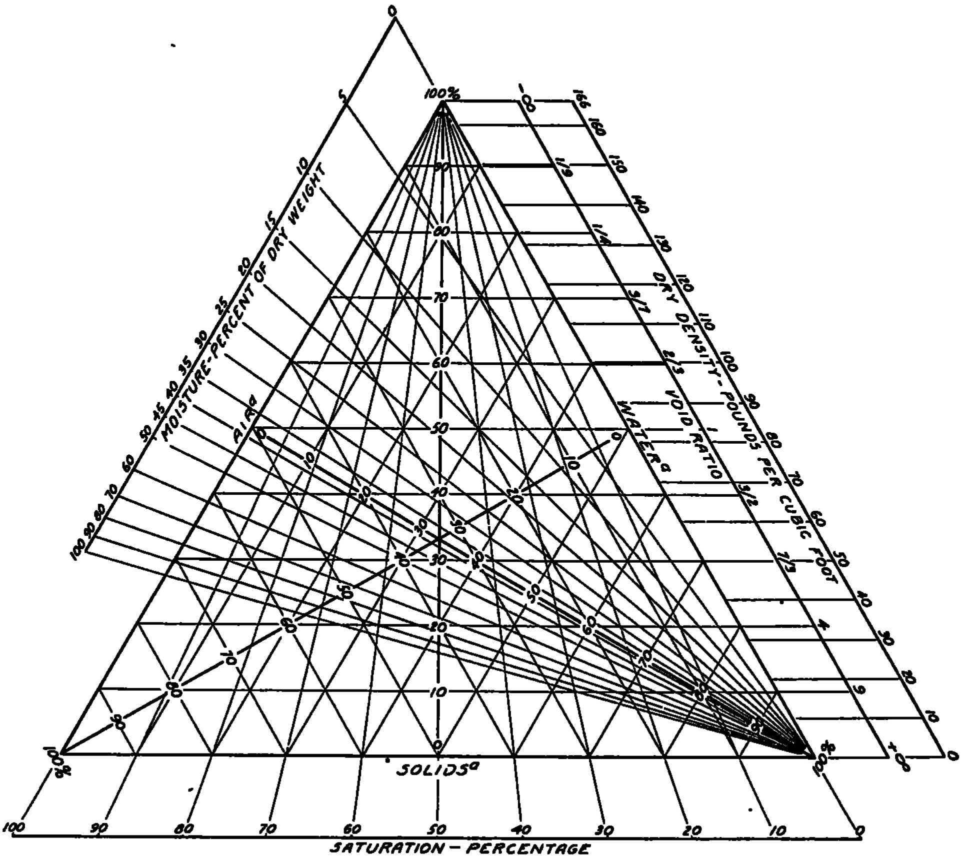

Figure B. Soil Relationships, Specific Gravity = 2.65.
[a] **Solids, water and air are expressed as percentages of the total volume.**

eralizations collectively point to the detriments of the soil fraction in soil-aggregate combinations. This is a matter that is highly significant when evaluating the engineering properties of soil-aggregate combinations.

One might legitimately question the validity of this reasoning on the grounds that the soil-aggregate relationship chart from which the generalizations were taken assume 100 per cent saturation, and that this is not necessarily compatible with the conditions encountered in the field. While it is true that the chart is theoretical in assuming complete saturation, it can be shown that the average degree of saturation at the optimum moisture content and maximum Proctor density is approximately 90 per cent. This applies to the complete range of texture and composition. Therefore, the chart might well have been constructed on the basis of probably 90 per cent saturation instead of 100 per cent. Although the quantitative values for such a chart would differ from those shown, the same general trends between the variables would still prevail.

The two charts (Figs. A, B) have been presented in the hope that they may be of assistance to the reader in interpreting the influence that the soil fraction has upon the density and moisture relationships of saturated soil-aggregate combinations. These charts could also be used as an aid in computation or as a correlation chart for test data.

Mr. George H. Beddoe, *The Asphalt Institute:* This paper utilizes performance survey data of Indiana roads in an effort to correlate pavement performance with an interesting hypothesis on the influence of moisture on the cohesive portion of soils composed of various proportions of granular and cohesive constituents. The performance data make a genuine contribution to correlation of pavement service with subgrade support. It is felt, however, that the analysis of the field data has not yet been conducted in such a way that significant conclusions can be drawn with respect to the theory presented. It is believed a correlation has been established between performance and unstable subgrade conditions which occurred predominantly in areas of fine-grained cohesive soil combinations. In this respect, I think certain recommendations advanced in the synopsis by the authors based upon their field studies should be discussed, particularly as to emphasis and the impression which is apt to be created by the conclusions stressed.

The first conclusion to which attention is directed is the statement, "The need for increased use of semi-granular and granular materials for embankments, subgrades, and base courses is indicated." The good performance of low cost pavements in granular soil areas has long been observed. The presence of a high percentage of granular materials in subgrades, and particularly in base courses, has not only been the goal of paving engineers but has been the most important single economic factor in the selection of pavement types. Furthermore, the observations made by the Purdue investigators showing that the presence of subgrade sands of shallow depth underlain by impervious cohesive soils results in pavement failures almost if not equal proportionately to those observed in pavements constructed directly upon cohesive soils, indicates that considerable modification is called for in the over-all statement quoted. It seems that the factor of drainage both during and subsequent to embankment, subgrade, base and surface course construction, is at least equivalent in significance to soil texture, and is probably of greater weight from an economical point of view. Since as a general rule the locations of road systems are influenced by concentrations of population and commerce and not by a choice of soil, it appears that a more logical conclusion from the field data would be a recommendation that a further study be made to determine the cause of a high proportion of failures in cuts and the relation of this to drainage, as well as a study of the construction methods and efficiency of inspection in use 10 to 20 years ago which resulted in the subgrade containing sufficient moisture and insufficient density to promote failed areas.

The authors emphasize the importance of obtaining good compaction, with which we all agree. However, why should not the next statement—"Performance surveys of flexible pavements made during adverse weather conditions indicate a wide variation in performance which can be directly attributed to the variations in soil textures and differential pavement thickness"—be written, "... which can be directly attributed to the effect of moisture in combination with variations of soil textures," so that emphasis would be placed upon the principal cause of failure? In other words, although soil texture, compaction, thickness of pavement and moisture are shown in the performance survey to influence failure, it appears that the conclusions concentrate upon recommendations to correct the first three deficiencies, in the expectation that the fourth factor, moisture, would in this way be taken care of.

It is the writer's contention that in a majority of the cases it is more economical to control moisture content during and after construction than to counteract its effect entirely by importation of granular materials and by increase of pavement thickness to the extent recommended in many instances.

This writer does not want to be misunderstood by having these remarks interpreted as a criticism of the field analysis or of the value of these data as a contribution to accumulated knowledge, without which it would be impossible to correlate empirical methods of design of flexible pavements with time-service. The paper is an excellent study of the relationship between soil texture and the percentage of failures in existing pavements, thickness and all other factors being equal.

The main question raised was one of emphasis upon conclusions drawn by the authors. We are always going to be faced with the necessity of constructing roads and airports in areas dominated by clay soils. No matter how much granular soil is imported as sub-base material before constructing the pavement, the cohesive impervious material will still be beneath the sand or gravel blanket. The findings presented in this paper, and observed by the writer in other areas such as Ontario and Michigan, that shallow sands overlying clays are not invariable guarantees of good performance indicate that porous granular sub-bases as much as 1 to 3 ft. deep may not be the answer to construction in clay areas. It therefore appears that rather than pointing to plastic soils as detrimental and to be avoided at great expense if necessary for subgrades and embankments, and substantiating this position by pointing to relative percentage failure of roads constructed on such soils, it might perhaps be better to emphasize the construction and drainage difficulties to be expected in such soil regions in contrast to the relatively simple task when all drainage is vertical.

Unquestionably when during construction support of the equipment by the soil is assumed to be the only moisture and density limitation, more danger of ultimate failure is present in cohesive soil areas. The results of these practices in the past are now being experienced. But this is not necessarily a criterion for modern construction on which such dangers are recognized and can be dealt with. What of the great areas of pavement of the same thickness and over the same critical soils which are carrying the same loads as areas which failed. Cannot this difference, to a great extent be attributed logically to weather encountered during construction, and to unsolved drainage conditions?

To illustrate briefly what is meant by precautionary measures in cohesive-soil-area-construction, the following requirements are well-known, but unfortunately, too infrequently practiced:

(1) Maintain an average grade line higher than a normally balanced cut and fill.
(2) Scarify and recompact all cut and no-cut-no-fill areas to standard subgrade density and moisture requirements.
(3) Maintain surface drainage at all times during construction to shed as much rainfall as possible.
(4) Exaggerate depth of drainage on the up-hill side of the road section with the main object of intercepting ground water in the form of seepage or springs.
(5) Remove all pockets of frost-heaving or "quick" soils to a depth below finish grade approximately 1½ times the depth of average annual frost penetration, and backfill with either impervious roadside soil typical of the average section, or with non-frost-heaving granular materials.
(6) When a stretch of clay subgrade has been brought to required density and maximum moisture content and approved by inspector for base or sub-base, follow up as soon as possible with a protective layer of impervious base material; under no circumstances allow a layer of porous granular base course material to accumulate rain water during construction, thereby changing the

moisture and probably the density condition of the underlying clay subgrade. Such a possibility makes very risky the use in rainy areas of any porous granular course directly on top of cohesive subgrades.

Some of these precepts for construction on clay soil areas are followed, to a considerable extent, in normal pavement construction in all areas, and thus would not be considered as items of extra time or expense. The remaining practices are not only relatively low in cost when compared to the importation of granular materials, but are often necessary even when select aggregates are brought in. Furthermore, it has been our experience that such precautionary and systematic procedures more than paid, as insurance against costly delays, set-backs, and reconstruction.

To support the contention that subgrades properly constructed of cohesive soils and properly drained will not progressively accumulate excessive moisture with time, reference is made to a report by Miles Kersten entitled[1] "Survey of Subgrade Moisture Conditions." He has shown in this report that, although moisture under existing pavements follows the same trend with respect to soil texture as that shown by Woods and Gregg, there is no preponderance of evidence to support the supposition that excessive moisture accumulated with time. It can be concluded from the portion of Kersten's report under "Variations of Subgrade Moisture Content with Amount of Annual Precipitation in Four States," and by later data comparing average subgrade moisture content under pavements in arid and semi-humid regions, in service for an average of 13 years, that the amount of moisture beneath impervious flexible pavements is a function of the rainfall zone rather than time-accumulation. If moisture were going to accumulate progressively with time, irrespective of the climatic zone, it should do so within 13 years. This points strongly to the conclusion that the greater rainfall in humid regions during construction, together with faulty drainage subsequent to the time the impervious surface was applied, are the dominating influences causing detrimental accumulations of moisture in pavement subgrades.

[1] This volume, page 497.